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Estimation of soft ground tool life in TBM tunnelling

Thesis for the degree of Philosophiae Doctor

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Abstract

Increased urbanisation constantly demands more infrastructure, often requiring the construction of tunnels and facilities underground. The complexity of Tunnel Boring Machine (TBM) function and the complicated nature of soft ground and soil working environments make the estimation of wear a challenging issue.

The following tests and procedures are included in the original contribution to this PhD study; 1) an overview and presentation of various laboratory methods designed to estimate and assess soil abrasivity in connection with soft ground TBM tunnelling, 2) the development of models, based on simplified laboratory tests, for the estimation of TBM tool life when excavating soil and soft ground, 3) the development of the Soft Ground Abrasion Tester (SGAT), designed to increase the validity of simplified estimation tools.

The simplified laboratory tests incorporate the Soil Abrasion Test (SAT™), quartz content measurements, and the geotechnical uniformity index C_u. Test results have been correlated with, and validated against, TBM tool life and performance data from 16 TBM projects. Laboratory test results obtained from the SAT™ provide a good estimation of soft ground excavation tool life. Furthermore, an empirical formula obtained by means of multiple regression analysis using SAT™ and C_u values as variables, and soft ground tool life as the dependent variable, has been derived, and provides a good estimation of soft ground excavation tool life. In addition, the validity of the formula is evaluated against an on-going European TBM tunnelling project.

The SGAT has been developed in order to study how variation in geotechnical parameters such as soil compaction and density, water content, groundwater pressure and soil conditioning additive's influence the abrasivity of soils. Furthermore, the SGAT provides opportunities to measure the influence of abrasive wear by varying TBM parameters such as thrust, rpm and torque. The main results obtained from the SGAT are that the moisture content of a soil sample, and thus its compactibility, influences soil abrasivity by as much as ±250%. There is a clear correlation between measured weight loss and torque requirement, and a reduction of torque by approximately 40% is achievable with proper soil conditioning. In addition, measured wear can be as low as 20% of that for an unconditioned sample.

Research results have been achieved mainly by using the following four approaches, 1) literature studies, 2) laboratory tests, 3) field research, and 4) discussions and experience sharing with individuals, users and experts in the tunnelling industry. These methods were chosen since they offer a variety of approaches to the complex problem of soil abrasivity in soft ground TBM tunnelling, and to avoid an exclusive focus on any single source such as ideal laboratory tests, published literature or field experience.

Preface and acknowledgements

This PhD study has provided an extraordinary opportunity to develop, systematise and publish hypotheses and results linked to soft ground TBM excavation tool wear. The problem formulation has been relevant, and the results of the study have been the subject of requests from project owners, contractors and TBM manufacturers. This has provided a source of extra motivation during the study.

The use of soft ground TBM tunnelling technology is not widespread in Norway, and research thus necessitated numerous field trips abroad to gather information. The field trips have provided much inspiration since contractors have communicated a great deal of information. The opportunity to experience new countries and cultures has also provided much personal motivation.

The collection of real TBM production data has been the most time-consuming activity. Field trips have also been a challenge for my small family. During the first year of the study, my wife and mother-in-law took care of my son Theodor. Having my mother-in-law living under the same roof in a 70m^2 apartment provided a perfect excuse for numerous getaways. I am very grateful to my lovely Senobia, my mother-in-law Leonarda, my son Theodor, and my parents. Without their support, the travelling and completion of the doctorate would have been very difficult.

All field data have been provided by helpful contractors, clients and TBM manufacturers such as Tim E. E. Becker (previously at Lemme Tiefbau Berlin, and now at Becker Engineering and Consultants), Impregillo S.p.A., Mannfred Köhler (öbb Austria), and Lutz Zur Linde (Herrenknecht). The results presented in this thesis would not have been achieved without feedback from the tunnelling industry.

The laboratory results and developments presented in this thesis and other papers would not have been achieved without the help of Filip Dahl (SINTEF Rock Engineering). Filip´s interest, assistance and feedback have provided me with much motivation during the four years of the doctorate study. The development of the new apparatus *Soft Ground Abrasion Tester* has been achieved by means of a collaboration between Torkjell Breivik (NTNU Department of Rock Engineering and Geology), and Lars Langmaack and Herbert Egli (BASF Construction Chemicals). The numerous frustrations experienced during this process have finally resulted in a useful outcome. For tribology explanations and guidance as well as discussions on laboratory set-ups, associate Professor Nuria Espallargas have been very helpful.

Combining field and laboratory research approaches has been an expensive process, and the financial support provided by the Norwegian Tunnel Society (NFF, www.tunnel.no) has been invaluable.

As regards the acquisition of field and laboratory data, several students have written their theses on relevant subjects taken from the PhD work. I am very grateful to Anders Palm (who obtained data and samples from a project in the Middle East), Wojtek Smolen and Marek Multan (who were following up an ongoing soft ground TBM project in Europe), and Ivar Sletta, Andreas Hauso, Ole Fredrik Brattberg and Leon Eide for their contributions during initial testing of the Soft Ground Abrasion Tester.

Jardar Lohne has made considerable contributions in terms of discussion and the structuring of published papers. Fellow PhD student Wolfgang Kampel has been a great source of information in relation to the interpretation of statistics and use of the SPSS software. Recently qualified PhD students Vegard Olsen and Yangkyun Kim have provided excellent advice on structuring the thesis and have helped in revealing inconsistencies in earlier drafts.

Last, but not least, I would like to show my appreciation to Professor Amund Bruland, who has supervised this work. Without his quick decisions and assistance in obtaining funds to finance field work, laboratory tests and other activities, there would be nothing to show for this work but desktop and literature studies.

Contents

1 Introduction

1.1 Background

The Norwegian University of Science and Technology (NTNU) has, together with SINTEF, established a long tradition in the testing of engineering rock properties as a basis for evaluating tunnelling performance.

The development of the NTNU estimation model for hard rock TBM performance and drill and blast (D&B) tunnelling performance has been active for several decades. The first model to address hard rock TBM tunnelling applications was published in 1976, and was followed by updates in 1986, 1993, 1994 and 1998 (Bruland 2000). NTNU has also developed estimation models for rock quarrying (Olsen 2009), and for drill and blast (D&B) tunnelling costs and capacity (Zare 2007).

The current hard rock drillability database, incorporating parameters such as Drilling Rate Index™, Bit Wear Index™ and Cutter Life Index™, contains data from more than 3000 unique rock samples from 50 countries (Dahl et al. 2012). The NTNU estimation model for hard rock TBM tunnelling performance, time and costs (Bruland 1998b) is currently being revised by PhD student F. Javier Macias as part of a project funded by the Research Council of Norway (NFR) and the industry-financed research project Future Advanced Steel Technology for Tunnelling (FAST-Tunn), in co-operation with NTNU and SINTEF.

In addition to development of the drillability indices, NTNU and SINTEF have conducted several hard rock abrasiveness measurements using the Cerchar Abrasivity Index (CAI), mineralogical analyses by Differential Thermal Analyse (DTA), x-ray diffraction (XRD) and thin section analyses.

In 2004, a request to evaluate soil abrasivity properties from an on-going tunnelling project was received by the GEMINI Centre for Underground Technology. The request was submitted by a contractor experiencing short tool life, resulting in low TBM productivity and increased costs. The outcome of this request was a transition to abrasivity tests on soil, based on the existing Abrasion Value Cutter Steel (AVS) test, originally developed for hard rock (Nilsen et al. 2006a). Following the initial publications by (Nilsen et al. (2006a); Nilsen et al. (2006b); Nilsen et al. (2006c)), two Master's theses on this topic, (Jakobsen 2007) and (Klemetsrud 2008), were completed at NTNU, as well as a commercial test project using 34 soil samples from the Brightwater Conveyance tunnel. Testing was initiated by Jacobs Associates, a design company and consultancy preparing the geological baseline reports (GBR) for the Brightwater project. In order to provide information and estimations of soil abrasivity they wanted to include AVS test results. As the number of soil samples increased, the name "AVS test" was changed into Soil Abrasion Test™ (SAT). The actual measurement of abrasivity is the same for both test procedures with the exception of the sample preparations (Nilsen et al. 2007; Jakobsen et al. 2013a).

Both initial testing and the Master's theses focused on the Soil Abrasion Test™ (SAT) and its ability to measure soil abrasivity. Measurement of the benefits of soil conditioning additives in hard rock and soft ground using the Ball Mill Test has continued in parallel with SAT™ testing. In the period 2006-2010 testing was carried out in the absence of any particular plan to obtain an estimation model of tool life in soft ground TBM tunnelling. However, as the volume of commercial test results built up over the years, the need for a more systemised approach resulted in the present thesis. This PhD thesis on soft ground and soil abrasivity is a result of an initiative from the GEMINI Centre of Underground Technology[1].

1.2 Goals and Objectives of the Thesis

The initial main goals of this study addressing abrasive wear on TBMs excavating soil and soft ground were prepared as part of the 2010 PhD research plan (Jakobsen 2010). The main goals were:

1) To find a reliable and versatile methodology for determining the potential of soil and soft ground to cause abrasive wear on TBM tools.
2) To propose an index or simplified model for estimating tool life in connection with soil and soft ground tunnelling projects.

In order to achieve this, three underlying objectives and sub-tasks were defined and planned:

- To obtain TBM field data and soil samples for laboratory testing in sufficient amounts to generate a statistical model. The term sufficient at this initial stage is taken to mean data and corresponding samples from 5-10 projects carried out in varying ground conditions (e.g. clay, silt and sand).
- To evaluate the results of current laboratory methods against observed abrasive wear, based on correlations between laboratory measurements and field observations.
- To propose a new laboratory method which enables the testing of abrasive wear resulting from reconstructed in-situ soil and soft ground (involving the properties soil density, pressure, larger grain size distribution range, and the use of soil conditioning additives). To evaluate if the proposed new laboratory tests provide a better estimate than current (2010) procedures.

The goals proposed in 2010 have been addressed using the following problem formulations and research questions:

1) Is the Soil Abrasion Test™ (SAT, after Nilsen et al. 2007) adequate as an estimator of tool life in soft ground and soil TBM tunnelling?
    a. If it is applicable, what is the extent to which it can be used or,

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[1] A formalized co-operation between NTNU's Department of Civil and Transport Engineering, NTNU's Department of Geology and Rock Engineering, and SINTEF Rock Engineering.

   b. Is it necessary to adapt the SAT™ using other geotechnical properties in order to achieve an estimator?

2) Is a new soil abrasivity test apparatus capable of measuring the abrasivity of in-situ soils, and is this an advance in terms of estimating tool life for soft ground and soil TBMs?

1.3 Limitations and constraints on the research

The following limitations and constraints were placed on the work involved in this thesis:

- Work and data acquisition is limited to tunnel excavation using Earth Pressure Balanced Shield (EPB), slurry shield and pipe-jacking machines.
- TBM project data recorded in this thesis originates primarily from homogenous soil and soft ground, without mixed face and boulders. The absence of mixed face and boulders will most probably result in better correlations and empirical relations between the laboratory tests and field observations presented in Chapter 4.
- The systematic evaluation of the benefits of soil conditioning additives on abrasive wear shall be limited solely to laboratory trials.
- Recorded tool lives used in this thesis shall include both ripper and scraper tools. Disc cutter life is not included here, but is included in part in Jakobsen et al. (2013a).
- Tool life estimates does not take TBM operation and TBM design into account.
- Discussions concerning the various soft ground and soil Tunnel Boring Machines (TBMs), as they relate to variations in ground conditions, shall not be included in the thesis.
- There is insufficient data and samples to develop an estimator providing 100% certainty. The study shall present estimation trends and indications, and their associated uncertainties.
- There is insufficient data and samples to distinguish between different soft ground tool’s respective tool lives.

The proposal in the PhD plan (Jakobsen 2010) was to conduct field experiments using the same TBM, and with the same contractor, in order to evaluate tool life using equipment from different manufacturers under the same ground conditions. These experiments were not successful for two main reasons:

- The tool manufacturers were reluctant to participate in such experiments. This outcome was recognised in the PhD plan as a potential show-stopper.
- The contractor intended for the trial could not offer any large operative TBMs (> 4 m diameter) during the relevant time period. This meant that there were too few tools on the cutter head, such that positioning would most likely influence the outcome of the experiment to a greater extent than tool quality.

1.4 Structure of the thesis

The thesis is comprised of six chapters, together with an appendix containing the published papers.

Chapter 1 contains background information addressing the objectives of the study and the limitations and constraints on research. The chapter is linked to Papers 1, 2 and 3 listed in Table 1.

Chapter 2 presents theoretical considerations supporting the research, taken from literature searches and discussions with individuals in the tunnelling industry. More specifically, the chapter introduces the terminology and definitions linked to the fields of soft ground, soil and hard rock, wear theories and soil conditioning, as well as reviewing the work carried out by other researchers and research groups to estimate abrasive wear in soft ground and soil in connection with TBM tunnelling. The chapter is linked primarily to Papers 6 and 10, although information concerning research obtained from literature is included in all the published papers.

Chapter 3 discusses the research methodology, and includes general information about the literature search, the tunnel projects included in this thesis, laboratory research and analysis methodology. Also included are the reasons for selecting the research methodologies and a discussion of the various benefits and shortcomings linked to the methods in question. Furthermore, links are included to published papers dealing with the methodologies. The chapter is linked to Papers 1, 3, 6, 7 and 9 listed in Table 1.

Chapter 4 presents the results and statistics obtained from the field and laboratory research conducted during this study, and attempts to compare findings made in the field to those in the laboratory. The chapter is linked to Papers 2, 3, 4, 5 6, 8 and 9.

Chapter 5 discusses the findings from both this study and the published papers, including inconsistencies and weaknesses encountered during the research, as well as the reliability and validity of the results. It also includes a record of checks made of the validity of a variety of estimations against a current TBM excavation project. The chapter is linked to Papers 3, 6, 9, 11 and 12.

Chapter 6 presents the main findings of this thesis and the papers, and makes recommendations for further work.

The published papers referred to in this thesis are presented in the **Appendix.** A list of these papers is provided in Table 1.

1.5 Published papers

This PhD work has included the publication of 12 papers. The content of these papers varies somewhat, and the following is a brief summary of their relevance. The aim of their publication was to promote the acquisition of additional data and samples for use in the PhD study.

Paper 1: *Classifications of properties influencing the drillability of rocks, based on the NTNU/SINTEF test method* includes a summary of the results of tests on hard rock samples carried out at the NTNU/SINTEF drillability laboratory. The relevance of this paper is limited to research methodology. It also demonstrates how laboratory test results organised in databases can also provide valuable statistics for soft ground and soil abrasivity.

Paper 2: *Soil Abrasion in TBM tunnelling* represents a state-of-the-art statement on the research subject at the beginning of this present PhD work. The paper also presents some early results taken from a few sites concerning the relationships between SAT™ values and recorded tool life. However, these early correlations are affected by poor field data quality. They are based on considering several ripper tools on one cutter head spoke as a single tool, and for this reason should not be compared directly to the correlations presented by Jakobsen et al. (2013a) and Figure 45 and Figure 46 in this thesis. The usefulness of Paper 2 is that it provides early notification of the research plan and subject, and serves to promote the study.

Paper 3: *Review and assessment of the NTNU/SINTEF Soil Abrasion Test (SAT™) for determination of abrasiveness of soil and soft ground* presents an evaluation of the SAT™ test against variables such as soil mineralogy, grain shape, and recorded tool life from 9 different TBM projects. The paper also provides general presentations and discussions of the consequences of tunnelling in abrasive soil and soft ground.

Paper 4: *Tunnelling in abrasive soils – review of a tunnel project in Germany* presents pipe jacking performance data from 8 projects as well as a demonstration of how SAT™ values correlate with tool life data from these projects. This paper is also the first to demonstrate how the geotechnical uniformity index (C_u) influences tool life. The paper is the direct outcome of a joint project with a former contractor facing severe wear problems, and the results have been very valuable for providing hands-on dissemination of the SAT™ test, as well as promoting development of the SGAT test.

Paper 5: *Overview of pipe-jacking performance – review of tunnel projects* presents the same findings and discussions as in Paper 4, in German. It does not contain any additional information but has served to further disseminate research in this topic.

Paper 6: *Challenges of Methods and Approaches for Estimating Soil Abrasivity in Soft Ground TBM tunnelling* is a result of a paper (Paper 7) prepared for the NORDTRIB symposium, held in Trondheim in 2012. It presents and discusses various methods and approaches used for estimating soil abrasivity in soft ground TBM applications, and it attempts to compare available test methods with tribological literature and industry experience.

Paper 7: *Overview of Methods and Approaches used at NTNU/SINTEF to Estimate Soil Abrasivity in TBM tunnelling* was prepared for, and presented at, the NORTRIB symposium. The main aim of this paper was to promote feedback from mechanical engineers, tribologists, and materials scientists on the approaches used in this PhD study for estimating soil and soft ground abrasivity.

Paper 8: *Predicting the abrasivity of in-situ like soils* presents some early results from, and ideas developed by, NTNU, SINTEF and BASF which later resulted in the SGAT study presented in Paper 9. Unfortunately, Paper 8 was not widely disseminated.

Paper 9: *Development of the Soft Ground Abrasion Tester (SGAT) to predict TBM tool wear, torque and thrust* summarises how the SGAT apparatus was developed, together with SINTEF and BASF, as a part of this PhD work. The paper also presents results and lessons learned from observing the capabilities of the apparatus.

Paper 10: *Anti-wear and anti-dust solutions for hard rock TBMs* focuses mainly on hard rock TBM tunnelling. However, the early results regarding the reduction of abrasive wear using conditioning foam, as presented in this paper, have been applied in the soil and soft ground studies.

Paper 11: *Influence of corrosion on abrasion of steels used in TBM tunnelling* represents an outcome of participation with the NTNU/SINTEF Gemini Centre for Tribology. The paper demonstrates how a synergetic combination of abrasion and corrosion can accelerate wear rates on cutter tools. The paper is yet to be published, but is currently close to finalisation. An outline of the manuscript is attached to the thesis as a part of the collection of papers in the Appendix.

Paper 12: *TBM Cutter Steel – a challenge for Norwegian steel suppliers* summarises the activities which form part of the FAST-Tunn research project currently being carried out at NTNU and SINTEF. The paper demonstrates that the research groups (Gemini Centres for Underground Construction and Tribology) are working on topics such as steel development for cutter tools, the improvement of existing empirical methods, and the development of numerical methods to assess and estimate rock breaking and tool wear.

Table 1 List of published papers linked to this PhD work, sorted by subject[2].

Paper no.	Year	Title	Authors	Journal	Peer review
1	2012	Classifications of properties influencing the drillability of rocks, based on the NTNU/SINTEF test method	Dahl, F., Bruland, A., Jakobsen, P. D., Nilsen, B. and Grøv, E.	Tunnelling and Underground Space Technology	Peer-reviewed by two external reviewers
2	2010	Soil Abrasion in TBM Tunnelling	Jakobsen, P. D. and Dahl, F.	Korean Tunnelling Association, Mechanised Tunnelling Symposium	Peer-reviewed by the organisation committee
3	2013	Review and assessment of the NTNU/SINTEF Soil Abrasion Test (SAT™) for determination of abrasiveness of soil and soft ground	Jakobsen, P.D., Bruland, A. and Dahl, F.	Tunnelling and Underground Space Technology	Peer-reviewed by two external reviewers
4	2012	Tunnelling in abrasive soils – review of a tunnel project in Germany	Jakobsen, P. D. and Becker, T.	Korean Tunnelling Association, Mechanised Tunnelling Symposium	Peer-reviewed by the organisation committee
5	2013	Overview of pipe-jacking performance – review of tunnel projects	Becker, T. and Jakobsen, P. D.	Presented at NO-DIG Berlin	No peer-review
6	2013	Challenges of Methods and Approaches for Estimating Soil Abrasivity in Soft Ground TBM Tunnelling	Jakobsen, P. D. and Lohne, J.	WEAR	Peer-reviewed by to external reviewers
7	2012	Overview of Methods and Approaches used at NTNU/SINTEF to Estimate Soil Abrasivity in TBM Tunnelling	Jakobsen, P.D.	NORDTRIB Proceedings, Trondheim	Peer-reviewed by technical conference committee
8	2012	Predicting the abrasivity of in-situ like soils	Jakobsen, P.D., Langmaack, L., Dahl, F. and Breivik, T.	Tunnels and Tunnelling International	Accepted by magazine editor
9	2013	Development of the Soft Ground Abrasion Tester (SGAT) to predict TBM tool wear, torque and thrust	Jakobsen, P.D., Langmaack, L., Dahl, F. and Breivik, T.	Tunnelling and Underground Space Technology	Peer-reviewed by two external reviewers
10	2010	Anti-wear and anti-dust solutions for hard rock TBMs	Langmaack, L. Grothen, B. Jakobsen, P.D.	World Tunnelling Congress, Vancouver	Peer-reviewed by conference committee
11	NA	Influence of corrosion on abrasion of steels used in TBM tunnelling	Espallargas, N., Jakobsen, P. D., Macias, F. J., Langmaack, L.	**Under review** in Rock Mechanics and Rock Engineering	**Issued to the journal 11th of November 2013**
12	2013	TBM Cutter Steel – a challenge for Norwegian steel suppliers	Grøv, E., Jakobsen, P.D., Kane, A., Hoang, H., Smading, S., Sagen, T.B.	Tunnelling Journal	No peer-review

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[2] Paper 1 is related to background material, providing a description of the status of the NTNU/SINTEF drillability laboratory.
Papers 2-6 discuss tunnelling in abrasive soil and soft ground conditions, as well results from the Soil Abrasion Test.
Paper 7 summarises work carried out by other researchers on this topic.
Papers 8 and 9 present the development of the new Soft Ground Abrasion Tester developed during this Ph.D study.
Paper 10 provides background information on the use of polymer-enriched foam in TBM tunnelling.
Paper 11 provides an introduction to tribo-corrosive wear in TBM tunnelling.
Paper 12 summarises on-going research at NTNU/SINTEF into wear and tool life in TBM tunnelling.

2 Materials framework

2.1 General

The estimation and measurement of soil and soft ground abrasivity for TBM tunnelling applications are relatively recent developments in the tunnelling industry. An initial literature study identified various methods for predicting tool life in soft ground and soil. (Nilsen et al. (2006b); Thuro et al. (2007); Gwildis et al. (2010)) present various methods that have been used for measuring soft ground and soil abrasivity for TBM tunnelling applications. Initial studies have also presented examples of TBM excavations involving exposure to abrasive ground conditions and their impact on tunnelling performance (Nilsen et al. 2006a), (Holzhäuser and Nilsen 2006) and (Babendererde 2010). During this study, several papers on the topic of "*soft ground and soil abrasivity"* have been published, including (Barzegari et al. 2013), (Gharahbagh et al. 2010; Gwildis et al. 2010; Rostami et al. 2012), (Köhler et al. 2011) and (Drucker 2011).

Similar studies identified during this work include the following; 1) Mr. Florian Köppl at Herrenknecht is preparing a PhD thesis on soft ground tool life and the influence of boulders in collaboration with the Technical University in Munich, 2) Mr. Eshan Alavi Gharahbagh has conducted his PhD work on the subject of soil abrasivity and the identification of a reliable soil abrasivity index, involving the development of a new test apparatus (Rostami et al. 2012), 3) Ms. Petra Drucker is conducting a PhD study on the estimation of soft ground and soil abrasivity, also involving the development of a new testing device and 4) the Japanese Tunnel Society has published a report concerning the estimation of tool life in connection with EPB and slurry shield tunnelling (personal communication with Mr. Nakamura Toshiaki, Obayashi Corporation, November 2010). Information about these studies has been communicated via contacts made at conferences, and not as part of the literature study.

The main outcomes of the initial literature study and review of theories are as follows:

1) Definitions (e.g. *soil, soft ground, abrasion, wear*)
2) An overview of laboratory methods used to measure and estimate soft ground and soil abrasivity for TBM tunnelling
3) An analysis of the limitations of existing laboratory methods for estimating soft ground and soil abrasivity
4) The establishment of a framework for linking general tribological experience regarding wear to applied theories developed in relation to tool life for TBMs excavating soft ground and soil
5) An understanding of explanations and theories related to the mechanics of soft ground and soil excavation
6) The benefits and influence of soil conditioning additives
7) An understanding of soft ground and soil excavation mechanics.

2.2 Materials understanding

2.2.1 Soil, soft ground and rock

In an engineering perspective, the terms soil, soft ground, soft rock and rock are poorly defined. The ISRM (1978) defines the terms rock and soil on the basis of a material's uniaxial compressive strength (UCS):

- Soil < 0.25 MPa UCS
- Soft rock <25MPa - ISRM definition: Extremely low strength, very low strength and low strength rock
- Hard rock >25MPA - ISRM definition: Medium strength, high strength, very high strength and extremely high strength rock

The term "rock" as defined by the NTNU/SINTEF Engineering Geology laboratory is a material possessing a brittleness value of $20 < S_{20} < 80$. "Soft rock" may be defined as having a brittleness value of $65 < S_{20} <80$, and "hard rock" $65 > S_{20}$.

In this thesis, as in Jakobsen et al. (2013a), the term soil is defined as a sample that can be indented with a hand, finger or nail. Samples that cannot be indented, and which have a brittleness value $S_{20} < 80$ are defined as rock. Soft rock is defined as a material occupying a transitional area between soil and rock, where UCS values ≈ 1 – 10 MPa. The term soft ground covers soil and soft rock, which is applicable for Soil Abrasion Test™ evaluation. Figure 1 shows the relationship between UCS and Brittleness, and the corresponding classifications developed by Dahl et al. (2012) and ISRM (1978).

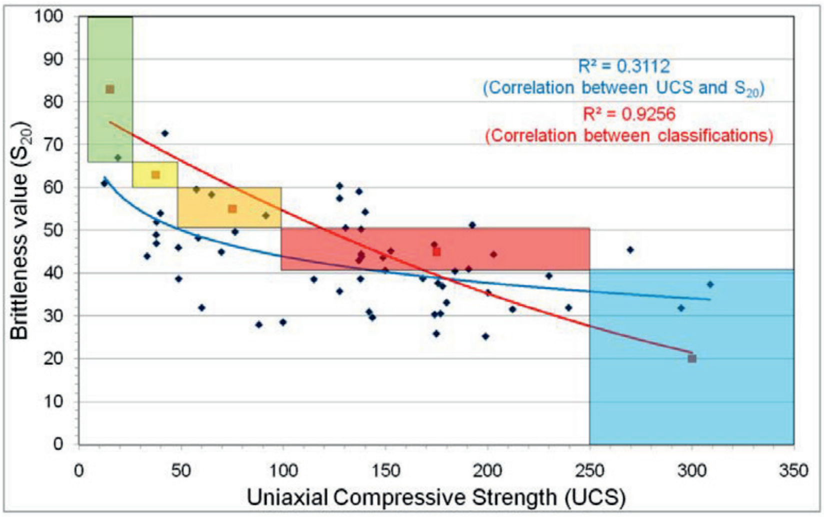

Figure 1. Correlation between uniaxial compressive strength (UCS) and Brittleness (S_{20}). The coloured boxes refer to the UCS classification ranges provided by the ISRM and corresponding ranges in the S_{20} classification (the green box includes extremely low strength, very low strength and low strength materials according to the ISRM classification). From Dahl et al. (2012).

2.2.2 Tribological framework

Tribology is defined as the science and technology of interacting surfaces in relative motion, and encompasses terms such as wear and abrasion. This chapter presents wear theories relevant to steel tools interacting with soft ground and soil materials encountered during soft ground TBM tunnelling. The theories originate from research work looking into the applied subject "TBM tunnelling", and are taken from publications addressing general wear laws linked to tribology. The researchers involved define terms such as *wear, abrasion, primary wear, secondary wear,* etc. in slightly different ways.

Frenzel and Babendererde (2011) define *primary wear* as the loss of material from the cutting "blade" of the excavation tool. This is what is normally understood as wear in connection with excavation tools. *Secondary wear* is defined as the effects on other excavation tool components such as disc cutter hubs and bearings, and is a result of passive interaction between the excavation tool and the tunnel face or muck (Frenzel and Babendererde 2011). Finally, according to Frenzel and Babendererde (2011), wear on the cutter head structure is referred to as *subsequent wear*.

Nilsen et al. (2006a) define primary wear as wear on excavation tools and surfaces such as drag bits, disc cutters, scrapers and buckets/reamers. These components are designed to be replaced at appropriate intervals. Secondary wear occurs when primary wear, as described above, becomes excessive, leading to wear of the structures such as the cutter head, spokes and cutter head mounting saddles, which are designed to hold the tools in place (Nilsen et al. 2006a; Nilsen et al. 2007).

Köhler et al. (2011) defines the term *abrasiveness* as the capacity of a given type of ground to remove material from tools, and refers to Plinninger (2007) who combines all geological influences on tool wear into the term. However, according to Köhler et al. (2011) and Plinninger (2007), this definition is unsatisfactory, since the term does not include the influence of non-geological factors.

In the tunnelling industry, the terms *wear, abrasive wear and abrasion* are commonly used to provide a measure of tool life, even though the terms are not necessarily descriptive of wear mechanisms. Bruland (2000) defines the term *cutter life* in hard rock TBM tunnelling, based on the time the cutter tools are exposed to abrasion caused by the rock.

The tribological literature (Hutchings 1992; Stachowiak and Batchelor 2004) clearly defines the terms *abrasion* and *abrasive wear* as forms of wear caused when a material is loaded against particles with equal or greater hardness. In tribology, two abrasive wear models are described; *two-body abrasive wear* and *three-body abrasive wear*.

Two-body abrasive wear occurs when particles harder than the tool, or firmly-held grits, act like a cutting tool against solid material. Three-body abrasive wear occurs when the abrasive particles are free to roll and slide over the surfaces of two solid materials.

In general, two-body abrasive wear causes greater wear and material removal rates than three-body abrasive wear (Hutchings 1992). The main reason for this is that in a two-body abrasion system the interacting particles are more confined, thus increasing the contact forces between them.

Scanning Electron Microscope (SEM) observations can be used to demonstrate whether a worn surface has been exposed to two- or three-body abrasive wear. In two-body abrasive wear, SEM photos commonly reveal parallel scratches, whereas three-body abrasive wear most often produces grooves. In terms of TBM tunnelling, three-body abrasion is the result of low confinement friction soils interacting with excavation tools, while two-body abrasive wear occurs in hard rock tunnelling, where disc cutters interact with a hard rock face containing fines. In the case of cohesive soils containing harder and coarser particles or mixed face conditions, combinations of two- and three-body abrasive wear effects will be expected. Table 2 lists the tribological terms and definitions frequently used in soft ground TBM tunnelling.

Figure 2 shows worn-out ripper tools (primary wear) and worn-out hard facing as well as structural damage to the cutter head structure (secondary wear). The wear on this pipe-jacking machine lead to unscheduled maintenance, resulting in increased costs and low performance (Jakobsen and Becker 2012). Figure 3 shows close-ups of the worn ripper tools (primary wear), and Figure 4 shows secondary wear on the outer rim of the cutter head, causing the actual TBM diameter to be reduced. This phenomena is also mentioned by Nilsen (Nilsen et al. 2006a; Nilsen et al. 2007). Figure 5 shows worn out reamer tools designed to protect the cutter head structure from wear along its rim.

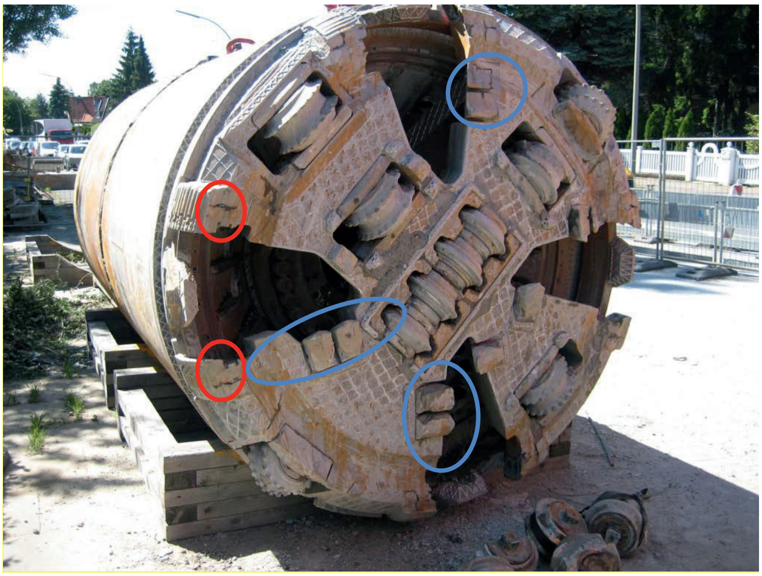

Figure 2. Worn-out pipe-jacking slurry shield cutter head and tools from the Sammler Ost project in Hamburg. The TBM diameter is 2.24 m. Red circles show fractures (secondary wear) in the cutter head. The contractor failed to replace the excavation tools in time. Blue circles show worn-out ripper tools resulting from abrasive wear (primary wear). Photo by Tim E. E. Becker.

Figure 3. Worn-out ripper tools abrasive wear. Photo by Tim E. E. Becker.

Figure 4. Reduced cutter head diameter due to abrasive wear to hard facing.
Photo by Tim E. E. Becker.

Figure 5. Worn-out carbide inserts and hard facing on a scraper/reamer tool due to abrasive wear.
Photo by Tim E. E. Becker.

Table 2 Tribological terms relating to degradation mechanisms identified in relation to soft ground TBM tunnelling.

Term	**Definition**	**Remarks**	**Reference**
Adhesive wear	Material degradation due to high temperatures and contact stresses	Unlikely in soft ground tunnelling due to low contact stresses.	(Lislerud 1997)
Abrasion	Degradation mechanism caused by friction – synonymous with abrasive wear.		(Hutchings 1992)
Abrasivity	Ability of rock and soil to induce abrasive wear on excavation tools		(Lislerud 1997)
Abrasiveness	Quantitative indication of the abrasive properties of a given material. Equivalent term to abrasivity		(Lislerud 1997)
Abrasive wear	Degradation resulting from abrasion. Tribological literature distinguishes between two- and three-body abrasive wear	Three-body abrasive wear is likely to be the most prevailing abrasion process in soft ground TBM tunnelling	(Lislerud 1997)
Fatigue and fretting wear	Results from minor oscillatory movement between two solid surfaces in motion		(Hutchings 1992)
Impact and erosive wear[3]	Material degradation due to particle impact	May cause plastic deformations (overload of materials). Impact wear explains the degradation of soft ground tools excavating boulder ground	(Hutchings 1992)
Primary wear	Wear on TBM excavation tools designed to be replaced		(Nilsen 2007)
Secondary wear	Wear on TBM parts not designed to be replaced (cutter head structural wear, wear on slurry lines, screw conveyor, etc.).		(Nilsen 2007)
Two-body abrasive wear	Abrasive wear which occurs when harder particles or firmly held grits act like a cutting tool on a solid material	Likely to occur during hard rock cutting	(Hutchings 1992)
Three-body abrasive wear	Abrasive wear which occurs when abrasive particles are free to roll and slide over the surfaces of two solid materials	Likely to occur in friction soils	(Hutchings 1992)
Tribo-corrosion	Degradation consisting of abrasive and corrosive wear		(Espallargas et al. under review)
Wear	Degradation of materials in the absence of a specific degradation mechanism		(Hutchings 1992)

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[3] *Impact and erosive wear* and *three-body abrasive wear* mechanisms both involve loose particles (e.g. sand), but the systems differ in terms of the origin of the forces acting between the particles and surfaces. In abrasive wear the particles are pressed against the surface (Hutchings 1992).

2.2.3 Excavation tools in soft ground TBM tunnelling

A variety of excavation tools are used for tunnelling in soil and soft ground (Figure 2 to Figure 5). Disc cutters are generally used if the rock mass exhibits a compressive strength in excess of 20 MPa (Khaligi 2011). In mixed ground conditions, involving layers of varying strength, and in soft ground conditions containing boulders, disc cutters are used to break the hard faces into smaller fractions which can then be mucked out through slurry lines or the EPB screw conveyor.

Soft ground TBMs are also fitted with disc cutters designed to penetrate concrete reception shafts, since excavation of the concrete lining may be too hard for conventional soft ground tools. If friction is too low, disc cutters are deployed in a fixed position which causes flat-edge wear and blocked bearings.

All TBM parts in contact with the soil are exposed to wear. Figure 6 shows a typical slurry shield TBM fitted with a variety of tools exposed to abrasive wear. Excavation tools such as disc cutters, ripper and scraper tools are designed to be replaced when they become worn. The cutterhead structure and the openings (“buckets”) are also exposed to wear, but these are not replaceable TBM components.

Figure 6. Mixed condition cutter head fitted with scraper/ripper tools and disc cutters. Photo; Herrenknecht.

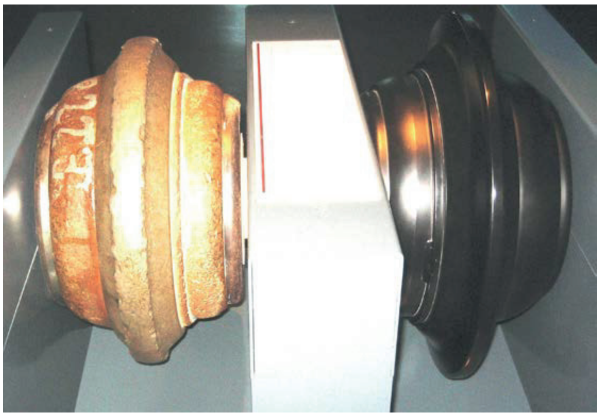

Figure 7. Photos of a worn-out 17-inch disc cutter (left) and a new disc cutter (right).

Drag bits, teeth and picks are used in cohesive ground where the greater part of the excavated material consists of clay and silt. Scraper tools are commonly used in sandy ground, and ripper tools in coarse ground conditions, including gravels. Figure 8 shows the excavation tools commonly used in soft ground tunnelling. In addition to these tools, reamers are commonly used to protect the cutter head rim, and to enable an over cut.

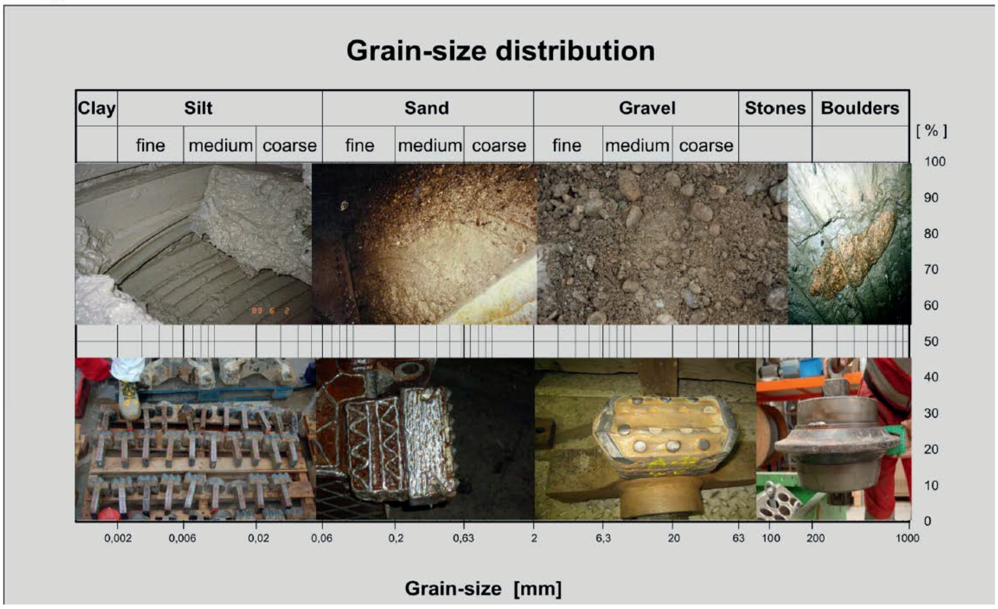

Figure 8. Photos of a selection of soft ground tools as they relate to ground conditions (Babendererde 2010). The upper row of photos shows the different soil types involved.

The materials used in disc cutters typically consist of high-alloy tool steels and hardened and tempered steels, with hardness values of up to 56-60 Rockwell C (HRC). Cutter tools are selected according to the hardness of the rock, and the need for toughness and resistance to wear. In soft ground applications, disc cutters are occasionally fitted with carbide buttons. The main aim of these buttons is to achieve greater friction between the rolling disc and the face. Tools used in soft ground conditions, such as drag bits, teeth and scrapers typically consist of a steel body of high-alloy tool steel (42 Cr Mo, equal to AISI 4140) fitted with wolfram carbides (WC) with HRC values above 70 (90% WC and 10% CO) (Smading 2013). Materials selection guarantees an extremely hard and wear-resistant WC tool tip, and a tougher steel body to hold the WC buttons.

2.2.4 Influence of soil conditioning additives and bentonite

In soft ground tunnelling soil conditioning additives or bentonite are used extensively in order to achieve suitable soil rheology and sufficient face support pressure. In some cases involving a self-stable face, soil conditioning is either not implemented, or is limited to the use of water.

Suitable soil rheology should be assessed in terms of the following; a) the mucking-out operation (conveyor belt, train or muck pumps), b) the type of disposal area and machinery used, c) the experience and preferences of the contractor, d) the TBM design (available torque, length of the screw conveyor), and e) the type of soil (clay, silt, sand or gravel).

Figure 9 shows typical face support options as they relate to ground conditions. In general, to ease the mucking-out operation, the consistency of the conditioned soil should be solid or plastic (Langmaack 2009). Slurry face support is appropriate in highly permeable ground conditions such as gravels, since the water and the fines in the bentonite combine to form a filter cake between the TBM and the tunnel face. EPB is most appropriate in cohesive ground conditions. Here, fines under pressure will contribute towards establishing a stable face.

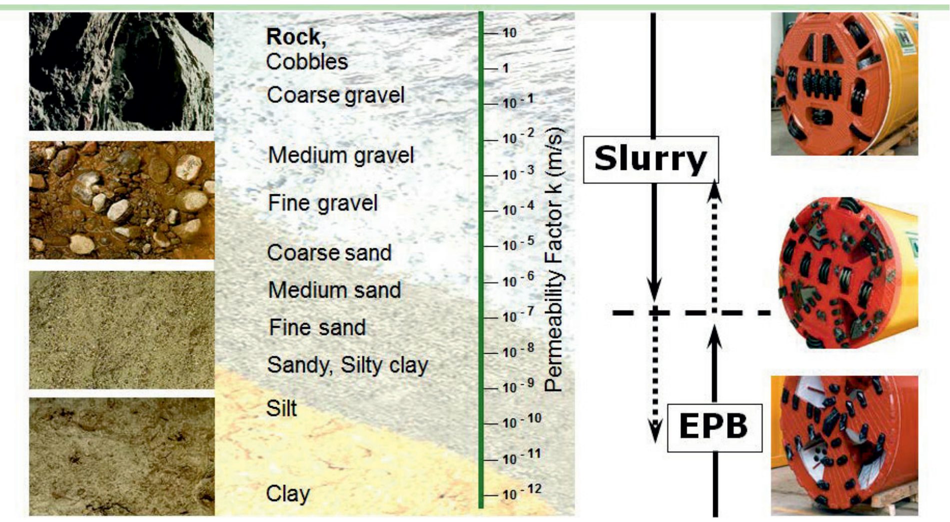

Figure 9. Selection of face support under various ground conditions (Herrenknecht 2013). By using appropriate soil conditioning, tunnelling using EPB face pressure can achieve higher permeabilities (10^{-3}).

In general, there are three types of soil conditioning additives used in connection with EPB tunnelling; 1) foams, which fill the working chamber and reduce wear on the excavation tools and cutterhead structure, 2) anti-clay additives which reduce clogging between the soil and cutterhead and excavation tools, and which improve soil rheology prior to mucking-out, and 3) polymers which increase soil adhesion and make the soil less permeable (Langmaack 2009).

The use of appropriate soil conditioning additives enables EPB TBMs to excavate in nearly all ground conditions where water pressures are less than 9 bars. In very coarse friction soils such as gravels, a combination of foam, polymers and filler materials increase soil permeability, thus making it possible to maintain earth pressure for face support. In sands and silts, foams are widely used to provide adequate filling of the EPB working chamber, and clay foam and anti-clay additives are used to reduce adhesion and clogging (Langmaack 2009).

In slurry shield TBM tunnelling, a bentonite suspension (water and bentonite) is used both to lubricate the slurry lines for mucking out and to achieve proper face support. Bentonite is a natural material consisting mainly of montmorillonite. Slurry shield TBM tunnelling is carried out mainly in permeable soil and soft ground conditions, where the bentonite suspension is used to establish a membrane called “filter cake”*,* which assists in maintaining face pressure during excavation (Min et al. 2013).

The use of soil conditioning additives and a bentonite suspension is vital in order to make it possible to excavate soft ground and soil. Both are injected at the TBM cutterhead, and their use is thus very relevant to studies related to the estimation of excavation tool life during soft ground TBM tunnelling (Peila et al. 2012). However, most research on soil conditioning additives carried out so far has concentrated on soil rheology and face stabilisation, and water inflow control (Langmaack 2002; Vinai et al. 2008; Thewes and Budach 2010). However, studies of the benefits of soil conditioning in relation to TBM operation parameters, such as torque requirements and abrasive wear reduction, are now emerging (Peila et al. 2012; Gharahbagh et al. 2013; Jakobsen et al. 2013b).

2.3 Soft ground excavation mechanics

The mechanical cutting of geological materials, including drilling, involves the use of indenters or drag bits. Indenters are more widely used than drag bits, even though theoretical considerations would suggest that the former require more energy to excavate a given volume of rock or soil (Hood and Roxborough 1992). Drag bits are exposed to shear loading which causes shear stresses leading to tool deformation or bit breakage. It is this loading mechanism which prevents the more widespread use of drag bits during rock excavation.

In the case hard rock, indenter bits break the rock by inducing a force acting normal to the rock surface. A drag bit breaks the rock by inducing a force acting almost normal to the rock surface (Hood and Roxborough 1992). Figure 10 and Figure 11 illustrate the basic principles of rock breaking using indenters and drag bits.

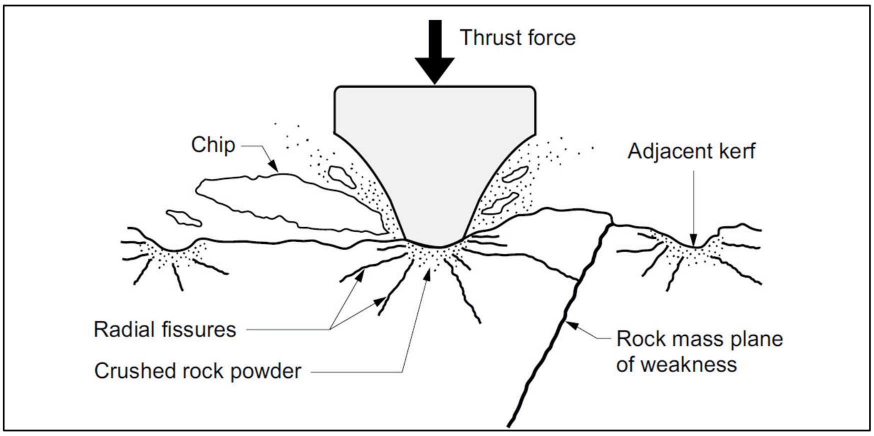

Figure 10. Rock-breaking using a disc cutter (indentation bit). After Bruland (1998c).

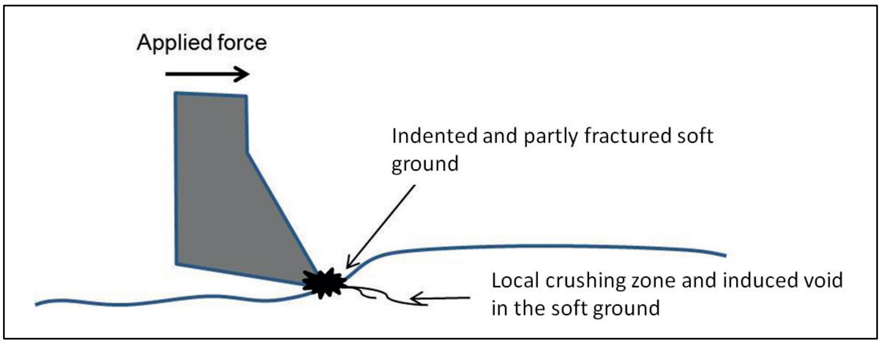

Figure 11. Rock/soft ground excavation using a drag bit. After Hood and Roxborough (1992).

Several researchers have developed models to describe rock-breaking using indentation bits (Hood and Roxborough 1992). Most of these models consider a situation in which a single disc cutter is in contact with hard rock. However, this situation is not relevant to soft ground excavation mechanisms, even though rock cutting today is mainly carried out using indentation cutters (Hood and Roxborough 1992).

According to Verhoef (1997), theories of rock cutting using drag picks were developed by Evans (1962) and Evans (1965). These early theories were based on observations during experiments involving coal-breaking. The Evans (1962) and Evans (1965) model considers the breaking of coal along a failure surface to be a highly tensile process. It demonstrates that a crushing zone exists close to the steel tool’s contact with the coal, and fractures develop. Chipping occurs between the open surface and the fracture. This mechanism agrees well with that of Bruland (1998c), who explains how hard rock breaks using disc cutters.

Soil and soft ground materials behave more like plastic than rock, and as such the basic theories of Evans and Bruland do not always apply to the excavation of soft ground materials.

Hard rock excavation involves a combination of compressive crushing to induce tensile stresses in a relatively brittle rock mass. Soft ground excavation, on the other hand, involves the ripping of a plastic or elastic material. In single-grade sand, the excavation process involves controlling the flow of the excavated material rather than inducing high contact stresses between the tools and the tunnel face. Thus, the process of crushing intact grains is assumed to be less intense during soft ground and soil excavation, than for operations in hard rock. In cases of compacted moraine materials, a combination of ripping and the induction of tensile failure is believed to occur.

2.3.1 Excavation of mixed face and boulders

Mixed face conditions exist when the tunnel face contains sections exhibiting variable properties (Bruland 1998e). According to Tóth et al. (2013), an industry accepted standard definition for a mixed face situation is where the uniaxial compressive strength ratio between the weakest and strongest material in the face is less than 1/10. However, mixed face effects such as high peak loads on excavation tools and high cutter head torque are experienced in connection with tunnel faces exhibiting higher ratios. The Singapore Circle Line Project encountered mixed face problems such as high peak loads, destructive wear, inconsistent performance and face pressure. Here, the UCS ratio was greater than 1/10. As a result of cases such as these, the term mixed face has been redefined (Tóth et al. 2013) as follows;

"*Mixed face ground is the ground, where there are two or more geological materials simultaneously present on the tunnel face with significant differences in material properties that influence significantly, a) penetration rate of the TBM or b) operational parameters of the TBM or c) support system installed behind the TBM."*

Tóth et al. (2013) also present an overview of recent publications documenting problems encountered under mixed face conditions. The SMART tunnel in Kuala Lumpur is one example where the face consisted of a limestone formation overlain by silt and sand. The limestone was weathered into an irregular and inhomogeneous rock mass which caused a number of difficulties for TBM operations (Klados and Yeoh 2006).

Mixed face conditions were also encountered in the Porto Metro line excavation. The geology consisted of massive granite overlain by soil deposits with a set of variously weathering strata in between (Tóth et al. 2013). Figure 12 shows disc cutter consumption data for the various weathering grades of the granite and soil conditioning schemes. However, it is difficult to conclude a relationship between weathering grade and tool life from these data.

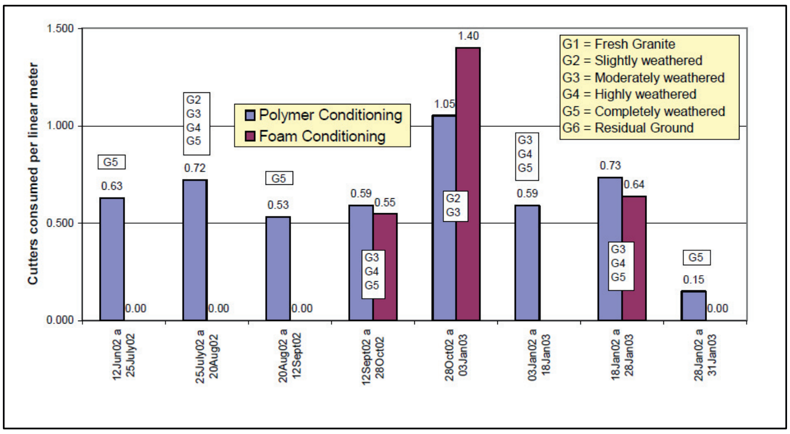

Figure 12. Disc cutter consumption during excavation in granites of various weathering states. From the Porto Metro line S (Nilsen et al. 2007).

Jung et al. (2011) present tool life and TBM performance data from a 1.66 km tunnel section along the Bundang subway line in Seoul, excavated under the Han river. The geology consisted mainly of hard and soft rock with some transition zones where both the hard and soft rock types are present. The soft rock exhibited RQD values from 20 to 30, Q values from 0.17 to 0.92 and an elastic wave velocity less than 2500 m/s. In terms of tool life, the TBM manufacturer estimated a consumption of 237 disc cutters, while the NTNU hard rock TBM prognosis model predicted 634. The actual consumption was 1263 cutters. According to Jung et al. (2011), the high consumption was the result of the fact that a single set of cutters was used for all rock types (from soft rock to hard rock), and the mud from the excavated soil clogged the chamber and cutter tools causing uneven wear on the cutters. In terms of disc cutter consumption and wear type, about 75% of the cutters were changed due to abrasive wear, while the remaining 25% were unevenly worn, cracked (due to mechanical overload) and dislocated. This example may indicate that high tool consumption represents a major consequence of mixed face situations.

Steingrimsson et al. (2002) presented data from the hard rock Karanjukar project in Iceland, which included sections of mixed face consisting of a variety of different basalts. Based on experience from the Karanjukar project and NTNU drillability indices, a TBM penetration rate estimation model was suggested, assuming that it is the hardest parts of the face which control net penetration of the TBM. In order to estimate net penetration rate, that resulting from the NTNU TBM prognosis model is multiplied by a correction factor K_{AB}, which is derived from the proportion of the hard layer divided by that of the soft layer. Tóth et al. (2013) compared the Steingrimsson model with the Singapore Circle Line Project, concluding that this approach was not applicable to a rock/soil mixed face situation. In order to address this, Tóth et al. (2013) presented a linear multivariate data analysis approach.

Occasionally, boulders are encountered during soft ground tunnelling projects in glacial till deposits. In some projects major problems have been encountered when boulders obstruct tunnelling progress by causing wear and destroying cutter tools (Dowden and Robinson 2001). Having survived glacial or fluvial transport, such boulders are generally considered to be harder than the indigenous rock (Tarkoy 2008).

Ozdemir (2008) presented initial test results obtained from a linear cutter test on the influence of boulders on the excavation process. In an attempt to simulate a soft ground matrix containing boulders, the test was performed on concrete blocks containing hard rock boulders. The initial results showed how measured forces and peak forces varied according to boulder density, although no results in terms of tool life estimation and impact wear were forthcoming.

In open excavation mode, boulders encountered in a face can be accessed relatively easily, broken into smaller fragments and excavated. In closed mode, the breaking of boulders is more difficult. If the location of a boulder is anticipated, it is common to fit the cutterhead with disc cutters specifically designed for breaking boulders. This procedure works if the surrounding soil matrix has sufficient stiffness to lock the boulder in position during excavation. If the boulder is relatively soft (UCS < 100 MPa), conventional soft ground tools such as rippers will be sufficient to break it (Dowden and Robinson 2001).

In closed mode slurry shield excavation, crushers are sometimes installed in the cutter chamber. Provided that the cutter head opening is sufficiently large, the boulder will pass through and can be crushed into smaller fragments (< 15 cm), before being extracted through the slurry line. However, tunnelling using EPB TBMs may encounter screw conveyor problems. In general, fragments which are one-third of the screw conveyor diameter may be extracted (Dowden and Robinson 2001).

If boulder fragmentation fails, contractors may have to resort to manual intervention by divers equipped with hydraulic rock splitters. Boulders with diameters of between 0.5 to 1.5 metres take between 10 to 90 minutes to remove. If the intervention is carried out in open mode, grouting of the tunnel face may be required in order to achieve adequate stability.

There exists no recognised model for estimating the impact of boulders on tool life and TBM performance. However, Dowden and Robinson (2001) suggest that geophysical methods be applied to enhance boulder visualisation during TBM tunnelling. If the TBM operator is aware that a boulder is located ahead of the TBM, parameters such as thrust, rotation and performance can be reduced in order to minimise potential breakage of the TBM tools and cutter head structure. Thorough pre-investigations using core drilling, probe drilling or geophysical methods may be used to determine density and boulder size. If the project tender documents provide estimates of the average amount of boulders and their estimated sizes, contractors will be able to submit bids including appropriate TBM designs.

As mentioned previously, the influence of boulders and mixed face situations are not considered in this study which focuses on estimating soft ground excavation tool life.

However, it is clear that both may reduce excavation tool life and net penetration considerably due to the levels of impact wear and high peak loads they cause.

2.4 State-of-the-art testing and estimation of abrasive wear for soft ground and soil TBM applications

The accurate simulation of wear is a recurrent problem in tribological engineering and research (Stachowiak and Batchelor 2004). In the case of abrasive wear testing, the tribological literature distinguishes between the following generic approaches (Hutchings 1992):

- Pin-on-disc test (e.g. Soil Abrasion Test™, Dorry Abrasion Test)
- Pin on abrasive plate (e.g. Cerchar Abrasivity Index, reciprocating the pin-on-disc and Miller slurry tests)
- Pin on abrasive drum
- Rubber wheel abrasion test

Mill tests have been used in order to measure abrasive wear on geological materials in which the type of contact and environment is similar to those in rubber wheel abrasion tests (Langmaack et al. 2010; Ojala et al. 2012; Rostami et al. 2012).

The selection of laboratory apparatus for the estimation of abrasive wear depends on the type of contact and environment we wish to simulate. The following sections describe various methods and apparatuses found during the literature search for the estimation of abrasive wear on shield TBMs excavating soft ground and soil.

2.4.1 LCPC Abrasivemeter

The LCPC Abrasivemeter has been developed by the Laboratoires des Ponts et Chaussées (the French Laboratory for Bridges and Roads; (LCPC 1990); see Figure 13). The test apparatus and procedure are based on a steel impeller rotating for 5 minutes in a 500g sample consisting of crushed rock and natural or crushed soil of 4.0 – 6.3 mm fraction size. The impeller's dimensions are 25 mm x 50 mm x 5 mm and it is composed of a relative soft steel alloy with a Rockwell B hardness value of between 60 and 75.

The impeller rotates at 4500 rpm. In the case of coarse soils, the 4.0 - 6.3 mm fraction can be sieved out. The LCPC Abrasivemeter standard test procedure is not suitable for clay, silt and sand samples (Jakobsen and Lohne 2013).

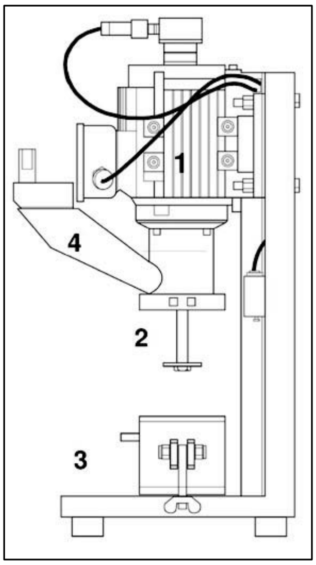

Figure 13. The LCPC test apparatus. 1) motor, 2) rotating impeller, 3) jar containing the abrasive, 4) funnel tube. (Käsling and Thuro 2010)

The impeller's weight loss is measured after each test, and this value represents the abrasivity parameter. The LCPC abrasivity coefficient (LAC) is calculated as

$$LAC = (m_0 - m) / M$$

where (m_0 - m) is the weight loss of the impeller after a single test, and M is the soil or rock materials weight (0.0005 t; (normalization 1990). The soil's brittleness properties can also be measured by the LCPC Abrasivemeter by comparing the sieve curves of the initial 4.0 - 6.3 mm sample fraction with the particle size distribution after the test.

In 2006, the Technical University of Munich started to conduct research into soil abrasivity assessment using the LCPC abrasivemeter. The LCPC abrasivemeter is also designed to measure hard rock abrasivity, in a manner similar to the AVS approach used at NTNU. Thuro et al. (2006) demonstrate clearly that an increase in quartz content increases the LCPC abrasivity coefficient, and that coarser particles (gravels) produce higher abrasivity coefficients than finer particles (clay, silt and sand). Furthermore, Thuro et al. (2007) compared the LCPC abrasivity coefficient with the Cerchar Abrasivity Index (CAI) in order to utilise existing relationships between the CAI and tool life for the LCPC abrasivemeter. Köhler et al. (2011) studied the relationship between the LCPC abrasivity coefficient (LAC) and equal quartz content (EQC). This correlation proved to be very poor, resulting in no clear relationships in a data set consisting of 22 samples taken from the recently completed Inntal railroad tunnel project in Austria (contract H3-4 and H8). It was also concluded based on results from the same project that it is not possible to predict tool wear by using just one parameter, such as the LCPC value, and that the greatest influences on wear are the grading curve and compaction of the soil (Köhler et al. 2012).

Figure 19 and Figure 44 show LCPC LAC / ABR values correlated against Los Angeles Abrasion Values, Micro Deval values and SAT™ values respectively.

An evaluation of the LCPC abrasivemeter based on published data suggests that it provides a measure of abrasive wear and impact/erosive wear resulting from the very high rotation speed of the steel impeller.

2.4.2 Mill tests

The Nordic Ball Mill Test, the Los Angeles Abrasion Test and the Micro Deval Test are similar in many ways. The test apparatuses and procedures consist of a rotating drum containing a soil sample mixed with steel balls or pins. These tests have been developed to determine road surface quality by measuring the degradation of geological materials (Gudbjartsson and Iversen 2003).

These mill tests expose steel samples to a combination of impact and abrasive wear. However, abrasive wear on these samples is likely to be less significant due to low contact stresses between the steel and soil. Water and other additives can be introduced to mill tests in order to evaluate their influence on abrasive wear (Langmaack et al. 2010) and (Gennari 2004).

Nordic Ball Mill Test

The Nordic Ball Mill Test has been used to determine the influence of soil conditioning additives on the abrasivity properties of crushed rock and natural soil samples. The test used in the NTNU/SINTEF laboratory is a modified version carried out without the use of steel ribs, and with a rubber-lined drum designed to reduce wear caused by steel interacting with steel. The test procedure is easy and straightforward. A 1500g sample, made up of grains less than 16 mm in diameter, is exposed to 20 circular steel bits (composed of ordinary construction steel, each 16 mm in diameter) for 5400 revolutions that are equivalent to a test duration of 60 minutes. The rotation speed of the drum is 0.97 m/s. The weight loss among the steel bits is measured after testing and represents the abrasivity value as defined in the Ball Mill Test (Jakobsen and Lohne 2013) and (Klemetsrud 2008).

Figure 14. The Ball Mill Test apparatus can be used to assess the reduction in abrasivity resulting from introducing water and/or soil conditioning additives. The test apparatus consists of a rotating drum filled with soil (0 - 16 mm diameter) and 20 steel bits.

The addition of foam-enriched soil conditioners clearly reduce the weight loss of the steel samples, as shown in Figure 16 (Klemetsrud 2008). As is shown in Figure 15, test results also indicate that the abrasivity of most geological materials (rock and soil) increases up until a certain level of moisture content is reached.

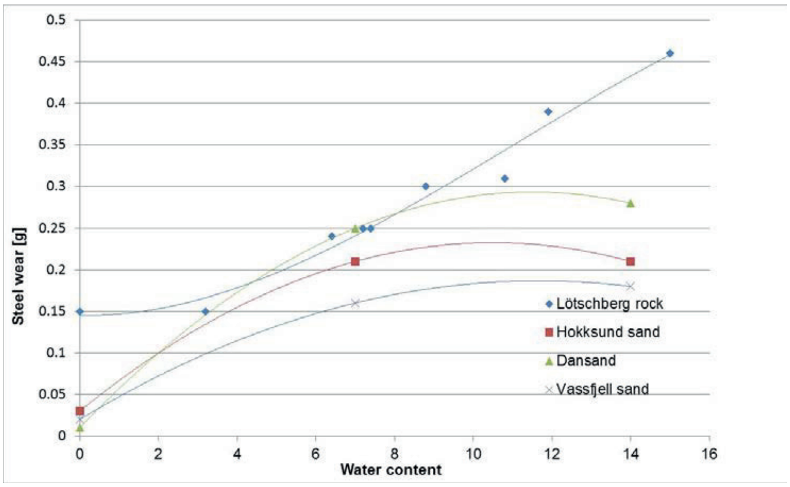

Figure 15. The influence of water content on steel wear using the Ball Mill Test for 4 different soil and crushed rock samples (Klemetsrud 2008). The figure shows a clear tendency towards increased steel wear as water content increases up to a certain level.

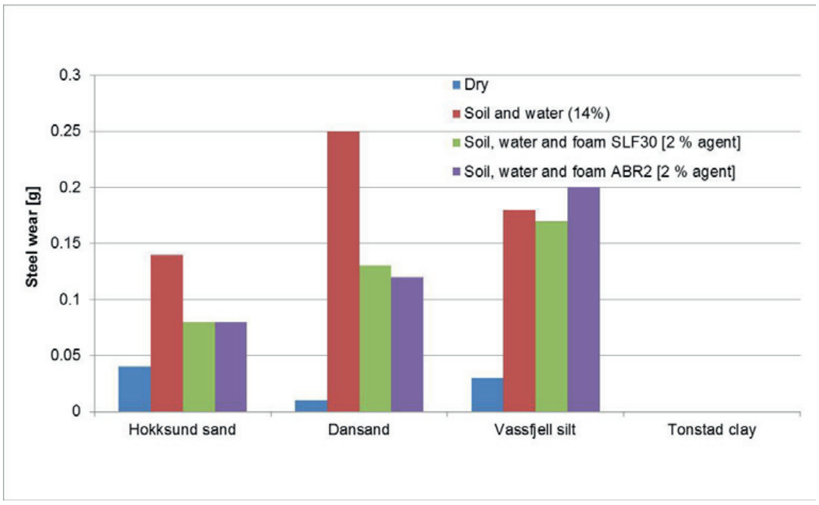

Figure 16. Reduction in abrasivity due to the introduction of a soil conditioning foam (Klemetsrud 2008). The Tonstad clay sample produced no measureable steel wear.

The contact forces between the steel and soil particles resulting from gravity and the tumbling of the drum are relatively low. However, this low degree of contact is not representative of real situations and cannot simulate the relatively high thrust values, torque ripping and scraping of the soil which occurs during TBM excavation operations (Jakobsen and Lohne 2013).

Los Angeles Abrasion Test

The Los Angeles Test apparatus (Figure 17) consists of a cylinder with a rotation speed of between 30-33 rpm. The test duration may be between 100 and 500 revolutions. The steel samples comprise between six and twelve 47 mm diameter balls, each ball weighing between 390 and 420g (Ugur et al. 2010).

The quantity of soil or aggregates used during a single test is 5000g, with a sample size > 1.6mm diameter. In order to determine road aggregate properties, soil or aggregate degradation indices are measured after first 100, and then again after 500, revolutions (Ugur et al. 2010).

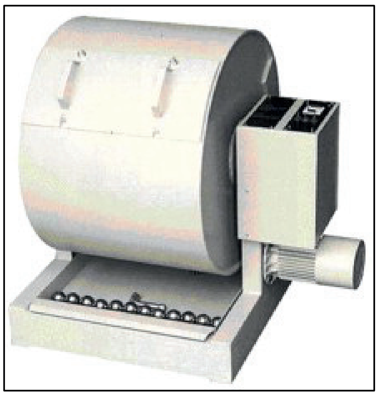

Figure 17. The Los Angeles Abrasion Testing apparatus (Ugur et al. 2010).
The rotating drum contains 4 paddles for lifting the soil and steel balls.

As an alternative to evaluating the degradation of soil and aggregates, the Los Angeles Abrasion Test can also be used to measure weight loss incurred by the steel balls for soft ground abrasivity applications (Nilsen et al. 2006b).

Micro Deval Test

The Micro Deval test (see Figure 18) is commonly used in Canada to determine abrasion caused by aggregates. The test principle is to place an aggregate sample together with a fixed volume of water in a jar mill. The jar mill contains steel balls similar to the Los Angeles Abrasion Test (Fowler et al. 2006).

The aggregate sample, weighing 1500g, is soaked in two litres of water for one hour prior to testing. Following preparation, the sample is placed in the Micro Deval jar mill together with 5000g of steel balls, each 9.5 mm in diameter. The drum is sealed and rotates at 100 rpm. The test duration is dependent on the grain size curve of the aggregate, and varies between 95 and 120 minutes (Fowler et al. 2006).

Material degradation is measured by sieving the aggregates after testing. Figure 19 shows the relationship between the LCPC abrasion value and the Micro Deval Value.

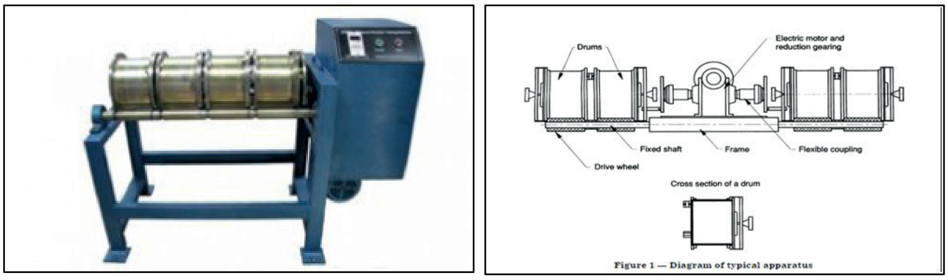

Figure 18. The Micro Deval Test apparatus (left) and schematic set-up (right)
(Serveal-Instruments 2013)

In addition to the degradation of soil and aggregates, the Micro Deval test can be used to measure weight loss incurred by the steel balls for soft ground abrasivity applications (Nilsen et al. 2006b).

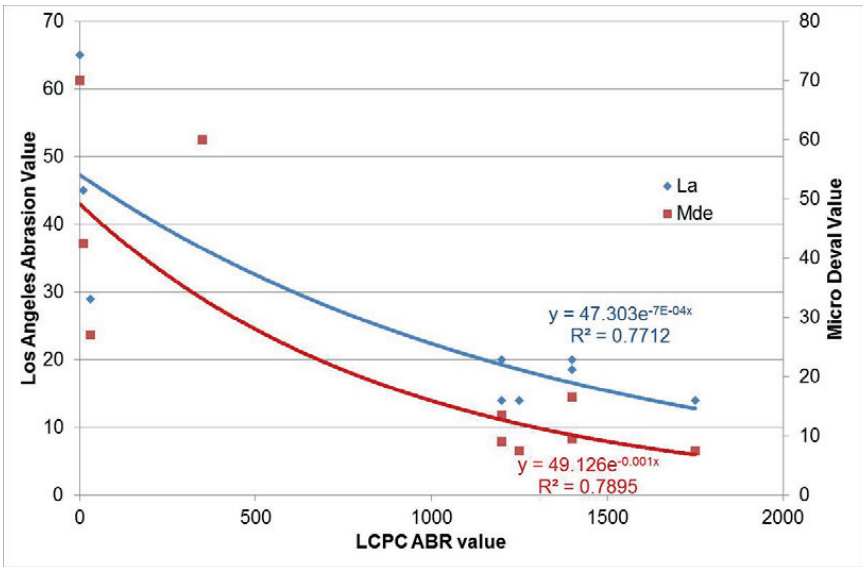

Figure 19. Correlations between LCPC ABR values and corresponding Los Angeles Abrasion Values and Micro Deval Values. The data are obtained from the LCPC (2006).

2.4.3 Dorry Abrasion Test

The Dorry Abrasion Test (Figure 20) employs the resistance of aggregates to surface wear by abrasion induced by a rotating steel plate. The test measures the volumetric loss of the aggregate and provides a value for the aggregate's resistance to abrasion (Nilsen et al. 2006b).

The test is also referred to as the AAV test and is described in the UK Standard EN 1097-8 BS 912. In the test, two samples of the soil or crushed rock material material, are prepared and placed in rectangular moulds. The steel samples are mounted against a circular rotating steel wheel in diametrically opposing clamps (Klemetsrud 2008). The aggregate abrasion value (AAV), is given by the percentage of weight loss incurred by the samples.

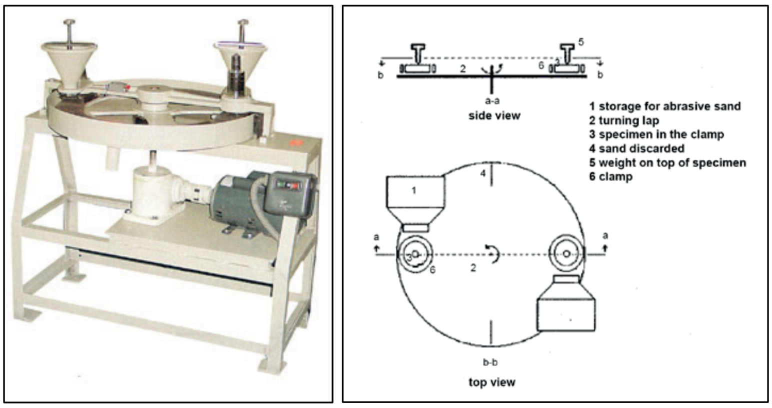

Figure 20. The Dorry Abrasion Test (Zeal-International 2013)

2.4.4 Miller Slurry Test and reciprocating ball-on-plate test

The development of the Miller test originates from vertical excavation operations carried out in the petroleum industry (Nilsen et al. 2006b; Rostami et al. 2012) (ASTM 2001), which have later been applied to soft ground tunnelling projects in order to estimate wear (Gwildis et al. 2010).

The test apparatus (Figure 21) consists of a tray-shaped sample container filled with a test slurry such as soil mixed with bentonite. A standard steel block moves back and forth with a fixed normal force (22.24 N). The test duration is 6 hours, and the weight loss of the steel block provides the so-called Miller Number. The test is also able to measure Slurry Abrasion Response (SAR), which is determined by testing various types of steel block on the same slurry suspension (Nilsen et al. 2006b).

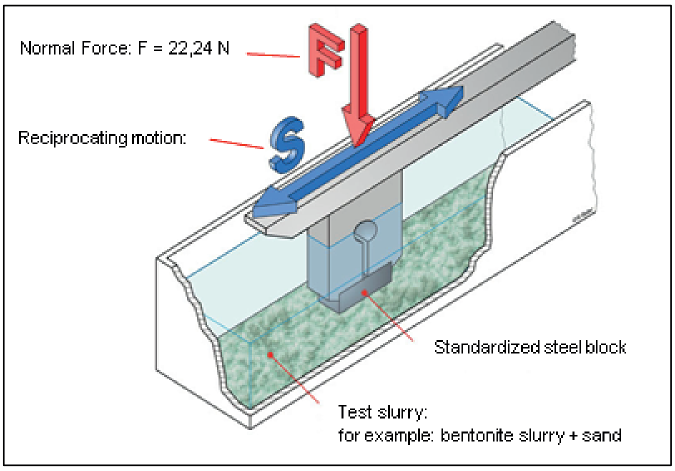

Figure 21. The Miller Slurry Test Machine (Nilsen et al. 2006b)

Gwildis et al. (2010) collected TBM performance data, tool wear data and geotechnical data from the Brightwater Conveyance project carried out in Seattle. Based on these data, a Normalised Wear Parameter (NWP) is proposed, given by (10^8 * W) / L, where W represents wear (in mm) and L is the travel length of the tool (also in mm).

The NWP is then correlated against SAT™ values, Miller Slurry Test Numbers and quartz content, and compared with the average energy consumption of the TBM (MJ/m^3). The analysis indicated that the driving factors behind tool wear linked to soft ground TBMs are a combination of high values for the abrasiveness descriptors (e.g. Miller Slurry Test Number, SAT™ or quartz content) and cutter head energy consumption, thus the soil strength.

The Tribology Gemini Centre at NTNU and SINTEF has been conducting tribological tests similar to the Miller Slurry Test, in order to determine abrasive and corrosive wear. The tests have been run both on reciprocating ball-on-plate apparatus (Figure 22) and by using the Rubber Wheel Test (Figure 23).

The reciprocating ball-on-plate test consists of a 6 mm diameter steel ball moving back and forth with a stroke length of 10 mm, either across a rock sample or in a slurry environment. The steel ball has a normal force of 5 N (Espallargas et al. under review).

The degradation of the steel ball is measured using an SEM microscope, and is used to provide a qualitative evaluation of the wear mechanism (abrasive wear, corrosive wear or a combination known as tribo-corrosion).

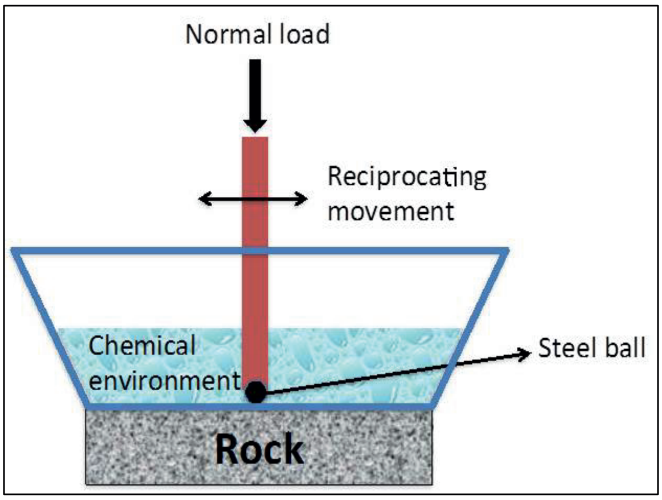

Figure 22. Reciprocating ball-on-plate test (Espallargas et al. under review).

Evaluations based on the Miller Slurry Test and the reciprocating ball-on-plate test indicate that they are both able to measure abrasive wear on particles, and tribo-corrosive wear when liquid and additives are introduced (Grødal et al. 2012).

2.4.5 Rubber Wheel Test

The Rubber Wheel Test consists of a container holding slurry (a chemical environment including soil) and a rubber wheel which lifts the slurry and exposes it to a steel sample applying a force of 220 N (Figure 23) (Espallargas et al. under review). The rubber wheel has a linear speed of 2 m/s, equivalent to 200 rpm.

The degradation of the steel sample is measured using an SEM microscope in a similar manner to that used for the reciprocating ball-on-plate test.

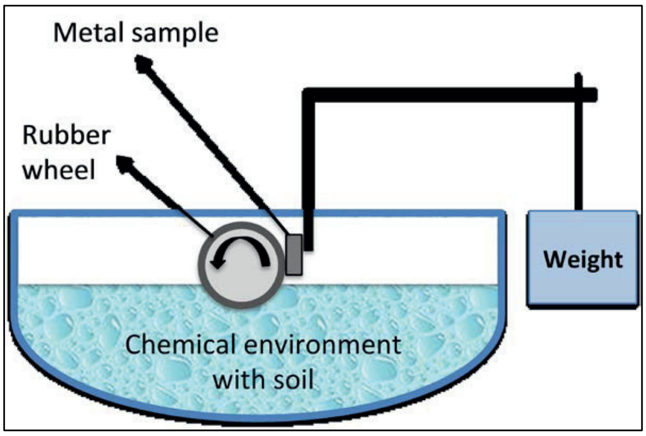

Figure 23. Schematic diagram of the Rubber Wheel Test (Espallargas et al. under review).

Evaluation of the rubber wheel test shows that it is able to measure abrasive wear particles and tribo-corrosive wear on the introduction of liquid and additives (Grødal et al. 2012).

2.4.6 Predictive method developed by the Japanese Tunnelling Society

The Japanese Tunnelling Society has developed a formula for the estimation of ripper tool wear (Nakamura 2011). Tool wear (δ) is expressed by the following equation:

Equation 1 $$\delta = K * \pi * D * N * L/V$$

where
K is a coefficient of wear (mm/km)
D is the TBM diameter (mm)
N is the cutter head rpm
L is the tunnel length (km) and
V is the TBM performance (mm/min.)

The wear coefficient K is the most problematic factor included in the formula, and the Society supplies no information about how the coefficient is measured other than by the application of experience data (see Table 3). According to Nakamura (2011), Japanese contractors use their own, empirically-derived, wear coefficients.

Table 3. Coefficient of wear prepared by the Japanese Tunnelling Society (Nakamura 2011)

	EPB TBM	**Slurry shield TBM**
Alluvial clay	3.0 – 3.5 * 10^{-3} mm/km	1.7 – 2.4 * 10^{-3} mm/km
Diluvial clay	8.0 – 15.9 * 10^{-3} mm/km	5.0 – 11.3 * 10^{-3} mm/km
Sand	10.6 – 19.7 * 10^{-3} mm/km	4.8 – 15.2 * 10^{-3} mm/km
Gravel sand	15.9 – 29.6 * 10^{-3} mm/km	9.8 – 23.0 * 10^{-3} mm/km

2.4.7 Penn State Soil Abrasion Testing System

The Penn State University research group was the first to develop and describe a dedicated abrasion test for in-situ (and similar) soils (The Penn State Soil Abrasion Testing System (PSAI)) (Gharahbagh et al. 2010; Gharahbagh et al. 2011; Rostami et al. 2012; Gharahbagh et al. 2013) (Figure 24). The apparatus consists of a rotating blade located at a fixed position (depth) within the soil sample (Figure 25). It provides an opportunity to evaluate the influence of water content variations and rotation speeds on a soil sample. The consolidation of the soil is not controlled and the excavation tool does not penetrate fresh soil material during testing. The PSAI testing system is capable to test soils consisting up to cobble dimensions, at 0 to 10 bars pressure.

The research conducted at Penn State University shows that overpressure shows no significant influence on the rate of wear of the propeller. However, it clearly demonstrates that water content, and thus the compactibility of the soil, influences the rate of wear, and that finer-grained soils produce less wear than coarser particles.

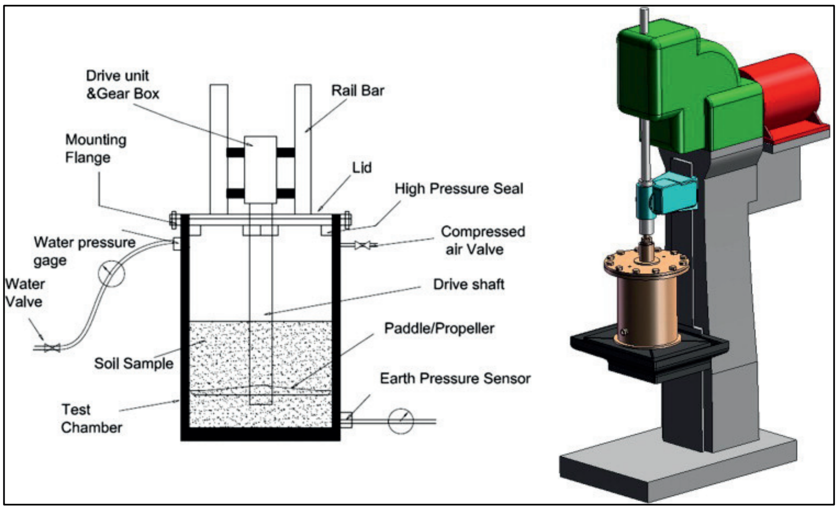

Figure 24. Illustration of the Penn State Abrasion Testing System (Gharahbagh et al. 2011).

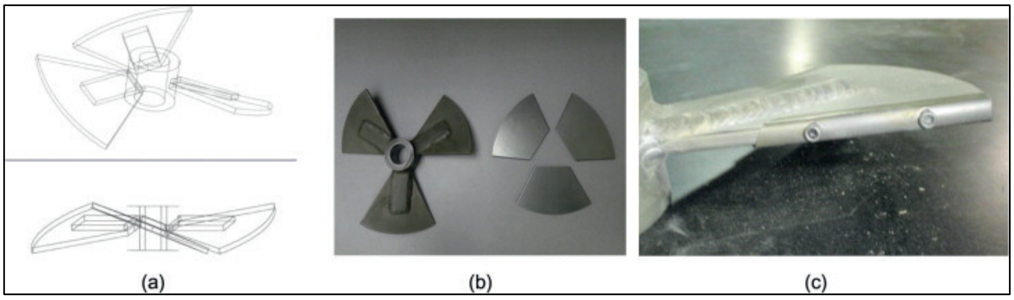

Figure 25. Examples of the Penn State Abrasion Testing System's paddle/propeller (Gharahbagh et al. 2011).

An evaluation of the literature concerning the Penn State Soil Abrasion System apparatus suggests that it is able to measure abrasive wear, impact/erosive wear (when coarse particles are introduced), and tribo-corrosive wear on the introduction of liquid and additives.

2.4.8 "Newly-Developed Abrasion Test (NDAT)"

Barzegari et al. (2013) have developed a test called the "Newly-Developed Abrasion Test (NDAT) (Figure 26). The test apparatus consists of a rotating steel plate exposed to samples of soil or crushed rock. The apparatus can carry out tests under pressure and can also test the influence of soil conditioning additives.

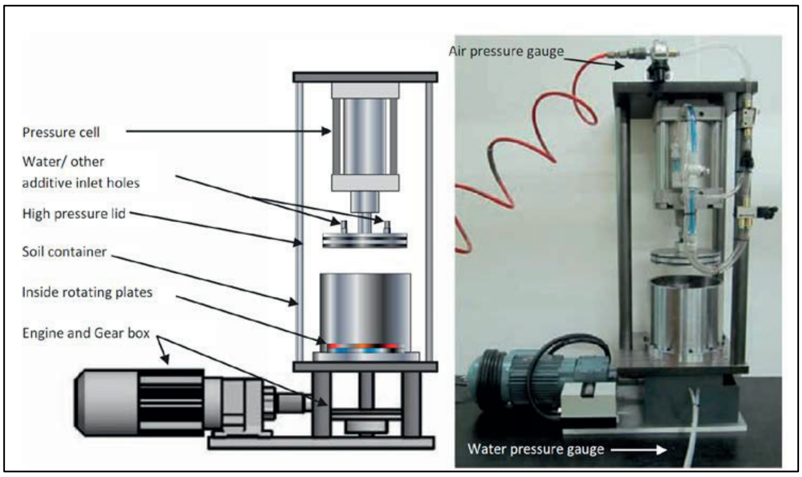

Figure 26. Illustration of the NDAT device (Barzegari et al. 2013).

An evaluation of the literature concerning the NDAT apparatus demonstrates that it can measure abrasive wear particles and tribo-corrosive wear on the introduction of liquid and additives. Due to the large contact area between the rotating plate and the soil, the influence of impacts is expected to be less than that observed for tests such as the "Turin Test" (see below) and the Penn State Soil Abrasion System.

2.4.9 "Turin Test"

The University of Turin (Politecnico Torino Tunnelling and Underground Space Center and Laboratory) has collaborated with UTT Mapei to develop a laboratory apparatus to carry out comparative wear tests on conditioned soils (Peila et al. 2012). The test comprises a tank containing a soil sample and a circular metal disc exposed to wear (Figure 27). The soil sample is compressed with 2 kPa confinement pressure both prior to and during testing. The tool is maintained in a fixed position, and as such no penetration is involved.

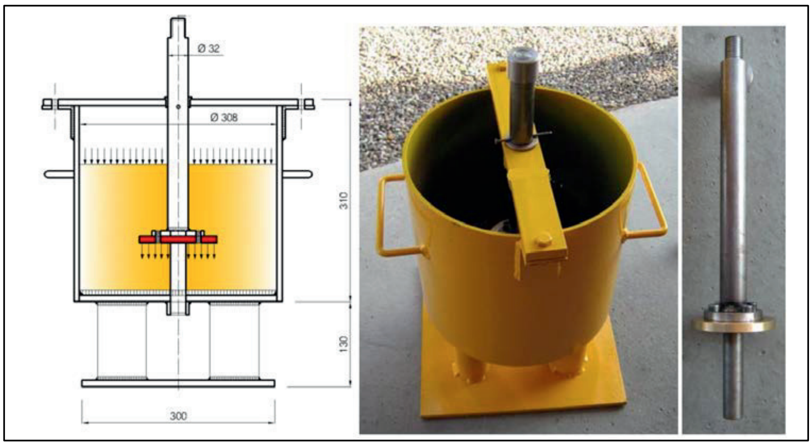

Figure 27. Illustrations of the Turin Test device (Peila et al. 2012).

An evaluation of the literature concerning the “Turin Test” apparatus demonstrates that it can measure abrasive wear, impact/erosive wear (when coarse particles are introduced) and tribo-corrosive wear on the introduction of liquid and additives.

2.4.10 Soil Abrasion Test™

For information about the NTNU/SINTEF Soil Abrasion Test™, the reader is referred to Section 4.2 and Papers 2, 3, 4, 5, 6 and 7 (Jakobsen and Dahl 2010; Jakobsen 2012; Jakobsen and Becker 2012; Becker and Jakobsen 2013; Jakobsen and Lohne 2013; Jakobsen et al. 2013a).

2.4.11 Soft Ground Abrasion Tester

For information about the Soft Ground Abrasion Tester, the reader is referred to Section 4.3 and Papers 6, 8 and 9 (Jakobsen et al. 2012; Jakobsen and Lohne 2013; Jakobsen et al. 2013b).

2.4.12 Discussion and summary

Several of the laboratory procedures and methods used to estimate soil abrasivity are derived from hard rock abrasivity procedures and road aggregate testing. In recent years (since 2010) a change has occurred in the sense that researchers are now attempting to design new test devices dedicated to the measurement of wear in connection with applications related to complex soils and soft ground. At present, there are several tests available, and there are in fact more tests and apparatuses than there are results and predictive models related to each respective test. This corresponds with general tribological findings documented in (Meng and Ludema 1995), who conclude that due to the complexities involved in estimating wear, small differences in wear tests and resulting estimates, such as for materials life, often spawn new tests and resulting empirical relationships.

The Cerchar Abrasivity Index (CAI) is one of the most common approaches used for measuring rock abrasivity (Deketh 1995; Plinninger et al. 2003; Rostami et al. 2005; Michalakopoulos et al. 2006; Alber 2008; Käsling and Thuro 2010)). The test apparatus is a type of pin-on-plate device, consisting of a steel pin which scratches the rock sample surface over a length of 1 cm (see Figure 28).

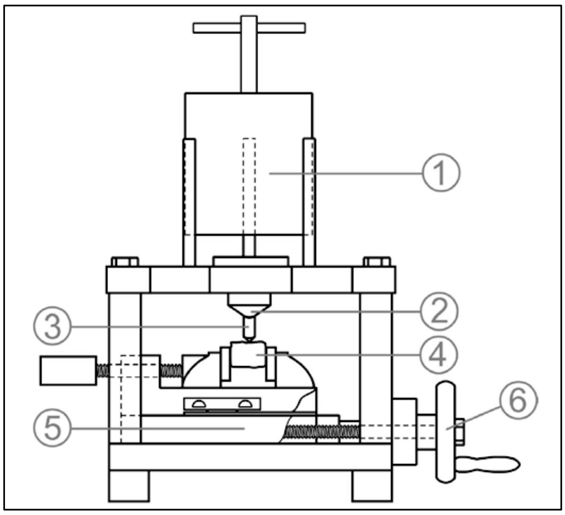

Figure 28. Diagram illustrating the Cerchar Abrasivity Index (CAI) apparatus (after West (1989)) .
1) load, 2) pin guidance, 3) steel pin, 4) rock sample, 5) vice sled, 6) hand crank.
After (Käsling and Thuro 2010).

Even though the Cerchar Abrasivity apparatus is one of the most commonly used approaches for measuring rock abrasivity, the initial literature study failed to reveal any CAI results relating to soft ground and soil fragments. The most likely reason for this is that the CAI apparatus is designed to carry out abrasivity tests on a rock samples measuring typically 5 x 5 cm. It is not impossible to run tests on soil samples as small as this. However, it is possible using this apparatus to carry out measurements on coarse soil particles such as gravel and stone. At the same time, assessments of the abrasivity properties of gravel and cobbles are also absent from most of the other approaches discussed in the literature study. An alternative possibility would be to combine fine soil particles (silt and sand) with coarser particles (gravel) in a Hoek cell as suggested by Alber (2008). This might provide an opportunity to evaluate the soft ground abrasivity of an in-situ (or similar) material using the Cerchar apparatus.

3 Research methodology and design

This chapter provides a description of the methodological approaches used to acquire data, as well as general information about the data analysis methods used in this PhD work. The data acquired consists of empirical findings from the literature review, field data and laboratory data, as well as experience-sharing with contractors, clients and TBM manufacturers. Throughout this Chapter the terms "validity" and "reliability" are used. Validity is an expression of the extent to which an "indicator", such as a value obtained in the laboratory, represents an adequate measure of what it is intended to measure. Reliability is an expression of the extent to which repeated use of the same indicator would produce identical results (i.e., a measure of reproducibility) (Samset 2008). Figure 29 is a diagram illustrating high validity and reliability versus low validity and reliability.

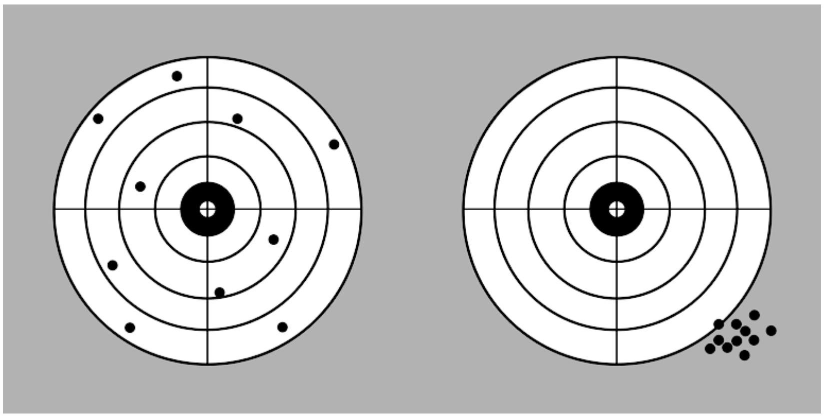

Figure 29. Diagram showing high validity and low reliability (left) and low validity and high reliability (right) (Samset 2008).

The general aim of this research is to find empirical relationships between laboratory test results and actual tool life observations. Hopefully, the research and its proposed methodology will continue as more data and experience accumulate.

3.1 Literature study

Initially as part of this PhD study, a literature search was carried out with the aim of establishing a knowledge platform obtained from other researchers' work (Jakobsen 2010). A variety of search words and strings were input to several online databases in order to obtain literature sources and background information. The process of searching and reading literature in journals, books and magazines has been a continuous process throughout this PhD study.

References found during the literature search have also been used to track down additional information about specific subjects. Most of the references used in this thesis are available on the internet via NTNU's online library service, while other sources have been purchased.

Publications found during the literature study consist mainly of papers published in international journals and scientific monographs which employ peer-review processes. The information in these sources is thus quality-assured by journal reviewers and editors. However, the tunnelling industry also shares its experience and knowledge by means of channels such as conference proceedings and industry journals and magazines. Information sources of this type have been used in this thesis, as they provide documentation of hands-on experience, and may themselves also act as sources of further research and contacts. The insights into hands-on experience obtained from such material have been assessed more critically in cases where peer review quality assurance is lacking.

As the PhD study progressed, other studies on soft ground and soil abrasivity were being carried out elsewhere. References to some of these studies were found entirely by accident. This suggests that it is likely that some relevant sources remain undiscovered.

The literature has been evaluated in terms of; 1) its relevance to the research work, 2) validity and 3) reliability. Criterion 1) "*relevance to my work"* has been subdivided into sub-criteria such as *general background information* (facts about TBMs, soil conditioning, tribology, etc.), *laboratory methods for evaluating soil abrasivity,* and *case studies on soft ground TBM tunnelling.* This Chapter provides a summary of the findings derived from the literature search.

The process of repeating such a literature research on the same subject would involve an equivalent utilisation of the same search words and online databases as presented here. A suggested modification would be to improve the organisation of the literature collected by sorting it according to relevance, validity and reliability.

3.2 Field research

3.2.1 General

In the TBM tunnelling industry, data showing a contractor's performance and consumption are often treated confidentially. This has made data acquisition for this thesis a challenging process. In order to obtain sufficient amounts of data, it was necessary to establish confidentiality agreements with contractors. The field data acquired are stored at NTNU and can be made available to other researchers under certain conditions. Table 4 provides a summary of the tunnel sites included in this PhD study. The information has been simplified in order to safeguard confidentiality issues, and reduce the risk of third parties linking a project number to an actual site[4].

The projects have been selected on the basis of the following;

- a variety of ground conditions

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[4] The normalised presentations of tool life from the various tunnels (Figure 39 - Figure 45) do not contain approximations.

    - soil lithology – in order to include data from clay, silt, sand and gravel
    - overburden
- a variety of excavation methods (EPB and slurry face support)
- variation in TBM diameter
- a variety of contractors and clients.

The field data are derived mainly from projects involving the use of small diameter TBMs (< 4 m). Moreover, the ground conditions in these projects consist mainly of homogenous soils. Ground involving mixed face and boulders are not included. Tunnels driven using small-diameter TBMs are usually excavated by small contractors. These companies are easier to approach in terms of data and knowledge sharing. Larger contractors, which excavate both small and large tunnels, generally operate with a larger organisational structure, and obtaining decisions regarding data sharing is more problematic.

The expansion of data sets by including a larger number of projects involving large cross-section tunnels (> 10 m), combined with the inclusion of mixed face and boulder condition cases, would be possible if time was not a constraint on such work. Table 4 and Figure 30 provide summaries of the sources of data and general information related to the field work.

Table 4. Tunnel sites included in this PhD study.

Project number	**Face support**	**Approximate diameter [m]**	**Approximate tunnel length included in the study [m]**	**Region**	**Site visit**
1	Slurry	5.5	5500	North America	
2	Slurry	13	5700	Central Europe	
3	Slurry	3.125	3300	Middle-East	
4	EPB	6.2	3 x 3000	Middle-East	√
5	Slurry	3.04	375	Central Europe	√
6	Slurry	2.2	1200	Central Europe	√
7	Slurry	2.2	900	Central Europe	√
8	Slurry	3	140	Central Europe	√
9	Slurry	3	200	Central Europe	√
10	Slurry	3.1	1200	Middle-East	√
11	EPB	6.2	7500	South Europe	
12	EPB	6	2 x 2500	North America	
13	EPB	6.5	2 x 3000	South Europe	
14	EPB	9.5	6000	South America	
15	EPB	6	7500	South Europe	
16	EPB	2	700	South-east Europe	√

Permission to visit sites and collect tool life data was obtained via direct contact with contractors and machine manufacturers. The actual collection of data was carried out by the author, Master’s students in the process of their theses (one project), and by the contractors operating the TBMs.

Tool replacement rates are determined based on the individual contractors’ own criteria and empirical experience in relation to tool life. Some contractors attempt to excavate using worn out tools in order to reach a shaft, while others employ a systematic approach to the replacement and inspection of tools involving scheduled hyperbaric interventions. The various criteria adopted for replacing and inspecting tools influence the information quality of tool life records.

The field data vary in terms of both quality and extent. These variations are the result of inconsistencies in agreements and relationships between myself and the contractors. Some contractors and clients are willing to share data only after the completion of projects, making soil sampling very difficult. Such data have been accepted and used, because they are valuable for ranking purposes (for parameters such as tool life or distribution of tool life).

Field work has not included an evaluation of the various tool types (design and material quality). Nor does it encompass the influence of soil conditioning additives on abrasive wear. The reason for not including these factors is the relatively long tool life associated with tunnelling in soft ground and soil. This makes such tests both time-consuming and costly (see Section 1.2). An evaluation of soil conditioning additives is included as part of the laboratory work (see Section 3.3).

Detailed information about TBM performance, including sheets containing detailed data on tool replacements, have been obtained for eight projects, together with soil samples and pre-investigation reports and results. For the remaining projects, soil samples and tool life data is less detailed.

Excavation tool life consumption, as described in this thesis, has been recorded on the basis of tool replacement logs obtained from the tunnel projects. Tool life consumption logs have been collected both during site visits and from contractors who participated in this study. For several of the tunnels listed in Table 4, tool changes were carried out only after the TBM had finished the tunnel, or had entered an intermediate shaft. For projects 1, 2, 4, 8 and 10 replacements were carried out along the tunnel drive, and in these cases tool life has been calculated and expressed as “instantaneous tool consumption” (Bruland 1998b). The instantaneous tool life parameter includes varying “tool life” (e.g. sm^3/pcs) for the various sections along the tunnel in question. The most recent tool replacement carried out at a given tool position is also taken into account when calculating instantaneous tool life, meaning that the tool life at each position on the TBM cutter head is calculated.

Sections 3.2.2-3.2.6 provide detailed descriptions of various sources of information used during the field research, while Section 3.2.7 discusses the geographical distribution of field data locations.

3.2.2 Tender documents and pre-investigation reports

Pre-investigation results from tender documents are available for projects 4, 5, 6, 7, 8, 9, 10 and in part for project 11. The data typically consist of information suggested by Deutsche Vereiningung für Wasserwirtshcaft (2008) and include the following;

- Sieve curves of the soil
- Contaminated ground
- Longitudinal drawings and maps
- Shear strength on a limited number of samples and/or SPT number
- For project 11 the tender included abrasivity test results using the Soil Abrasion Test™

Pre-investigation results provide important information for building a database of the various soil parameters' influences on tool life. This information is valid, but it must be kept in mind that disputes may arise in situations where contractors disagree with clients regarding the information contained in pre-investigation reports.

3.2.3 TBM data logger system

Modern TBMs are equipped with data logger system that records a number of machine parameters. The main parameters collected for this thesis are thrust, torque, rpm, power consumption (A), station/chainage and penetration rate. Data log files are available for projects 1, 5, 6, 7, 8 and 9.

3.2.4 Monthly and final reports

Monthly reports are generally compiled for tunnel projects as a means of informing clients about progress, problems, and other issues that may impact on costs and time. Such reports have been obtained for projects 1, 3, 5, 6, 7, 8, 9 and 16. These reports do not reveal any details about tool life, but they do provide good indications as to overall production and time consumption related to a variety of operations. They may also contain data on TBM downtime due to interventions and the replacement of excavation tools.

3.2.5 Records of tool replacements

Contractors make records and log excavation tool consumption. The quality of such records is dependent on contractor experience and tool consumption. In projects where tool consumption is low (e.g. involving the replacement of only a few tools after finalising a drive), such records do not exist. In contrast, for projects where consumption is high, tool records are generally very detailed. The unit adopted for tool life in this study is "excavated in-situ solid cubic metres per tool" (sm^3/t).

3.2.6 Site visits

Site visits have varied from a few days to weeks in duration. Contractors operating the TBMs at these sites have been welcoming, and have shared their data and experience. They have also provided assistance in collecting soil samples for laboratory tests. In addition to quantitative data, the site visits have provided an excellent source of personal feedback and an opportunity for me to disseminate my research.

3.2.7 Geographical distribution of field data

The geographical variation exhibited by the field data involves 11 countries from North-America, Europe and Middle-East (Figure 30). The study has been unsuccessful in obtaining data from projects in the booming Asian market. However, soil samples have been obtained from a few projects in East-Asia, although TBM performance data and tool replacement records are lacking for these projects. Agreement was reached with a Chinese contractor to exchange data and results, but due to difficulties in shipping the soil samples to Norway, the only data obtained were TBM performance figures. No tool life data were obtained. A combination of linguistic and cultural difficulties, customs administration procedures and geographical distance are the likely reasons for this. In Africa, mechanised tunnelling is used mainly in mining projects. A recently completed southern African TBM project, which included a section of clay, was approached during this study, but no data exchange took place. The lack of relevant TBM field work results from Scandinavia is related to the predominance of hard rock conditions in this region. Some tunnels in Malmö and Copenhagen have been excavated using EPB TBMs. However tunnelling in rocks such as limestone containing flint is not considered relevant to this study. In summary, there are no indications that the data are influenced by geographical location. Thus, regardless of location, all sources are valuable as providers of more empirical data.

Figure 30. Countries with soft ground TBM tunnelling projects included in the field research part of this study. (Excel template from Choropleth Maps[5]).

3.3 Laboratory research

3.3.1 General

Several laboratory tests are included in this study, as follows;

- Testing carried out by myself (mainly using the Soft Ground Abrasion Tester (SGAT) and Soil Abrasion Test (SAT)™)
- Testing carried out by Master's students employed as research assistants (SGAT). The testing has been supervised by myself and laboratory personnel at SINTEF Geology and Rock Engineering.
- Testing carried out by Master's students in connection with their theses (SGAT and SAT). The theses have been carried out under my supervision.
- Purchased testing by which NTNU pay for laboratory services provided by SINTEF (SAT™, sieve curves, quartz content by DTA, and x-ray diffraction)
- Ordinary commercial laboratory testing by which a SINTEF client purchases laboratory test results, and makes them available for further research (mainly SAT™ tests).

This approach has been quite useful because results have been obtained via several sources, thus increasing the amount of test results available to this thesis. All of the SAT™, SGAT and XRD laboratory results have been obtained by means of close co-operation between myself,

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[5] http://www.clearlyandsimply.com/clearly_and_simply/2009/06/choropleth-maps-with-excel.html

students, and SINTEF laboratory personnel. In this way, the reliability of the results has been assured. LCPC results obtained from other sources (see Table 5) were provided by a TBM project owner who was paying for tests carried out at another laboratory. The results have been found to be valid, since the laboratory belongs to a university known for its high quality standards.

Table 5. Laboratory test results included in this study, and personnel who carried out the tests.

Source	**SAT**	**SGAT**[6]	**XRD**	**LCPC**
PDJ	20	3	17	
PDJ MSc	9		6	
SINTEF	284		17	
Employed students		2	2	
MSc students		2	2	
Other sources				21

Natural variations in soil materials influence laboratory test results. Figure 31 shows the difference in grain size distribution between two batches of material taken from the same natural soil deposit. Such variation has been a source of error, especially in the case of SGAT testing which permits the testing of grain sizes from 0-10 mm. Such variations are less influential in the case of SAT tests because these are carried out on a more limited range of grain sizes (0-4 mm).

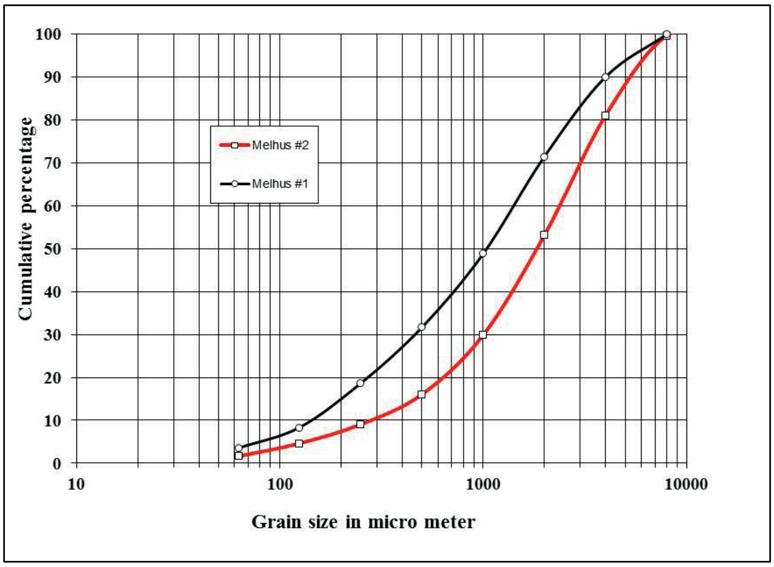

Figure 31. Variation in grain size distribution for two batches of a material used for calibration testing.

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[6] Each soil type has undergone to evaluate the influence of variations in water content, density and soil conditioning additives.

Some of the samples obtained from TBM projects originate from excavated material and contain soil conditioning additive residues. The influence of these residues is discussed in Section 4.3.

3.3.2 Soil Abrasion Test™ (SAT)

At the start of this PhD study, the published description of the Soil Abrasion Test™ (SAT) was accompanied by standard test procedure (Nilsen et al. 2007). The SAT™ procedure and apparatus are derived directly from the Abrasion Value Cutter Steel (AVS) test (Nilsen et al. 2006c). The procedure has not been changed in any major way during this PhD study. However, the influence of not using grains over 4 mm, thus the possible change of the mineralogical content of the soil samples is discussed by Jakobsen et al. (2013). The main sources of error linked to the SAT™ test are:

- Control of flow rate of abrasives (manually controlled)
- Alignment of the SAT™ steel piece on the rotating disc
- Re-grinding of SAT™ steel test pieces.

No quantification of sources of error has been carried out for the SAT™ test as part of this thesis. However, this can be achieved by processes such as running SAT™ tests on the same abrasive at various flow rates, or by making different operators run the same tests.

The SAT™ procedure provides reliable test results (see Figure 32). A comparison of the validity, or robustness, of the test results is presented in Paper 3 and Section 4.2.

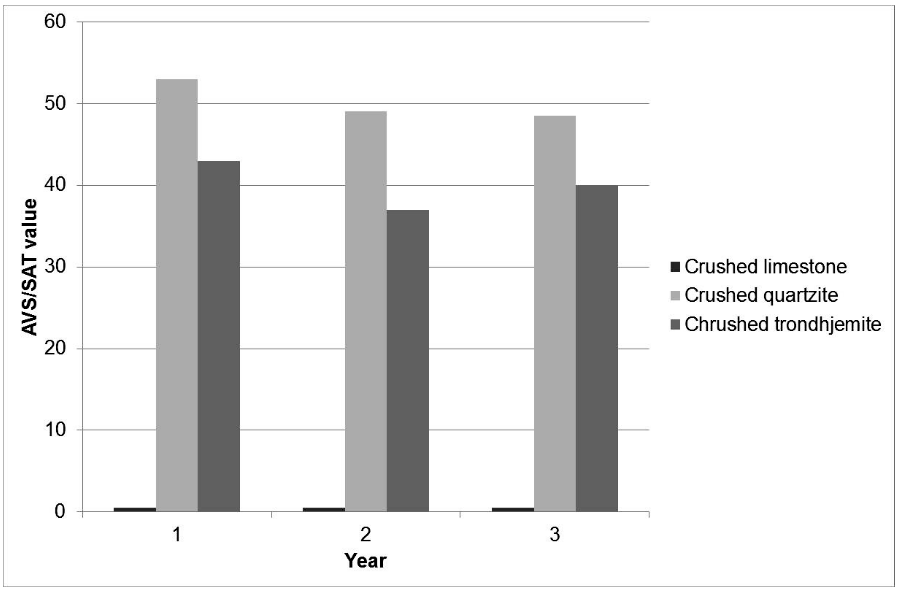

Figure 32. Reliability of the AVS/SAT™ test obtained by testing crushed limestone, quartzite and trondjemite. The x-axis (1-3) refers to three different years when tests were carried out.

Various references such as (RETC 2007), (Langmaack 2011), (Impregilo 2011), (Herrenknecht 2013) and (Robbins 2013), which discuss the SAT™, have directed criticism at the simplified test procedure. More specifically, the SAT™ tests the abrasive properties of cohesionless loose and dry soil materials, as shown in Figure 33. In fact, the real interaction between soft ground excavation tools and soil materials is more complex because factors such as compaction, the influence of water, and the use of soil conditioning additives all impact on abrasive wear potential (see Figure 34). In order to develop a test procedure with higher levels of validity, and capable of testing in-situ (or similar) soils, the Soft Ground Abrasion Tester (SGAT) was developed as part of this PhD study.

Figure 33. Interaction between dry and loose soil particles and the steel bit during an SAT™ test (Photo by Filip Dahl).

Figure 34. A soft ground face consisting of soft claystone (UCS < 2 MPa) and gypsum (UCS < 5 MPa).

3.3.3 Soft Ground Abrasion Tester (SGAT)

The development of the Soft Ground Abrasion Tester (SGAT) was carried out in order enable abrasion testing on in-situ (and similar) soils, and to increase the validity of tool life testing for soft ground and soils.

A detailed test procedure for commercial use of the SGAT is yet to be developed. The test apparatus is designed to evaluate the influence of several variables on abrasive wear and torque. For this reason, the test procedure must be decided prior to the testing of a new batch of sample material, on the basis of what the results are intended to show. A generalised preliminary test procedure is presented in (Jakobsen et al. 2013b). The main sources of error linked to the SGAT test are as follows:

- Precise control of water content and density distribution along the sample
- Re-use of tools which are becoming deformed
- Preparation of steel tool prior to first use
- Variations in soil sample properties such as grain size distribution and mineralogy
- Inconsistencies between the data logger and real world data.

The following tests and measurements have been carried out in order to assess and quantify the reliability of, and possible sources of error linked to, the SGAT tester;

- Tests on the same abrasive (soil sample) with different grain size distributions. This measurement also includes re-use of the abrasive
- A comparison of results obtained from running tests on a new tool with those using a used tool (after 5, 10 and 20 tests)
- Manual control of thrust and torque according to measurements using a scale and torque wrench (see Figure 35 and Figure 36).

Reliability testing of the SGAT concluded that variations in the grain size distribution of the abrasive influence measured wear. Re-use of the abrasive should not be carried out because crushing of the sample material introduces more fines, which in turn promote increased potential cohesion and wear. The findings shown in Figure 36 demonstrate that there are no inconsistencies between the thrust and torque values measured in the SGAT apparatus. The decrease in torque over time is due to reduced resistance in the gear mechanism as it reaches approximately 40°C. This normally occurs after 20-30 minutes of operation at room temperature (see Figure 37).

Figure 35. Control of thrust and torque on the SGAT apparatus.

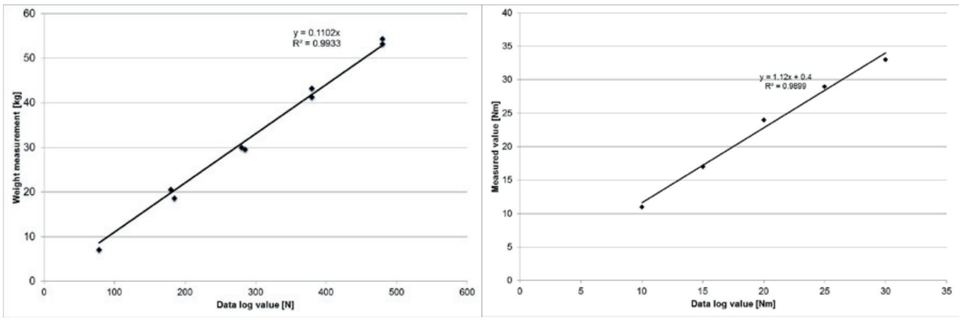

Figure 36. Relationships between data log values and measured values for torque and thrust using the SGAT apparatus.

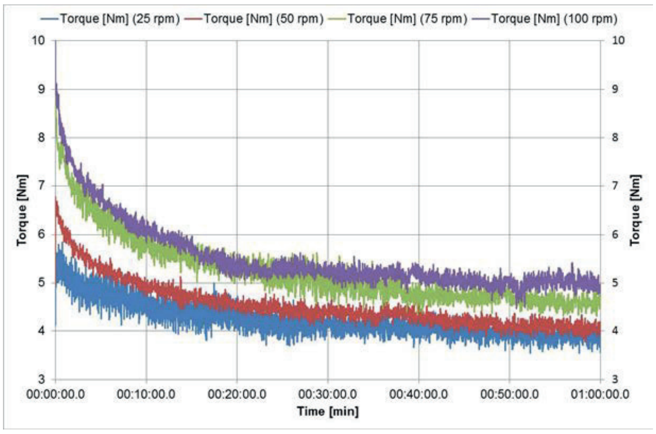

Figure 37. Development of torque plotted against time at various rotations without soil samples using the SGAT apparatus.

3.3.4 Relating laboratory research to tool life recorded in the field

Tool life data from the TBM projects have been correlated with measured laboratory values in order to establish a statistical relationship between actual tool life and laboratory data. Thus, an important part of this thesis is to establish correlations between variables such as soft ground TBM tool life recorded in the field and various geological and geotechnical parameters. Tool life is expressed in the units “solid cubic metre excavated soil or soft rock per excavation tool” (sm^3/pcs). This unit is adopted mainly with the aim of including a variety of TBM diameters in the same correlation. Bruland (1998b) starting point for the relationship between tool life and the Cutter Life Index™ is based on TBM boring hours. However, the “boring hours” parameter is not known for all projects used in this thesis (Table 4). As a result this parameter has been rejected for the purposes of this thesis, since the resulting tool life consumption data would be less based on less data. However, a correlation between the parameters “boring hour tool life” and “volume tool life” is provided in Figure 38 for those projects for which TBM operation and tool life data are available.

Correlation coefficient and statistical significance

The R^2-value (correlation coefficient) is commonly used to demonstrate the relationship between two variables. R^2 provides an expression of the proportion of the total variation of one of the variables that can be accounted for, or explained by a relationship with a random value in the other variable (Walpole et al. 1998). An R^2 value of 0.5 (50%) shows that the total variation of values of variable 1 in a given sample is accounted for by a relationship to values of variable 2. Thus, R^2 demonstrates how well a correlation expresses the variation between two variables, and does not include the variation among the variables.

Kim (2009) discussed a number of geoscience authors’ criteria for validity in relation to calculated correlation coefficients. Geoscience-related regression values are often very low because influences on geological and operational parameters are most commonly multivariate.

Cesano et al. (2000) states that *geological or hydrogeological variables that are correlated at ± 0.5 (R^2 = 0.25) often can be considered as a high correlation.* Holmøy (2008) refers to R^2 values of 0.04 ≈ 0.09 as providing low to medium statistical support for several hypotheses. Henriksen (2008), however, considers regression values of $R^2 < 0.09$ as indicative of weak correlations. Based on the literature examined in this study, values of $R^2 < 0.1$ are not regarded as significant correlations. Correlation coefficients greater than $R^2 \approx 0.1$ are assigned the following qualitative expressions of validity:

$R^2 < 0.1$	No correlation
$0.1 < R^2 < 0.25$	Weak to medium correlation
$0.25 < R^2 < 0.5$	Medium to strong correlation
$0.5 < R^2 < 0.75$	Strong correlation
$0.75 > R^2$	Very strong correlation

In addition to the correlation coefficient, statistical significance has been evaluated. Statistical significance is an expression of how certain we are that a difference or relationship exists among the variables under consideration, and of the extent to which the calculated probability of a result is not due to coincidence. For bivariate correlations (correlation between two variables), the Pearson Significance is used for normally distributed variables, and the Spearman correlation for values not normally distributed (Helbæk and Westgaard 2008). In cases where one variable is normally distributed and the other not, the Spearman Significance is used. Calculations of the correlations and the Pearson and Spearman Significance parameters have been made using Microsoft Excel and IBM SPSS respectively. In order to determine whether a data set is normally distributed or not, the one-sample Kolmogorov-Smirnov Test in SPSS has been used.

Qualitative and subjective assessment has also been used to evaluate the validity and usefulness of the correlations. Multiple regressions (correlations between a dependent variable and several independent variables) have been carried out using the software SPSS for tool life estimates involving several variables.

3.4 Discussion – the experiences and opinions of individuals and experts

Discussions and the sharing of ideas and experience with contractors, clients and TBM manufacturers has been shown to be a very useful way of obtaining feedback on work in progress, and a useful means of gaining access to more data (see also Section 3.3 concerning the reason for developing the SGAT apparatus). The SGAT apparatus is a direct outcome of discussions and experience-sharing with other individuals and experts, specifically those from the BASF Construction Chemical Company (Langmaack 2011). The process of carrying out research and development together with manufacturers and suppliers is helpful in the following ways:

- Quick and direct feedback from product and research end-users is obtained

- Access to relevant experience and data is facilitated. In the case of development of the SGAT, this involved access to real soil samples, soil conditioning additives and field experience
- Financial support can be obtained.

However, joint development and research involving manufacturers and suppliers may lead to a monogamous situation, excluding other suppliers, thus experiences. Due to time constraints, all tests involving development of the SGAT apparatus carried out to date (medio 2013) have been performed jointly with BASF. However, there exists no prohibition on carrying out testing using other supplier's products, and in autumn 2013 testing of the response of bentonite on the SGAT apparatus was carried out. This will be repeated in winter 2014.

Discussions and experience-sharing have been carried out in connection with Projects 2, 4, 5, 6, 7, 8 and 9 listed in Table 4. This dialogue has provided a valuable source of feedback and new ideas concerning what might be included in further research. In some cases, the information obtained via discussions with experts can be biased, so in order to not to base all data acquisition on the subjective opinions of contractors and site owners, a large proportion of the soil samples and TBM data have been collected by the authors during site visits.

As a supplement to the projects listed in Table 4, consultancy work involving soil abrasivity measurements has been carried out. The findings of this work are not included in this thesis due to an on-going dispute between the contractor and the client, although it is hoped that these findings can be published after the dispute has been settled.

It is possible that information obtained by means of discussions with individuals representing the various parties to the dispute is selective, and that this will influence the soil samples they send for testing. SINTEF was contracted to measure abrasion properties and drillability for both the client and the contractor for both a soft ground project in the US, and a hard rock project in Europe. The contractors tended to select abrasive samples for testing, while the client selected less abrasive samples.

In addition to discussions with the tunnelling industry, a GEMINI Centre for Tribology has been established at NTNU from which I have obtained tuition in tribology from experts at NTNU and SINTEF.

3.5 Research methodology related to the published papers

Table 6 shows the research methodologies used in the preparation of the published papers included in this thesis. As the table demonstrates, several of the papers include literature data, field data and laboratory data. The reasons for this are as follows;

1. An increase in the volume of literature which became available on the subjects of soil abrasivity and the estimation of tool life in soil and soft ground TBM tunnelling during the PhD study.
2. The main approach adopted in this study is to find empirical relations between laboratory and field.

Table 6 also reveals the lack of field data related to the recently proposed SGAT tester. The reason for this is the delay in completion of the SGAT tester, which in turn resulted in delays in establishing a systematic correlation study between SGAT results and tool life. However, as already mentioned, an evaluation of the SGAT apparatus’ response to testing soil with bentonite is currently on-going. In this project, SGAT results will be evaluated against actual TBM performance and tool life data obtained from an ongoing slurry TBM project.

Table 6. Research methodologies used in the preparation of the published papers included in this thesis.

Paper	Title	Literature	Field research	Lab. research	Dialogue input
1	Classifications of properties influencing the drillability of rocks, based on the NTNU/SINTEF test method			X	
2	Soil Abrasion in TBM Tunnelling	X	X	X	
3	Review and assessment of the NTNU/SINTEF Soil Abrasion Test (SAT™) for determination of abrasiveness of soil and soft ground	X	X	X	
4	Tunnelling in abrasive soils – review of a tunnel project in Germany		X	X	X
5	Overview of pipe-jacking performance – review of tunnel projects		X	X	X
6	Challenges of Methods and Approaches for Estimating Soil Abrasivity in Soft Ground TBM Tunnelling	X			
7	Overview of Methods and Approaches used at NTNU/SINTEF to Estimate Soil Abrasivity in TBM Tunnelling	X			
8	Predicting the abrasivity of in-situ like soils	X		X	X
9	Development of the Soft Ground Abrasion Tester (SGAT) to predict TBM tool wear, torque and thrust	X		X	X
10	Anti-wear and anti-dust solutions for hard rock TBMs	X			X
11	Influence of corrosion on abrasion of steels used in TBM tunnelling			X	
12	TBM Cutter Steel – a challenge for Norwegian steel suppliers			X	

4 Results and analyses

The main results of this PhD study are set out in the research papers listed in Table 1. This Chapter describes supplementary results, updates and as yet unpublished results such as the following;

- A statistical overview of recorded tool life
- An update concerning the relationship between SAT™ values and recorded tool life data obtained from soft ground TBMs
- An update of the statistical overview of recorded results (SAT™ values and other estimators such as quartz content and mineralogy)
- A correlation between various abrasivity estimators such as quartz content and SAT™ results
- Current research work on the recently developed Soft Ground Abrasion Tester (SGAT)
- Correlations between parameters such as TBM diameter, overburden, quartz content, soil uniformity index and recorded soft ground TBM tool life.

4.1 Field research

The field data and experience-sharing (collectively referred to here as “Field research”) obtained as part of this study comprises approximately 500 replaced tools from a total of 49 downtimes during 14 separate projects. The reader is referred to Section 3.2 for more information about the sites selected for this study.

Bruland (2000) records cutter tool life in hours, and back calculates cutter life using the units m/h and sm^3/h. The reason for expressing tool life in hours is to include the TBM operation in the tool life estimate. However, excavation tool life data available to this study is expressed largely in terms of sm^3/h, due to a lack of TBM performance data (which demonstrates the relationship between chainage and TBM machine hours). Figure 38 shows the relationships between tool life in terms of h/tool and tool life in $sm^3/tool$ for projects where TBM performance data were available. The black regression line and formula includes all data sets, while the red line and formula excludes two outliers (data points 370 and 190). The outliers are derived from data from the Bergedorf pipe-jacking project in Germany, where performance was high (12 m/shift gross production, corresponding to 4 m/h net penetration rate).

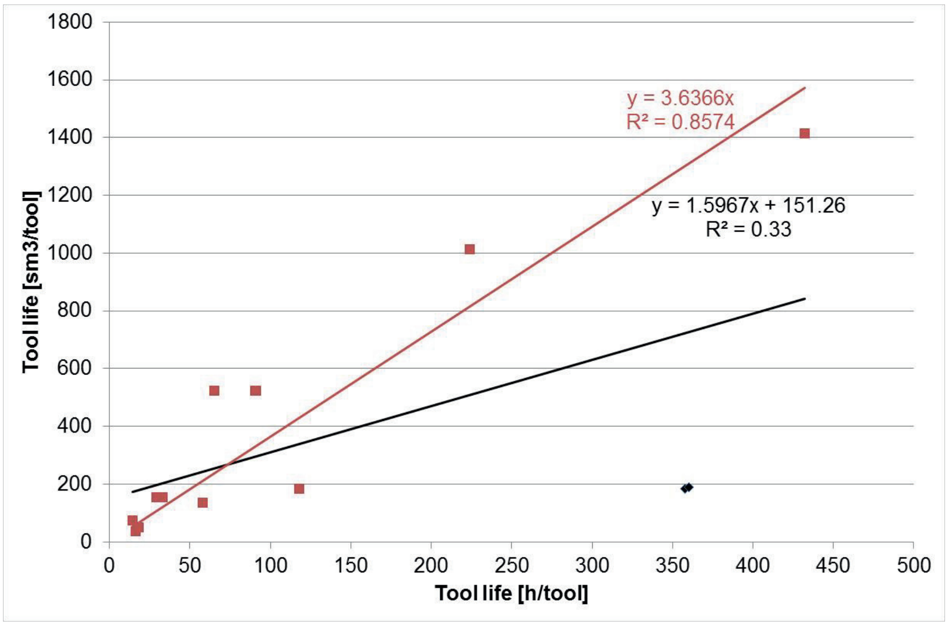

Figure 38. Relationship between recorded tool life (in hours per tool) versus solid cubic metre per tool. The black regression line and formula are derived from all available data, while the red regression line and formula are derived from all data excluding two outliers obtained from the Bergedorf pipe-jacking project.

Figure 39 shows the range of recorded soft ground tool life expressed in sm^3/h. Recorded tool life values range from approximately 50 sm^3/h to 3500 sm^3/h. The lowest value is derived from a pipe-jacking project using a small diameter TBM in a well-graded soil with high quartz content, while the highest values are derived from a soft ground project in weathered limestone and claystone (UCS < 2 MPa comprising mainly calcite). The figure also illustrates EPB and slurry shield tool life data. Due to the small number of data sets for EPB tool life, it is inadvisable to carry out a direct comparison between slurry shield tool life and the EPB tool.

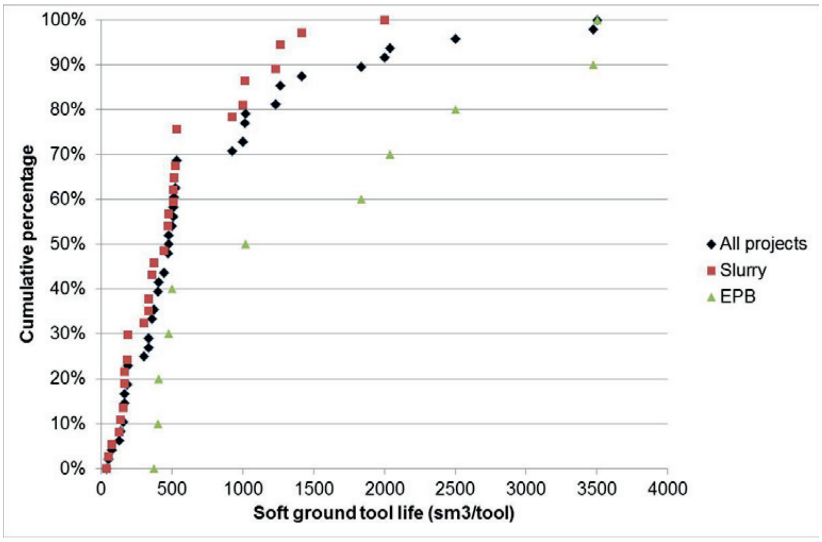

Figure 39. Cumulative distribution of recorded soft ground tool life.

Figure 40 is a box whisker diagram showing the distribution of recorded tool life (sm^3/h) for slurry and EPB face support approaches. According to SPSS, the data points on the right of the slurry whisker are outliers[7]. The figure shows the wide range covered by the few EPB tool life data points available, and serves to emphasise that a direct comparison between slurry and EPB tool life cannot be made based on available data.

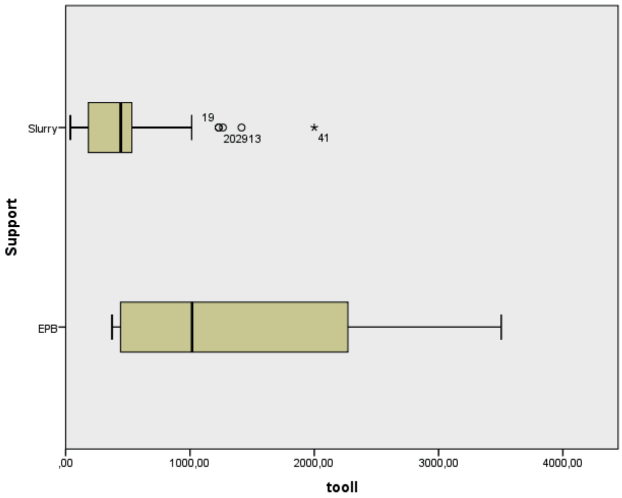

Figure 40. A box whisker plot (SPSS) showing data distribution for EPB and slurry soft ground tool life.

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[7] Outliers are defined as values greater than 1.5 interquartiles from the 25th or 75th percentiles. An interquartile is 3rd quartile – 1st quartile, and is represented by the width of the box in the box whisker plot.

At the time of writing, a field study is in progress at a major slurry TBM project in Europe. At present, the TBM has experienced one episode of downtime of about 1 week's duration due to the need to replace approximately 50% of the ripper and scraper tools after 300 metres of tunnelling. Both the field data and laboratory measurements will be published in a paper following completion of this PhD study.

4.2 Soil Abrasion Test™

A total of 313 unique SAT™ samples are included in this study (see Table 5 for information regarding the origin of the samples). Descriptions of the SAT™ test procedure and the geological samples used during SAT™ testing can be found in Paper 3 (Jakobsen et al. 2013a).

Since publication by Jakobsen et al. (2013a), the number of SAT™ tests has increased from 254 to 313 such that the distribution of SAT™ values can now be updated. Figure 41 shows how the cumulative distribution of SAT™ values has developed as more tests have been conducted. Visual inspection of the figure would suggest that there has been no significant change in the distribution in the period 2010 to 2013.

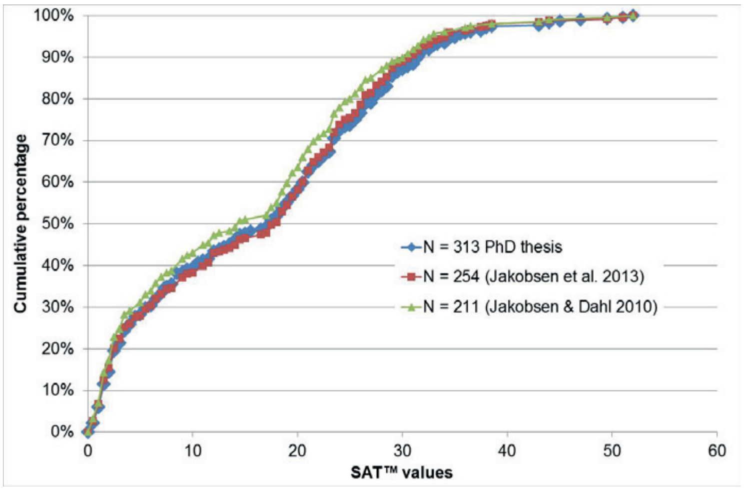


Figure 41. Historic development of the cumulative distribution of recorded SAT™ values.

The classification system as presented in Jakobsen et al. (2013a) is retained because the more recent results did not change the data distribution pattern. The classifications of SAT™ values according to Jakobsen et al. (2013a) are as follows;

- SAT™ ≤ 7 is classified as "low"
- 7 < SAT™ < 22 is classified as "medium"
- 22 ≤ SAT™ is classified as "high"

Similarly, the correlations between SAT™ values and quartz content have been updated in the light of the more recent test results (Figure 42). The new data have resulted in no change to the trend presented by Jakobsen et al. (2013a). The bivariate correlation between SAT™ values and quartz content has been found to be statistically significant (Table 7).

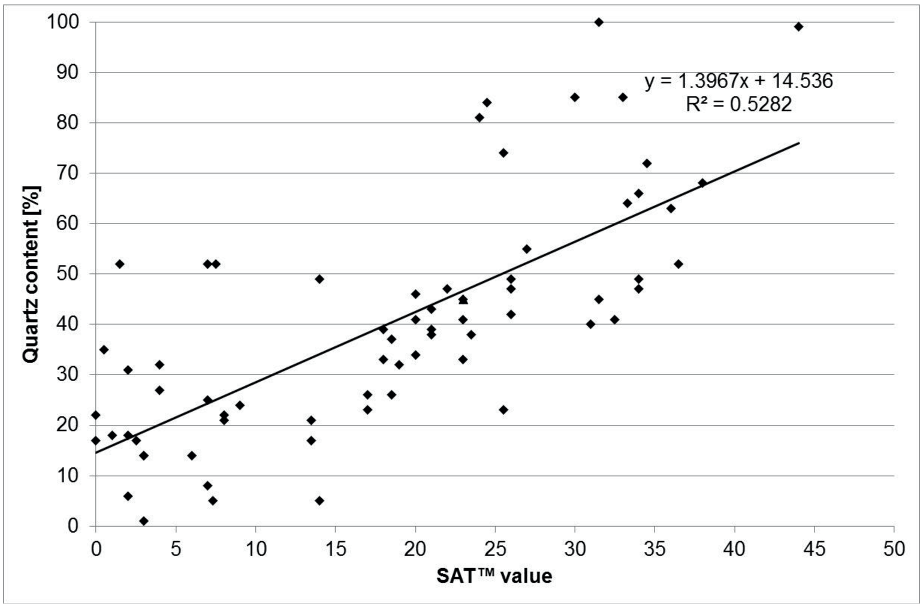


Figure 42. Correlation between SAT™ values and quartz content. N=70.

Table 7. SPSS output data on the bivariate correlation between SAT™ values and quartz content.

	SAT-QUARTZ
Pearson Correlation	.528
Sig.	.002
N	69

Figure 43 shows that the correlation between SAT™ values and the Vickers Hardness Number Rock (VHNR) contains data supplementary to those presented in Jakobsen et al. (2013a).This correlation has also been found to be statistically significant (Table 8).

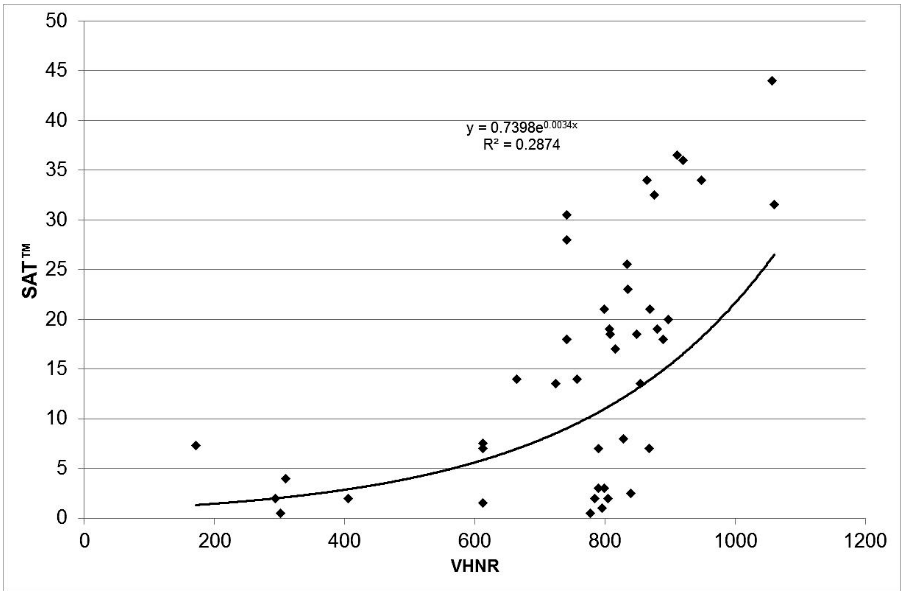


Figure 43. Correlation between SAT™ values and Vickers Hardness Number Rock (VHNR). N=30. (from Jakobsen et al. 2013a).

Table 8. SPSS output data on the bivariate correlation between SAT™ values and VHNR.

	VHNR-SAT
Pearson Correlation	.287
Sig.	.000
N	44

Some LCPC data have been obtained from a tunnel project owner following a recently completed TBM project in Austria. Some SAT™ values have been evaluated against these LCPC data (Figure 44). The figure shows a predominance of LCPC values of approximately 500, with SAT™ values vary from between 3 and 26. The variation in the SAT™ and LCPC values requires further analysis when new data becomes available. The relationship between SAT™ and LCPC values is classified as “weak to medium” according to the definitions presented in Section 3.3, and the correlation is not found to be statistically significant (Table 9). However, the volume of data available is insufficient as a basis for determining whether there is any form of correlation between the SAT™ and LCPC values.

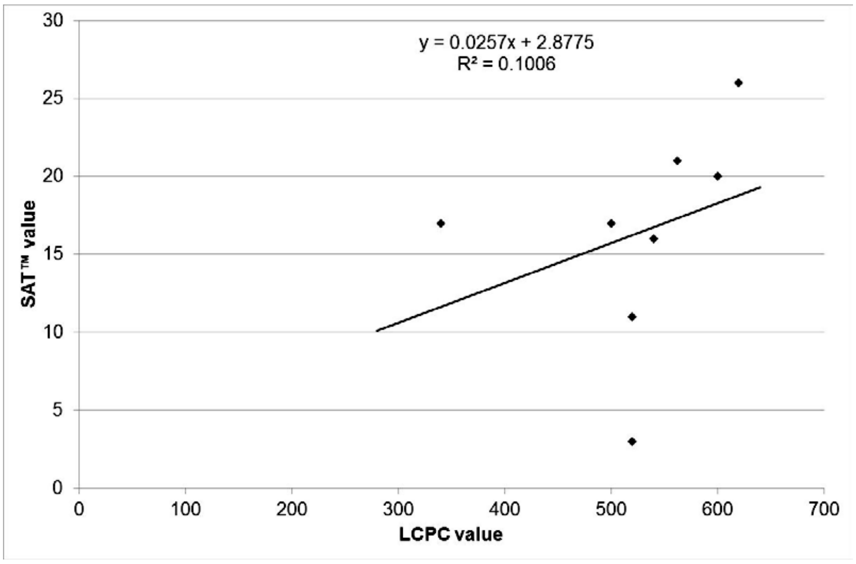


Figure 44. Correlation between LCPC and SAT™ values. N=8.

Table 9. SPSS output data on the bivariate correlation between SAT™ and LCPC values.

	SAT-LCPC
Pearson Correlation	.317
Sig	.444
N	8

Since the publication of Jakobsen et al. (2013a), which includes a correlation between SAT™ and soft ground tool life, new numerical and empirical data have been obtained (Figure 45 and Table 10). The main difference in terms of the correlation is the influence of data obtained from a project with low SAT™ values and corresponding high tool life, which suggests that a logarithmic correlation provides a better fit to the data than the earlier exponential relationship. Table 11 has been prepared as a means of assessing the differences between the correlation presented in Figure 45 and that presented in Jakobsen et al. (2013a).

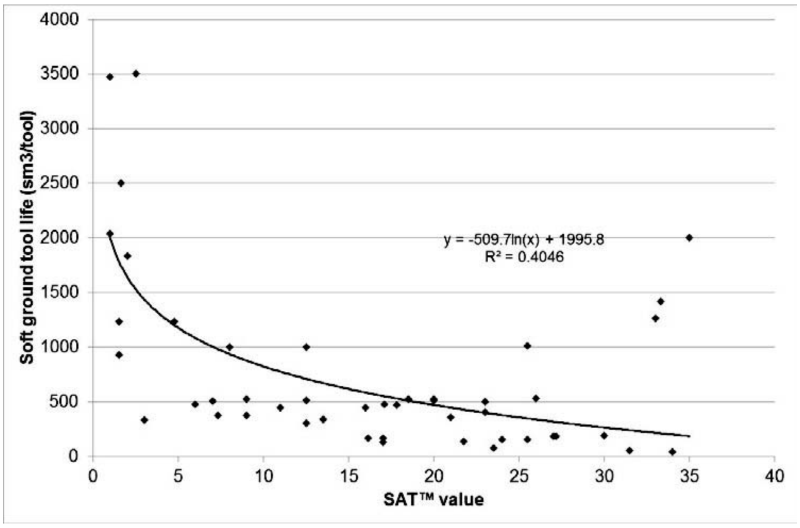
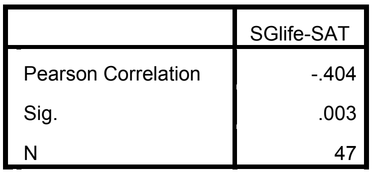


Figure 45. Correlation between SAT™ values and soft ground tool life.

Table 10. SPSS output data on the bivariate correlation between SAT™ values and soft ground tool life.



	SGlife-SAT
Pearson Correlation	-.404
Sig.	.003
N	47

Table 11. A sensitivity analysis between SAT™ tool life estimates referred to in this thesis.

SAT™ values	Estimate from Jakobsen et al. 2013a	Updated estimate
0.5	1171	2349
5	851	1175
10	597	822
15	418	615
25	206	355
35	101	183
50	35	2

The difference between the previous estimate (Jakobsen et al. 2013a) and the updated version is due to the introduction to the data set derived from a single project containing low SAT™ values with corresponding high tool life. One conclusion to be drawn from this is that the relationship between SAT™ values and soft ground tool life is not empirically saturated in the sense that the introduction of new data has had a major influence on the empirical relationship.

The introduction of new data since the publication of Jakobsen et al. (2013a) has made it possible to make rough comparisons of tool life data for EPB and slurry shield face support methods. Figure 46 shows; a) the correlation between all available soft ground tool life data and SAT™ values (black regression line and corresponding formula), b) for EPB soft ground tool life and SAT™ values (green line) and c) for slurry soft ground tool life and SAT™ values (red and purple lines). The red line includes all slurry data, while the purple line excludes four outliers (see also Figure 40). These outliers are derived from slurry shield tunnelling projects carried out in single-graded sands with high quartz contents and correspondingly high SAT™ values. Due to their single-graded distributions, these soil types did not generate high contact forces between the excavation tool and the tunnel face, hence the reduced incidence of abrasive wear and longer tool life.

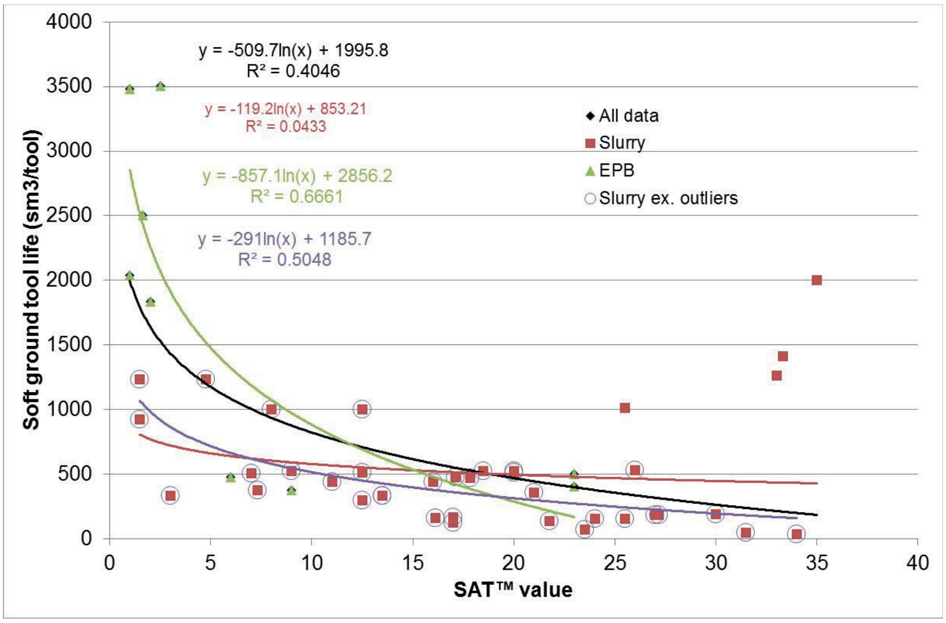


Figure 46. Correlation between SAT™ values for slurry and EPB tool life.

4.3 Soft Ground Abrasion Tester

The design and development of the Soft Ground Abrasion Tester (SGAT) is a direct outcome of this PhD study. Almost all the results obtained to date are available and have been published (Jakobsen et al. 2013b). They demonstrate the ability of the SGAT apparatus to measure torque and thrust requirements in connection with small-scale drilling operations in soft ground. The apparatus also enables an evaluation of how variation in parameters such as compaction, water content, soil conditioning type and quantity influence thrust, torque and tool life.

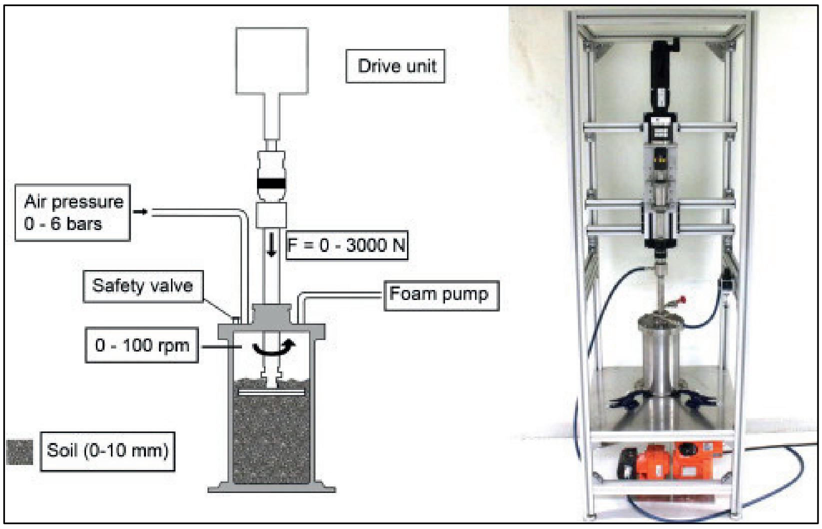


Figure 47. The SGAT apparatus.

There is currently no field data against which to test the validity of the SGAT. However, one of the samples tested by the SGAT was obtained from a formation known to have caused severe wear problems during an unnamed tunnel project completed in the mid-2000s. The SGAT values from this formation are high, ref. soil sample no. 3 described in Jakobsen et al. (2013b). This qualitative observation indicates that the SGAT provides promising results, and further research is currently being carried out (2013 - 2014).

The on-going research is focused on two areas; 1) the validity and usefulness of the SGAT for estimating thrust, torque and wear on soft ground TBMs in different soft ground conditions, and 2) the reliability of the test results (variation within the test results). Item 1 has already been commenced and involves the previously mentioned investigations in connection with the follow up at a major slurry TBM project in Europe. Figure 48 shows the grading curves for 3 soil samples obtained from this project, and Figure 49 SGAT wear measurements on 3 samples with varying water content, and with and without bentonite. The use of bentonite reduces wear by 50% compared to an unconditioned sample. This finding corresponds with those presented in Jakobsen et al. (2013b), which reported that rates of wear can be reduced to 20% of that observed for an unconditioned sample if the correct type and amount of soil conditioning foam is used.

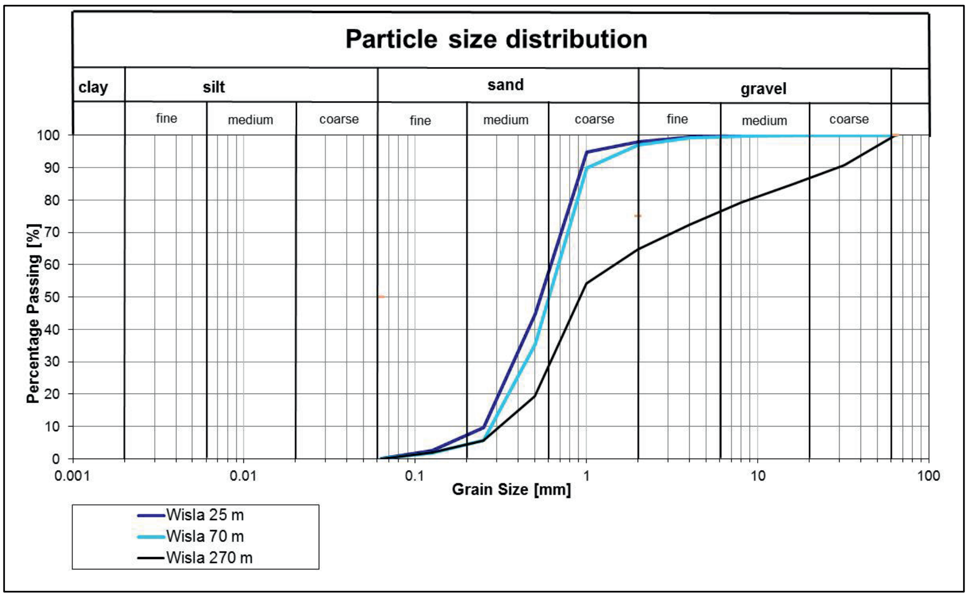


Figure 48. Grading curves for some of the samples obtained during follow up at the ongoing slurry project in Europe.

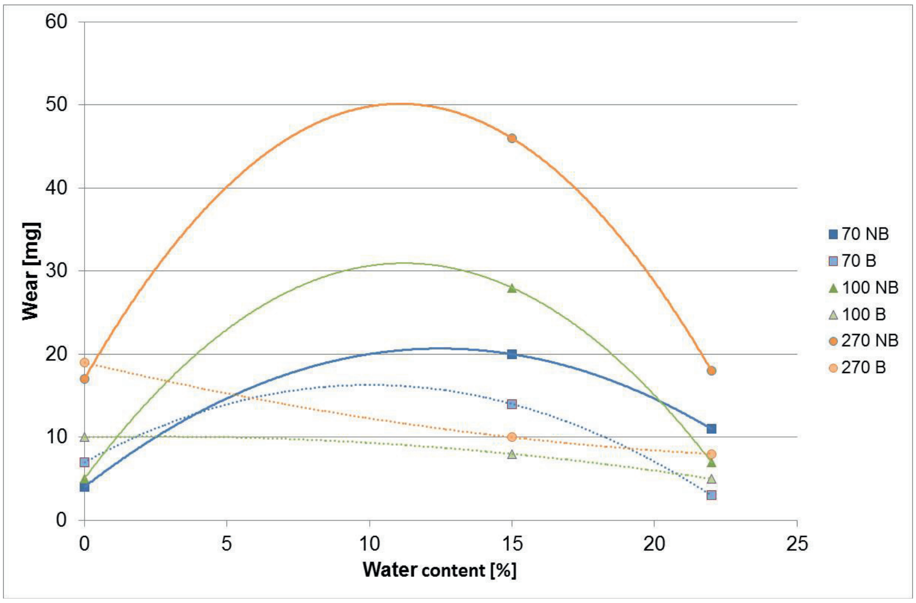


Figure 49. SGAT wear measurements on 3 soil samples an ongoing European slurry TBM project. The legend indicates the tunnel length in metres and the presence (B) or absence (NB) of *bentonite*.

4.4 Other estimators

During the collection of soft ground tool life data and soil samples for laboratory testing, several other parameters were acquired. In this Chapter, the following factors are investigated:

- The influence of soil mechanical strength as measured by the Index of Uniformity, also referred to geotechnical Uniformity Index and C_u on soft ground tool life
- The influence of overburden on soft ground TBM tool life
- The influence of TBM excavation diameter on soft ground TBM tool life
- The influence of quartz content on soft ground TBM tool life
- The influence of rock hardness as measured by the Vickers Hardness Number Rock (VHNR) on soft ground TBM tool life.

These factors have been investigated using bivariate correlations against the variable "recorded soft ground tool life".

Overburden data have been investigated using the One-Sample-Kolmongorov-Smirnov Test to see whether or not they exhibit normal distributions. The results showed that the data were not normally distributed, so the relationship between soft ground tool life and overburden has been evaluated using the Spearman significance test.

4.4.1 Geotechnical Uniformity Index, C_u

The Geotechnical Uniformity Index (C_u) is a measure of the range of grain sizes (uniformity of grain size distribution) within a given soil sample (Emdal 2002). The uniformity of grain size of a soil influences its mechanical properties such as compressibility and shear strength, and is relatively easy to obtain using sieve tests. The index is calculated using the following equation;

Equation 2 $$C_u = \frac{D_{60}}{D_{10}}$$

where D_{60} and D_{10} are the grain diameters of the 60% and 10% passing fractions, respectively.

Figure 50 shows the correlation between C_u and soft ground tool life, and the data in Table 12 indicates that the bivariate correlation is statistically significant. The correlation is biased significantly by a single outlier C_u value equal to 12. According to ASTM (2011), C_u values for well gravel are greater than 4, and for well graded sands greater than 6. Sieve curves obtained from moraine deposits in Norway have produced C_u values ranging from 22 to 180 (Emdal 2002). In order to achieve such well graded materials, rock fractions including fines are required. A C_u of 180 is thus regarded as an extreme value.

The absence of C_u values between 6 and 12 indicates that this trend is far from having achieved empirical saturation.

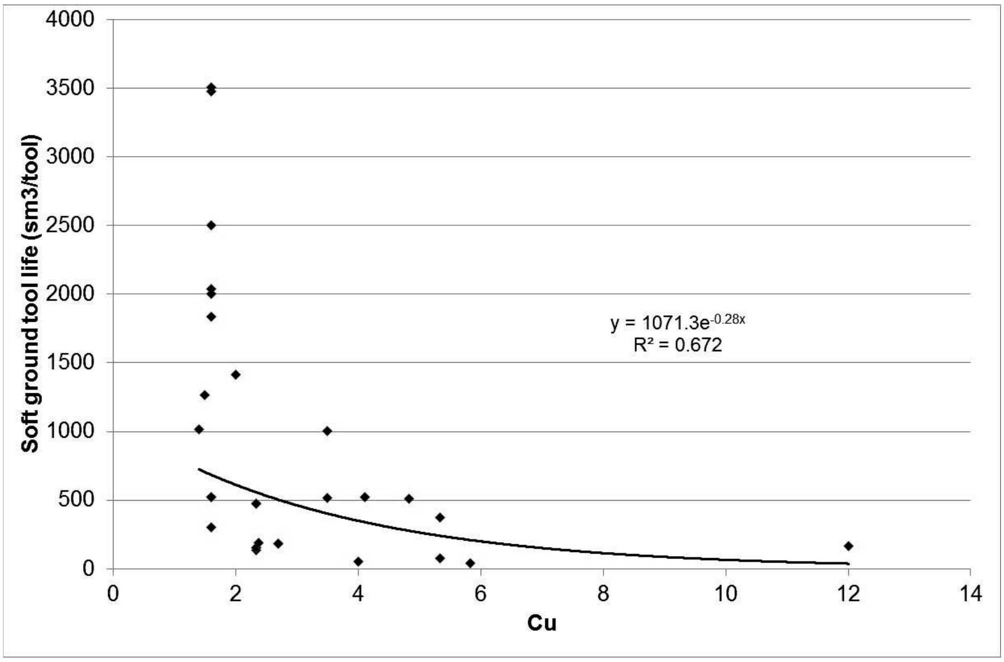


Figure 50. Correlation between the Geotechnical Uniformity Index (C_u) and soft ground tool life.

Table 12 SPSS output data on the bivariate correlation between the Geotechnical Uniformity Index (C_u) and soft ground tool life

		Cu-SGlife
Spearman's rho	Correlation Coefficient	-.672
	Sig. (2-tailed)	.000
	N	29

4.4.2 TBM diameter

Experience from hard rock TBM tunnelling demonstrates that an increase in TBM diameter results in longer cutter life (Bruland 2000). The main reasons for this are as follows;

- The ratio of face cutters to centre and gauge cutters increases with increasing TBM diameter. The face cutters are exposed to more favourable working conditions than the centre and gauge cutters.
- As TBM diameter increases, the average cutter on a cutter head has a less curved rolling track which probably results in lower lateral forces on the cutter ring (Bruland 2000).

In order to check if this also applies to drag bits, ripper tools and scrapers in soft ground tunnelling, TBM diameter has been correlated against soft ground tool life (Figure 51). The figure shows that, based on the collected data, TBM diameter must be disregarded as an appropriate estimator independent of other variables. The correlation was also found not to be statistically significant (Table 13). However, it is expected that excavation diameter may influence relative tool life in connection with projects involving soft ground and soils with similar abrasivity properties.

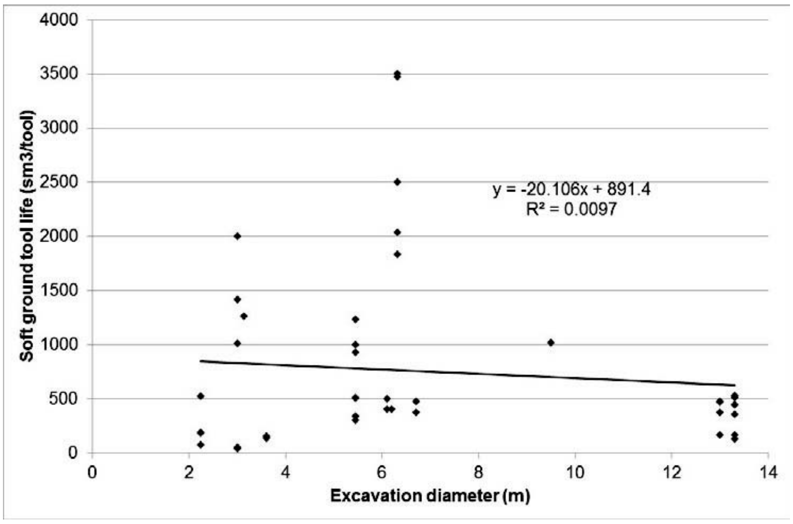


Figure 51. Correlation between TBM excavation diameter and soft ground tool life.

Table 13. SPSS output data on the bivariate correlation between TBM diameter and soft ground tool life.

	Diameter-SGLife
Pearson Correlation	.009
Sig. (2-tailed)	.693
N	41

4.4.3 Overburden

Köhler et al. (2012) presented the relationship between tool wear (pieces per metre of tunnel) and overburden thickness from the recently completed Inntal project in Austria, and a meaningful correlation was achieved. This would be as expected since increasing overburden thickness usually increases compaction and in-situ density, which in turn require higher torque and thrust from the TBM, thus resulting in higher contact forces between the excavation tools and the tunnel face. This reasoning has been investigated using a bivariate correlation between recorded tool life and overburden thickness for all the projects in this thesis (Figure 52).

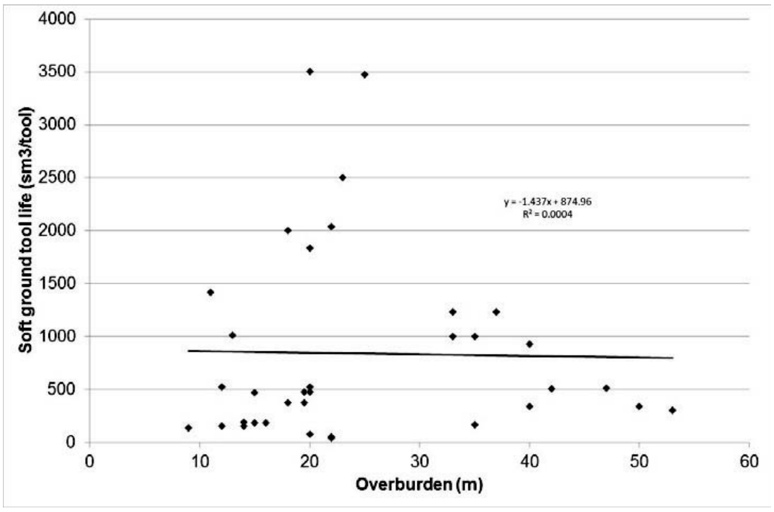


Figure 52. Correlation between overburden and soft ground tool life.

Table 14 shows the statistical output for the bivariate correlation between soft ground tool life and overburden. It can be seen that based on the low correlation coefficient of 0.0004 and the high Sig (0.413 > 0.05), no correlation emerges from the current data set. However, it is expected that overburden may influence the tool life in connection with projects involving soft ground and soils with similar abrasivity properties.

Table 14. SPSS output data on the bivariate correlation between overburden thickness and soft ground tool life.

		Overburden-SGlife
Spearman's rho	Correlation Coefficient	.000
	Sig. (2-tailed)	.413
	N	36

4.4.4 Mineralogical content

The mineralogical content of rock and soil is expected to influence soft ground tool life. Several researchers have used abrasivity tests to demonstrate relationships between the presence of quartz and other hard and abrasive minerals and tool life (Tamrock 1999; Nilsen et al. 2006a; Deutsche Vereiningung für Wasserwirtshcaft 2008; Frenzel et al. 2008; Dahl et al. 2012). In order to validate the influence of various minerals on soft ground tool life, correlations have been carried out using the parameters quartz content and Vickers Hardness Number Rock[8] (VHNR).

Quartz content is found to provide a statistically significant, medium to good, correlation with soft ground tool life (Figure 53 and Table 15). The correlation is influenced somewhat by four data sets in which the quartz content was zero (0%), and which all recorded high soft ground

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[8] See paper 6 for explaination of Vickers Hardness Number Rock (VHNR).

tool life values – greater than 1500 sm^3/tool. By changing these quartz content values from 0% to 0.5%, a logarithmic correlation would have been achieved, resulting in a correlation coefficient of around 0.5.

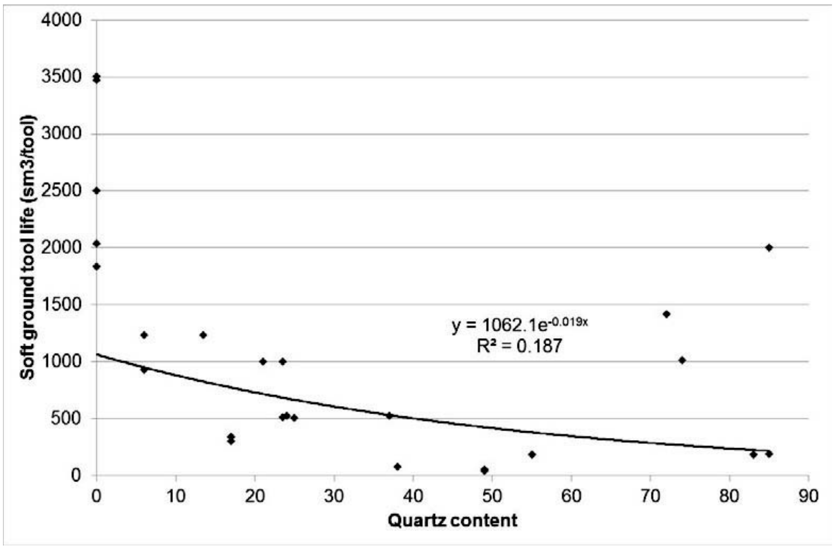

Figure 53. Correlation between quartz content and soft ground tool life.

Table 15. SPSS output data on the bivariate correlation between quartz content and soft ground tool life.

Correlations

		Quartz-SGlife
Spearman's rho	Correlation Coefficient	-,187**
	Sig. (2-tailed)	,003
	N	26

The total mineralogical content of the soil samples, as expressed by the VHNR parameter, is found to result in a statistically significant, medium to good, correlation with soft ground tool life (Figure 54, Table 17). However, the correlation shows that tool life increases with increasing VHNR (representing the presence of a higher fraction of harder minerals). This trend is also observed in the correlation with quartz content (Figure 53), and is clearly the opposite of what is expected. The reason for this is most likely the lack of sufficient data sets on which to base the correlation.

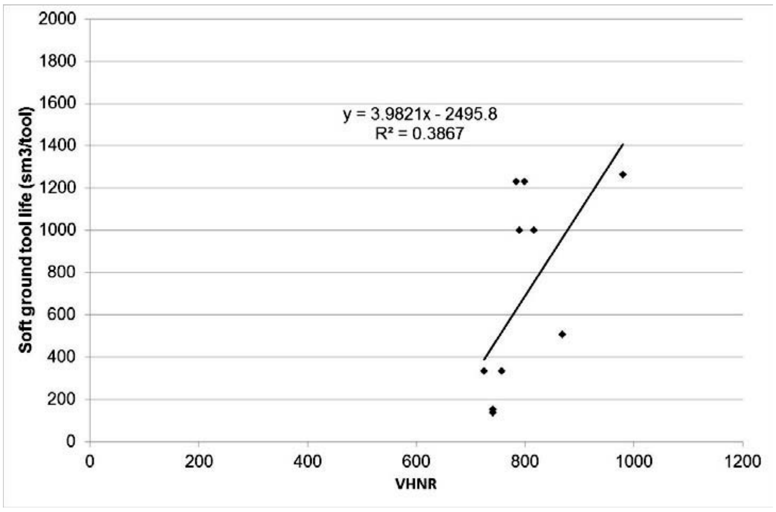

Figure 54. Correlation between VHNR and soft ground tool life.

Table 16. SPSS output data on the bivariate correlation between VHNR and soft ground tool life.

		VHNR-SGlife
SGlife	Pearson Correlation	.387
	Sig. (2-tailed)	.041
	N	11

4.5 Comments and analyses

The results from the current data sets described in Sections 4.2 and 4.4 demonstrate that there is a relationship between SAT™ values and the C_u coefficient and soft ground tool life, and that we observe statistically insignificant correlations between the parameters overburden thickness and TBM excavation diameter, and soft ground tool life. The SAT™ and Cu parameters are found to be independent variables (Figure 55), and can thus be used as independent predictors in a multivariate regression analysis.

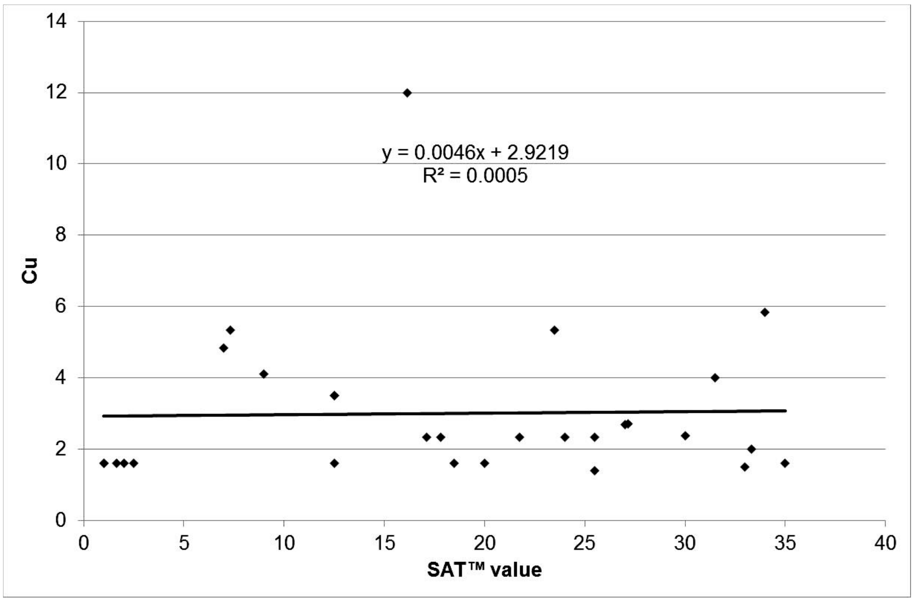

Figure 55. Correlation between the Geotechnical Uniformity Index (C_u) and SAT™ values.

Based on the linear relationships encountered between SAT™, C_u and soft ground excavation tool life, and their possible application as tool life estimators, the following empirical formula is proposed (see Table 17):

Equation 3 $$SGTL = 2245 - (44.7 * SAT™) - (180.3 * C_u)$$

where *SGTL* is soft ground tool life, *SAT* is the SAT™ value, and C_u is the Geotechnical Uniformity Index. The formula is obtained on the basis of the value ranges $0.5 < SAT < 35$ and $1.6 < C_u < 12$ taken from the field data.

Figure 56 shows the validity (or applicability) of Equation 3 for SAT™ values between 0.5 and 50, and C_u values between 1 and 12. The estimation results for the 90 percentiles of the SAT and C_u values (31.8 and 5.33) indicate a negative soft ground excavation tool life. The equation is found valid for the 85 percentiles of the SAT and C_u values (27 and 4.58), resulting in a soft ground excavation tool life estimate of 200. Thus, the equation is found valid for current 85 percentile values, but not valid for values greater than the 90 percentiles of the SAT™ and C_u values. The reason for the invalidity of the 90 percentile values can be explained by the low incidence of (very) well-graded soil material in the data sets. As already mentioned in Section 1.3, the scope of this thesis is limited to relatively homogenous soils, excluding the influence of boulders and large tunnelling obstacles. The reliability of Equation 3 is discussed in Section 5.4.

Table 17. SPSS data output of the multiple regression between soft ground tool life (dependent variable) and SAT™ values and C_u (independent variables)

	B	Sig
(Constant)	2244,544	,000
SAT	-44,724	,002
Cu	-181,382	,013

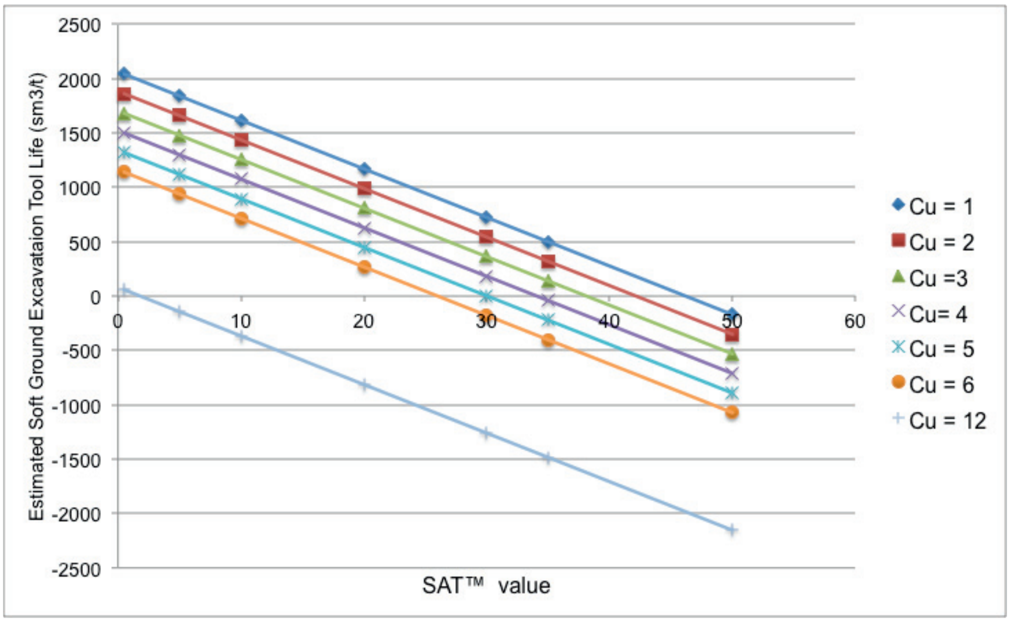

Figure 56. Validity analysis for equation 3.

The bivariate relationships shown in Figures 45, 46 and 50 are logarithmic and exponential, whereas equation 3 exhibits a linear relationship between SAT™, C_u values and soft ground excavation tool life.

5 Discussion

5.1 General

The estimation of soft ground tool life is important at nearly all stages of a TBM tunnelling project. A description or quantification of the abrasivity properties of the soil is essential during the design and preparation of tender documents. This information is assessed by tendering contractors and is used to plan project schedules and costs. Disputes related to ground conditions that arise during tunnelling projects often result in a process to obtain quantitative measurements of soil properties in order to make comparisons with data submitted in the tender documents. Hopefully, the results obtained from this PhD study can provide documentation and a methodology to assist the calculation of estimates of soft ground TBM tool wear based on soft ground and soil abrasivity. These results can be evaluated and applied in pre-investigations, disputes and risk management, as well as in further research.

Some of the soil samples used for abrasivity testing have been derived from excavated muck containing soil conditioning additive residues such as foam and bentonite. A series of tests has been carried out to investigate the reliability of the results. The sample preparation procedure was as follows;

- The drying of virgin soil samples not exposed to bentonite or foam
- The addition of 15 weight per cent of water to the virgin soil samples
- The addition of FIR 50 foam and a corresponding 50 volume per cent of bentonite suspension to the moist virgin soil sample
- The drying of conditioned soil samples
- The addition of 15 weight per cent water to soil samples prior to testing.

Figure 58 shows SGAT results demonstrating that the influence of foam and bentonite residues is within the expected variation of SGAT apparatus results as described by Jakobsen et al. (2013b). Similarly, SAT™ values for soil samples containing conditioning residues are found to be within the expected variation of SAT™ test results.

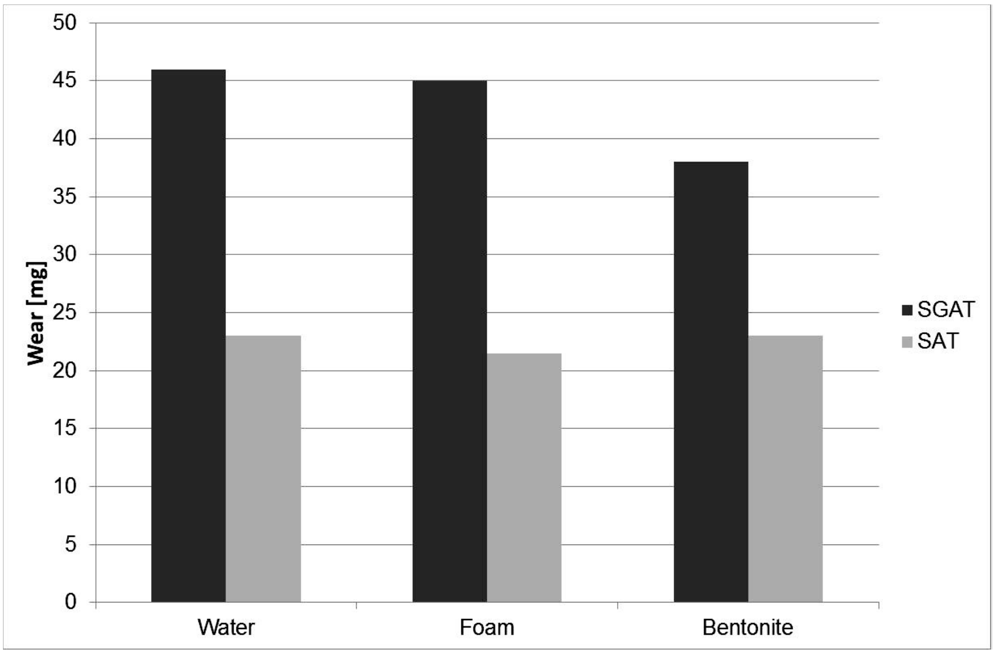

Figure 57. SGAT wear measurements on soil both with (foam and bentonite*)*
and without (water only) soil conditioning additives

The C_u values were obtained by sieving and grain size distribution evaluations carried out in Trondheim. Clients may have removed coarse particles and fragments from some of the samples prior to shipment, which would result in lower than true C_u values for the in-situ soils.

The parameters overburden thickness and TBM diameter did not produce statistically significant correlations with soft ground tool life. However, it is proposed here that in the presence of constant geological conditions and geotechnical properties, an increase in overburden thickness should in fact decrease tool life, since an increase in overburden thickness should promote compaction of in-situ soil. As a result, overburden probably does influence tool life in some projects, given that ground conditions along a tunnel are often fairly constant, having a similar mineralogical content, grain shape and grain size. Thus, in projects involving tunnels driven through a homogenous geology (with constant geotechnical properties) it is likely that increased overburden thickness will in fact decrease tool life. This is also a likely explanation for some results published in the literature (Köhler et al. 2012).

The predictive model for tool wear developed by the Japanese Tunnelling Society provides an interesting approach worthy of further study and development. However, due to language difficulties, attempts to obtain empirical data from the model were unsuccessful. The main weakness of the Japanese model is the use of the wear coefficient (K), which is not at present a measureable entity. A measurement and evaluation of the wear coefficient, involving a relatively simple test (SAT™ or LCPC) would be of great interest.

In the following, inconsistencies found during the research, and the validity of the results, will be discussed.

5.2 Inconsistencies observed during research

Some inconsistencies have been observed during both development of the SGAT apparatus and parallel attempts to develop an estimation model for soft ground and soil abrasivity using this device.

Figure 58 shows that there are inconsistencies between the range of measured wear values obtained from the SAT™ and SGAT tests. Soil sample 3 exhibits the lowest wear value using the SAT™ test, but the highest wear using the SGAT test. This can be explained by the following;

- SGAT wear incorporates the compactibility of the soil sample, which in turn also influences wear
- The mineralogy of soil sample 3 consisted of fine particles (silt) combined with minerals exhibiting low abrasivity such as mica and calcite, and coarser particles (sand and fine gravel) containing quartz. In the SAT™ procedure a fraction of the abrasive minerals are sieved out, thus reducing the wear value obtained from this test. In the SGAT test, the fines created a cohesive paste resulting in higher abrasivity and consequently a higher wear value.

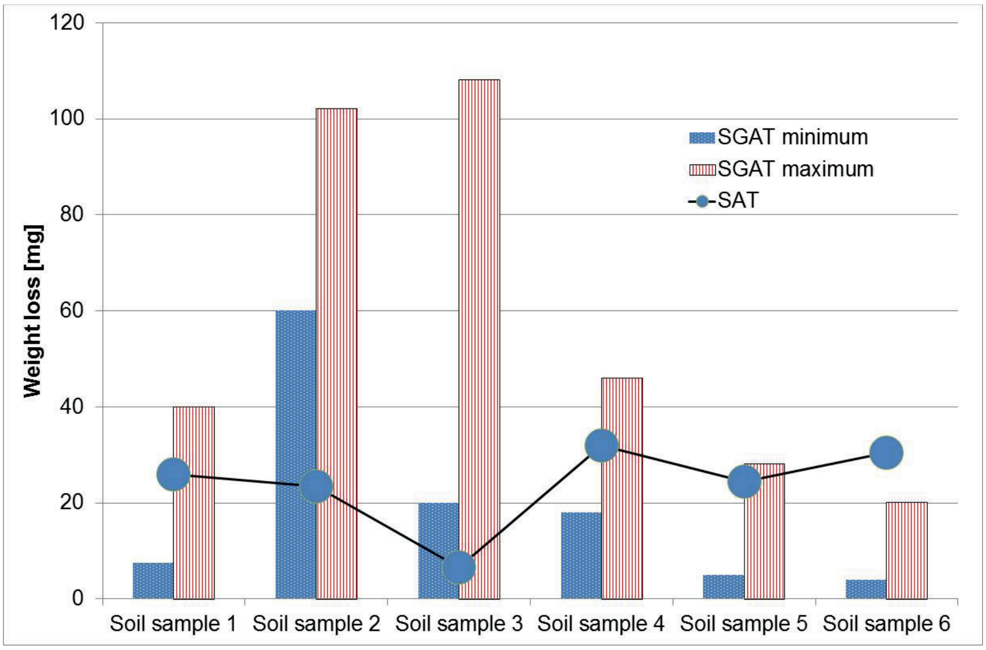

Figure 58. Relationships between wear values derived from SAT™ tests and weight loss measured using the SGAT apparatus.

As is demonstrated in Paper 8 and Figure 49 (this thesis), the SGAT apparatus has the ability to evaluate the effects and benefits of soil conditioning. An increase in wear and required torque is observed in the case of all dry soil samples tested containing conditioning additives (various foams and bentonite). This is the opposite of what is expected in the presence of soil conditioning. The likely explanation for this is that dry soil absorbs the moisture in the conditioning medium, thus increasing the cohesion of the soil. This effect is also reported from two EPB projects carried out in Switzerland and Germany, where the introduction of low concentrations of soil conditioners reduced TBM tool life (Jakobsen et al. 2012).

The correlation between Vickers Hardness Number Rock (VHNR) and soft ground tool life (Figure 54) demonstrates that tool life increases with increasing VHNR. This is contrary to observations made of the relationship between quartz content and soft ground tool life. The reason for this inconsistent result is explained by insufficient data.

5.3 Literature

The initial literature search revealed a lack of available material addressing estimations of abrasive wear in connection with soft ground TBM tunnelling. During the period of this PhD study (2010-2013) the volume of relevant literature has increased. Test apparatuses used prior to my PhD studies were designed to determine hard rock abrasivity, and as such lacked the ability to measure the influence of in-situ conditions such as water content, density/compaction and undisturbed grain size distribution.

During the latter phase of the study (2012-2013), some “in preparation” literature concerning dedicated test apparatuses for the determination of soil and soft ground abrasivity was encountered. Most of the papers and other available literature address the details of laboratory tests, wear problems related to a specific project, or relevant re-published empirical experience and theories. There is a lack of literature dealing with comparisons of estimation models for tool life in connection with real soft ground TBM projects. The likely reasons for this are as follows;

- This topic is a relatively “new” area of industrial research, resulting from the construction of longer and more complex tunnels in soil and soft ground
- It is difficult to obtain soil samples and corresponding field data, and data owners (mainly contractors, sometimes clients) wish to keep their data confidential

5.4 Estimation of soft ground TBM tool life

The results presented in Figures 45 and 46 indicate that the relationship between the Soil Abrasion Test (SAT) ™ value for wear and soft ground tool life is logarithmic. Current correlations have used a total of 49 TBM downtimes due to tool changes. These downtimes includes several replaced tools. Since the existing correlation has not reached empirical saturation, the addition of more data is likely to influence the result. The best correlation coefficients shown in Figures 45 and 46 lie in the range 0.4 to 0.5. This means that 40 to 50 per cent of the variation in the recorded soft ground excavation tool life data is accounted for by the estimator derived from the SAT™ tests. The remaining 50 to 60 per cent can be explained by the following;

- The SAT™ samples are selected as being representative for the longer section of the tunnel in question. However, samples are in practice derived from a very small portion of the tunnel, and as such laboratory testing cannot account for all the variation in the soil material along a tunnel.
- The influence of TBM design is not taken into account.
- The influence of TBM operation is not taken into account.
- The influence of the types and concentrations of soil conditioning additives is not taken into account.
- Some of the projects consist of soil material larger than 4 mm, meaning that a portion of the sample is removed prior to SAT™ testing.

By combining SAT™ values and the geotechnical uniformity coefficient, an estimation of tool life is derived which incorporates both the grading curve (representing compactibility), and the abrasive properties of the soil. The tool life estimate derived from this approach is found to be more reliable than that derived from bivariate analysis. One advantage of using this estimate is that it only requires a small quantity of sample. This greatly speeds up sample collection, shipping and laboratory testing. The disadvantages of this estimate are the lack of precise soil compaction data and the fact that it fails to take the influence of soil conditioning additives into account.

The reason for not introducing approaches such as multivariate logarithmic regression is that the current data sets are too small to enable the interpretation of cut-off values. A cut-off value divides a data set in two groups, and is a prerequisite for the multivariate logarithmic regression approach. In the context of this study, such groups might be characterised as “non-problematic soft ground excavation tool life” and “problematic soft ground excavation tool life”. Such studies may be evaluated at a later stage as the number of data sets available increases.

Tool life data from an ongoing slurry TBM project are used to evaluate the validity of equation 3 and the empirical regression formulae presented in Figures 45, 46 and 50.The project consists of a 2-tube sub-river tunnel excavated using a single 12.5 m-diameter slurry shield TBM (Figure 59). The ground conditions consist mainly of three strata; 1) silt and sand, 2) sand, and 3) sand and fine gravel. After excavating 470 metres at drive 1, a total of 208 scraper tools were replaced due to abrasive wear and some impact wear (Figure 60). The tool life at tunnel metre 470 is calculated as 57650/208 = 277 sm^3/t.

Figure 59. The slurry shield TBM being used to excavate the ongoing TBM project used for assessment of the validity of the estimators in the PhD study. (Photo taken from www.tunneltalk.com).

Figure 60. Worn-out scraper tools from slurry TBM used for assessment of the validity of the estimators in the PhD study (Photo by Wojtek Smolen).

SAT™ values have been measured at tunnel metres 10, 25, 70, 100, 250 and 350, and exhibit an average of 28.7 with a standard deviation of 2.5%. The low standard deviation indicates that abrasivity encountered between tunnel metres 10 and 350 is relatively constant.

The geotechnical uniformity index (C_u) has also been measured, exhibiting an average value of 4.08 with a standard deviation of 32.2%. This relatively high standard deviation is the result of variation among the grading curves between tunnel metres 10 and 350.

Figure 61 shows a comparison between different soft ground tool life estimates and the recorded actual tool life from the followed up slurry TBM project. The validities of the soft ground tool life equation (equation 3), and the C_u (see Figure 46) and SAT (see Figure 45) parameters are good, as their values depart from the real tool life data by less than 20%.

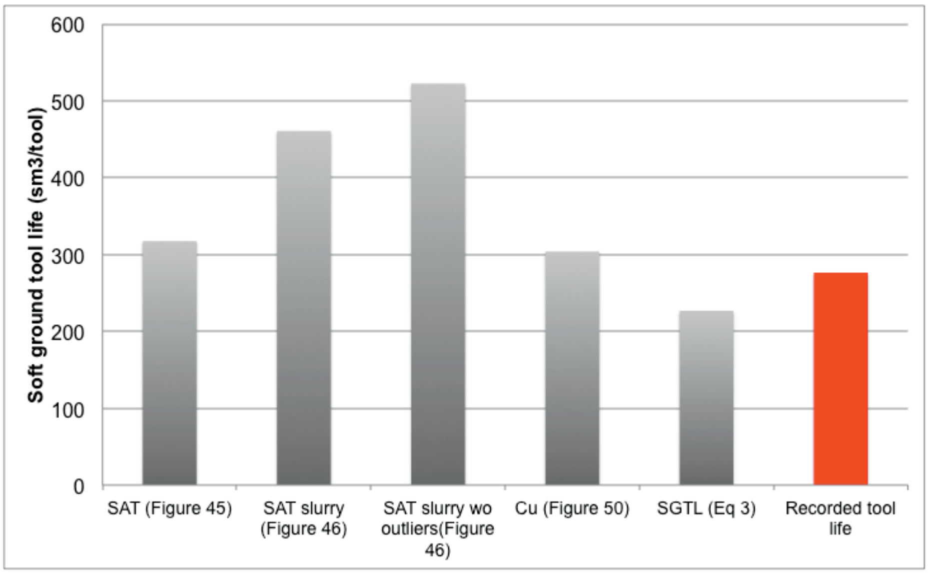

Figure 61. Various soft ground excavation tool life estimates compared with real tool life data from the followed up onging slurry project in Europe.

The Soft Ground Abrasion Tester (SGAT) has been developed even though the various simplified estimators exhibit good validity (Figure 61), because in the form of a single test it provides a direct value which takes into account the influence of factors such as water content, density/compaction and the use of soil conditioning additives on steel life. It is expected that this test procedure will exhibit improved validity compared to SAT™ estimates, since the real world contact relationship between the steel and the soft ground contact is better reflected by this approach. At present no measurements are available to confirm or otherwise as to whether the SGAT provides more valid results than other estimators.

The SGAT test requires approximately 8 kg of soil material, compared to the 0.5 kg requirement of the SAT™. In the case of abrasivity measurements and assessment, the SAT™ test remains dominant, while the SGAT apparatus is useful for specific applications such as the optimisation of soil conditioning additive concentrations. Test results obtained using the SGAT apparatus indicate a reduction in wear in the presence of high water content, indicating that water is a good conditioning additive. However, exposure of a tunnel face in soil to too much water will significantly affect soil rheology. If the soil is too fluid, face stability may be affected, creating difficulties for soil transportation through the screw conveyor or slurry lines.

6 Conclusions and recommendations

6.1 Comparison between thesis findings and the PhD plan

The initial main goals of this study on abrasive wear on TBM tools used to excavate soil and soft ground were as follows;

1. To find a reliable and versatile methodology for determining the potential of soil and soft ground to cause abrasive wear on TBM tools.
2. To propose an index or simplified model for estimating tool life in connection with soil and soft ground excavation projects (Jakobsen 2010).

In order to achieve this, three underlying objectives and sub-tasks were defined and planned;

a) To obtain TBM field data and soil samples for laboratory testing in sufficient amounts to generate a statistical model. The term sufficient at this initial stage is taken to mean data and corresponding samples from 5-10 projects carried out in varying ground conditions (e.g. clay, silt and sand).
b) To evaluate the results of current laboratory methods against observed abrasive wear, based on correlations between laboratory measurements and field observations.
c) To propose a new laboratory method which enables the testing of abrasive wear resulting from reconstructed in-situ soil and soft ground (involving the properties soil density, pressure, large grain size distribution range, and the use of soil conditioning additives). To evaluate if the suggested new laboratory tests provide a better estimate than current (2010) procedures.

Main goal 1 has been achieved by means of the SAT™ test procedure, 313 SAT™ tests and accompanying documentation. *Main goal 2* has been met by means of the correlations documented between SAT™ values and soft ground tool life, and between SAT™ values and the geotechnical uniformity index's relationship to soft ground tool life.

Sub-task (a) has been achieved following the acquisition of relevant field data from 16 unique projects (Table 4). *Sub-task (b)* has been achieved following the results presented in Chapter 4 and summarised in Paper 6. *Sub-task (c)* has been partly achieved by means of the development of the SGAT apparatus. However, no clear conclusion can be drawn at present as to whether estimations of wear from the SGAT apparatus are better than those generated by other, more simplified, approaches such as SAT™ or LCPC.

6.2 Conclusions

The main contributions of this research fall into three groups; 1) general findings, 2) recommendations related to the Soil Abrasion Test and simplified estimators, and 3) the development of the Soft Ground Abrasion Test and subsequent recommendations.

1) General findings

- Soil and soft ground abrasive wear results in reduced TBM performance, which often leads to disputes between project owners.
- TBM downtime resulting from tool replacement is expensive, and should be taken into account both in tendering contractors' bid documents and project owners' schedules. Pre-investigations should thus be carried out prior to the tender process to provide a basis for assessing tendering contractors.
- There are several methods which can be used to provide an estimate of soil abrasivity in order to assess soft ground TBM tool wear. These include the NTNU Soil Abrasion Test™, the LCPC abrasivemeter, and the Penn State Soil Abrasion System.

2) Recommendations related to the Soil Abrasion Test™ and simplified estimators

- Results from the Soil Abrasion Test (SAT™) provide a good correlation with recorded soft ground excavation tool life.
- Results from the SAT™ can be used to schedule downtime and maintenance of TBM excavation tools.
- SAT™ values correlate well with grain mineralogy and grain shape.
- SAT™ values should be assessed together with in-situ soil parameters, such as the geotechnical uniformity index (C_u), in order to estimate soft ground tool life.
- The C_u value correlates well with recorded soft ground tool life.
- Quartz content provides a medium to weak correlation with recorded soft ground tool life.

3) The development of the Soft Ground Abrasion Tester and subsequent recommendations

- The development of the Soft Ground Abrasion Tester (SGAT) has been an important contribution of the PhD study.
- Steel wear measured by the SGAT is influenced by properties of the soil such as mineralogy, grain size distribution and compaction.
- The moisture content of the soil influences wear due to its influence on compactibility.
- Soil conditioning additives and their applications can reduce rate of wear, and this reduction can be measured using the SGAT apparatus.

- The SGAT apparatus provides an indication of the thrust and torque necessary to drill a soil sample to a given penetration. There is a clear correlation between wear and the required torque.

6.3 Further work and future perspectives

The scope of, and results included in, this study are limited to soft ground and soil fragments less than 10 mm in diameter, and abrasive wear on soft ground TBM tools. A natural extension of this work would be to conduct a systematic and extensive study on all the wear processes listed in Table 2, and to include the influence of boulder and mixed face conditions on TBM excavation tools.

Studies addressing the impact on excavation tools caused by boulders and mixed face conditions are lacking, even though the tunnelling industry is eager to obtain knowledge on this issue. Estimates based on pre-investigations are available in part in publications such as (Gudbjartsson and Iversen 2003; Zhao et al. 2007; Ozdemir 2008; Jung et al. 2011; Tóth et al. 2013). However, these articles direct their focus on single project issues with no attempt to collate and normalise data from other projects for parameters such as variation in ground conditions and TBM diameter. Such research would provide a sound basis for a doctorate thesis provided that funding for field work is made available.

It may be possible to obtain an evaluation of the influence of mixed face at small laboratory scale using the Soft Ground Abrasion Tester. One possibility might be to introduce a loose material in to hardened and cemented material, and evaluate the effect by the SGAT. Another possibility might be to use a Hoek cell containing a mixed material (e.g. a variety of gravel clast sizes of varying hardness) and conduct Cerchar Abrasivity Index (CAI) tests according to the procedure suggested by Alber (2008).

In terms of the influence of soil conditioning additives, the work presented in this thesis consists only of a few laboratory trials and the consideration of a limited number of qualitative field observations. In order to fully understand, and provide quantitative estimates of, soil conditioning additives on TBM thrust, torque and tool life, further field and laboratory studies will be required. Future laboratory studies on soil conditioning additives should include testing to assess soil rheology.

Human factors linked to TBM operation and design have not been addressed in this thesis. It would be impossible, or at best extremely difficult, to carry out large-scale trials comparing different TBM designs and operational approaches under constant ground conditions. However, the work conducted on EPB tunnelling and soil conditions at TU Ruhr provides some indications about soil rheology behaviour, also following conditioning. These results indicate that there may be opportunities to extrapolate conditions in front of the TBM cutter head. Numerical analyses may provide another approach to the assessment of the influence of

TBM operation and design. The Research Council of Norway, Robbins TBM, BASF, *Jernbaneverket* (the Norwegian State Railways Administration), Scana Steel Stavanger and BMS Steel have together funded the FAST-Tunn research project which includes the development of a numerical model designed to evaluate rock breaking under disc cutters. This model may be adapted to address excavation in soft ground using drag bit tools, and to analyse the influence of TBM operation (Grøv et al. 2013).

The relatively small amounts of tool life data available to this thesis demand further studies to establish the ability of the SAT™ to estimate wear on ripper and scraper tools, and to provide distinct tool life wear estimates for EPB and slurry shield tunnelling. Moreover, the findings presented in Table 11 and Figure 45 indicates that more SAT™ values and recorded tool life data are required to improve the current estimator. However, it is highly unlikely that there will ever be sufficient data and samples available to provide an estimate with 100% predictive certainty.

The recently developed Soft Ground Abrasion Tester (SGAT) has not been evaluated against real TBM operations. Current test results (Jakobsen et al. 2013b) are promising, but do not provide a quantitative comparative analysis with real TBM data. However, data is currently being obtained from the previously mentioned ongoing slurry TBM project. The results of this work, including the influence of bentonite additives on thrust, torque and excavation tool life, will be published. There is also lack a comparative assessment of the SGAT conditioning scheme with real TBM operations. It is hoped that this will be addressed as part of the ongoing follow up at the slurry TBM project (which involves the collection of soil samples at 50 - 200 metre intervals) after tests on the soil's mechanical behaviour, mineralogy and/or grain size distribution variations have been carried out. Measured torque, thrust and wear values from the SGAT will be correlated with real TBM operations data taken from the project.

Concerning the reliability of the SGAT, this is currently under evaluation by PhD student Javier Macias as part of the "*Future Advanced Steel for Tunnelling Applications*" (FAST-Tunn) project funded jointly by the industry and the Research Council of Norway. This study will involve a systematic evaluation of test result variation, the re-use of steel tools, and the SGAT's response to crushed rock fragments.

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8 Published papers

Paper 1

Classifications of properties influencing the drillability of rocks, based on the NTNU/SINTEF test method

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Classifications of properties influencing the drillability of rocks, based on the NTNU/SINTEF test method

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ABSTRACT

The demand for representative rock property parameters related to planning of underground excavations is increasing, as these parameters constitute fundamental input for obtaining the most reliable cost and time estimates. The Brittleness Value (S_{20}), Sievers' J-Value (SJ), Abrasion Value (AV) and Abrasion Value Cutter Steel (AVS) have been used extensively at NTNU/SINTEF since the 1960s in connection with drillability testing of rock samples. Nearly 3200 samples originating from projects in 50 countries have so far been tested, and the method and associated prognosis model are internationally recognised for giving reliable estimates of time and cost for tunnelling. A classification of the NTNU/SINTEF drillability indices Drilling Rate Index™ (DRI), Bit Wear Index™ (BWI) and Cutter Life Index™ (CLI) has been available since 1998, but until now no official classification has been available for the individual tests used to calculate these indices. In this paper, classifications of the NTNU/SINTEF drillability test methods Brittleness Value (S_{20}), Sievers' J-Value (SJ), Abrasion Value (AV) and Abrasion Value Cutter Steel (AVS) tests will be described in detail. The presented classifications of the individual tests are based on statistical analysis and evaluations of the existing test results recorded in the NTNU/SINTEF database.

1. Introduction

Producing reliable and robust prognoses on cutter wear, drilling progress and related costs is becoming an increasingly sensitive issue for machine manufacturers and contractors dealing with operation of mechanical excavation systems in mining, tunnelling, and underground construction. Equally important for the clients and owners; cost and time estimates must have adequate quality. Representative and trustworthy parameters describing various rock properties, along with rock mass properties, are crucial as these constitute the fundamental input for obtaining the most reliable cost estimates. This is equally important when it comes to risk assessments described by terms such as "low" and "good" in tender documents, and situations where claims are filed during or following the construction period (Dahl et al., 2010).

The original NTNU/SINTEF drillability test method, formerly known as the NTH test (Selmer-Olsen and Lien, 1960), was developed in 1958–1961 for evaluation of the drillability of rocks by percussive drilling. The Drilling Rate Index™ (DRI) (Selmer-Olsen and Blindheim, 1970) is assessed on the basis of two laboratory tests, the Brittleness Value (S_{20}) test (Matern and Hjelmer, 1943) and the Sievers' J-Value (SJ) miniature drill test (Sievers, 1950). The DRI™ may be described as the S_{20} of rocks, also defined as the ability to be crushed by repeated impacts, corrected for the surface hardness determined by the SJ. The Bit Wear Index™ (BWI), which is used to estimate the wear rate of drill bits, is assessed on the basis of the DRI™ and the Abrasion Value (AV) (Selmer-Olsen and Lien, 1960). The AV is a measure of time dependent abrasion on tungsten carbide by crushed rock powder. The development of the Cutter Life Index™ (CLI) (NTH, 1983), which took place in the years 1980–1983, was based on the original NTH test method. The CLI™ has since the 1980s provided the possibility of estimating cutter life in connection with rock excavation by use of TBM. The CLI™ is assessed on the basis of SJ and the Abrasion Value Cutter Steel (AVS). The AVS test uses test pieces of steel from TBM disc cutter rings with specific properties, and it is regarded as a measure of time dependent abrasion on cutter ring steel.

Performance prediction and cost evaluation models for drill- and blast tunnelling, TBM tunnelling and rock quarrying have been developed by correlating laboratory tests and in situ geological data with production data from tunnelling projects. The models are continuously updated and revised as new tunnelling data become available (Dahl et al., 2010). In recent years the NTNU/SINTEF method has been used extensively in connection with cost/time estimates and planning of major international underground

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projects, and it is gaining acceptance as a recognised and widely used method for TBM performance prediction testing.

The NTNU/SINTEF drillability indices have recently been registered as trademarks (Dahl et al., 2010). NTNU/SINTEF is committed to ensure that all end users have confidence in these quantitative methods for describing drillability characteristics of rock by performing consistent and repetitive testing. Quality assured and reliable drillability test results is of vital importance in order to obtain the best possible time and cost estimates, which is the main reason for labelling the NTNU/SINTEF indices as trademarks.

A classification of the NTNU/SINTEF drillability indices DRI™, BW I™ and CLI™ has been available since 1998 (Bruland, 1998), but there has until now not been any officially published classification available for the individual test values used to calculate these indices. The increasing use of the NTNU/SINTEF drillability test method has generated a demand for a classification of the individual tests, in addition to the existing classification of the drillability indices. This paper presents classifications of the S_{20} test, SJ-Value test, AV test and AVS test, based on the existing test results, recorded in the NTNU/SINTEF database.

It is essential for everyone involved in planning of underground excavations to gain a proper understanding of how various individual rock properties can influence the drillability of rock and hence time and cost. The classifications are intended to act as an important aid in that respect.

2. Principle and specifications of the NTNU/SINTEF test methods

2.1. Rock brittleness determined by the Brittleness Value (S_{20}) test

There are several different methods used for determination of rock brittleness (Yarali and Kahraman, 2011). The brittleness test method, utilised by NTNU/SINTEF, was originally developed in Sweden by Matern and Hjelmer (1943). The original test was initially intended for determination of strength properties of aggregates, but several modified versions of the test have later been developed for various purposes. The version of the S_{20} test developed for determination of rock drillability has been used since the end of the 1950s (Fig. 1).

S_{20} constitutes a measure of the rock brittleness or ability to be crushed by repeated impacts, and it is determined by use of an impact apparatus. S_{20} is defined as the percentage of a pre-sieved fraction that passes through the finer sieve after 20 impacts. The S_{20} test is normally performed on three extractions from one representative and homogenised sample of crushed and sieved rock material. The reported S_{20} is hence the mean value of three parallel tests. A screening of tests performed at the NTNU/SINTEF laboratory indicates that this test, correctly performed, normally will show a standard deviation of three parallel tests on homogenised material (homogenised through the crushing and sieving process), less than 2 units (i.e. 4% for a mean S_{20} of 50). Local variations in the lithology and texture of the sample would most likely provide larger differences, if the sample material not was homogenised prior to the testing.

The lowest and the highest S_{20} of the 3002 values recorded in the NTNU/SINTEF database are 15.0 (*amphibolite*) and 95.1 (*limestone*). The measuring range and the distribution of the recorded test results are shown in Fig. 2.

2.2. Rock surface hardness determined by the Sievers' J-Value (SJ) test

The Sievers' J-miniature drill test (Sievers, 1950) was originally developed by Sievers (1950s). SJ constitutes a measure of the rock surface hardness or resistance to indentation. SJ is defined as the mean value of the measured drillhole depths in 1/10 mm, after 200 revolutions of the 8.5 mm miniature drill bit, see Fig. 3. The standard procedure is to use a pre-cut surface of the sample which is perpendicular to the foliation of the rock. SJ is hence measured parallel to the foliation. The SJ test is normally performed as 4–8 drillings, depending on variations in the texture of the sample. The SJ values may however in some specific cases show a variability, which necessitates more than 8 drillings in order to achieve a representative average value.

SJ is reported as the mean value of the performed drillings. Foliated rocks like gneiss or schist can often show a texture with distinct bands of minerals with different hardness. This can result in significant variations in penetration depth. It should therefore always be aimed at placing the drillholes in soft and hard layers

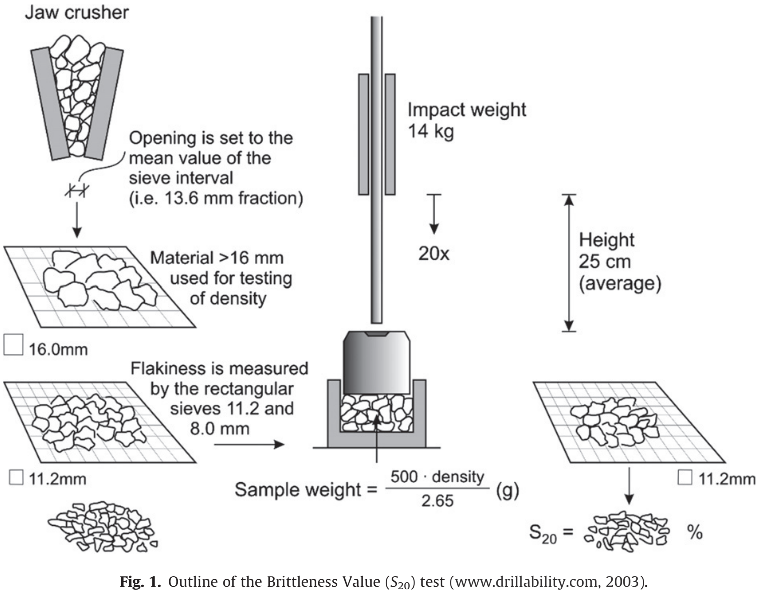

Fig. 1. Outline of the Brittleness Value (S_{20}) test (www.drillability.com, 2003).

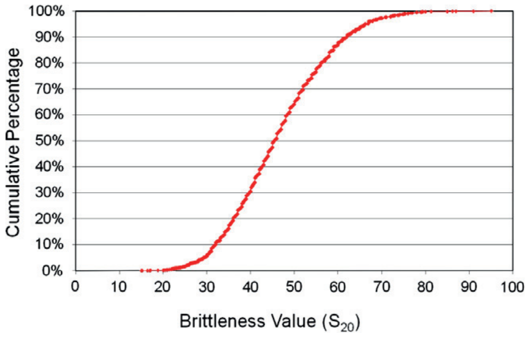

Fig. 2. Cumulative distribution of the recorded Brittleness Values (S_{20}).

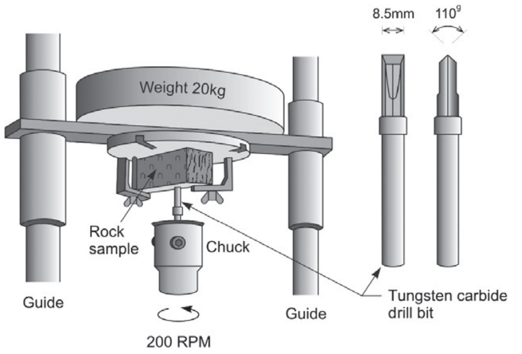

Fig. 3. Outline of the Sievers' J-Value (SJ) miniature drill test (www.drillability.com, 2003).

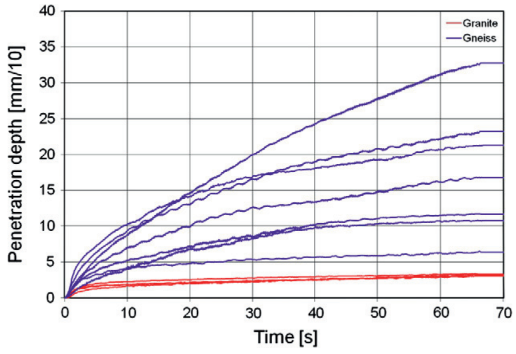

Fig. 4. Sievers' J-Value (SJ) drillings in a granite and a gneiss sample.

according to a visual interpretation of the composition of the rock. Drilling in the soft/hard combination should be avoided, but this might sometimes be impossible due to e.g. thin layers of alternating mineral composition.

The very low degree of variation found in the SJ-Value drillings for a sample of homogenous granite (red lines) and the high degree of variation found for a sample of mica gneiss with garnet (blue lines) are shown in Fig. 4.

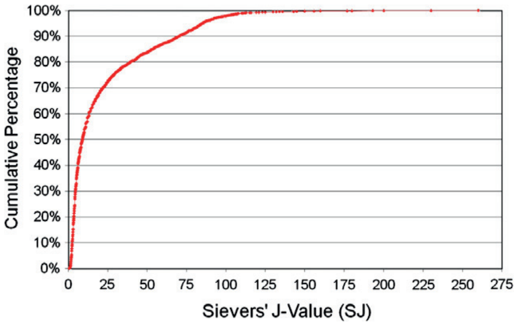

Fig. 5. Distribution of the recorded Sievers' J-Values (SJ).

The lowest and the highest SJ of the 3046 values recorded in the NTNU/SINTEF database are 0.5 (*quartzite*) and 260 (*alumn schist*), respectively. The measuring range and the distribution of the recorded test results are shown in Fig. 5.

2.3. Rock abrasion on tungsten carbide and cutter ring steel determined by the Abrasion Value (AV) and Abrasion Value Cutter Steel (AVS) tests

The AV test developed at the Department of Geology at NTH in the beginning of the 1960s, constitutes a measure of the rock abrasion or ability to induce wear on tungsten carbide. The development of the AVS test was based on the AV test method. The same test equipment as for the AV measures the AVS, but the latter uses a test piece of steel taken from a TBM cutter ring. The AVS constitutes a measure of the rock abrasion or ability to induce wear on cutter ring steel. The abrasion powder used for both the AV and the AVS is normally prepared by use of test material from the extractions used to determine S_{20} and should hence be regarded as representative and homogenised sample material.

An outline of the AV and the AVS tests is shown in Fig. 6.

AV is defined as the weight loss of the test piece in milligrams after 5 min testing. AVS is defined as the weight loss of the test piece in milligrams after 1 min of testing. The AV and AV S tests are normally performed on 2–4 test pieces. The variation is found to be very low and it should, if the testing is correctly performed, not exceed 5 units (milligrams of weight loss). The reported AV and AVS are the mean value of 2–4 parallel tests.

The lowest and the highest AV of the 2621 recorded values in the NTNU/SINTEF database are 0.0 (*limestone*) and 116.0 (*quartzite*). The measuring range and the distribution of the recorded test results are shown in Fig. 7.

The lowest and the highest AVS of the 2621 recorded values in the NTNU/SINTEF database are 0.0 (*limestone*) and 68.5 (*quartzite*). The measuring range and the distribution of the recorded test results are shown in Fig. 8.

3. Classifications of drillability parameters

The NTNU/SINTEF database does presently contain recorded test results for nearly 3200 samples from various rock excavation projects. Approximately 60% of the samples are originating from projects in Norway and the remaining from projects in 49 other countries. The increasing use of the NTNU/SINTEF drillability test method has, as mentioned in the introduction, generated a demand for a classification of the individual tests as supplement to the existing classification of the drillability indices.

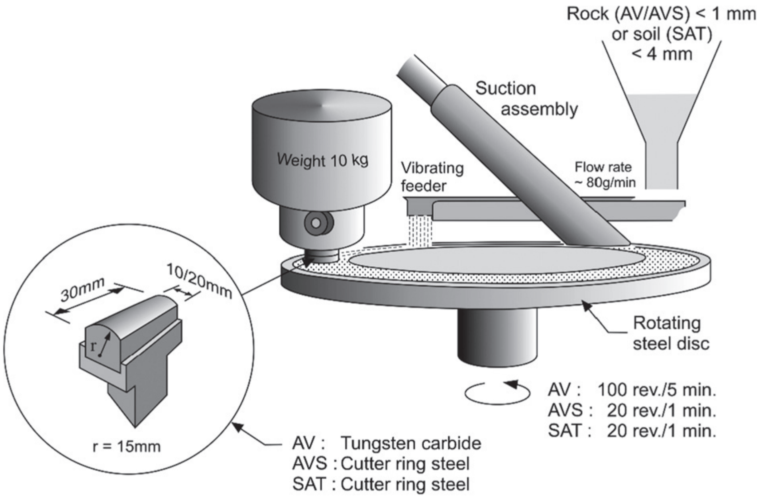

Fig. 6. Outline of the Abrasion Value (AV) and Abrasion Value Cutter Steel (AVS) test (www.drillability.com, 2003).

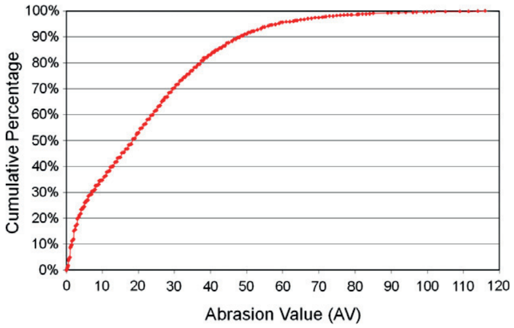

Fig. 7. Distribution of the recorded Abrasion Values (AV).

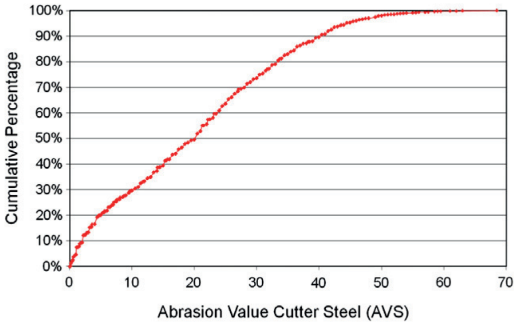

Fig. 8. Distribution of the recorded Abrasion Values Cutter Steel (AVS).

The respective NTNU/SINTEF drillability tests provide consistent and reproducible measurements of rock properties:

- Brittleness or ability to be crushed by repeated impacts.
- Surface hardness or resistance to indentation.
- Abrasivity or ability to induce wear on tungsten carbide.
- Abrasivity or ability to induce wear on cutter ring steel.

These properties are as previously mentioned the input for calculations of the DRI™, BWI™ and CLI™ (Dahl et al., 2010). The NTNU/SINTEF drillability indices represent combinations of various rock properties, as opposed to e.g. UCS or CAI, which represents one specific rock property.

The NTNU/SINTEF tests show very good reproducibility and consistency. The variations found in the individual values from each test are, as shown in Section 2, normally very low and the measured individual test values will usually not deviate much from the reported average test value.

The measuring ranges (defined as the range from the lowest to the highest recorded average test value) of the NTNU/SINTEF tests are very extensive. An extensive measuring range contributes substantially to a test methods ability to distinguish and classify specific properties. The NTNU/SINTEF tests methods are in that respect well suited to classify rock properties which influence the drillability. This is illustrated by the box whisker charts in Figs. 9–12, where the recorded distribution and range of average test results for some selected, common metamorphic, eruptive and sedimentary rock types are shown. The large variation found within each rock type emphasises that certain rock properties cannot be generalised solely based on a determination of rock type.

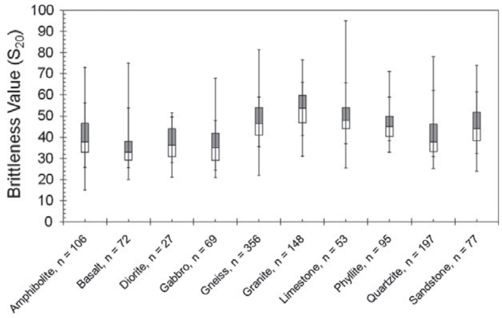

Fig. 9. Box whisker chart showing the recorded range of Brittleness Value (S_{20}) for a selection of common rock types.

3.1. Statistical evaluation and classification of test results

The NTNU/SINTEF database does currently contain 3125 rock samples. The samples have been analysed for various purposes and based on different test series. The total number of recorded test values from each test hence vary from 3046 (SJ) to 1590 (AVS). The available results from each test have been statistically analysed and the distribution of the results are shown in Figs. 2, 5, 7 and 8. The classifications given in Tables 1–4 are based on the statistical distribution (cumulative percentage) of the available existing values from each test. It was, due to the close relationship between the drillability tests (SJ, S_{20}, AV and AVS) and the drillability indices (DRI™, BWI™ and CLI™), decided to use the same method of classification of intervals and categories as originally used for the existing classification of the indices (Bruland, 1998).

3.1.1. Brittleness Value (S_{20})

The S_{20} is influenced by the mineralogical composition of the rock as well as grain size and grain binding, but also to a great extent by the degree of weathering/alteration, microfracturing and foliation.

The classification given in Table 1 is based on the distribution of the recorded results of the 3001 samples which have been tested for determination of S_{20}.

The S_{20} ranges for a selection of common metamorphic, igneous and sedimentary rock types are given in Fig. 9.

The box whisker charts given in Figs. 9–12, illustrate the distribution and range of recorded test results for a selection of common rock types. An explanation of how to read these charts and some examples of the information which can be found are given in the following.

The lowest and highest recorded value for each rock type is shown by the start and end point of each vertical line in Fig. 9. The lowest and highest S_{20} for e.g. the 106 recorded amphibolites are respectively 15.0 and 73.0, indicating that amphibolites can show S_{20} ranging from extremely low to extremely high. The marker above the lowest value indicates the upper limit of the 10*th percentile* (25.8 for amphibolites). The split box in the middle starts at the 25*th percentile* and ends at 75*th percentile*. The colour change in the middle is the *median* of the recorded values (37.7 for amphibolites). The marker below the maximum value indicates the lower limit of the 90*th percentile*, which means that only 10% of the recorded amphibolites have S_{20} above 56.2.

3.1.2. Sievers' J-Value (SJ)

SJ is influenced by the same factors as the S_{20}. The mineralogical composition has however normally the most significant influence on the surface hardness and hence on the SJ.

The classification given in Table 2. is based on the distribution of the recorded results of the 3046 samples which have been tested for determination of SJ.

Table 1
Classification of rock brittleness, or the ability to be crushed by repeated impacts.

Category – brittleness	S_{20}-value (%)	Cumulative percentage (%)
Extremely high	⩾66.0	95–100
Very high	60.0–65.9	85–95
High	51.0–59.9	65–85
Medium	41.0–50.9	35–65
Low	35.0–40.9	15–35
Very low	29.1–34.9	5–15
Extremely low	⩽29.0	0–5

Table 2
Classification of rock surface hardness, or resistance to indentation.

Category – surface hardness	SJ value (mm/10)	Cumulative percentage (%)
Extremely high	⩽2.0	0–5
Very high	2.1–3.9	5–15
High	4.0–6.9	15–35
Medium	7.0–18.9	35–65
Low	19.0–55.9	65–85
Very low	56.0–85.9	85–95
Extremely low	⩾86.0	95–100

Table 3
Classification of rock abrasion or the ability to induce wear on tungsten carbide.

Category – abrasion on tungsten carbide	AV (mg)	Cumulative percentage (%)
Extremely high	⩾58.0	95–100
Very high	42.0–57.9	85–95
High	28.0–41.9	65–85
Medium	11.0–27.9	35–65
Low	4.0–10.9	15–35
Very low	1.1–3.9	5–15
Extremely low	⩽1.0	0–5

Table 4
Classification of rock abrasion or the ability to induce wear on cutter steel.

Category – abrasion on cutter steel	AVS (mg)	Cumulative percentage (%)
Extremely high	⩾44.0	95–100
Very high	36.0–44.0	85–95
High	26.0–35.9	65–85
Medium	13.0–25.9	35–65
Low	4.0–12.9	15–35
Very low	1.1–3.9	5–15
Extremely low	⩽1.0	0–5

The SJ ranges for a selection of common metamorphic, igneous and sedimentary rock types are given in Fig. 10.

3.1.3. Abrasion Value (AV) and Abrasion Value Cutter Steel (AVS)

The mineralogical composition of the rock is normally the factor which has the most significant influence also on the AV and AVS. The AV and AVS tests use test pieces of different material and hardness, tungsten carbide and cutter ring steel respectively, and quartz and other hard minerals will cause different amount of abrasion on the test pieces. The general rule is that low quartz content will give AV and AVS of the same magnitude, while high quartz content will give an AV higher than the AVS. The explanation for this observation is most likely related to the high hardness of quartz, which enables quartz to cause a significantly higher degree of abrasion on tungsten carbide than other minerals are able to do. Grain shape, size and grain binding are other factors which are believed to contribute substantially to the abrasiveness of rocks.

The classification given in Table 3 is based on the distribution of the recorded results of the 2621 samples which have been tested for determination of AV.

The classification given in Table 4 is based on the distribution of the recorded results of the 1590 samples which have been tested for determination of AVS.

The AV and AVS ranges for a selection of common metamorphic, igneous and sedimentary rock types are given in Figs. 11 and 12.

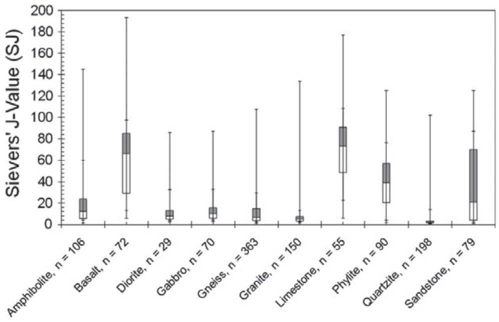

Fig. 10. Box whisker chart showing the recorded range of Sievers' J-Value (SJ) for a selection of common rock types.

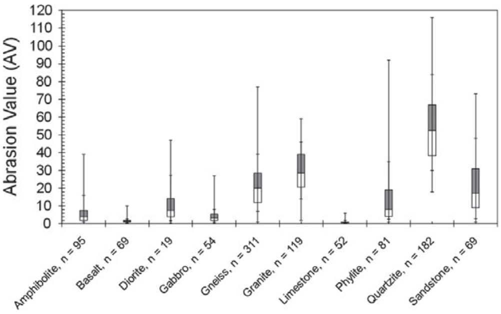

Fig. 11. Box whisker chart showing the recorded range of Abrasion Value (AV) for a selection of common rock types.

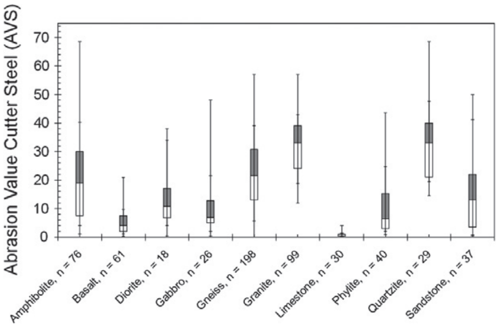

Fig. 12. Box whisker chart showing the recorded range of Abrasion Value Cutter Steel (AVS) for a selection of common rock types.

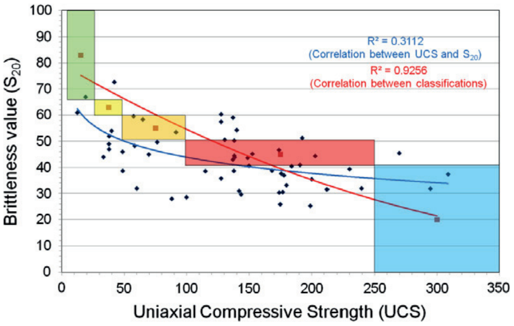

Fig. 13. Correlation between UCS and S_{20}. The coloured boxes refer to UCS classification ranges given by ISRM and corresponding ranges in the suggested S_{20} classification.

4. Correlations and comparisons with other test methods

There are also several other internationally recognised test methods for determining properties influencing the drillability of rocks. Uniaxial Compressive Strength (UCS), Point Load Index (I_{s50}) and Cerchar Abrasivity Index (CAI) are probably some of the most well known and widely used test methods in that respect. Correlations of the recorded results for samples which have been tested for determination of UCS, I_{s50} and CAI in addition to the NTNU/SINTEF test methods are shown as charts in Section 4 (Figs. 13–17). All tests are performed at the NTNU/SINTEF Engineering Geological Laboratory. UCS and I_{s50} are determined in accordance with ISRM standards and CAI according to West (West, 1989). At present, no internationally recognised standard for the CAI exists, and there are currently several different approaches to this test (Rostami et al., 2005). It should however be noted that an ASTM standard for CAI recently has been proposed.

4.1. Correlation of tests used to determine strength properties

S_{20} and UCS are two very different test methods for determining strength properties of rock. There are currently 57 samples, representing 18 different rock types, in the NTNU/SINTEF database which have been tested by use of both test methods. The tested samples have S_{20} values in the range from 25.3 to 72.7 (*extremely low to extremely high*) and UCS values in the range from 12.4 MPa to 308.8 MPa (*low to extremely high strength*, *according to ISRM*). The coloured boxes which are given in the chart in Fig. 13 show the span of the two respective classifications, S_{20} (Table 1) and UCS (ISRM, 1978), while the red points indicate the arithmetic midpoints of the classifications. Figs. 14–17 show the same presentation for the other classifications of mechanical rock properties which have been correlated. Fig. 13 shows a relatively poor relation between S_{20} and UCS. This might be explained by the fact that S_{20} is performed by applying repeated impacts on the sample material, causing crushing of the sample material, while UCS is performed by applying load on the sample, at a relatively slow constant rate, until failure occurs.

The values presented in Table 5 outlines numbers of corresponding values in the two classifications, S_{20} and UCS, e.g. there are eight tested samples which have a very high UCS and a very low S_{20}. Tables 6–9 show the same presentation for the other classifications of mechanical rock properties which have been correlated.

The Point Load Strength (I_{s50}) is another commonly used test method for determination of rock strength properties. There are currently 23 samples, representing seven different rock types, in the NTNU/SINTEF database which have been tested for determination of both S_{20} and I_{s50}. The samples show S_{20} values in the range from 28.6 to 58.4 (*extremely low to high*) and I_{s50} values in the range from 4.8 MPa to 15.7 MPa (*high strength to very high strength*, *according to Bieniwiaski*, 1984). The two tests (Fig. 14) show no explicit relation. I_{s50} is a determination of the indirect tensile strength of the rock and it is, as the UCS, performed by applying load on the sample, at a constant relatively slow rate, until failure occurs. The lack of correlation might be explained by the same differences as described for S_{20} and UCS. It should however also be noted that the available statistical basis for this correlation analysis is limited.

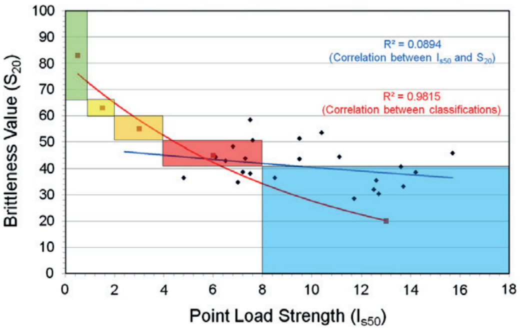

Fig. 14. Correlation between I_{s50} and S_{20}. The coloured boxes refer to I_{s50} classification ranges given by Bieniawski (1984) and corresponding ranges in the suggested S_{20} classification. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

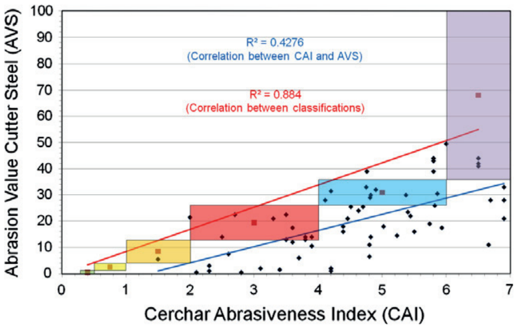

Fig. 17. Correlation between CAI and AVS. The coloured boxes refer to CAI classification ranges given by Cerchar Institute, 1986 and corresponding ranges in the suggested AVS classification. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

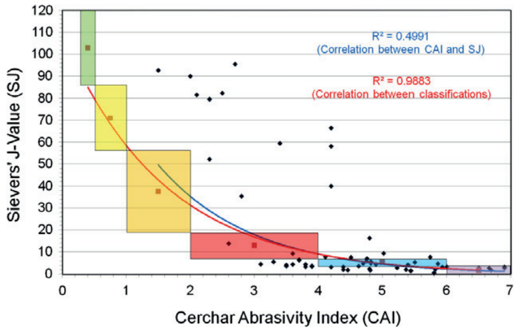

Fig. 15. Correlation between CAI and SJ. The coloured boxes refer to CAI classification ranges given by Cerchar Institute, 1986 and the corresponding ranges in the suggested SJ classification. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

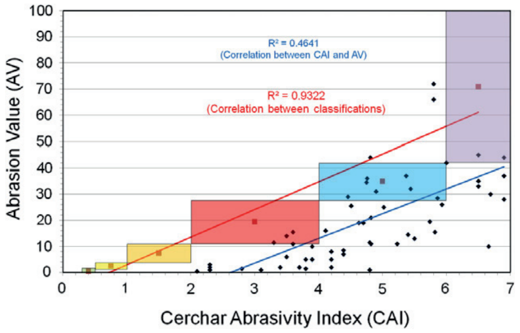

Fig. 16. Correlation between CAI and AV. The coloured boxes refer to CAI classification ranges given by Cerchar Institute, 1986 and corresponding ranges in the suggested AV classification. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. Correlations of tests used to determine surface hardness and abrasiveness

The SJ and the CAI are used to determine the surface hardness and the abrasiveness of rock, respectively. The correlation shown in Fig. 15 could hence be regarded as prevailing for two different rock properties. The SJ test can however also be used to determine the abrasiveness of rock, by calculating a Sievers' J Interception Point (SJIP) (Dahl et al., 2007). On the basis of this observation these two tests can be regarded as related, and to a great extent affected by the same rock properties. This hypothesis is also supported by the fairly clear relation found between SJ and CAI. There are currently 66 samples, representing 20 different rock types, in the NTNU/SINTEF database which have been tested by use of both test methods. The samples show SJ values in the range from 1.6 to 95.5 (*extremely high to extremely low surface hardness*) and CAI values in the range from 1.5 to 6.9 (*medium abrasiveness to quartzitic, according to* Cerchar Institute, 1986).

The AV and the CAI are two different test methods used to determine abrasiveness of rock. There are currently 60 samples, representing 16 different rock types, in the NTNU/SINTEF database which have been tested by use of both test methods. The samples show AV values in the range from 0.5 to 72 (*extremely low to extremely high*) and CAI values in the range from 2.3 to 6.9 (*very abrasive to quartzitic, according to* Cerchar Institute, 1986). The correlation shown in Fig. 16 is for two test methods which to some degree can be expected to be comparable. The relatively clear relation found for the two tests is regarded as logical, and it emphasises that the AV and the CAI to a great extent are affected by the same rock properties and characteristics.

The Abrasion Value Cutter Steel (AVS) is, like the AV and the CAI, a test method used to determine the abrasiveness of rock. These three tests do however make use of test pieces consisting of different materials. AV is performed by use of test pieces of tungsten carbide, AVS by use of test pieces of TBM cutter ring steel and CAI by tempered steel pins of HRC 43 (according to West, 1989, but commonly performed by pins of HRC 56).

There are currently 66 samples, representing 19 different rock types, in the NTNU/SINTEF database that have been tested by use of both test methods. The samples show AVS values in the range from 0.5 to 49.5 (*extremely low to extremely high*) and CAI values in the range from 1.5 to 6.9 (*medium abrasiveness to quartzitic, according to* Cerchar Institute, 1986). The correlation between the two tests (Fig. 17) show a similar relation as the one found for AV and CAI. This can be regarded as logical and indicates that AVS and CAI also are affected by the same rock properties and characteristics.

The lowest degree of correlation between the NTNU/SINTEF tests used to determine abrasiveness and the CAI was found for AVS. It is difficult to find an explicit explanation of this and it should be noted that the correlations in general show relations which are in the same range. It is also likely that the found variation to some extent is related to the spread and distribution of the tested samples.

Table 5
Number of corresponding classifications between Brittleness Value (S_{20}) and Uniaxial Compressive Strength (UCS).

UCS S_{20}	Extremely low	Very low	Low	Medium	High	Very high	Extremely high
Low strength						1	1
Medium strength			1	4	2		1
High strength	2			3	3		
Very high strength	2	8	10	10	4	1	
Extremely high strength		1	1	1			

Table 6
Number of corresponding classifications of Brittleness Value (S_{20}) and Point Load Strength (I_{s50}).

I_{s50} S_{20}	Extremely low	Very low	Low	Medium	High	Very high	Extremely high
Very low strength							
Low strength							
Medium strength							
High strength		1	3	5	1		
Very high strength	1	4	3	3	2		

Table 7
Number of corresponding classifications of Sievers' J-Value (SJ) and Cerchar Abrasivity Index (CAI).

CAI SJ	Extremely low	Very low	Low	Medium	High	Very high	Extremely high
Not very abrasive							
Slightly abrasive							
Medium abrasive to abrasive	2						
Very abrasive	1	5	2	2	7	6	
Extremely abrasive		2	1	5	9	9	6
Quartzitic						8	1

Table 8
Number of corresponding classifications of Abrasion Value (AV) and Cerchar Abrasivity Index (CAI).

CAI	AV	Extremely low	Very low	Low	Medium	High	Very high	Extremely high
Not very abrasive								
Slightly abrasive								
Medium abrasive to abrasive								
Very abrasive	3	7	6	4				
Extremely abrasive	1	1	4	14	6	2	3	
Quartzitic			1		5	3		

Table 9
Number of corresponding classifications of Abrasion Value Cutter Steel (AVS) and Cerchar Abrasivity Index (CAI).

CAI AVS	Extremely low	Very low	Low	Medium	High	Very high	Extremely high
Not very abrasive							
Slightly abrasive							
Medium abrasive to abrasive			1	1			
Very abrasive	4	3	6	10			
Extremely abrasive	1	2	2	14	9	3	1
Quartzitic			1	1	3	2	2

5. Conclusions

Different samples from one single rock type can show extensive variation when it comes to properties which are affecting the drillability, and it should be emphasised that it neither is recommended nor possible to generalise and predict the drillability of rock samples only by determining the rock type. Extensive and reliable laboratory testing is an essential factor when it comes to obtaining reliable predictions.

The NTNU/SINTEF tests have been proven to have very good reproducibility and consistency. The extensive measuring ranges of the tests are well suited to distinguish and classify specific rock properties which significantly influence the drillability. The NTNU/SINTEF tests have therefore been used in connection with numerous underground excavation projects, and the method is gaining increasing international acceptance and recognition as a reliable tool for predicting the drillability of rocks.

The extensive amount of recorded data in the NTNU/SINTEF database provides unique possibilities for analyzing correlations, research and further developments. The classifications given in this paper are based on statistical analysis of the test values recorded in the database so far. The reliability and consistency of the data used for the classifications are regarded as being very high, since they are originating from one single laboratory using the original reference test apparatuses. It should however be emphasised that the NTNU/SINTEF database still has a certain predominance of recorded samples which could be regarded as hard rock types and that the classifications presented in this paper hence are not equally representative for soft rock types.

It is of vital importance for everyone involved in planning of underground excavations to gain as much knowledge and understanding as possible on how specific properties will influence the drillability of rock. The classifications are in that respect intended to provide new valuable information and to constitute an important aid and guideline.

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Paper 2

Soil Abrasion in TBM Tunnelling

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Soil Abrasion in TBM Tunnelling

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ABSTRACT: Worldwide urbanization demands more infrastructures in densely populated areas. When the surface is fully utilized, subsurface construction often proves itself to be the most viable solution. In urban areas, excavation with tunnel boring machines (TBMs) is in many cases preferred compared to drill and blast or cut and cover. Full face excavation in soil now ranges from less than 2 metres (pipejacking) to over 15 metres in diameter. In the last decades, there has been a focus on predicting abrasive wear on hard rock TBMs, and there are currently several recognized methods to predict cutter life. In 2005, SINTEF and NTNU together with Jacobs Associates and Babendererde Engineers, started to investigate how soil abrasion can be predicted. Since 2005, the engineering geology laboratory at NTNU/SINTEF has tested over 200 different soil samples originating from 20 projects in 8 different countries. The intention of this paper is to examine various methods to predict abrasive wear, show the consequences of abrasive wear on TBMs and how project owners can describe abrasive wear in their tender documents and geotechnical baseline reports, as well as how contractors can assess the available information.

1. INTRODUCTION

Worldwide urbanisation demands more infrastructure (road, railroad, light railroad, waste- and potable water transport and cable tunnels) in densely populated areas. If the surface ground is fully utilised subsurface construction often proves itself to be the most viable solution. Many of the world's urban areas are situated on soil or weathered rock. The reason for that is quite logical and originating from old settlements which were settled close to rivers, sea and good agricultural areas. The demand for more subsurface infrastructure is confirmed by Home (2010), where the total number of Tunnel Boring Machines (TBMs) working in soil the last five years are approximately 350 units.

In addition to utilisation of TBMs for urban infrastructure projects there are also ongoing research activities on tunnel boring to off-shore oil fields, in order to be able to exploit the oil from a tunnel system instead of today's off-shore production oil platforms.

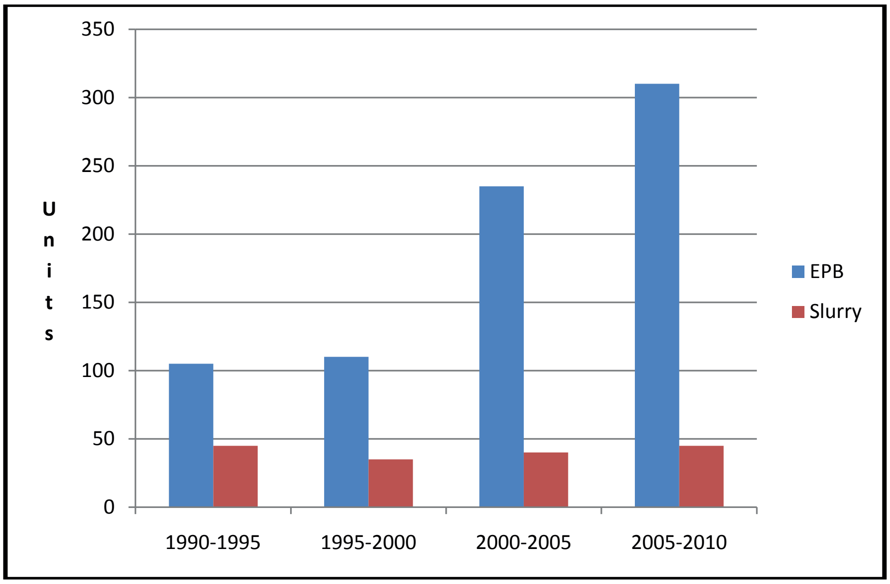

Figure 1, Units of TBMs working in soil (after Home 2010).

Abrasive wear causes replacement and repair of cutter tools on TBMs. A cutter tool is a piece of hardened steel or a steel matrix with carbide inserts used to break and excavate the soil. Experiences from several TBM projects (Johansen 2000, Klemetsrud 2007, Log 2010) in hard rock conditions shows that cutter tool life can vary by several hundred percent. In hard rock tunnelling the abrasiveness of the rock mass can decide whether a contractor can achieve a profit or loss in a tunnel project.

For TBM tunnelling in soil the actual cutter consumption (in replacement per metre tunnel or by amount of excavated soil) is generally less than in hard rock conditions, due to the relatively soft behaviour of a soil compared to a rock mass. However, the consequences of worn out tools in soil excavation by TBM is more challenging, more time consuming and requires maintenance in extreme working conditions. The reason for this is lack of stand up time or stability, and water and ground pressure of a soil in comparison with hard rock. Hence, most repair work and changing of cutter tools have to be done by divers in hyperbaric conditions.

2. CONSEQUENCES OF TUNNELLING IN ABRASIVE SOIL

According to Hutchings (1992) abrasive wear is a process where material is removed or displaced from a surface by hard particles or sometimes by hard protuberances on a counter surface. Abrasive wear is according to tribological literature dependent on the following particle properties (i.e. the following soil properties); hardness, shape and size.

In contradiction to hard rock excavation, which is a combination of compressive crushing and inducing of tensile fracturing, soil excavation is a ripping of plastic or elastic material if the soil is cohesive. Friction soils such as sand flows more or less if it is dry, single graded and without shear strength. Thus mechanical excavation of soil requires less thrust on the cutter tools compared to hard rock excavation. Still, the machines have powerful cutterheads with high torque. The torque is needed as the soil together with bentonite or additives are rotated in the TBM cutter chamber in closed face mode. The other reason is that the ripping of soil demands higher torque as some soils are relatively ductile materials.

Excavation of soil generally causes less wear on cutter tools than excavation in hard rock, by comparing the frequency of cutter tool changes. However, the consequences of worn out tools in soil excavation compared with hard rock excavation are higher with more time consuming and challenging repair and replacement work, in extreme working conditions. The reason is the lack of stand up time of the tunnel face in soil compared to the rock’s self supporting behaviour. This limits the repair works either to be done in shafts or as hyperbaric interventions. As an example, an intervention in 3 bars should not last more than 2.8 hours, following 2 hours of decompression according to some given regulations in Europe and America. One diver, working under hyperbaric condition, is able to change 1 - 2 disc cutters per hour and roughly 6 soft ground tools (ripper and teeth) per hour. The working space is confined and regarded as an extremely harsh environment. Own studies shown in Figure 3, shows that the majority of replacement of soft ground cutter tools is done as hyperbaric interventions.

Figure 2. Working environment for cutter tools changes and interventions at face. (After Babenderede et al.2010).

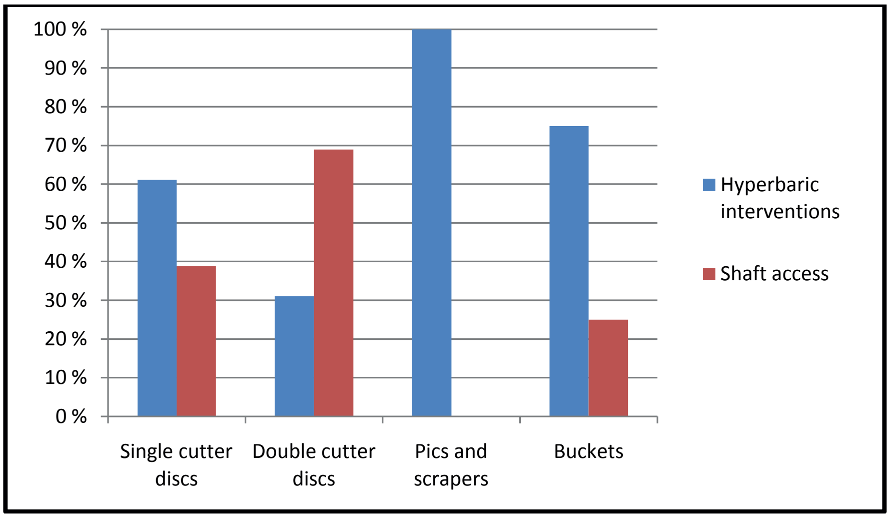

Figure 3. A graph showing distribution of worn out tools on a slurry TBM and the condition where the replacement took place.

Another wear related problem experienced in TBM tunnelling in soil is destruction and wear on the cutterhead itself. If the wear reaches a certain level, a complete tunnelling project can be jeopardized. Figure 4 shows a cutterhead exposed to abrasive wear, resulting in a gap between the cutterhead structure and the steel shield of approximately 4 cm. The consequences of this are a smaller diameter tunnel which complicates installation of concrete elements, wear on the shield and lower advance rates (Dahl et al.2007). The repair work can take several months, and it will in some cases justify a construction of an extra shaft in order to be able to conduct the repair work.

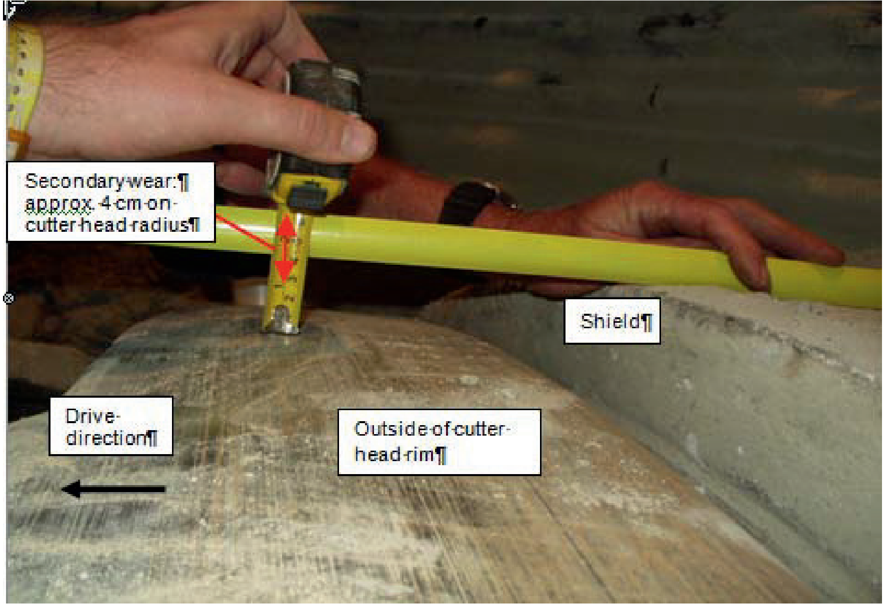

Figure 4. Wear on the cutterhead structure (Dahl et al.2007).

3. STATE OF THE ART

LABORATORY METHODS AND PREDICTION OF ABRASIVE WEAR IN SOIL

NTNU/SINTEF together with two tunnel consultants initiated some research on the subject soil abrasion in 2005. (Nilsen et al.2006a, b, c). The research was initiated by a contractor experiencing severe abrasive wear problems in connection with a project in the US. The contractor wanted to convince their current Client that the soil was extraordinary abrasive. Some minor revisions on the subject soil abrasion was introduced in 2007 (Dahl et al.2007) by the "Soil Abrasion Test" (SAT^{TM}). The PhD candidate also made his Master thesis on the soil abrasion subject (Jakobsen 2007). Another Master thesis was conducted on the same subject, but by use of another approach using a different laboratory apparatus (Klemetsrud 2008) and (Jakobsen et al.2009). Since the start in 2005, the NTNU/SINTEF Engineering Geological Laboratory has tested over 200 soil samples originating from 8 different countries and 20 tunnel projects, i.e. the testing is commercially available. However, the current stage of testing has several limitations causing a "healthy scepticism" from the tunnel industry. Firstly, the current method is based on testing on disturbed soil, which means that in-situ density, water content and in-situ water and soil pressure are not taken into account. Secondly, there are not yet published any classifications or relations to the laboratory measured soil abrasion and the actual observed wear on TBMs excavating soil.

The TBM manufacturer Herrenknecht has together with the Technical University of Münich currently a PhD student on the subject boulder abrasion. The study seems to be focusing on abrasive wear caused by boulders interlaying soil matrix (Köppl et al.2009).

Another parallel research is conducted at the German geotechnical institute CDM. The research focuses mostly upon actual conditions along the tunnel versus the conditions described in tender documents and Geotechnical Baseline Reports (GBRs) (Gwildis et al.2010). The subject does amongst other include observed variation between actual abrasive wear and potential abrasive wear in the tender documents. The university partner to CDM on this research is the Technical University of Darmstadt, Germany. Gwildis (2010) also addresses the use of a test procedure called Miller Slurry Test to test the abrasion properties of slurries. The article shows a relation between energy consumption for the excavation correlated against tool life, i.e. if a soil requires high amount of energy to be excavated it will cause more abrasive wear than a soil requiring a small amount of energy.

Additionally the Technical University of Münich has performed testing on soil by their hard rock abrasiveness equipment LCPC (Thuro et al.2007, Frentzel et al.2008). At the current stage their laboratory methodology is limited to testing on the 4.0 – 6.3 mm fraction. The NTNU/SINTEF Engineering Geology Laboratory has purchased the same laboratory apparatus as used by TU Münich, in order to evaluate if the test procedure can be altered allowing a wider span of soils to be tested. The intention is also to evaluate soil abrasion by use of various apparatuses.

The Penn State University in the US has initiated a study of soil abrasion and its impact, and how soil abrasion can be predicted. Rostami (2010) presents an evaluation and limitations of the two currently existing test methods, the SAT™ and the LCPC. The Penn State University will proceed their study by designing a new apparatus, which intend to allow testing on similar conditions as in-situ, and also by allowing hyperbaric test conditions up to 15 bars earth/water pressure.

CURRENT TENDER DOCUMENT PRACTICE:
The content of the Geotechnical Baseline Report[1] (GBR) or geotechnical support documents for the tender documents should contractually define the predicted ground conditions along a project (Freeman 2009).

There are no standardised content of tender documents and geological baseline reports in tunnelling. The content and layout of this valuable information depends on clients and project owners and their consultants, hence abrasion properties of a soil can or cannot be quantified dependent of the project owners and their consultants.

Generally, project owners quantify their soil with respect to some geotechnical values (soil strength, water content, grain size distribution etc.) and from known problems in neighbouring projects. Data from neighbouring projects is a valuable source of information, but it sometimes causes the following statement in the tender documents; "The soil is expected to have a medium abrasivity, but it should be expected extreme abrasivity". This tends to over-protect the project owners and move the risk to the tendering contractors.

Several project owners in the US are now using the NTNU/SINTEF Soil Abrasion Test™ (SAT) to describe the pre-investigated soil abrasion properties in their projects (Dahl et al. 2007, Gwildis et al.2010, Caufield et al.2009). However, the outcome of this test has been an abrasion value which can range various sections along the tunnel drive with each other, but without any specific soil classification. A suggested preliminary classification of SAT™ will therefore be presented in the following chapter.

Baselines can also be conflicting with respect to abrasive wear and prediction of cutter life (Freeman 2009). For hard rock cutter life prediction both the Cerchar Abrasivity Index (CAI) and the NTNU/SINTEF Cutter Life Index™ (CLI) are widely used and acknowledged. If the two estimates are not corresponding, the contractor is free to choose the most suitable estimate for him (Freeman et al.2009) If several soil abrasion estimates such as SAT™, LCPC and the SAR number from the Miller Slurry Test is presented in the geotechnical report this provides more information than using a single method, but it might also cause conflicting abrasion properties and cutter life estimates.

4. THE NTNU/SINTEF SOIL ABRASION TEST™

TEST PROCEDURE
The NTNU/SINTEF Soil Abrasion Test™ (SAT) is a further development of the existing abrasion tests for rock. Compared with the AVS test only one detail has been changed: instead of crushed rock powder <1 mm, a sieved soil sample <4 mm is used in the SAT™ test. The initial SAT™ tests were performed with an upper grain size limit of 1 mm (Nilsen et al. 2006a, b, c), but was in 2007 modified to allow grains up to 4 mm. (Dahl et al.2007).

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[1] Term widely used in the US

Figure 5. The NTNU/SINTEF Abrasion Test apparatus.

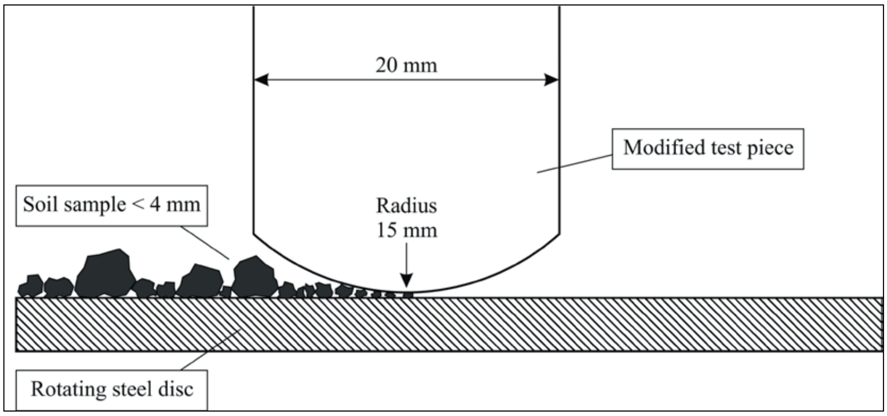

Figure 6. Interaction between soil fragments and steel test piece. (After Dahl et al.2007)

To enable comparison with previous test results and to take advantage of the extensive NTNU/SINTEF database it is considered important to follow the standardized NTNU/SINTEF abrasion test procedures as closely as possible. The following preparation of soil samples is therefore recommended, and has been followed for the soil testing described here:

In order to reduce or avoid changes of the original grain shape and size, soil samples should be dried gently in a ventilated oven at 30^o C for 2 - 3 days. The following techniques should be used after drying in order to disintegrate and separate the particles for the abrasion powder:

1) Disintegration by use of a soft hammer.

2) Sieving with steel balls as gentle milling/disintegration aid.
3) Initial disintegration in a jaw crusher if the samples contain very hard lumps of cohesive material after drying. Crushing of intact grains should be avoided

..

SAT^{TM} testing of the sieved fraction is carried out according to the same procedures as for AVS-testing, and the SAT-value is calculated as the mean value of the measured weight loss in mg (to be accepted, the results of 2-4 parallel tests should not deviate by more than 5 units).

PRELIMINARY CLASSIFICATION OF TEST RESULTS

The number of samples that has been tested according to this procedure is currently 210. The samples are originating from 20 different tunnelling projects in 8 countries. This provides a sufficient span in sample types for suggesting a preliminary classification of SAT™ results. The given classification is based only on the SAT™ value. Other factors that might influence the abrasive wear on TBMs such as in-situ soil density, water content and pressure and compaction are not taken into account.

The preliminary classification is based on a cumulative distribution of the test results recorded in the NTNU/SINTEF soil abrasion database.

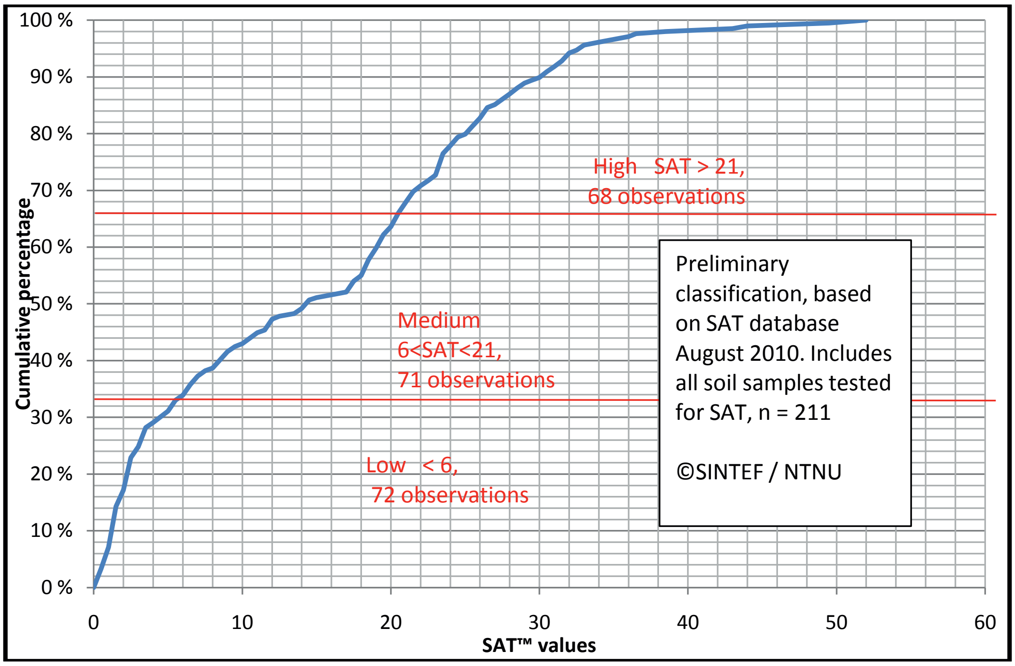

Figure 7. Cumulative distribution and classification of recorded SAT™ values.

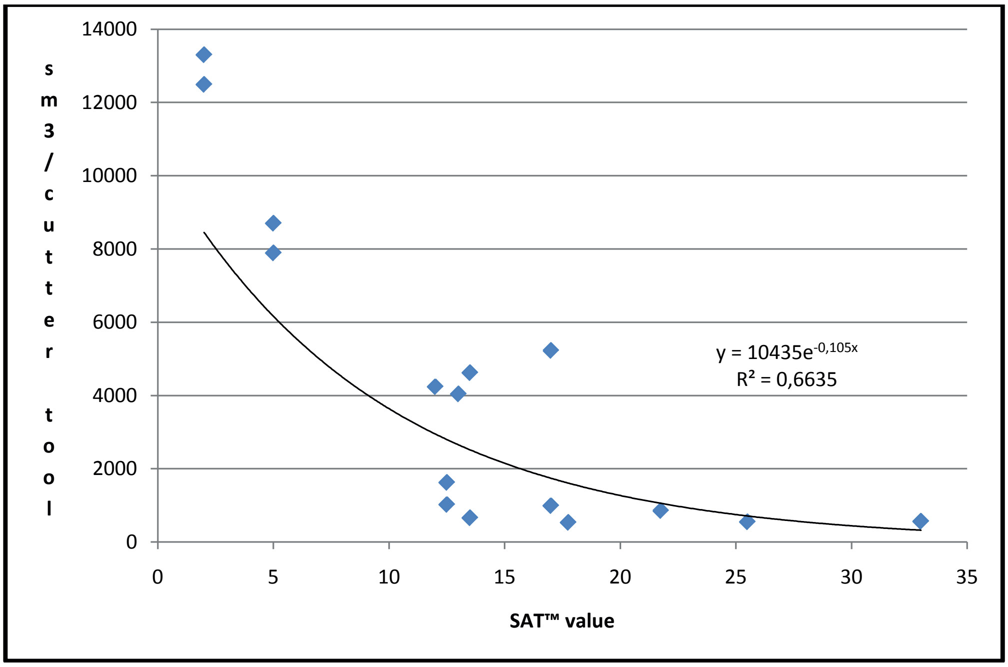

Figure 8. Exponential relation between SAT™ values and cutter tool life based on 4 TBMs in 3 different projects.

The R^2 value indicates 66 % of the total variation of cutter life (average solid cubic metres per cutter tool) in terms of excavated cubic metres can be explained with an exponential relation to the SAT™ value.

5. ONGOING DEVELOPMENT WORK

NTNU/SINTEF is working towards finding a recognized and accepted methodology to determine a soil's potential to cause abrasive wear on cutter tools. We are currently evaluating several methods, such as the SAT™, the LCPC, the Ball Mill Test and various combinations of geotechnical parameters, in order to find the most accurate and suitable approach. Common for all these tests are that the testing is done on disturbed soil material. I.e. water content, compaction, in-situ density, water and ground pressures are disregarded. The disadvantages of testing disturbed soil are of course lack of influence on in-situ factors on the cutter tool life and the benefits from excavation additives. An advantage however is simple and affordable testing and comparable values. Therefore, a major part of the further development work will be to gather more samples for laboratory testing and corresponding field observations for comparison and correlations. A more accurate cutter tool life estimate can most likely be achieved by a combination of a laboratory measured abrasion value with in-situ soil strength.

We are in addition currently designing an apparatus which will allow testing conditions which are more similar to conditions experienced in-situ. The scope of this apparatus is to evaluate how and to what extent water and soil pressure, compaction and density influence abrasive wear processes in soil tunnelling, and also to try to determine torque requirements for various soils.

Finally, at the current stage of research we intend to try to determine whether the abrasive process in the laboratory is similar to excavation with TBMs by SEM analyses on cutter tool steel.

6. CONCLUSIVE REMARKS

The impact of abrasive wear on steel material in contact with soil needs to be coped with in tunnel projects. It is of great interest for the tunnelling industry to establish a model that can predict and estimate tool and support structure replacements and repairs.

Given that surface condition allows it, additional shafts can be designed and constructed if the soil is predicted to be extremely abrasive. This can in some cases give less construction time and lower project costs.

If an acknowledged prediction tool is available for abrasive wear in soil tunnelling, the project owners should take it into account and classify the soil as extremely low abrasive to extremely high abrasive. Tendering contractors should assess the abrasiveness properties of the soil in relation to pricing and scheduling.

For the total tunnelling industry a reliable prediction tool for abrasive wear in soil will reduce the risk in tunnelling project related to cost, construction time, health and safety, and also reduce the risk of claims.

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Paper 3

Review and assessment of the NTNU/SINTEF Soil Abrasion Test (SAT™) for determination of abrasiveness of soil and soft ground

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Review and assessment of the NTNU/SINTEF Soil Abrasion Test (SAT™) for determination of abrasiveness of soil and soft ground

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ABSTRACT

Measuring soil abrasivity for excavation tool life estimation, is becoming more necessary as tunnels are longer and with limited access to execute interventions and tool changes from shafts. The tool life is a major contributor to the tunnel excavation costs and tunnelling progress. The aim of this paper is to explain the consequences of tunnelling in abrasive soil and soft ground conditions, and explain the NTNU/SINTEF Soil Abrasion Test™ (SAT) which is one approach to measure soil abrasivity. In this paper a total of 254 different soil samples (clay, silt, sand and gravel are represented) originating from 8 different countries have been tested and included in the discussion of the SAT™ procedure's applicability. Further, the paper relates the SAT™ test values to commonly known tribological theories regarding abrasion as well as presenting trends and correlations between the measured SAT™ value and measured scraper, ripper and disc cutter life from a total of nine completed TBM/pipe jacking projects, excavated with slurry shield face support.

1. Introduction

During the last decade a variety of methods for determination and prediction of abrasivity of soil and soft rock has been published. The use of the Labroatoire Central de Ponts et Chaussées (LCPC) abrasivemeter (Thuro et al., 2007), the use of linear cutter test for determining boulder abrasivity in soft ground matrix (Ozdemir, 2008) and the Soil Abrasion Test™ (SAT™) (Nilsen et al., 2007) are some of the relatively new methods. The LCPC abrasivemeter and SAT™ methods are testing a steel sample's resistance to abrading soil, where the soil is disturbed. Disturbed means that the soil samples are lacking several of their in situ properties, e.g. natural water content, water pressure, original grain size distribution, in situ density and compaction. Gharahbagh et al. (2010, 2011) have suggested a new method for testing soil abrasivity on in situ-like soils, including the water content, possible excavation additives and a wider range of grain sizes and compaction of the soil material. A similar approach is also recently suggested by Barzegari et al. (2013). There are also some purely experience-based models (e.g. published by the Japanese Tunnelling Society) where the soil abrasivity coefficient is chosen based on experience, and without any direct measure or observation (personal communication Nakamura March 2010).

One reason for this relatively recent approach of the research subject "soil abrasion" can be explained by the worldwide urbanization, which constantly demands more infrastructure (road, railway, light rail, waste and potable water transport and cable tunnels). Where the urban surface area is fully utilized, subsurface excavation often proves to be the most viable and less disturbing solution. Home (2010) clearly illustrates this with an example of the total units of earth pressure balanced (EPB) and slurry shield TBMs operating in five year periods. From 2005 to 2010 the operating soft ground TBMs were approximately 350 units, while from 1990 to 1995 the approximate number was 150.

In order to estimate TBM tool life for the booming market of soft ground and soil TBM tunnelling, SINTEF and the Norwegian University of Science and Technology (NTNU) initiated a soil abrasion test in 2005. Since the initial introduction of the SAT™ in 2005 a total of 254 samples have been tested, originating from eight countries (2011).

The intention of this paper is to show the distribution of laboratory results with respect to soil lithology, in order to suggest a classification system for soil abrasivity when it comes to predicting TBM tool life. Further, some qualitative explanations on how the SAT™ values correspond with tool life in soil TBM tunnelling will be addressed together with suggestions for further work on this relatively new subject.

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2. Abrasive wear on TBM soft ground excavation tools

2.1. Defining abrasion and wear

According to Hutchings (1992), abrasive wear is a process where material is removed or displaced from a surface by hard particles or hard protuberances on a counter surface. The potential of abrasive wear is dependent on the abrasion properties of the material such as particle hardness, shape and size, meaning that abrasivity is a material property while wear is a physical result of a degradation process.

Nilsen et al. (2007) defines primary wear and secondary wear. Primary wear refers to wear on excavation tools such as drag bits, scraper tools, disc cutters and excavation buckets. These tools are designed to be changed and replaced as they are wearing down. Secondary wear refers to wear processes which degrade steel structures, e.g. the cutterhead. Frentzel and Babendererde (2011) uses the same definition of primary wear, but defines secondary wear as a wear process due to the passive interaction of the excavation tool with the tunnel face or muck in the excavation chamber.

TBM tools are also exposed to other degradation mechanisms than abrasive wear, which influence the tool life. The mechanisms can be mechanical overload of the tools due to poor operation of the TBM, instable face with large fragments that break the tools, blocked disc cutters and fractured tools due to poor metal processing, and blocked disc cutters due to worn out cutter bearings or blocking due to adhesive soil behaviour. Such breakdown mechanisms should not be neglected, but they are not a part of the scope for this paper, which focuses on the abrasion properties of soil and soft ground and their influence on TBM excavation tools.

2.2. Defining soil, soft rock and hard rock

ISRM (1978) defines rock and soil according to the Uniaxial Compressive Strength (UCS); where *Soil* is defined as UCS less than 0.25 MPa, soft rock is defined as UCS between 0.25 and 25 MPa and hard rock is defined as UCS over 25 MPa.

The ISRM definitions of soil, soft rock and hard rock based on laboratory strength measurements do not take into account how the soil is deposited. For instance basal till, stiff or hard soils can have considerable higher UCS than 0.25 MPa. A clear definition of soil – soft rock – hard rock is therefore difficult to give. The definition of soil and soft rock applicable for the Soil Abrasion Test™ is defined according to Table 1.

2.3. Tool types and wear mechanisms

While hard rock excavation is a combination of compressive crushing and inducing tensile stresses and thus fractures in the rock mass, excavation of soil is based on ripping plastic or elastic material, and in some cases just control the flow rate of a single graded material with low or no cohesion. For soil excavation only a limited amount of intact soil grains is crushed down due to the excavation. The tool life in soil excavation without boulders is therefore assumed to be more influenced by the material flow, rather than high contact forces between the excavation tools and the geo-material.

Tunnelling in soil and soft ground utilizes a variety of different cutter tools. Use of disc cutters is generally necessary in rock masses exceeding 20 MPa compressive strength (Khaligi, 2011). Disc cutters are also used in mixed geological conditions with a mix of rock and soil, and where boulders needs to be broken down into smaller fractions in order to enter the pressurized muck system. Disc cutters are also sometimes fitted to the TBM cutterhead to penetrate the reception shaft, after the actual tunnel boring. In soil excavation the discs are occasionally fitted with carbide inserts, in order to achieve a higher friction between the tools and the tunnel face, avoiding blockage due to clogging around the disc cutter, and thus a flat edged worn out cutter ring. The disc cutters are exposed to several types of wear. The most common wear processes for the disc cutters are abrasive wear which results in an even material loss around the disc profile, and blockage of the bearing resulting in a flat edged or single side worn ring.

Drag bits, teeth or picks (soft ground tools) are utilized in cohesive ground conditions where the majority of the material consists of clay and silt with a plastic behaviour. Scrapers are commonly used in sandy ground conditions and ripper tools are used in coarser ground conditions typically including gravel (Babendererde, 2010). The periphery of soil excavation cutterheads is also often fitted with reamers to ensure a suitable overcut (sufficient space for the shield and concrete lining rings). The reamers are also exposed to wear, and due to their position on the outer edge of the cutterhead they are exposed to longer travel distances compared to tools fitted closer to the centre of the cutterhead. The most common wear processes causing tool replacements in soft ground are worn out steel matrix holding the carbide steel inserts, and worn out carbide steel inserts.

The wear process can accelerate on the cutterhead structure if the tools are not changed in proper time. The repair work on the cutterhead structure is challenging with surrounding soil and water, often resulting in long downtimes (Fig. 1).

2.4. Indicative TBM downtime and cost of tool changes

The most obvious consequence of tunnelling in abrasive ground conditions is the increased demand for tools, and the tool cost. The TBM downtime, i.e. unproductive time for the TBM crew and potential need for hyperbaric interventions are also contributing to

Table 1
Simple identification of soil – rock description and approximate strength (UCS). The descriptions are adapted from ISRM (1978) and the corresponding identification and approximately UCS originates directly from ISRM (1978).

Description	Identification	Approx. UCS (MPa)	Remarks
SAT™: Very soft soil to soft soil ISRM (1978): *Very soft clay (S1) and Soft clay (S2)*	Easily penetrated by fist or thumb	0.0025–0.05	Applicable for SAT™ testing
SAT™: Firm – stiff soil ISRM (1978): *Firm clay (S3), Stiff clay (S4) and Very stiff clay (S5)*	Penetrated by thumb with effort	0.05–0.5	Applicable for SAT™ testing
SAT™: Extremely weak to very weak rock ISRM (1978): *Hard clay (S6), Extremely weak rock (R0) and Weak rock (R1)*	Indented by thumbnail – easily peeled by pocket knife.	0.5–5	Applicable for SAT™ testing
SAT™: Weak rock ISRM (1978): *Weak rock (R2)*	Can be peeled by a pocket knife. Shallow indentations made by point of geological hammer	5–25	Not applicable for SAT™ testing without crushing of intact grains

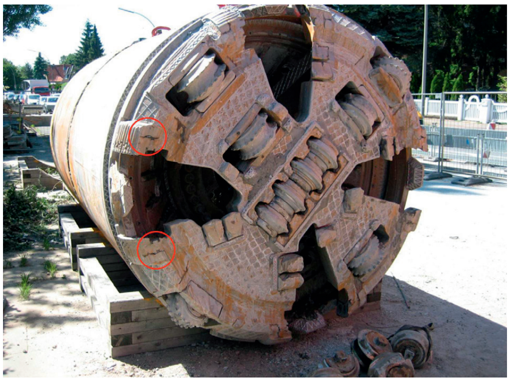

Fig. 1. Damaged and worn cutterhead structure on a pipe jacking machine (outer diameter ~2 m) due to worn out disc cutters and scraper tools (Photo by Tim Becker). The red rings marks fractures in the cutterhead structure itself. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Inputs and assumptions for calculation of TBM depreciation cost.

Input	Quantity
Interest rate per annum	5%
TBM purchase cost	7 mill USD
Calculated depreciation cost of TBM per shift (8 h)	1973USD

increase the cost for TBM tunnelling in abrasive ground conditions (see Table 2).

In the following, two scenarios of tool change operations will be presented together with a cost estimates for the tool changes and cost of TBM downtime (Table 3). The investment costs for the TBM and the tools have been obtained from the Robbins Company (personal communication Lok Home, August 2011) and from Herrenknecht Utility Tunnelling Department (personal communication Lutz Zur Linde, December 2011). In the calculation it is assumed that one tool cost 540 USD.

Table 3
Estimation of tool change operations.

Items	
Number of TBM crews	6
Number of crew used for tool changes and other maintenance during downtime	4
Daily wage per tunnel worker incl. insurance, taxes etc.	700 USD/ shift
Cost of non-productive TBM crew (2 × 700 USD/shift)	1400 USD/ shift
Number of divers	1
Assumed face pressure at intervention	1.5 bars
Time needed for diver preparation and decompression[a]	2 h
Time needed for tool changes	6 h
Assumed mobilization cost for divers	1000 USD/ diver
Daily wage for hyperbaric divers	1200 USD/ shift
Payment cost for divers	1200 USD/ shift
Tool cost	540 USD/ pcs

[a] After Babendererde and Elsner (2009).

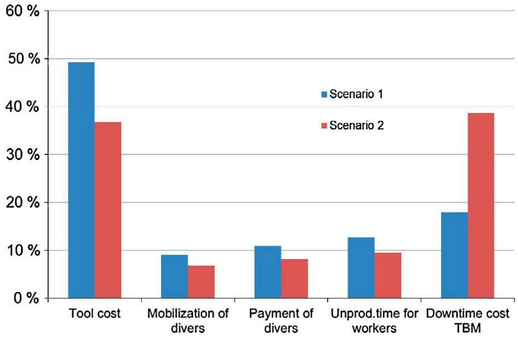

Fig. 2. Distribution of percentage of cost for material, work and downtime for TBM tool changes. Scenario 1 has a total estimated cost of 10,973 USD, and Scenario 2 has a total estimated cost of 88,020 USD.

The indicative TBM downtime and cost estimation is done for two scenarios. In scenario 1 it is assumed a 1000 m section with low abrasivity (1200 s m^3/c), and in scenario 2 it is assumed a 1000 m section with high abrasivity (200 s m^3/c). For a hyperbaric intervention of 8 h, it is assumed that 15 tools can be replaced For the low abrasivity this involves one intervention to change 10 tools and for the high abrasivity a total of six interventions is needed.

The TBM depreciation cost (TBM_{dc}) per 8 h is calculated by the following equation:

$$TBM_{dc} = TBM_{pc} * (1 - buyback\%) * 8\ \mathrm{h} * \frac{interest^{y}}{(y * 365) * 24\ \mathrm{h}} \qquad (1)$$

In the financial scheme it is assumed that the TBM is financed with an interest rate of 5% (*interest)* and a 20% *buy-back agreement*, and that the TBM is depreciated after 3 years operation (*y)* with a purchase cost (TBM_{pc}) of 7,000,000 USD.

The total cost for replacing 10 tools in Scenario 1 is 10,973 USD, and for replacing 63 tools in Scenario 2 is 88,020 USD. Fig. 2 shows Scenario 1 and 2 and h.

The indicative calculation of the tool change cost is included in this paper to show the economic effect worn out tools may have on tunnelling projects.

3. The NTNU/SINTEF Soil Abrasion Test (SAT™)

3.1. Background

The NTNU/SINTEF Soil Abrasion Test (SAT™) is an outcome and further development of the NTNU/SINTEF abrasion tests for rock, referred to as the Abrasion Value (AV) and Abrasion Value Cutter Steel (AVS). Fig. 3 shows the schematic overview of the test apparatus, which consists of a rotating steel disc, which is fed with soil grains less than 4 mm. As the soil is transported on the rotating disc it passes underneath a steel sample, originating from a TBM disc cutter. This contact cause abrasive wear on the steel sample. Compared to the AVS test, which is performed by use of a crushed rock powder less than 1 mm, a dry and disintegrated soil sample with grain size less than 4 mm is used in the SAT™ test. Fig. 4 shows the interaction between the steel and soil sample for the initial AVS and the modified SAT™ test piece.

Initially the SAT™ test was performed with an upper grain size limit of 1 mm (Nilsen et al., 2006a,b,c). Due to the relatively limited fraction size (0–1 mm), the test pieces were modified in order to include grain sizes up to 4 mm (Nilsen et al., 2007), meaning that the SAT™ is applicable for testing clay, silt and sand fractions. The test cannot be performed on fragments larger than 4 mm. Dur-

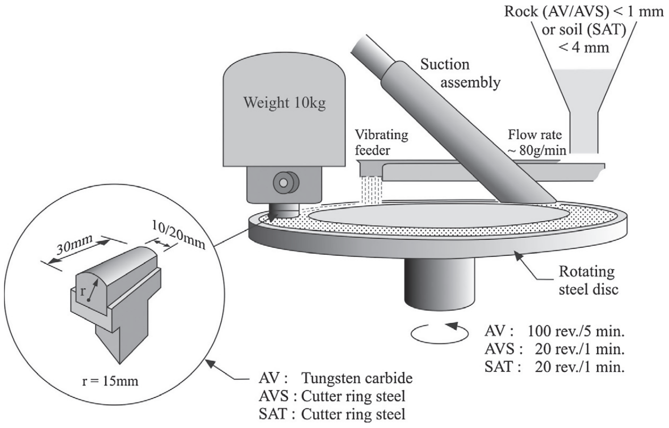

Fig. 3. Schematic overview of the SAT™ test procedure.

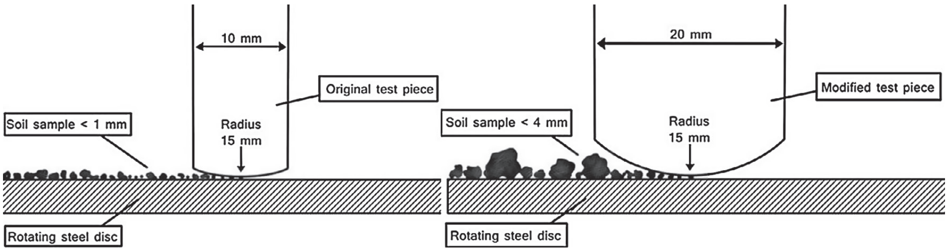

Fig. 4. The initial AVS (left) and modified and current SAT™ (right) test pieces.

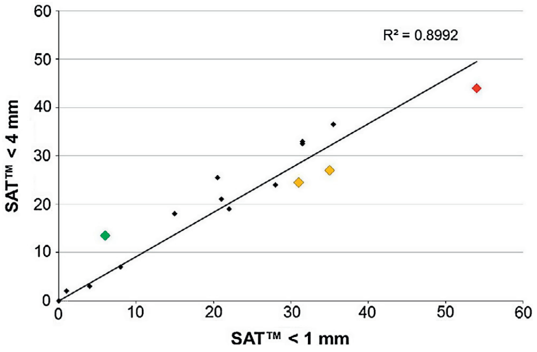

Fig. 5. Relationship between 15 soil samples tested by SAT = 1 mm and SAT = 4 mm.

ing the modification of test pieces some studies were conducted in order to investigate if there was a systematical change of the measured abrasivity with the two test pieces. The deviation shown in Fig. 5 can[1] be explained by either different abrasivity properties of the particles less than 1 mm compared to particles <4 mm (for green, red and yellow points), or by normal variation of properties in geomaterials, which are within the test procedure's variation as explained in Section 3.2.

In Fig. 5, the green point is a clay sample with some coarser grains in the matrix, the yellow points are from well graded samples where varying grain sizes most likely have varying abrasivity properties, and the red point is a single graded sand with 100% quartz. The amount of tests are too few in order to conclude whether the SAT™ test procedure systematically differentiates $\text{SAT}_{1\text{mm}}$ from $\text{SAT}_{4\text{mm}}$.

3.2. Test procedure

To be able to make comparisons with previous test results and the NTNU/SINTEF database for hard rock it is decided to follow the NTNU abrasion test procedure as closely as possible. The following preparation of soil samples is therefore suggested.

In order to reduce and avoid changes of the original soil properties, the soil samples should be dried gently in a ventilated oven at 30 °C for 2–3 days. In order to disintegrate and separate particles into an abrasion powder the following techniques are suggested:

(1) Disintegration by use of a soft hammer (plastic head) or manually by hand.
(2) Sieving the sample with steel balls as a gentle disintegration aid. The sample material is sieved on 4.0 mm and 1.0 mm sieves. The disintegration aid is applied by use of 20 small steel balls with a diameter of 15 mm weighing 14 grams each.
(3) Disintegration in a jaw crusher if the sample contains hard lumps of cohesive material after initial drying. Crushing of intact and original grains should be avoided, in order to keep the original grain shape and size (Nilsen et al., 2007).

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[1] For interpretation of colour in Fig. 5, the reader is referred to the web version of this article.

After the drying and disintegration procedures, the material should be sieved on 4.0 mm and 1.0 mm in order to verify the grain size distribution after preparation. Mark that if disintegration of the sample requires jaw crushing and the soil sample is not indentable by hand, finger or nail the abrasion result should be reported as Abrasion Value Cutter Steel (AVS), used for measuring rock abrasivity.

Fractions above 4 mm in soil samples are sieved out prior to testing. In order to include the mineralogy for the grains larger than 4 mm, crushing is an option. However, by crushing the grains it is difficult to achieve the correctly distributed grain sizes for each mineral, as well as the original grain shape is influenced. If the soil sample consists of a large portion of fragments larger than 4 mm, the SAT™ test should be used with caution. Hence in this paper, it is assumed that mineral composition of the fraction larger than 4 mm is identical to the fraction less than 4 mm.

The SAT™ value is calculated as the mean value of the measured weight loss on the steel bit in milligrams after testing. To be accepted as a SAT™ value, the results of 2–4 tests should not deviate by more than 5 mg (Nilsen et al., 2007).

3.3. Test dynamics and relation to TBM excavation

The drive length of one test is 20 m with a velocity between the soil particles and steel bit of 0.33 m/s. The velocity is relatively low compared to a TBM cutter tool located on the periphery on the cutterhead. However, the velocity is of the same magnitude as a TBM tool close to the average radius of the cutterhead.

The contact force between the steel and soil particles is 100 N, which is distributed over a line (SAT™ test piece). The Herzian contact equations can be used when one material indent into a second material and causes changes in the contact area (Hutchings, 1992). The contact area is given by the following equation (Wood, 2009):

$$a = \left(\frac{W/l * r}{\pi E}\right)^{1/2} \text{ (after Wood 2009)} \tag{2}$$

The maximum contact pressure is given by the following equation:

$$P_m = \left(\frac{W/l * E}{\pi r}\right)^{1/2} \text{ (after Wood 2009)} \tag{3}$$

where a is the contact area between the spherical specimen and the plane. W the normal load, for SAT™ (100 N), l the length of the SAT™ test piece (30 mm), r the radius of the SAT™ test piece (15 mm), and E is the elastic modulus which is dependent on the Young's modulus and the Poisson's ratios for the SAT™ test specimen and the dry soil given by the following equation:

$$\frac{1}{E} = \left(\frac{1-\upsilon_1^2}{E_1}\right) + \left(\frac{1-\upsilon_2^2}{E_2}\right) \text{ (after Hutchings 1992)} \tag{4}$$

For the calculation of the contact pressure the following elastic properties have been used:

$$E_1 = E_{steel} = 210 \text{ GPa}$$

$$\upsilon_1 = \upsilon_{steel} = 0.3$$

$$0.2 < \upsilon_{soil} = \upsilon_2 < 0.5 \text{ and}$$

$$0.1 \text{ GPa} < E_{soil} = E_2 < 5 \text{ GPa}$$

The outcome of the Herzian maximum pressure calculation is then that the maximum contact pressure is ranging from 200 to 370 MPa (dependent on the elastic properties of the soil sample). The contact pressure range is close to what a TBM disc cutter faces in hard rock application (Gong et al., 2006).

The steel type used in the SAT™ test originates from a disc cutter. The steel type is a heat treatable, low alloy steel containing nickel, chromium and molybdenum. The steel has a good resistance against wear and fatigue degradation and is relatively ductile, similar to steel types used for TBM excavation tools. The steel type in the SAT™ test is chosen due to its similar properties compared to steel on cutter tools (disc cutters and soft ground tool steel matrix), and due to its properties making it possible to detect and measure weight losses over a wide range of geological material.

The feed of soil to the rotating disc is controlled by the operator. The criterion for adjusting the vibrating feeder is to avoid steel against steel contact (test piece against the rotating disc) and to avoid a pile of grains in the front of the test piece. These two criterions make the test dependent on the operator. However, the steel of the rotating disc is a softer steel than the SAT™ test piece. When the test is performed without any soil fed to the disc (steel against steel testing), there has not been any measurable weight loss of the SAT™ test piece recorded.

4. Assessment of the Soil Abrasion Test (SAT™)

4.1. Statistical overview of SAT™ values

The NTNU/SINTEF Soil Abrasion Test™ database contained 254 unique abrasivity measurements on soil samples by medio 2011 (Fig. 6). The maximum recorded value is 52, which is a quartz rich sand with sharp edged grains. The lower values (SAT™ < 5) are generally representing clay samples with low content of quartz or other hard minerals.

By defining classification limits at the 33 and 66 percentile the following classification of SAT™ results is obtained.

- SAT™ ⩽ 7 is classified as low.
- 7 < SAT™ < 22 is classified as medium.
- 22 ⩽ SAT™ is classified as high.

The reason for suggesting only three classification categories is due to relatively low amount of data. For the classification of Abrasion Value Cutter Steel (AVS), the categories are seven and the number of observations is more than 1500 (Dahl et al., 2012).

Some studies on correlation between SAT™ values and soil properties like mineralogy and grain shape have also been done. Figs. 7 and 5 indicate a relationship between SAT™ values and quartz content and SAT™ and Vickers Hardness Number Rock (VHNR). The VHNR is a factor taking into account the percentage

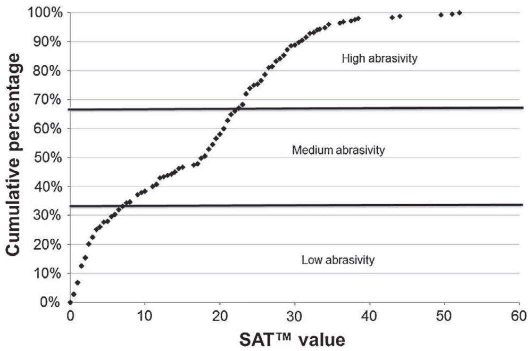

Fig. 6. Cumulative distribution of the recorded SAT™ values in the NTNU/SINTEF soil abrasion database (medio 2011).

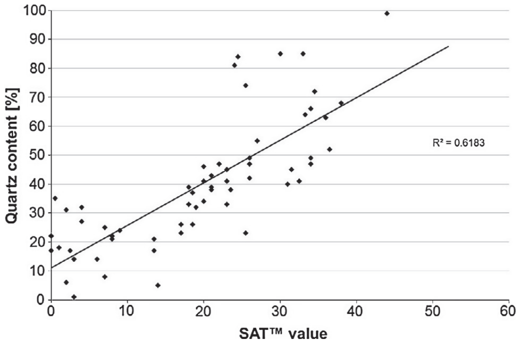

Fig. 7. Correlation between SAT™ value and content of quartz. *N* = 62.

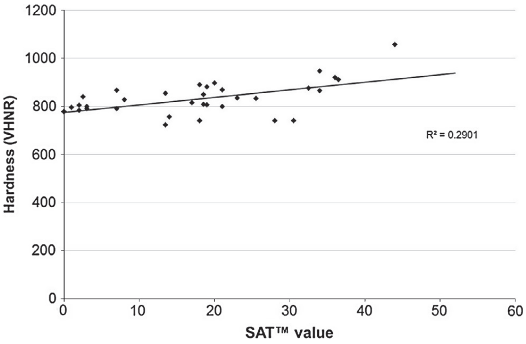

Fig. 8. Correlation between SAT™ value and Vickers Hardness Number Rock (VHNR). *N* = 30.

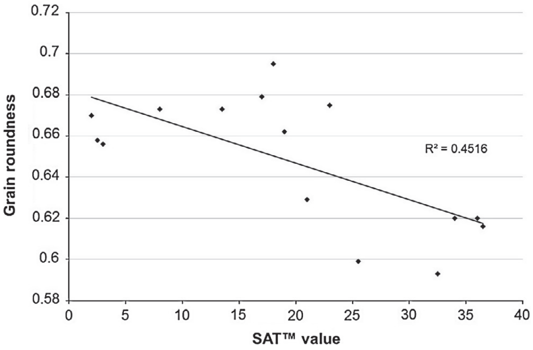

Fig. 9. Correlation between SAT™ values and grain roudness. *N* = 15.

of each mineral and its hardness. There is also some relationship between SAT™ values and grain roundness as shown in Fig. 9.

The grain roundness, *R*, is measured according to Eq. (5) after Russ (2006):

$$R = \frac{4 * \text{grain area}}{\pi * \text{grain max diameter}^2} \tag{5}$$

The content of quartz is measured by Differential Thermal Analysis (DTA) and other minerals by X-ray Diffraction (XRD).

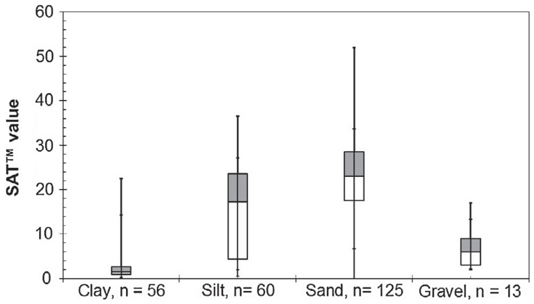

Fig. 10. Box plots showing the range of SAT™ values for clay, silt, sand and gravel.

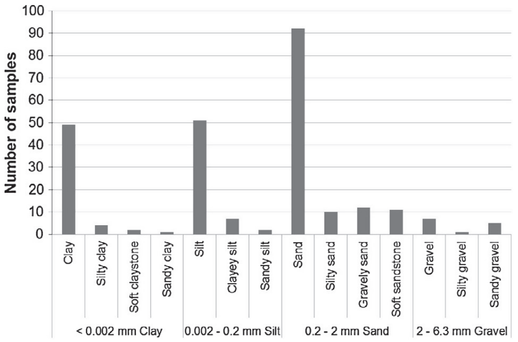

Fig. 11. Overview of sub groups of clay, silt, sand and gravel recorded in the NTNU/SINTEF Soil Abrasion Database.

The correlation between the SAT™ and quartz content for 62 samples proves to be good, see Fig. 7.

The correlation between SAT™ values and the sample mineralogy, represented by the Vickers Hardness Number Rock (VHNR) (Fig. 8) is found less significant than the SAT™ quartz correlation. This is unexpected, as the SAT™ value is expected to be highly influenced by the total mineralogical content of soil samples. One likely explanation for this is the relative low amount of data points in Fig. 9.

The grain shape (according to Eq. (5)) correlates well with the SAT™ values for the relative few data points shown in Fig. 9.

The relation between the measured abrasivity with the SAT™ test, mineralogy and grain shape corresponds well with general tribological laws in Hutchings (1992), where a material's abrasion properties is defined by particle hardness, shape and size. A clear and well defined influence of particle size is not proven by the SAT™ procedure see Fig. 10.

In Fig. 10 the term gravel could be confusing, as the SAT™ procedure does not allow gravel particles to be tested. The results for gravel in Fig. 10 refer to the sieved fraction less than 4 mm from the gravel samples, meaning that the distribution is not based on gravel size particles. Fig. 10 also shows that the grain size of the soils do not seem to influence the SAT™ value systematically regarding grain size, but it gives an indication that sand particles in general are more abrasive than clay and silt particles according to the SAT™ test.

Fig. 11 shows sub-groups of clay, silt, sand and gravel in the NTNU/SINTEF Soil Abrasion Database. The total amount of samples including grains larger than 4 mm (gravely sand, gravel, silty gravel and sandy gravel) is 25. As mentioned in Section 3.2, results obtained from samples containing fractions above 4 mm should be used with caution.

4.2. Relation between SAT™ values and actual tool life

Some correlations between SAT™ values and recorded tool life from TBMs have been prepared to show the possible applicability of SAT™ as a direct estimation method for tool life. The current correlation is based on a total of nine TBM projects (three projects in Northern America, five in Germany and one in the Middle East). The tunnel lengths are ranging from 200 m (pipe jacking) up to 5500 m with relatively small excavation diameters ranging from 2.0 m to 5.5 m. The total tunnelling length in the data set is approximately 17,500 m. All projects are based on pressurizing the tunnel face with bentonite slurry, meaning that there are no Earth Pressure Balanced (EPB) TBMs included in the data set. The relative short tunnel drives and small TBM diameters might also influence the total applicability of the charts to some extent. The data set do not contain any projects with boulders. This is most likely contributing to the correlation coefficient R^2 positively, as excavating boulders is not only an abrasive process, but something which is still influencing the TBM tool life.

The tool life presented in Figs. 12–16 is presented as solid cubic metre per cutter tool (s m^3/c) in order to include various TBM diameters in the correlations. The tool life has been calculated as instantaneous cutter consumption meaning that each tunnel section between tool changes has a calculated tool life (Bruland, 1998a).

Due to the relatively low amount of data for tool changes, the correlations are distinguished between disc cutter life and soft ground tool life (rippers and scrapers). The data set at present is too small in order to introduce tool life for varying tool sizes, shapes, design and metallurgy.

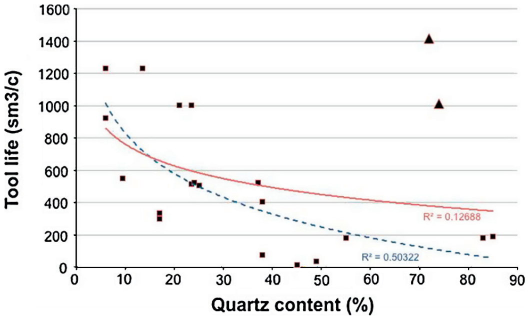

Fig. 14. Correlation between quartz content and recorded soft ground tool life. The red trend line represents all available data sets. The blue dashed trend line represents data sets without the two outliers shown in Fig. 12. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The two outliers (marked as triangles) in Fig. 12 are from two projects where the SAT™ values were high (25.5 and 33.3) and with high tool life. The soils at the two specific projects were single graded sand without fines. Such soils are very easy to excavate as it is almost flowing by itself, saving the TBM tools from high contact forces and impacts. The grain size distribution and cohesive properties of the soils are not taken into account in the SAT™ test,

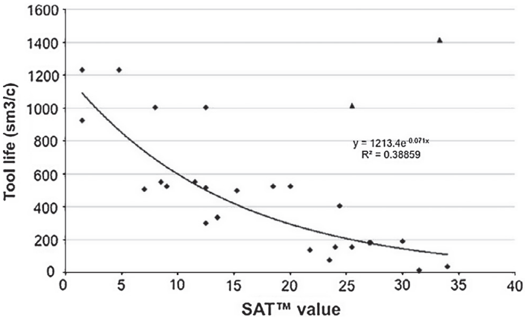

Fig. 12. Correlation between SAT™ values and recorded soft ground tool life.

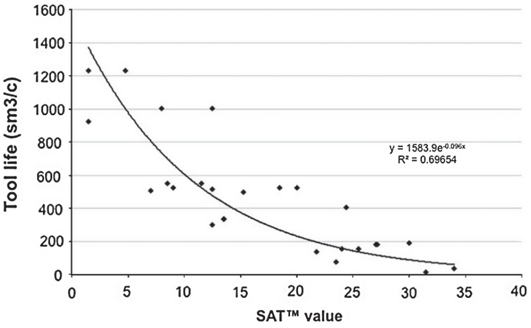

Fig. 13. Correlation between SAT™ values and recorded soft ground tool life after removing the two outliers in Fig. 12.

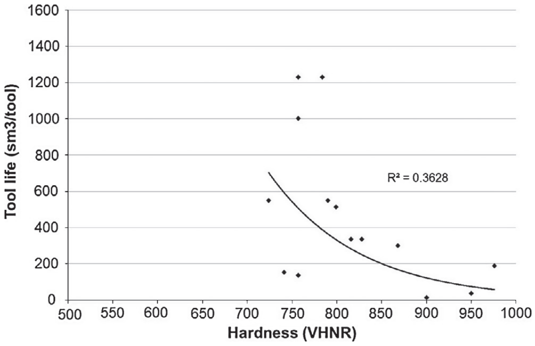

Fig. 15. Correlation between the Vickers Hardness Number Rock (VHNR) and the recorded soft ground tool life.

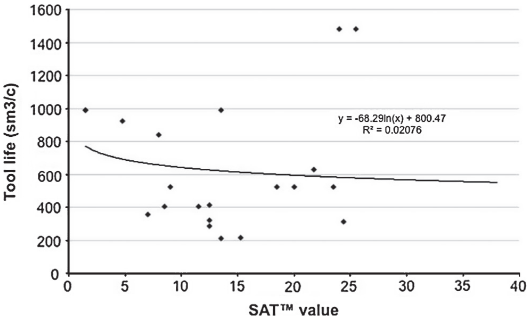

Fig. 16. Correlation between SAT™ values and recorded disc cutter life.

although it seems to have a high influence and importance when making a soft ground and soil tool life estimation.

By removing the two projects from the data set the R^2 increases and the correlation becomes better, see Fig. 13. The increase of the R^2 by removing to points also shows the sensitivity of the current correlation when introducing new data. It should therefore be emphasized that the current correlation is based on relatively few data and by later adding tool life data and SAT™ values from other projects the relation may be significantly changed.

For comparison, a similar correlation has been prepared to compare quartz content with recorded soft ground tool life. The correlation between quartz content and tool life based on the collected data is non-existing by including all available data sets, as shown in Fig. 14.

An attempt of showing tool life correlated to the mineralogical hardness by the VHNR is shown in Fig. 15. The correlation is found better than the quartz-tool life correlation. The correlation coefficient is however highly influenced by the low amount of data.

In Fig. 16, a correlation between SAT™ values and disc cutter life is presented. There is no relationship with the current data set. The work done by disc cutters in soil is limited to crushing boulders, enter the reception shafts and tackling possible other hard obstacles along the tunnel alignment. In the disc cutter changes included in Fig. 16 a common reason for changing the cutters were blocked bearings, assumed to be caused by soil clogging around the tools.

4.3. Further work and conclusive remarks

The main findings of this paper are:

- The Soil Abrasion Test (SAT)™ has a good correlation to recorded soft ground tool life, thus the SAT value can be used to schedule and price tool cost and downtime for soft ground tunnelling projects.
- The SAT values correlates good with grain roundness and soil mineralogy.

However, there are some limitations basing a TBM excavation tool life estimate purely on abrasion testing of a disturbed soil sample. The soil samples applicable for SAT™ testing do not contain water and the in situ compaction/density. The test is done without soil conditioning additives, and the applicable grain size for testing is limited to 0–4 mm. The findings presented in Figs. 12 and 13 clearly show the effect of the grading of the soil sample, which can be related to the in situ compaction of the soil. Thus, in order to make the estimates more reliable, the SAT™ value should be adjusted with cohesion/in situ density, potential influence of boulders and use of excavation additives.

The influence of cohesion/in situ density can be done by introducing geotechnical parameters or measurement for the soil, for example the grade of compaction, C_u (ratio of grain size D_{60} and D_{10}). The parameters can then be included in a multivariate regression or as input into a ''Soil Abrasivity Index''. The boulders influence can be introduced by a statistical factor related to the downtime to crush boulders into smaller fractions and how much this can affect the tool life.

Testing on in situ like soils as suggested by Gharahbagh et al. (2010) and Barzegari et al. (2013), is also an approach which should be followed up. By including as many as possible soil parameters, e.g. more representative grain size distribution, water content, compaction and density together with possible excavation additives, the measured test results may be more understandable and less dependent on empirical relationships. NTNU/SINTEF is currently working on a similar approach as suggested by Gharahbagh et al. (2010), in order to measure the influence of soil compaction, excavation additives and the soil confinement on the tool life (Jakobsen et al., 2012).

In an estimator for tool life in TBM tunnelling, the influence of the TBM operator and tool replacement scheme will also influence the tool life. How to include the human influence into the estimate will be a challenge, but might be done, as more empirical data is available.

A continuation of collecting soil samples for testing together with corresponding TBM production and tool data is necessary to build a better model for predicting tool life in soil and soft ground.

Acknowledgements

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Paper 4

Tunnelling in abrasive soils – review of a tunnel project in Germany

Jakobsen, Pål Drevland
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Presented at Korean Tunnelling Association, Mechanised Tunnelling Symposium 2012

Tunnelling in abrasive soils – review of a tunnel project in Germany

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Abstract

Pipe jacking is a well-recognized method for mechanical excavation of small cross-section tunnels with diameters from 0.25 to 4 m, with limited length from 50 to 1,200 m. The excavation method is suitable in soft soil (clay, silt and sand), soft rock (UCS < 50 MPa) and even hard rock (50 < UCS < 200). The pipe jacking advance is based on applying thrust on pipe elements which are installed from a start shaft, oppositely to typical segmental lining tunneling for larger diameters. The geotechnical conditions form a major factor for the excavation rates which may vary between 50 m per day in favorable conditions and only a few centimeters in worst cases. In unfavorable geotechnical conditions such as varying water pressure, occurrence of boulders or abrasive soil conditions the performance can be highly influenced. The aims of the paper are to (1) give a brief introduction to the pipe jacking methodology, (2) introduce how unfavorable ground conditions can be pre-investigated, and (3) how contractors can adapt the both the tendering and decision taking at site having the necessary information about the ground conditions. The subjects are also relevant to segmental lining tunnelling as well as for EPB and slurry shield TBMs.

Introduction

Pipe jacking, also called “Microtunnelling” is a commonly used method for excavation of tunnels with small cross-sections (< 4 m diameter). The method is based on a moving front shield which has a rotating cutterhead with a variety of cutter tools. The selection of cutter tools is adapted to the expected ground conditions. Ripper tools are used in cohesion soils (clay and silt), scraper tools are commonly used in friction soils (sand and gravel) and disc cutters are installed on the cutter head when the tunnel alignment is subjected to boulders and hard rock conditions. The advance of the pipe jacking shield is driven by static energy applied to the jacking-pipes by a hydraulic cylinders located at the starting shaft. The jacking pipes, which are usually made out of concrete, are inserted piece by piece at the starting shaft and have a length of up to 4.0 m.

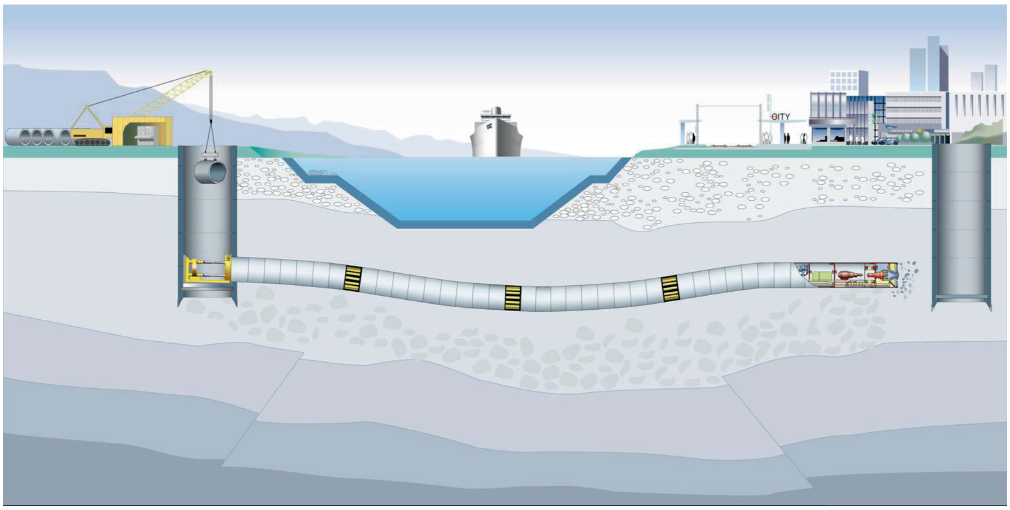

Figure 1 Scheme of pipe jacking project (starting and reception shaft, main and intermediate jacking stations (marked as yellow). (Scheme: Herrenknecht)

The soil is removed by a rotating cutterhead (Figure 2) which is capable to loose the soil at the shield front. The soil is then mixed with the transport slurry (bentonite suspension) and pumped to the starting shaft and the ground surface to the separation plant unit. The separation plant cleans the excavated soil from the bentonite slurry, which is recycled.

Figure 2 Newly manufactured pipe jacking machine, AVN 1600/1800 TB by Herrenknecht. (Photo: Tim E. E. Becker)

The operation of the pipe jacking machine, also referred to as AVN[1], includes the advance rate of the hydraulic station, and all other machine parameters. The operation and continuous monitoring of machine parameters are monitored from a control cabin located at the starting shaft. Since all necessary works are performed around the starting shaft, pipe jacking is regarded as very efficient in terms of required personnel, time consumption and capacity, for excavation of small cross-section tunnels.

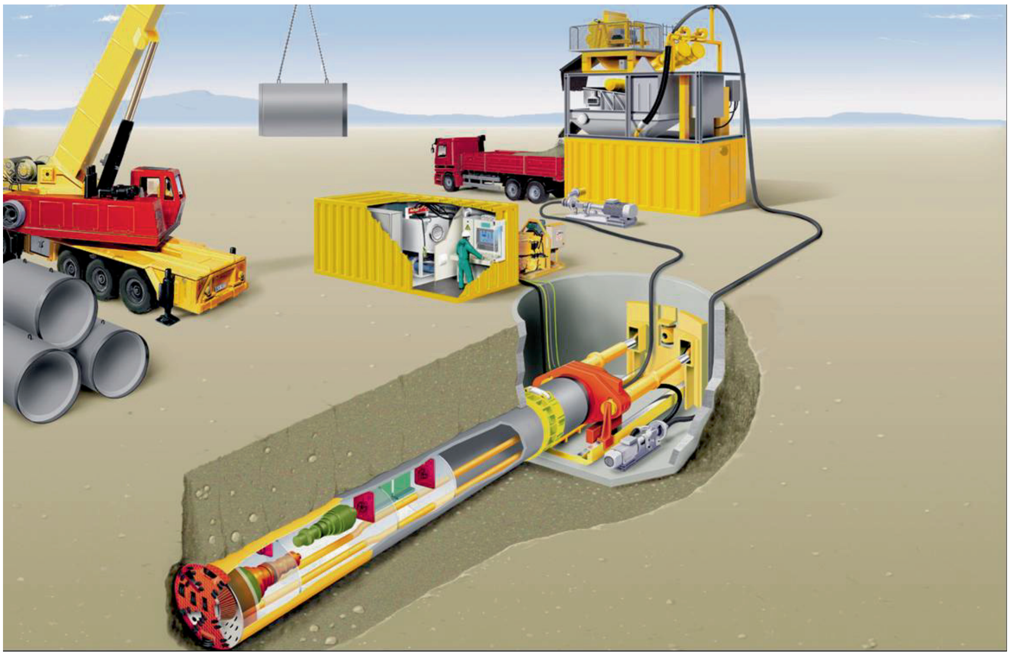

Figure 3 Typical pipe jacking set up). (Scheme: Herrenknecht)

The tunnel length between shafts gives the main limitation of pipe jacking. As there is a maximum allowed jacking force that can be applied to the pipes, intermediate jacking stations are installed in the tunnel. These small hydraulic stations are commonly activated in order to reduce the actual pushing length of the tunnel. Typically a 2.5 m diameter machine would require an intermediate jacking station every 50 to 200 m, depending on the pipe material and ground conditions. The distance between starting and reception shafts can be as high as up to 1,200 m.

In order to keep the machine steerable, the rotating cutter head produces a small overcut (annular gap) relatively to the actual outside diameter of the jacking pipes. During the complete jacking period, the annular gap of the tunnel is constantly lubricated by a bentonite suspension. This is done in order to support the annular gap, and secondly, in order to minimize settlements at the ground surface. The bentonite injection also decreases the friction between the pipes and the surrounding soil. The automatic lubrication system takes care of injecting the bentonite suspension. The quality of the bentonite lubrication needs to be checked in regular intervals and adapted if necessary.

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[1] AVN is a German abbreviation for *Automatisches Vortriebsystem mit Nassförderung,* which in English means automatic advance system with slurry.

The presented pipe jacking project in this paper was located in Hamburg, Germany. The project name is Sammler Ost with Hamburg Wasser as the project owner and client.
The client, Hamburg Wasser, has a lot of experience in acquiring pipe jacking projects for the city of Hamburg´s water and wastewater ways.

General Project Preparation for Pipe Jacking

During the planning process of a tunneling project, the owner needs to determine the requirement of the tunnel. Several purposes are typically required:

- Gravitation line for rain, mixed (rain & sewage) water or sewage water
- Pressure pipeline
- Mantle pipe for pressure pipelines (gas, oil, water, etc.)
- Mantle pipe for cables
- Pipe for infrastructure ways (pedestrians)

These individual project boundary conditions enable the demands of the needed pipe diameter, material, alignment and distance between shafts.

Figure 4 Reinforced concrete jacking pipe (inner diameter (ID) 2800 mm and outer diameter (OD) 3000 mm) (Photo:Tim E. E. Becker)

The tender/ project documents form an integral part of the project and describe the contractual boundaries for the contract between the client and the contractor. Within German contracts, *The German DWA Rules and Standards A 125 E for Pipe Jacking and Related Techniques* provides comprehensive guidelines for planning and construction that are:

- Surface and underground structures and systems (e.g. foundations, underground railways, existing networks as channels, cables, bunkers, anchors)
- Soil and groundwater conditions
- Supply and disposal facilities (e.g. water, waste water, power, roads/ streets)
- Jacking distance and line (e.g. alignment and elevation plans including results of soil survey)
- Dimensions and material of the jacking pipes
- Third party plannings and approvals
- Environmental aspects (e.g. degradable hydraulic oil for machines, noise limitations)
- Requirements by authorities (e.g. traffic regulation, working hours)

The careful preparation of the above mentioned documents represent an important duty of the client in order to implement a proper call for bids, which are highly important to achieve a successful project. A well-experienced engineer with expertise for such projects shall be able to perform a differentiated evaluation of the bids with a sense of proportion between the technical capability of the bidders and economical limitations of the client as shall be shown.

A thorough description of the soil and groundwater conditions is of great importance for tendering contractors. As the client delivers the “material soil” to the project, it should be one of his initial interests to produce a geological report including of the following parameters and information (according to DWA-A 125 E, here for soft soils):

- Maximum and minimum groundwater level and hydrograph curves
- Contamination level of soil, soil gas and groundwater
- Disposal advice according to legislation
- Concentration of abrasive minerals and quartz content to determine abrasiveness
- Deformation module
- Aggressiveness reaction of soil and groundwater
- Swelling potential
- Borehole logs
- Weight per unit volume
- Fault zones and cavities
- Particle size distribution and particle shape
- Water permeability coefficient
- Compactness
- Plastic limits and water content
- Shear parameter, friction angle and cohesion
- Earth pressure coefficient
- Cobble size and cobble proportion, uniaxial compressive strength
- Water content and water pressure
- Organic components and lime content
- Tendency towards liquefaction

The above-mentioned parameters shall be combined in a geology report, which provides sufficient information for a careful project preparation. Nevertheless, the deviation between the geological report and the actual conditions found on site may lead to disputes and possible claims between clients and contractors.

Tender documents of the Sammler Ost tunnel project in Hamburg, Germany

The project was according to the German Construction Contract Procedures, thus the project information consisted of a technical and a legal part, which is common in Germany:

- Legal project information:
    - Special Conditions of Contract
    - Additional conditions of Contract and
    - Standard Conditions of Contract
- Technical project information:
    - Technical Specifications
    - Additional Technical Specifications

- Standard Technical Specification

Due to the experienced client, the tender documents were thoroughly prepared. The technical specification contained information regarding:

1. General Information
2. Information on project boundaries
3. Available construction site areas
4. Special area conditions
5. Execution of the works
    a. Time schedule
    b. Order of works
6. Materials and Parts
7. Documents for execution
8. Technical rules, checks and permits
9. Attachments (e.g. drawings and maps)

Additionally, the bill of quantities described all necessary works to be executed and specified additional requirements to each element.

The documents establishing the formal framework for the pipe jacking works consisted of:

- General overview
- Ground view and longitudinal section (including borehole information) for each pipe jacking drive
- Technical requirements for all materials including pipes are defined in the Additional Technical Specification
- Geology report (as part of chapter 4. Special area conditions)

The geology report represented a major part of the project information. It contained detailed information about soil parameters. The geology report did also include a recommendation for machine type and technology for the Sammler Ost project. As the geology report was finished before the new DWA-A 125 was finally published, it did not provide any information regarding the concentration of abrasive minerals and quartz content, or any statement referring to the level of abrasivity. In our opinion, these shortcomings led to great problems in the later project process.

Project parameters of the Sammler Ost tunnel project in Hamburg, Germany

Client:	Hamburg Wasser, Germany
Contractor:	Hans Lemme Hoch-, Tief- und Stahlbetonbau GmbH & Co. KG, Berlin, Germany
Construction period:	January 2008 – September 2010
Works:	2,400 m sewage channel ID 1,600, OD 2,240, reinforced concrete jacking pipes with inner PEHD-liner, length 3.50 m, 3 jacking lines (910 m, 958 m and 532 m), curved drives with R = 1,000 – 500 m, 3 round jacking ∅ 10 m/ reception ∅ 7 m shafts by bore piles, depth up to 20 m

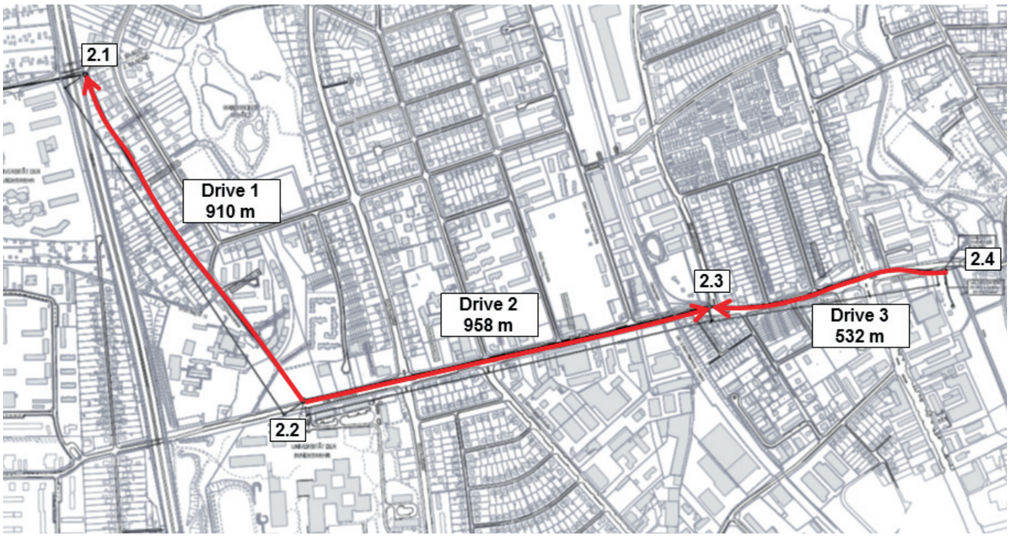

Figure 5 Project overview of the three pipe jacking drives. (Layout plan by Hamburg Wasser with additions by Tim E. E. Becker)

Factsheet for each drive:

Drive 1
Length: 910 m from shaft 2.2 to shaft 2.1
Alignment: radius R = 1,000 m and 3,000 m
Slope: straight 1.8 per mill
Depth: 20 m
Geology: 95% glacial drift, partly fluvial deposited sand and silt
Groundwater: appr. 10-12 m above pipe invert level

Drive 2
Length: 958 m from shaft 2.2 to shaft 2.3
Alignment: straight
Slope: straight 1.8 per mill
Depth: 20 m
Geology: 70% glacial drift, rest fluvial deposited sand, fine sand and basin silt
Groundwater: appr. 10-12 m above pipe invert level

Drive 3
Length: 532 m from shaft 2.4 to shaft 2.3
Alignment: R = 500 m and 600 m
Slope: straight 1.8 per mill
Depth: 12 m
Geology: 20% fluvial deposited sand, 80% fluvial deposited fine sand and basin silt
Groundwater: appr. 4-10 m above pipe invert level

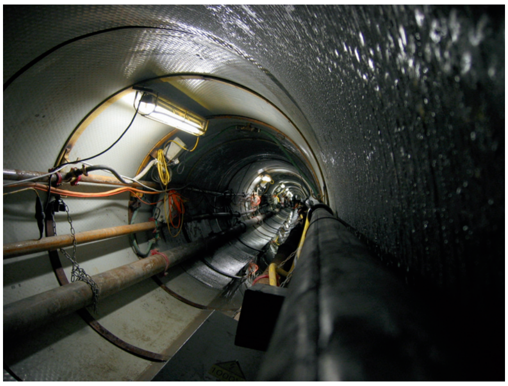

Figure 6 The Sammler Ost Tunnel (Photo: Tim E. E. Becker)

The geology report recommended the use of a pipe jacking machine with slurry transport of the AVN type. The contractor, Hans Lemme Hoch-, Tief- und Stahlbetonbau GmbH & Co. KG had a newly ordered and manufactured machine AVN 1600/1800 TB by Herrenknecht (Figure 2). The AVN machine was designed with a center door to get access to the shield front, and to the cutter tools as well as of an integrated air pressure regulation station. These provisions were essential for the later success of all three drives.

Figure 7 Photo of the cutter head of the Herrenknecht pipe jacking machine AVN 1600/1800. (Photo: Tim E. E. Becker)

Execution of the Sammler Ost project

Figure 8 shows the pipe jacking performance for all three drives in the Sammler Ost project. By comparing the performance in the three drives, one can see that the performance is varying even though the excavation is done by the same contractor, with the same equipment, and with experienced personnel in similar pre-investigated soil properties.

Drive 1 was completed with reasonable progress rates and without any interruptions. The excavated glacial drift produced additional separation effort and stones and boulders were passed successfully without damages or noticeable wear on the cutter head and its tools.

The following Drive 2 started similar as Drive 1. However, when the machine reached the shaft wall at shaft 2.3, the machine wasn't able to pass the concrete bore piles of the shaft wall. It was then decided to enter the cutter head chamber under air pressure (up to 1.2 bars) in order to check the condition of the tools. The cutter head and the tools were in a disastrous state, resulting in immediately replacement of 5 cutter discs in order to be able to enter the reception shaft. The damage of the cutter head structure was tremendous, resulting in a full replacement of the cutter head before Drive 3.

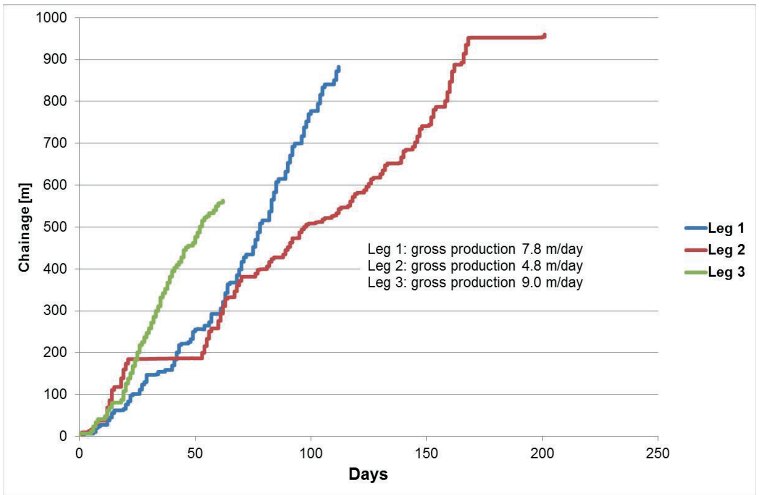

Figure 8 Summary of production rates for the three tunnels in the reviewed tunnel project.

Figure 9 Damaged cutter head after the second drive at the Sammler Ost project. (Photo:Tim E. E. Becker)

Figure 10 Photo showing blocked and destroyed double disc cutter (up left), worn out ripper tools (up middle), worn out scraper tools (up right), reduced cutter head diameter (down left) and worn out front of cone crusher (down right). (Photos: Tim E. E. Becker)

Drive 3 was completed successfully and without any problems.

Project Aftermath and Discussion

In order to show, and try to understand the reasons for the extraordinary problems that did occur at Sammler Ost´s second drive, a set of tests were done at NTNU/SINTEF. The testing comprised measuring soil abrasivity with the Soil Abrasion Test (SAT™), grain mineralogy by x-ray diffraction (XRD) and Differential Thermal Analysis (DTA), grain shape, grain size distribution.

Table 1 Summary of test results from the Sammler Ost project

Sample	**SAT™ value**	**Quartz content**	**Soil type**	**C_u**
#62	9	24	Silt	
#57	18.5	37	Silt	4.11
#36	20	N.A.	Silt	1.6
#90	23.5	38	Silt	5.33

Figure 11 Photo of typical grain shape of the sand and silt sections in the analyzed project (orange grid is 1/10 mm)

The SAT™ values indicate that the soil samples has medium to high abrasivity according to Jakobsen and Dahl (2010). The failure of the tools occurred after approximately 950 m of tunnelling which is equal to approximately 3,600 sm^3 (solid cubic meter) of soil. The cutter head was fitted with a total of 10 double disc cutters, 8 scraper tools and 10 ripper tools. This indicates an average tool life of 130 sm^3/tool[2]. This is a lower tool life that would be expected by studying Figure 12. However, by comparing it with Figure 13 and Figure 14 the Sammler Ost tool life corresponds better to the trend line.

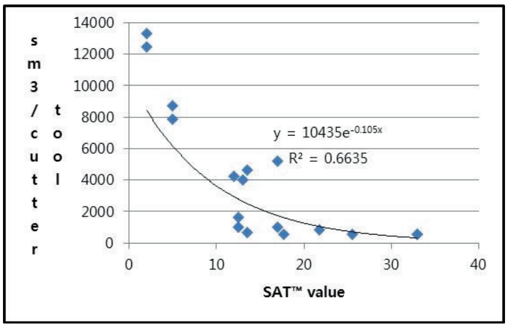

Figure 12 Exponential relation between SAT™ values and cutter tool life (ripper, scrapers drag-bits and disc cutters) (Jakobsen and Dahl 2010)

In Figure 12 the tool life is presented as tool life per solid cubic meters. The points with tool life above 1,500 sm^3 are dragbits mounted on a cutter head spoke. One spoke typically has 5 – 20 tools dependent on the size of the machine. Therefore a tool life of 14 000 sm^3/c may refer to 14,000 sm3/c / 5 or 10. The data in Figure 12 also includes disc cutters mounted on TBMs. Figure 13 and Figure 14 shows updated relations between the SAT™ value and recorded tool life (soft ground tools, thus disc cutters are not included).

At the time the wear problems occurred at the Sammler Ost project, the limited amount of data presented in Figure 12 was available for relating SAT™ values into tool life. Later, an extensive data collection from 9 projects, Figure 13 and Figure 14 shows the current empirical relation between SAT™ and tool life, based on tool life data from 9 TBM and pipe jacking projects (TBM diameter < 5.5 m).

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[2] Tools includes disc cutters, scrapers and rippers in this calculation.

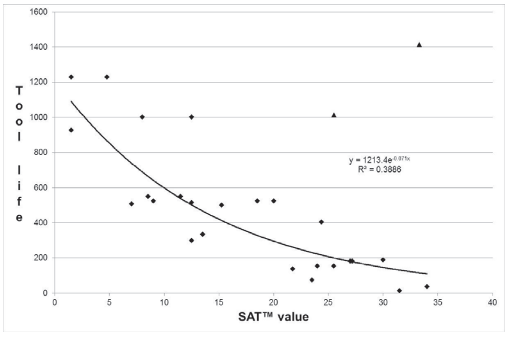

Figure 13 Correlation between SAT™ values and recorded soft ground tool life (to be published by (Jakobsen et al. under review)

The two outliers (marked as triangles) in Figure 13 are from two projects where the SAT™ values were high (25.5 and 33.3) and with high tool life. The soils at the two specific projects were single graded sand without fines. Such soils are very easy to excavate as it is almost flowing by itself, saving the TBM tools from high contact forces and impacts. The grain size distribution and cohesive properties of the soils are not taken into account in the SAT™ test, although it seems to have a high importance when making a soft ground and soil tool life estimation.

By removing the two projects from the data set the R^2 increases and the correlation becomes better. The increase of the R^2 by removing to points also shows the sensitivity of the current correlation when introducing new data. It should therefore be emphasized that the current correlation is based on relatively few data and by later adding tool life data and SAT™ values from other project the relation may be significantly changed.

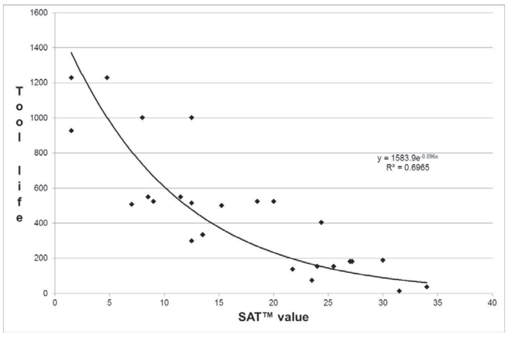

Figure 14 Correlation between SAT™ values and recorded soft ground tool life. (loose compacted material removed from the dataset).

The problems, that were observed in the Sammler Ost project led to conflicts between the involved parties regarding of who had to take care of the tremendous costs which resulted in the abrasivity of the soil. The client persisted that all necessary information was given in the provided geology report and that the abrasivity, that was met, did not exceed the commonly expected value. The contractor Lemme, which performed many projects in similar geology, had until then never experienced such wear on cutter tools and took up the position, that such high abrasivity was not be expected by the information of the geology report. Finally, a compromise finished the dispute. Latest tenders by Hamburg Wasser include information according to DWA-A125:2008.

Conclusive remarks

Pipe jacking is a common method for the excavation of tunnels. A thorough project preparation by the client is essential in order to obtain viable and comparable offers by the contractors. Comprehensive guidelines for the preparation and execution of such projects are given e.g. in the German DWA Rule and Standard A 125 for Pipe Jacking and Related Techniques.

The client provides the soil as a “material” to the project so that it should be described as detailed as possible in a geology report. Experiences show that the abrasivity of the soil may result in major wear of the cutter tools and the cutter head. As presented in the Sammler Ost project, missing parameters of the abrasivity that ought to be expected, led to significant extra costs, and conflict between the client and the contractor.

Latest research may provide values for the abrasivity which quality is so promising that they may give a conclusion to the expected in-situ parameters and actual wear. Contractors are now able to make a more precise estimation of the expected cutter tool wear, and are therefore able to define the necessary intervals of tool inspection and/ or tool changes and its costs. This helps in obtaining a better quality of the contractor’s bid calculation, and avoiding arguments about additional costs.

The use of the exponential relations between SAT™ values and recorded tool life for tool life prediction should be used with caution. The SAT™ values from Sammler Ost correspond somewhat to the recorded tool life for drive 2. The reason is that a simplified abrasion test only takes into account the abrasivity on a cohesionless powder, which is not close to a soil’s in-situ properties. After the completion of the Sammler Ost project the contractor moved on to excavate other projects in Germany with the same abrasive soil (measured by the SAT™ test), but did not encounter any wear problems.

On the other hand, the empirical relations are still quite promising. This means that further research should be done to include other in-situ parameters into the tool life estimate (e.g. in-situ soil density). Due to this, and the relative low amount of data in the correlation charts tunnel excavations should not be scheduled without any interventions.

To have a safe excavation the following schedule for cutter head interventions have been suggested (Babendererde 2010):

- First directly after the shaft wall if the TBM is launched from a shaft
- 50 – 75 m later
- Every 150 m (2-3 times)
- Then as frequent as necessary based on the experience from the first km – or after change in geology/geotechnical properties of the soil.

This approach may be considered to be time consuming, but it would only involve some hours downtime (for the intervention itself).

Since the initial findings presented in Figure 12, our research indicates that the influence of soil compaction and density influences the tool life. A loose compacted soil (e.g. single graded sand) would most likely not cause severe problems even though the SAT™ value is high. Opposite, if the SAT™ value is in the medium range and the in-situ density of the soil is high (above 2000 kg/m^3) the wear problems may be severe. The influence of the soil’s in-situ properties on the TBM tool life is the scope of current research activities at NTNU/SINTEF, in close cooperation with the tunnelling industry.

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StandardDWA-A 125 E "Pipe Jacking and Related Techniques", German Association for Water, Wastewater and Waste, December 2008

Paper 5

Overview of pipe-jacking performance – review of tunnel projects

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Jakobsen, Pål Drevland

Presented at the NO-DIG convention Berlin, 2013

1st NO DIG BERLIN 2013 Conference and Exhibition
23 - 26. April 2013

Paper 2A-2

Overview of pipe-jacking performance– review of tunnel projects

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Pipe jacking is a well-recognized method for mechanical excavation of small cross-section tunnels with diameters from 0.25 to 4 m, with limited length from 50 to 1200 m. The excavation method is suitable in soft soil (clay, silt and sand), soft rock (Uniaxial Compressive Strength (UCS) < 50 MPa) and even hard rock (50 < UCS < 200). The pipe jacking advance is based on applying thrust on pipe elements which are installed from a start shaft, oppositely to typical segmental lining tunneling for larger diameters. The geotechnical conditions form a major factor for the excavation rates which may vary between 50 m per day in favorable conditions and only a few centimeters in worst cases. In unfavorable geotechnical conditions such as varying water pressure, occurrence of boulders or abrasive soil conditions the performance can be highly influenced. This paper gives a brief introduction to the pipe jacking methodology, general project preparation for pipe jacking, and it shows recorded performance and tool life from 7 projects, with a total length of approximately 7,400 m. The subjects are also relevant to segmental lining tunnelling as well as for EPB and slurry shield TBMs.

Introduction

Pipe jacking, also called “Microtunnelling” is a commonly used method for tunnel excavation with small cross-sections (< 4 m diameter). The method is based on a moving front shield with a rotating cutterhead containing a variety of cutter tools. The selection of cutter tools is adapted to the expected ground conditions. Ripper tools are used in cohesion soils (clay and silt), scraper tools are commonly used in friction soils (sand and gravel) and disc cutters are installed on the cutter head when the tunnel alignment is subjected to boulders and hard rock conditions. The advance of the pipe jacking shield is driven by static energy applied to the jacking-pipes by a hydraulic cylinders located at the starting shaft. The jacking pipes, which are usually made out of concrete, are inserted piece by piece at the starting shaft and have a length of up to 4.0 m.

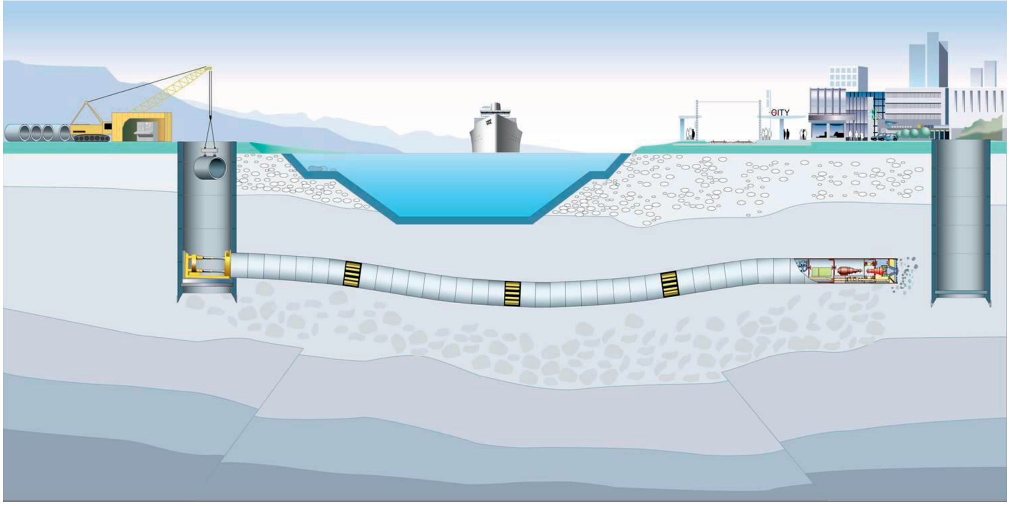

Figure 1 Scheme of pipe jacking project (starting and reception shaft, main and intermediate jacking stations (marked as yellow). (Scheme: Herrenknecht AG)

The soil is removed by a rotating cutterhead (Figure 2) which is capable to loose the soil at the shield front. The soil is then mixed with the transport slurry (bentonite suspension) and pumped to the starting shaft and the ground surface to the separation plant unit. The separation plant cleans the excavated soil from the bentonite slurry, which is reused.

Figure 2 Newly manufactured pipe jacking machine, AVN 1600/1800 TB by Herrenknecht AG. (Photo: Tim E. E. Becker)

The operation of the pipe jacking machine, also referred to as AVN[1], includes the advance rate of the hydraulic station, and all other machine parameters. The operation and continuous censoring of machine parameters are monitored from a

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[1] AVN is a German abbreviation for *Automatisches Vortriebsystem mit Nassförderung,* which in English means automatic advance system with slurry.

control cabin located at the starting shaft. Since all necessary works are performed around the starting shaft, pipe jacking is regarded as very efficient in terms of required personnel, time consumption and capacity, for excavation of small cross-section tunnels.

Figure 3 Typical pipe jacking set up). (Scheme: Herrenknecht AG)

The tunnel length between shafts gives the main limitation of pipe jacking. As there is a maximum allowed jacking force that can be applied to the pipes, intermediate jacking stations are installed in the tunnel. These small hydraulic stations are commonly activated in order to reduce the actual pushing length of the tunnel. Typically a 2.5 m diameter machine would require an intermediate jacking station every 50 to 200 m, depending on the pipe material and the ground conditions. The distance between starting and reception shafts can be as high as up to 1200 m.

In order to keep the machine steerable, the rotating cutter head produces a small overcut (annular gap) relatively to the actual outside diameter of the jacking pipes. During the complete jacking period, the annular gap of the tunnel is constantly lubricated by a bentonite suspension. This is done in order to support the annular gap, and secondly, in order to minimize settlements at the ground surface. The bentonite injection also decreases the friction between the pipes and the surrounding soil. In order to achieve an optimized lubrication, use of an automatic lubrication system is utilized for injecting the bentonite suspension. However, it is required to check the quality of the bentonite lubrication in regular intervals, and if necessary adapt the quantity and quality of the bentonite suspension.

General Project Preparation for Pipe Jacking

During the planning process of a tunneling project, the owner needs to determine the requirement of the tunnel. Several purposes are typically required:

- Gravitation line for rain, mixed (rain & sewage) water or sewage water
- Pressure pipeline
- Mantle pipe for pressure pipelines (gas, oil, water, etc.)
- Mantle pipe for cables
- Pipe for infrastructure ways (pedestrians)

These individual project boundary conditions enable the demands of the needed pipe diameter, material, alignment and distance between shafts.

Figure 4 Reinforced concrete jacking pipe (inner diameter (ID) 2800 mm and outer diameter (OD) 3000 mm) (Photo:Tim E. E. Becker)

The tender/ project documents form an integral part of the project and describe the contractual boundaries for the contract between the client and the contractor. Within German contracts, *The German DWA Rules and Standards A 125 E for Pipe Jacking and Related Techniques* provides comprehensive guidelines for planning and construction that are:

- Surface and underground structures and systems (e.g. foundations, underground railways, existing networks as channels, cables, bunkers, anchors)
- Soil and groundwater conditions
- Supply and disposal facilities (e.g. water, waste water, power, roads/ streets)
- Jacking distance and line (e.g. alignment and elevation plans including results of soil survey)
- Dimensions and material of the jacking pipes
- Third party plannings and approvals
- Environmental aspects (e.g. degradable hydraulic oil for machines, noise limitations)
- Requirements by authorities (e.g. traffic regulation, working hours)

The careful preparation of the above mentioned documents represent an important duty of the client in order to implement a proper call for bids, which are highly important to achieve a successful project. A well-experienced engineer with expertise for such projects shall be able to perform a differentiated evaluation of the bids with a sense of proportion between the technical capability of the bidders and economical limitations of the client as shall be shown according to Deutsche Vereiningung für Wasserwirtshaft (2008) (DWA-A 125 E).

A thorough description of the soil and groundwater conditions is of great importance for tendering contractors. As the client delivers the “material soil” to the project, it should be one of his initial interests to produce a geological report including of the following parameters and information (according to DWA-A 125 E, here for soft soils):

- Maximum and minimum groundwater level and hydrograph curves
- Contamination level of soil, soil gas and groundwater
- Disposal advice according to legislation
- Concentration of abrasive minerals and quartz content to determine abrasiveness
- Deformation module
- Aggressiveness reaction of soil and groundwater
- Swelling potential
- Borehole logs
- Weight per unit volume
- Fault zones and cavities
- Particle size distribution and particle shape
- Water permeability coefficient
- Compactness
- Plastic limits and water content
- Shear parameter, friction angle and cohesion
- Earth pressure coefficient
- Cobble size and cobble proportion, uniaxial compressive strength
- Water content and water pressure
- Organic components and lime content
- Tendency towards liquefaction

The above-mentioned parameters shall be combined in a geology report, which provides sufficient information for a careful project preparation. Nevertheless, the deviation between the geological report and the actual conditions found on site may lead to disputes and possible claims between clients and contractors.

As shown above, the new DWA-A 125 demands the determination of parameters apparently relevant to abrasion during pipe jacking which are amongst others:

- Concentration of abrasive minerals and quartz content to determine abrasiveness
- Particle size distribution and particle shape

Recently, clients include such references in their geology reports but still leave the estimation of abrasive wear up to the bidder / contractor. Mineral composition, grain curve, grain shape, density and water content are important factors to determine the abrasiveness of the soil. At the moment, there are no recognized prediction models taking all this parameters into account. However, a prediction model for estimating tool life for pipe jacking and soft ground TBMs are under development at NTNU.

The following presented results of the performed research at NTNU shall be able to reduce the calculative risk by estimating the expected wear of cutter tools and the necessity of tool changes during pipe jacking operation.

Estimation of abrasive wear

For all the 7 reviewed projects presented in this paper, abrasiveness properties have been measured by the NTNU/SINTEF Soil Abrasion Test™ (SAT) (Nilsen et al. 2007) and (Holzhäuser and Nilsen 2006). Figure 5 shows the schematic overview of the test apparatus, which consists of a rotating steel disc, which is fed with soil grains less than 4 mm. As the soil is transported on the rotating disc it passes underneath a steel sample, originating from a TBM disc cutter. This contact causes abrasive wear on the steel sample.

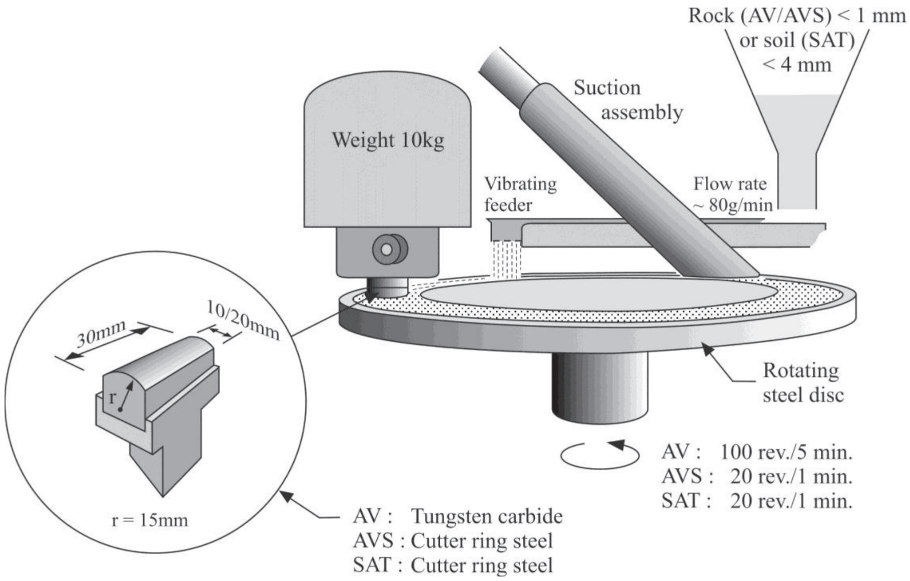

Figure 5 Schematic overview of the SAT™ test procedure, (Nilsen et al. 2007)

In addition to the SAT™ test, quantification of quartz content by Differental Thermal Analyses (DTA) has been executed except for Project No. 7, see Figure 6.

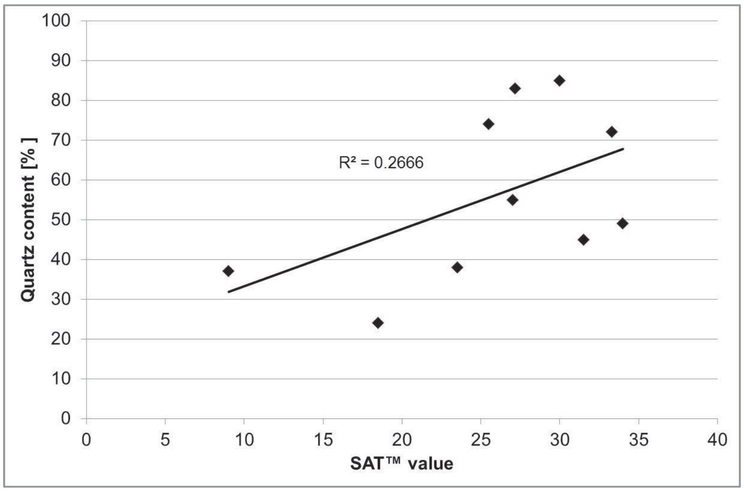

Figure 6 Comparision of SAT™ values and quartz content on samples from the reviewed pipe jacking projects.

The SAT™ values has been correlated to the grain sample mineralogy, represented by the Vickers Hardness Number Rock (VHNR) and the grain roundness, see Figure 7 and Figure 8. The VHNR is determined combining the percentage of each mineral and its corresponding Vickers Hardness in a soil sample (Dahl et al. 2012).

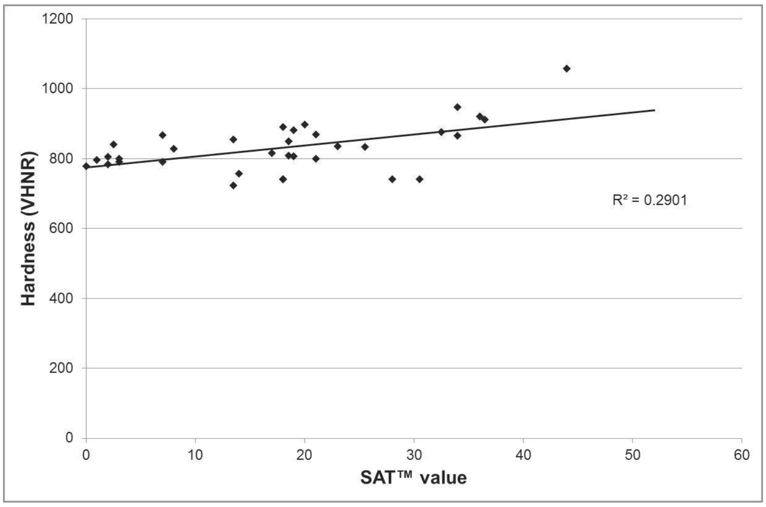

Figure 7 SAT™ values correlated with VHNR showing a linear relation between the measured abrasivity (SAT™) and the mineralogy (VHNR)

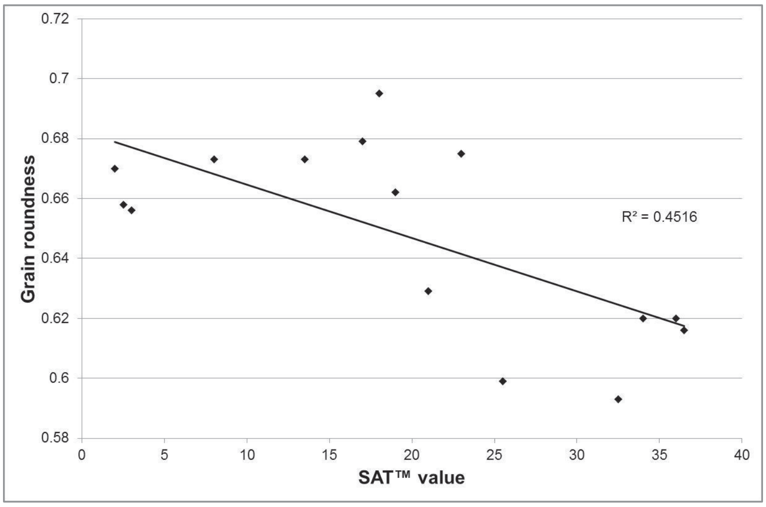

Figure 8 SAT™ values correlated with grain roundness showing a linear relation between the measured abrasivity (SAT™) and the grain shape. A grain roundness of 1.0 indicates a perfect circular grain.

The reviewed projects

A total of 7 projects is reviewed in this paper. Projects No. 6 and 7 are finished pipe-jacking tunnels in the Middle-East, where the Client and contractors have asked to keep site-specific data confidential. Thus, the amount of information from Projects No. 6 and 7 is less than for Projects No. 1 – 5.

Project No. 1 (Sammler Ost, 2. BA)

Client: Hamburg Wasser, Germany
Contractor: Hans Lemme Hoch-, Tief- und Stahlbetonbau GmbH & Co. KG, Berlin, Germany
Construction period: January 2008 – September 2010
Works: 2,400 m sewage channel ID 1,600, OD 2,240, reinforced concrete jacking pipes with inner PEHD-liner, length 3.50 m, 3 jacking lines (910 m, 958 m and 532 m), curved drives with R = 1,000 – 500 m, 3 round jacking ∅ 10 m/ reception ∅ 7 m shafts by bore piles, depth up to 20 m

Drive 1
Length: 910 m from shaft 2.2 to shaft 2.1
Alignment: radius R = 1,000 m and 3,000 m
Slope: straight 1.8 per mill
Depth: 20 m
Geology: 95% glacial drift, partly fluvial deposited sand and silt
Groundwater: appr. 10-12 m above pipe invert level

Drive 2

Length: 958 m from shaft 2.2 to shaft 2.3
Alignment: straight
Slope: straight 1.8 per mill
Depth: 20 m
Geology: 70% glacial drift, rest fluvial deposited sand, fine sand and basin silt
Groundwater: appr. 10-12 m above pipe invert level

Drive 3

Length: 532 m from shaft 2.4 to shaft 2.3
Alignment: R = 500 m and 600 m
Slope: straight 1.8 per mill
Depth: 12 m
Geology: 20% fluvial deposited sand, 80% fluvial deposited fine sand and basin silt
Groundwater: appr. 4-10 m above pipe invert level

Project No. 2 (Nebensammler Bergedorf, Abschnitt Billbrook)

Client: Hamburg Wasser, Germany
Contractor: Joint Venture “Nebensammler Bergedorf” Hans Lemme Hoch-, Tief- und Stahlbetonbau GmbH & Co. KG, Berlin, Germany and Grund- und Sonderbau GmbH, Berlin, Germany
Construction period: June 2009 – June 2012
Works: 2,100 m sewage channel ID 1,600, OD 2,240, reinforced concrete jacking pipes with inner PEHD-liner, length 2,00 - 3.50 m, 3 jacking lines (740 m, 660 m and 700 m), curved drives with R = 600 – 300 m, 1 round jacking shaft ∅ 10 m, one reception shaft ∅ 8 m and one rectangular shaft, all by bore piles (one additional pipe jacking with open shield under air pressure into existing operation shaft, appr. 15 m, sewage channel ID 1,600, OD 2,240)

Drive 1

Length: 740 m from shaft BS1 to shaft BS2
Alignment: radius R = 500 m
Slope: straight 0.33 per mill
Depth: 16 m
Geology: fluvial deposited middle and fine sand, partly organic silt
Groundwater: appr. 10-11 m above pipe invert level

Drive 2
Length: 660 m from shaft BS3 to shaft BS2
Alignment: radius R = 600 m - 500 m
Slope: straight 0.33 per mill
Depth: 15 m
Geology: fluvial deposited middle and fine sand, partly coarse sand and organic silt
Groundwater: appr. 10-11 m above pipe invert level

Drive 3
Length: 700 m from shaft BS3 to shaft BS4
Alignment: radius R = 300 m
Slope: straight 0.33 per mill
Depth: 14 m
Geology: fluvial deposited middle and fine sand, partly clay
Groundwater: appr. 10 m above pipe invert level

Project No. 3 (Harbour Undercut Lubmin, Germany)

Client: Wingas GmbH & Co. KG, Kassel
Contractor: Hans Lemme Hoch-, Tief- und Stahlbetonbau GmbH & Co. KG, Berlin, Germany
Construction period: August 2009 – May 2010
Works: 2x 190 m mantle pipe ID 2,400, OD 3,000 for high pressure gas pipeline ID 1400 (OPAL), reinforced concrete jacking pipes, length 4,00 m, straight alignment and gradient, one round jacking shaft ∅ 22 m, one reception shaft ∅ 14 m

Length: 2x 190 m parallel, light distance 3,00 m
Alignment: straight
Slope: straight in level
Depth: 22 m
Geology: glacial drift, sandy, peat clay
Groundwater: appr. 21 m above pipe invert level

Project No. 4 (Undercut of River Löcknitz, Kienbaum, Germany)

Client: Wingas GmbH & Co. KG, Kassel
Contractor: Hans Lemme Hoch-, Tief- und Stahlbetonbau GmbH & Co. KG, Berlin, Germany
Construction period: May 2010 – October 2010
Works: 365 m mantle pipe ID 2,400, OD 3,000 for high pressure gas pipeline ID 1400 (OPAL), reinforced concrete jacking pipes, length 4,00 m, straight alignment and curved gradient, one rectangular jacking shaft (sheet piles), machine recovery near to surface at reception point

Length: 365 m
Alignment: straight
Slope: radius R = 2,100 m
Depth: up to 11 m
Geology: fluvial deposited middle and fine sand, partly organic silt
Groundwater: appr. 10 m above pipe invert level

Project No. 5 (Undercut of Channel Oder-Havel, Oderberg, Germany)

Client: Wingas GmbH & Co. KG, Kassel
Contractor: Hans Lemme Hoch-, Tief- und Stahlbetonbau GmbH & Co. KG, Berlin, Germany
Construction period: June 2010 – May 2011
Works: 190 m mantle pipe ID 2,400, OD 3,000 for high pressure gas pipeline ID 1400 (OPAL), reinforced concrete jacking pipes, length 4,00 m, straight alignment and curved gradient, one rectangular jacking shaft and one rectangular reception shaft (sheet piles)

Length: 190 m
Alignment: straight
Slope: radius R = 2,100 m
Depth: up to 13 m
Geology: fluvial deposited middle and fine sand
Groundwater: appr. 11 m above pipe invert level

Project No. 6 (Located in the Middle-East. Ocean outfall)

Length: 1230 m
Alignment: Straight
Slope: NA
Depth: up to 18 m
Geology: Fine single graded sand with high quartz content
Groundwater: Subsea with overburden from 18 to 0 m.

Project No. 7 (Located in the Middle-East)

Length: 710 m
Alignment: NA
Slope: NA
Depth: Appr. 9 – 15 m
Geology: silt, sand and gravel
Groundwater: partly

Recorded performance and tool life at the reviewed projects

In the following, an overview of the recorded performance and tool life for the 7 projects will be given.

Performance

The project with the best performance (highest gross production per day) is Project 3 - Drive 2. The geology along Project 3 is a combination of marine clay with some sand. The geology was uniform along the drive, meaning that the pipe jacking machine could be operated at more or less constant thrust, face support and bentonite injection. Project 3 – Drive 1 had the same geological conditions, thus with lower performance. The reason for this is assumed to be learning curve of the crew operating the pipe jacking machine at both drives.

The project with the lowest performance is Project 1 – Drive 2. The first major downtime is due to Christmas holiday, which was scheduled. The second major downtime was due to worn out tools, which were an unscheduled downtime.

For Project 2, 4, 5, 6 and 7 the performance has been good and in relatively stable geological conditions. The soft ground has consisted mainly of single graded sand, which is easy to excavate, with some intrusions of finer material (silt) and coarser material (gravel).

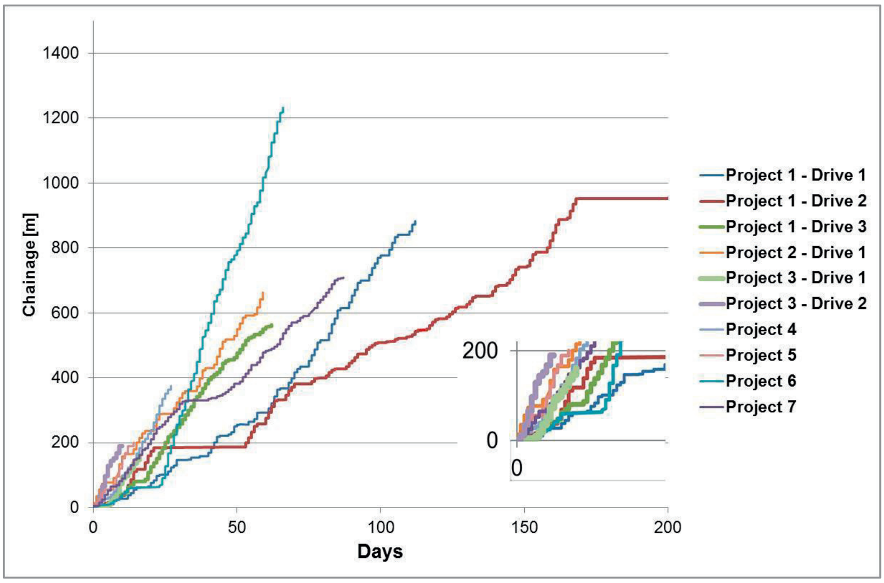

Figure 9 Overview of the performance for the reviewed projects.

Tool life

The recorded tool life is varying from approximately 50 to 1850 sm^3/tool. The unit sm^3/tool is chosen as it makes it easier to compare tool life from varying excavation diameters. The recorded tool life has been correlated with the SAT™ value and the quartz content, see Figure 10 and Figure 11.

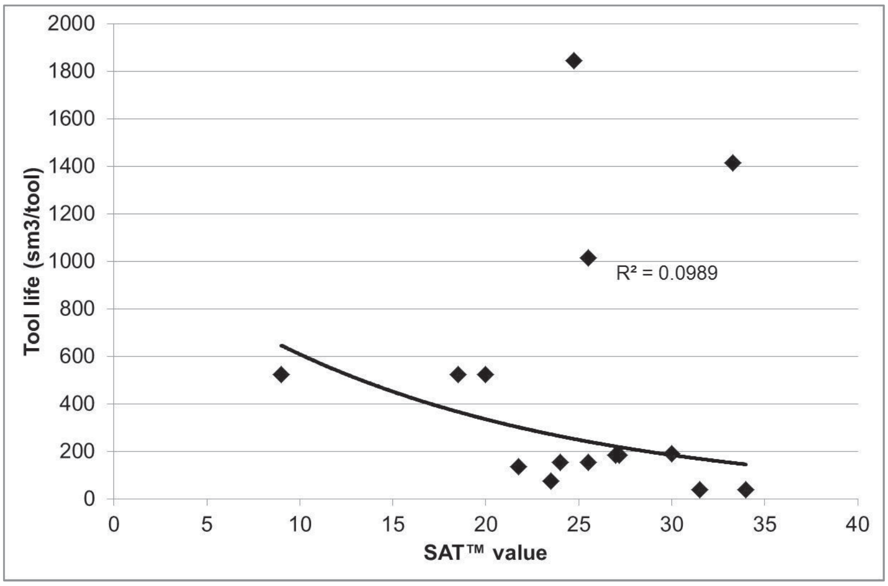

Figure 10 SAT™ correlated with excavation tool life for 7 projects.

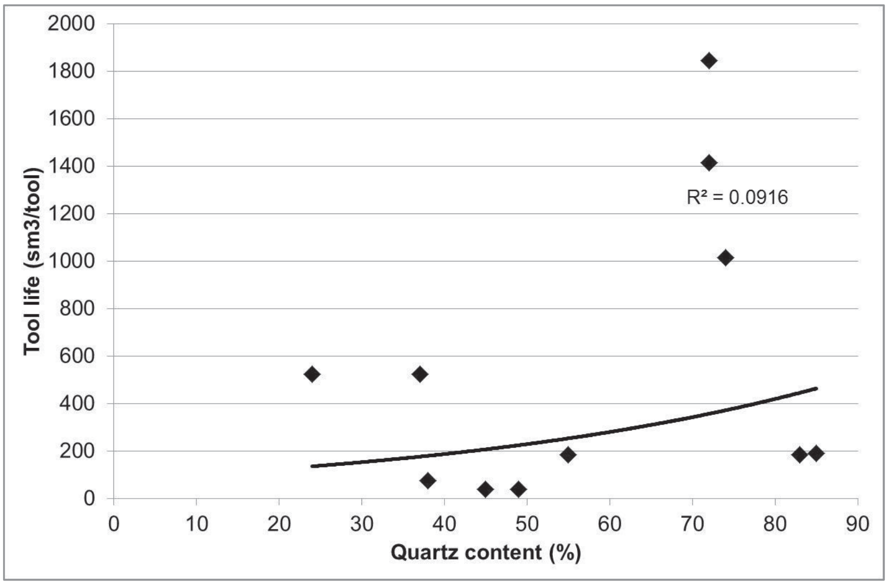

Figure 11 Quartz content correlated with excavation tool life for 6 projects (Project No 7 is not included due to missing measurements of quartz content).

The relation between the SAT™ value and tool life, as well as quartz content and tool life is relative poor for the current data set. It has been shown in a recent paper, by including the recorded tool life for other projects (slurry shield machines and EPB) the correlation is found better (*Jakobsen and Becker 2012*).

In order trying to achieve a better correlation for the 7 pipe jacking projects, the geotechnical index C_u has been used to adjust the SAT™ values. The C_u index indicates the uniformity of a soil sample, and is calculated by.

$$C_u = \frac{d_{60}}{d_{10}} \approx \frac{d_{75}}{d_{25}}$$

In

Figure 12, a very good correlation between the SAT™ value multiplied with C_u and the tool life is shown. One likely explanation for the improvement of the correlation, is that “simplified” abrasion tests are done on a cohesionless material lacking a lot of the in-situ properties of the soil. A low C_u index indicates a uniform soil, which is relatively easy to excavate – and oppositely a high C_u can indicate that higher thrust and torque is needed to excavate a soil.

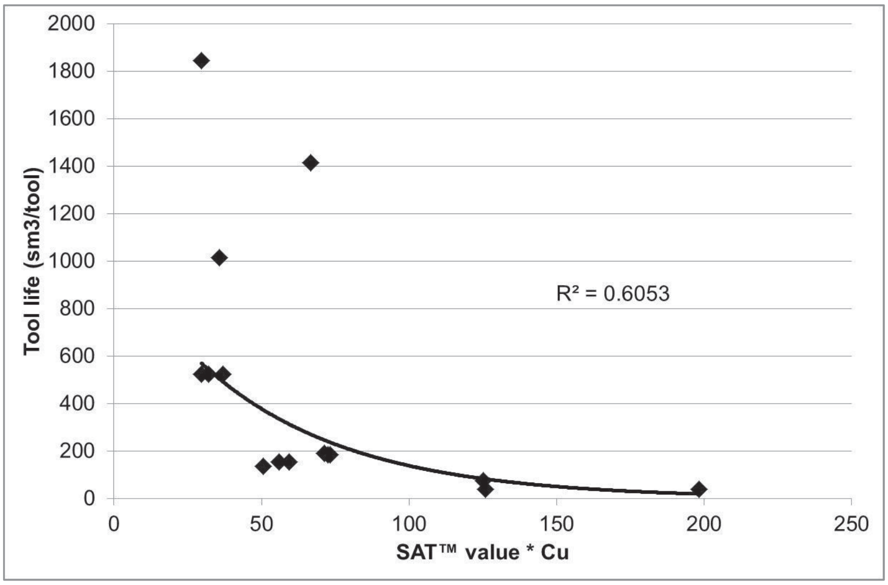

Figure 12 Correlation between the SAT™ value multiplied with C_u correlated with excavation tool life.

Conclusive remarks

Pipe jacking is a common method for the excavation of tunnels. A thorough project preparation by the client is essential in order to obtain viable and comparable offers by the contractors. Comprehensive guidelines for the preparation and execution of such projects are given e.g. in the German DWA Rule and Standard A 125 for Pipe Jacking and Related Techniques.

The main findings of this paper are:

- Pipe jacking performance is highly variable and influenced on the ground conditions.
- Gross production varies from 4.75 m/day to 17 m/day in the reviewed projects.
- Pipe jacking excavation tool life highly variable. For the reviewed projects, a combination of an abrasivity measurement (in this paper by the Soil Abrasion Test™ (SAT) and the geotechnical index Cu seems to provide a good estimate. However, the current estimate is only based on few data originating from only 7 projects in silt and sand. Thus, further studies and data collection is needed to validate this finding, and also to include gravely soils.

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Paper 6

Challenges of Methods and Approaches for Estimating Soil Abrasivity in Soft Ground TBM Tunnelling

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Challenges of methods and approaches for estimating soil abrasivity in soft ground TBM tunnelling

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ABSTRACT

The increase of urbanization constantly demands more infrastructure, which often requires to utilize the underground. The complex functioning of Tunnel Boring Machines (TBM) and the complexity of their working environment make arriving at wear predictability a challenging affair. The economic consequence of tool wear is, on the other hand, significant. There are several methods and approaches to estimate geo-material's abrasion properties in tunnelling with TBMs. The methods are mainly based on using empirical observations and experiences from completed tunnelling projects correlated with simplified laboratory test results. The simplified laboratory tests means that the soil's in-situ properties such as the cohesion, density, adhesion, water content and original grain size distribution are lacking or is disturbed. The intention of this research paper is to give a brief overview the respective test procedures of the different approaches and their pros and cons. In light of these, we assess a new methodological approach and examine the extent to which it is capable of advancing the understanding of predicting wear on TBMs with respect to general tribological experiences such as the influence of hard minerals or particles, grain shape and grain size. The applicability of the laboratory experiments from a practitioner's point of view is equally briefly discussed.

1. Introduction

Full face tunnelling with tunnel boring machines (TBMs) is a well-known and widely utilized method to excavate tunnels. 60–80% of tunnels build in the world today are excavated by TBMs [1]. According to Home [2] the total amount of TBMs working to excavate soil the last 5 years is approximately 350 units, with diameters ranging from approximately 3 m to over 15 m (Fig. 1).

In order to excavate the soil and soft ground, a combination of rotating disc cutters, scraper tools and ripper tools are installed on the TBMs cutterhead. Generally, the disc cutters are designed to apply a high thrust force (approximately 300 kN per disc) [3] in to rock mass, inducing tensile failures and chipping from rock, while scraper tools are designed to scrape coarse soil from the tunnel face and ripper tools are ripping cohesive soil material (clay and silt). These tools are exposed to relative high contact forces with abrasive material causing various degradation processes such as abrasive wear (which is the most pre-dominant), impact wear and chipping. Experiences from tunnel projects excavated with hard rock TBMs during the Norwegian hydropower era (1980 s), show that the abrasion properties of the rock mass can influence excavation cost and time in the range of ±30%.

The direct consequence of tunnelling in abrasive soil conditions is an increased demand for replacement of the excavation tools (disc cutters, scrapers and rippers). The disc cutters are equipped on TBMs if the rock mass exceeds a compressive strength of 20 MPa [4]. However, disc cutters are quite often installed to cope with boulders (large rock blocks) inside a soil matrix as well.

At the time being there is no recognized standard method or approach to estimate tool life in soil and soft ground TBM tunnelling. This is not surprising given the variety of determining factors, such as the cost of tools varying depending on size, manufacturer–customer relations, material quality and type. Generally speaking, the complex functioning of TBMs and the complexity of their working environment make arriving at wear predictability a challenging affair. The economic consequence of tool wear is, on the other hand, so significant that the need for such predictability is pressing. In addition to the direct cost for tools, the down time of a TBM, unproductive time for workers and possible delay of the tunnelling project should be included. In a recent hard rock TBM project in Hong Kong it has been stated 1 s downtime has the cost of USD 1, meaning that one working shift's downtime can cost as much as USD 30,000 excluding the direct cost for the tools [5].

Today, tunnelling works are in the most cases based on tender documents with pre-investigations of the soil or rock along the tunnel drive, and various contractors then have to assess the pre-investigation values in order to make a tender. However, there are

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currently numerous disputes between contractors and owners/consultants when it comes to TBM performance and tool life. The level of conflicts and their economic consequence highlight, in effect, the need for robust methodological approaches for predictability of TBM tool life in soil excavation.

A further complicating factor for predicting tool life is that in soft ground tunnelling the TBMs utilizes various soil conditioners. The objects of soil conditioners are several; to make the excavated soil more transportable and impermeable, to reduce the torque requirement of the TBM cutterhead, to avoid fines to clog at the cutterhead and cutter tools and to reduce the abrasive wear of the soil. The most common groups of soil conditioners are polymer enriched foams or anti-clay-agents and bentonite (a natural clay mineral). These additives are added in front of the cutterhead, which make it an important part of the steel—soil tribological system in tunnel excavation [6] (Fig. 2).

In soft ground tunnelling, the tools and cutterhead interventions are quite often subjected to hyperbaric working environments, meaning that the actual intervention and tool replacement is a diver operation. Hyperbaric support is needed to stabilize and avoid a collapse of the tunnel face. By assuming an 40 m overburden with hydrostatic water pressure, the working environment for divers involve mechanical work in 4 bars pressure in a mix of soil, additives and water. Such operations are risky with respect to both health and safety for workers. Equally they are more costly and time consuming to conduct compared with the same intervention in a self-stable tunnel without the need of hyperbaric stabilization of the tunnel face. In hard rock TBM tunnelling there is generally a higher consumption of tools than for soil tunnelling. However, the consequences of worn out tools in soil tunnelling are higher, due to the complicating hyperbaric operation that is needed.

Fig. 1. Earth Pressure Balance shield (EPB) TBM with foam nozzles (Courtesy by the Robbins TBM Company).

Fig. 2. Double disc cutter and scraper tools in contact with a mixed face consisting of claystone and gypsum. The simplified laboratory approaches presented in this paper cannot fully recreate the complex tribological system shown in the photo. Such approaches enable researchers to assess different soil grains abrasivity and impact on TBM tools separately (Photo by Pål Drevland Jakobsen).

2. Research methods and problem formulation

The complex behaviour of soft ground and soil material (ranging from plastic clay to soft but brittle sandstones) confirms findings and general tribological experiences [7]. The variety of soil material imposes a demand for numerous empirical relations between real tribological events, and simplified laboratory measurements in order to establish parameters of predictability.

A limitation prevailing for all tests mentioned in this paper is the relative limited amount of soil material tested. Excavating a 5000 m long tunnel involves moving of 15,000 to 850,000 m^3 of soil material depending on the tunnel diameter. In addition, influence of geotechnical parameters that are difficult to recreate in a laboratory environment should be taken into account as they influence the soil mass behaviour and strength.

This paper results from 3 year research project on TBM wear prediction. Extensive empirical testing is being carried out in order to provide the data that permit predictable real life wear assessment [8–11,1,5,12–16].

This research paper aims at examining the performance of four of the most common methods for measuring soil abrasivity. Further, comments on the various methods pros and cons and applicability from a practical point of view are presented. More in detail the paper examines firstly:

- To what extent do the existing laboratory methods and approaches answer the challenges involved in real-life TBM tunnelling?
  In order to answer this, we assess the:
  - Pros and cons of 4 state-of-the-art methods and approaches. Methodological restraints imposed by the in-vitro testing as opposed to the real wear phenomena on soil excavating TBMs. The 4 methods are the LCPC Abrasivemeter, the NTNU/SINTEF Soil Abrasion Test™, mill tests and mineralogical analyses. Test procedures will be presented in Chapter 3.

  Further, based on the results from this going-through, we wish to assess to what extent the last years of laboratory-based research has brought the tunnelling industry closer to a robust wear estimate for soil tunnelling with TBMs. The question guiding this analysis is:
- To what extent can the limitations identified in existing methods be remedied?

In order to examine this, we provide an initial presentation and initial test results of a new method for determining soil and soft ground abrasivity and soft ground matrix toughness against tunnel boring in terms of torque.

In general terms, whether simplified "index tests" such as LCPC abrasivemeter, SAT™ and mill tests can provide a good estimation approach for TBM tool life excavating soil needs to be concluded when more data and experiences are available.

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The choice of examined methodologies is done both in order to answer the ever-present questions of delimitation and representativeness.

Firstly, including all existing methodologies for in-vitro TBM testing will surpass the limits of a research paper such as the present one. Assessing the four methodologies in this paper, however, serve to illustrate the general challenges to laboratory test procedures and their relevance to the TBM industry.

Secondly, the NTNU/SINTEF tunnelling research cluster (the GEMINI-centre)[1] has been at the forefront of tunnelling and underground research since the mid-1970 s, and the methodologies used within this centre are widely recognised in the tunnelling industry. Since the mid-1970s NTNU/SINTEF has tested over 3000 unique rock samples in connection with hard rock TBM tunnelling performance and tool life estimates [17]. The assessment of existing methods therefore represents an up-to-date image of present day research capabilities and restraints.

3. State of the art in soil abrasivity testing for TBM applications

Several in-vitro approaches to the soil abrasivity testing for TBM applications exist. In this section we present 4 of these approaches, the LCPC abrasivemeter, the NTNU/SINTEF Soil Abrasion Test™, mill tests and a general assessment of soil mineralogy and grain properties, and discuss briefly their main advantages and disadvantages. On basis of this discussion on the state of the art within the field we present a novel approach. This approach seems to represent one step forward for in-vitro assessment of soil abrasivity testing allowing for a more precise predictability of real life wear on TBM tools.

The test results obtained on the LCPC abrasivemeter originates from other researchers, mainly at the Technical University of München. The results obtained on the NTNU/SINTEF Soil Abrasion Test™, the Ball Mill Test and using mineralogical analyses originates from the ongoing research on NTNU and SINTEF.

3.1. The LCPC abrasivemeter

The LCPC abrasivemeter test procedure and apparatus is described in the French Standard P18-570 [5]. The test is based on exposing 500 g of 4.0–6.3 mm fraction of crushed rock or natural soil for a rotating steel impeller for 5 min. The steel impeller is 25 mm × 50 mm × 5 mm.

The rotation speed of the impeller is 4500 rpm and the steel consists of a relative soft steel alloy with Rockwell B hardness of 60–75. For coarse soils the 4.0–6.3 mm fraction can be sieved out, while for clay, silt and sand samples the LCPC Abrasivemeter standard test procedure is not suitable (Fig. 3).

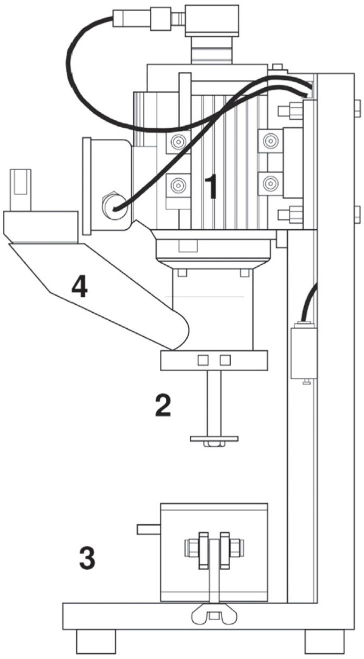

Fig. 3. The LCPC test apparatus (after [18]. (1) shows the motor, (2) the rotating impeller, (3) the jar containing the abrasive, and (4) the funnel tube [18].

The weight loss of the steel impeller is measured after each test, and this is the measured abrasivity parameter. The LCPC abrasivity coefficient (LAC) is calculated as

$$LAC = (m_0 – m)/M$$

where $(m_0 - m)$ is the weight loss of the steel impeller after one test and M is the soil or rock materials weight (0.0005 t) [19]. The soil material's brittleness properties can also be measured by the LCPC Abrasivemeter by comparing the sieve curves of the initial 4.0–6.3 mm sample fraction with the particle size distribution after the test.

The effect of different grain sizes outside the standard 4.0–6.3 mm has been studied by Thuro et al. [20]. The study indicates higher abrasivity for larger grain sizes. Whether this is a result of grain's abrasivity properties or caused by the influence of heavier grains which has the potential to cause more damage and degradation on the test steel bit is uncertain. Misra and Finnie [21] presents several observations on two- and three-body abrasive wear and the size effects of the abrasives. Their conclusion is that the abrasive wear rates decreases as the size of abrasives decreases below about 100 μm. Misra and Finnie's [21] general results correspond with [20] findings. However, Misra and Finnie's results are obtained on 20–250 μm abrasives sizes, while Thuro's trials are done on more natural composed soils ranging from 60 μm to 60,000 μm. In order to validate the degradation mechanism on the LCPC test, SEM analyses of worn out LCPC test pieces should be carried out.

Köhler et al. [22] studied the relationship between the LCPC abrasivity coefficient (LAC) and equal quartz content (EQC). The correlation proves very poor with no clear trend in the current data set consisting of 22 samples from the recently completed Inntal railroad tunnel project in Austria. Further, a relation between the Cerchar Abrasivity Index (CAI), which is a commonly used scratch test for measuring hard rock abrasivity, and LCPC is shown based on findings by Thuro et al. [20]. The CAI testing principle is based on a steel pin which is scratching a rough or cut rock surface over a 10 mm distance under 70 N load. The Cerchar Abrasivity Index is calculated as the measured diameter of the resulting wear flat on the pin [18], see Fig. 4.

The use of the correlation between CAI and LCPC values did not provide a good tool life estimate (based on back calculations of the real tool life in the Inntal project [22]). Some of the reasons found for this are:

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[1] GEMINI-centre at NTNU/SINTEF is a formalized strategic cooperation agreement between SINTEF and NTNU departments doing parallel activities. For more information see http://www.sintef.no/home/Building-and-Infrastructure/Infrastructure/Rock-and-Soil-Mechanics/Gemini-Centre-for-Underground-Technology/ and http://www.drillability.com

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- Soil abrasivity measured in lab does not always reflect the “soil mass abrasivity”.
- Influence of TBM operational parameters is not taken into account.
- Influence of face support is not taken into account (Fig. 5).

The LCPC abrasivemeter can be used to find gravel (4.0–6.3 mm) soil grain's ability to cause steel wear under high rotation speed. The applicability of the LCPC abrasivemeter is restricted to run tests under the 4.0–6.3 mm grain size, meaning that clay, silt and sand particles have to be removed from the soil sample.

3.2. *The NTNU/SINTEF Soil Abrasion Test™*

The NTNU/SINTEF Soil Abrasion Test™ is a development of the existing test procedure for hard rock *Abrasion Value Cutter Steel test* (AVS). Compared with the hard rock abrasivity test *AVS*, some details have been changed with respect to sample preparation and the steel test piece [11]. The relatively small changes have been carried out in order to achieve possibilities of comparing hard rock abrasivity measurements (test database contains around 2000 unique test values from hard rock samples) with soil abrasivity measurements (SAT™ database contains around 250 unique test values).

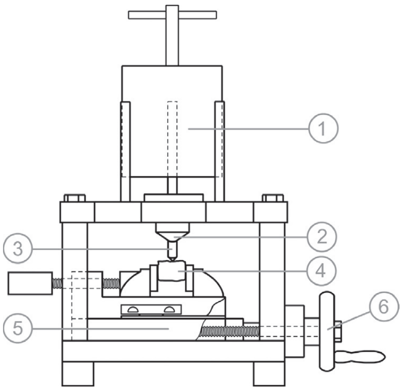

Fig. 4. Principal set up of the Cerchar Abrasivity Index (CAI) apparatus (after West [23]). (1) load, (2) pin guidance, (3) steel pin, (4) rock sample, (5) vice sled, and (6) hand crank [18].

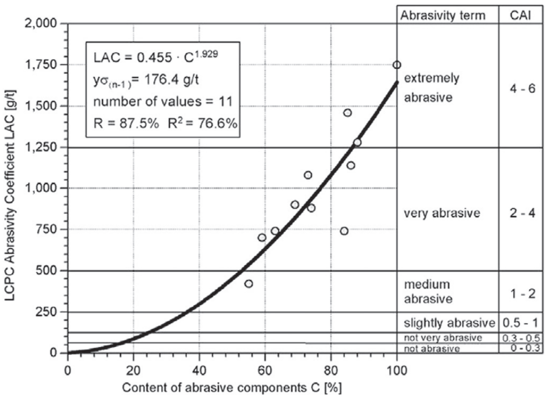

Fig. 5. LAC plotted against the content of abrasive (crystalline) components and CAI values in gravel samples [20].

In order to reduce or avoid changes of the original grain shape and size, soil samples need gently drying in an ventilated oven at 30 °C for 2–3 days. After the drying process, the following techniques are used in order to disintegrate and separate the particles for the abrasion powder:

(1) Disintegration by using a soft hammer.
(2) Sieving with steel balls.
(3) Initial disintegration in a jaw crushed if the samples contain hard lumps of cohesive material after the initial drying. Crushing of intact grains should be avoided.

The SAT™ value is calculated as the mean value of the measured weight loss in mg. In order to be accepted as a test results, weight losses of 2–4 parallel tests should not deviate by more than 5 mg (Fig. 6).

The maximum contact pressure between soil samples and the steel test piece ranges from 200 to 370 MPa, depending on the elastic properties of the soil material. The steel test pieces are machined from a TBM cutter disc ring, and it is a heat treatable, low alloy steel containing nickel, chromium and molybdenum. The hardness of the steel piece ranges from 54–56 HRC. The length of one SAT™ test is 20 m.

The relation between SAT™ values and the AVS classification system for hard rock abrasivity is shown in Fig. 7. The hard rock samples are generally found to be more abrasive than the soil samples. There is no clear explanation of this, but one indication can be that soil originates from degraded rock material. “Softer rock”, (which generally is less abrasive) will be transformed into soil before “harder rocks”. Another indication can be that in the hard rock abrasivity database, TBM projects with abrasivity problems are overrepresented in the data set.

The SAT™ value has good correlation coefficient with the soil samples' quartz content and Vickers Hardness Number Rock (VHNR). Relations between SAT™ values and “general tribological” parameters such as, grain mineralogy and grain size can be found in Chapter 3.4.

In order to evaluate the SAT™ procedure's applicability, some indications of SAT™ values relation to recorded tool life have been prepared (Fig. 8). However, the current data is based on few cutter changes, meaning that introduction of more data will influence both the strength of the correlation as well as the regression equation. The tool life has been calculated as instantaneous tool consumption according to [24]. Instantaneous tool consumption along is calculated between respective tool changes along a tunnel, causing different “tool life” for the different tunnel sections.

The SAT™ test can be used to find clay, silt and sand abrasivity properties. For grain sizes above 4 mm the test procedure cannot be used without crushing the coarse grains prior to testing. The SAT™ also shows a relation between the measured abrasivity value and tool life based on empirical wear data from the field and lab, but the current relation does not contain any influence of in-situ soil density and use of soil conditioning additives.

3.3. *Mill tests*

There are several mill tests available for determining soil and rocks resistance against crushing and abrasivity properties. At NTNU/SINTEF, the Ball Mill Test has been used in order to determine the influence of soil conditioning additives influence on the abrasivity properties of crushed rock and natural soil samples. The test procedure is easy and straight forward: A 1500 g sample consisting of grains less than 16 mm is exposed to 20 steel bits (consisting of ordinary construction steel) for 5400 revolutions which are equal to

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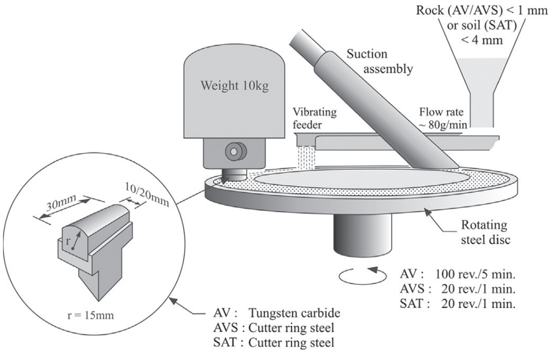

Fig. 6. Schematic overview of SAT™ and AVS (for measuring hard rock abrasivity) test procedure [11]. The test apparatus consists of a rotating steel disc which is fed by disintegrated soil powder (0–4 mm), which passes underneath a steel bit originating from a TBM disc cutter.

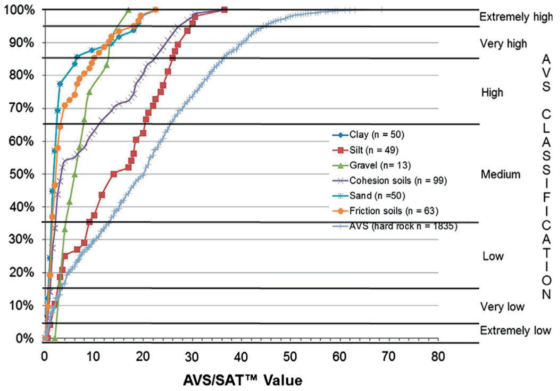

Fig. 7. Cumulative distributions of measured soil abrasion values and AVS classification. In the current data sets, sand and silt is found to have higher abrasivity than e.g. clay. Friction soils refers to sandy and gravely soils, while cohesion soil refers to silty and clayey soils.

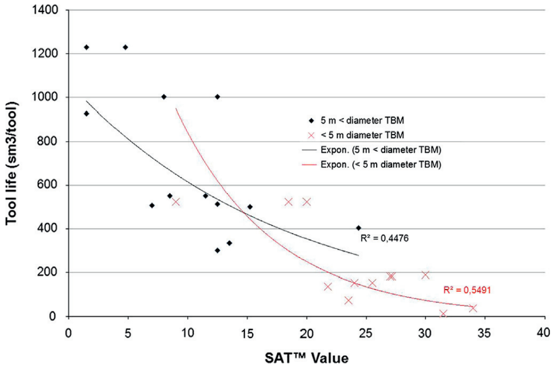

Fig. 8. Indications of SAT™ value's relation to recorded tool life (scrapers and rippers) for TBMs < 5 m diameter and TBMs > 5 m diameter. From hard rock TBM tunnelling it is known the large diameter TBMs have a relatively higher amount of excavation tools in the outer part of the cutterhead, would have a lower tool life than a small diameter TBM. The reason for this is that tools in the cutterhead periphery have a relative longer travel length due to higher speed.

60 min test duration. The rotation speed of the drum is 0.97 m/s, and the steel bits are circular with 16 mm diameter and length. The weight loss of the steel bits is measured after the testing. The measured weight loss is the abrasivity value detected in the Ball Mill Test (Fig. 9).

The influence of foam enriched soil conditioner clearly reduces the weight loss of the steel samples, shown in Fig. 11 [25]. Test results also indicates that the abrasivity of most geo materials (rock and soil) increases to a certain level of moisture content as shown in Fig. 10.

For the clay sample in Fig. 10 no weight loss was recorded under the present testing conditions. The test results in mill tests are highly influenced by which grain size that is included in the test. The procedure can provide good indications of various soil conditioning foams and moisture contents influence on abrasive wear for specific samples with a defined grain size distribution. The contact forces between the steel and soil particles are also relatively low (by gravity and tumbling of the drum). The low contact force is not in accordance with reality where TBMs have a relative high thrust and torque ripping and scraping the soil during excavation.

3.4. Abrasive wear estimate based on sample mineralogy

In rock engineering, the use of Vickers Hardness Number (VHN) is commonly used. The VHN is used for measuring the abrasiveness of each mineral in a rock or soil. By combining the percentage of each mineral and its hardness it is possible to calculate a *"Vickers Hardness Number Rock/Soil"* [26].

For determining the amount of different minerals in a rock or soil sample the most common measuring techniques are X-ray diffraction (XRD), differential thermal analyse (DTA) and thin section visual analyse. The XRD is a semi-quantitative approach to find minerals and mineral quantities in rock and soil samples. DTA is a quantitative approach to measure the amount of quartz in a rock or soil sample.

The correlation between SAT™ values and the quartz content proves good, see Fig. 12. The correlation between SAT™ values and the total content of mineral and their respective hardness, represented by the Vickers Hardness Number Rock (VHNR) proves less good, see Fig. 13. This finding is unexpected for the authors, as the abrasivity properties are expected to be highly influenced by the total mineralogical content of soil samples. The most likely explanation is that the collection of VHNR values originates from relative few projects compared the collection of quartz content values.

Worldwide, there is several laboratories and institutions that offer mineralogical content analyses. This is an advantage as project owners and contractors does not need to send soil samples to laboratories offering special tests and services. On the other hand, estimation of mineralogical content with XRD and thin section analyses, are semi-quantitative approaches, which acknowledge the subjectivity of the person that is analysing a sample.

4. Suggestion for a new test method taking into acount in-situ properties of soil

The last few years more advanced test approaches has been introduced in order to provide "self-explanatory" test result on soil abrasivity. The intention of such test is to rebuild an in-situ like soil, in order to perform a direct test on a similar material as the TBM will encounter. The tests allows the abrasivity measurement to be conducted on in-situ like soil meaning that water content, soil compaction and density, use of soil conditioner and influence of pressure can be modified and adjusted to simulate the real life conditions in front of a TBM cutterhead [28,29,16].

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Fig. 9. Ball Mill Test apparatus can be used to assess the reduction of abrasivity by introducing soil conditioning additives. The test apparatus consists of a rotating drum filled with soil (0–16 mm) and 20 steel bits. Water and/or soil conditioning additives can be applied.

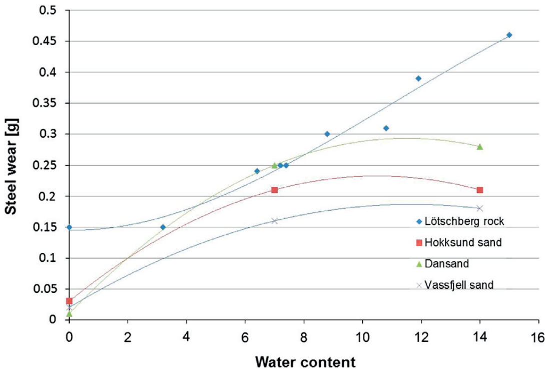

Fig. 10. Influence of water content on steel wear in the Ball Mill Test for 4 different soil and crushed rock samples [25]. The Figure shows a clear tendency of increased steel wear by increasing water content up to a certain level.

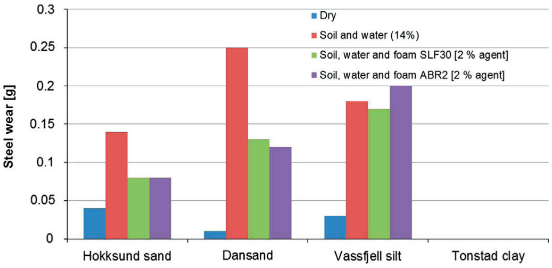

Fig. 11. Reduction of abrasivity due to introduction of soil conditioning foam [25]. The Tonstad clay sample did not show cause any steel weight loss.

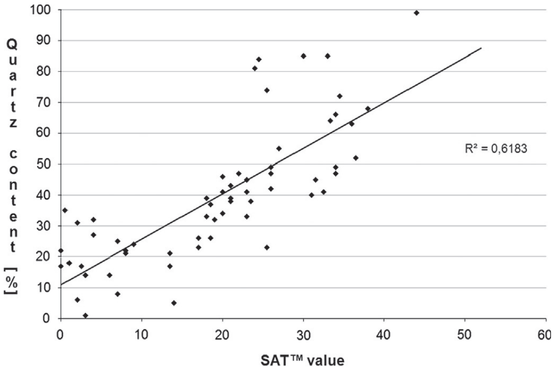

Fig. 12. Correlation between SAT™ value and content of quartz. $N=62$. The data shows a clear influence on SAT™ values by the quartz percentage in a soil [27].

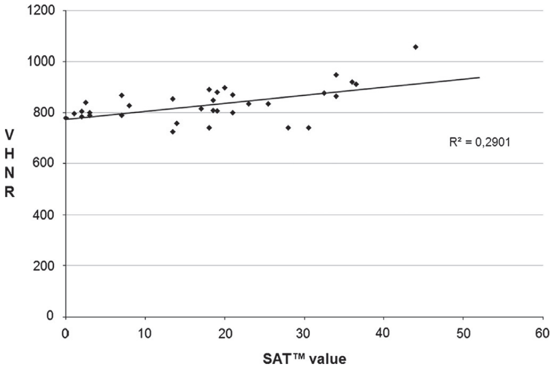

Fig. 13. Correlation between SAT™ value and Vickers Hardness Number Rock (VHNR) $N=30$. The data shows the influence on SAT™ values by the mineralogical content in a soil [27].

At NTNU/SINTEF, in close cooperation with BASF Construction Chemicals, there is an on-going work in developing such an apparatus. Some initial test results are available. The results clearly demonstrate the influence of moisture and various types of foam on tool life. More tests are being conducted to study the influence of soil compaction, soil moisture content, various foam types, as well as different soil conditioning scenarios. The test apparatus does also monitor the required torque for drilling with specified thrust and rotation speed, which also will be a valuable parameter in estimating tool life and performance. Fig. 14 (left) shows the principal set-up of the test with the range of operational parameters. Testing of 4 different soil samples have been carried out, and based on this the following test parameters will be used: 40 mm/min fixed penetration, 50 rpm fixed rotation speed, varying torque, varying thrust. The selection of parameters is done in order to measure torque and thrust requirements for various soils, which can be an important soil parameter for TBM tunnelling (Figs. 15–17).

In sum, based on the results obtained from the laboratory experimentations, the suggested Soft Ground Abrasion Test appears a major step forward for laboratory assessment of real-life tunnelling conditions.

5. Discussion

The tests LCPC abrasivemeter, the Soil Abrasion Test™ (SAT) and the mill tests are all based on a contact between loose soil missing

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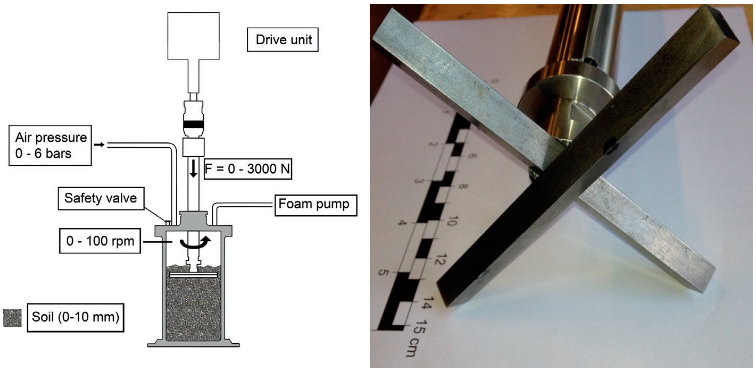

Fig. 14. Schematic setup of the test apparatus (left) and picture of drilling tool and drill rod (right). The test chamber is filled with soil material (0–10 mm) which is compacted to the desired density. The drilling tool has nozzles for using continuous foam injection during testing.

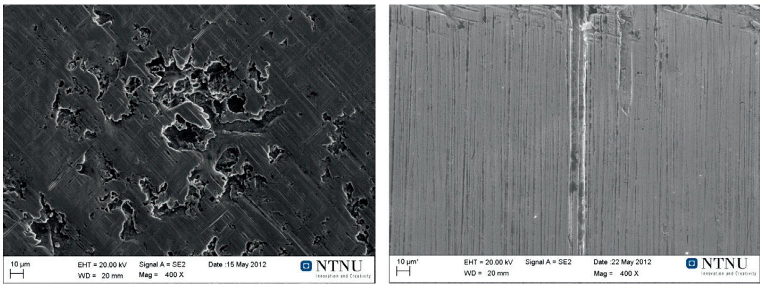

Fig. 15. SEM (Scanning Electronic Microscope) image showing a combination of abrasive wear and corrosion (left) on the suggested new test´s steel tool after exposure to a soil sample with 8 wt% water, compared to abrasive wear on the HSAT steel tool after exposure to a dry soil sample (right) (Photos Christian Kreyberg Grødal) [30].

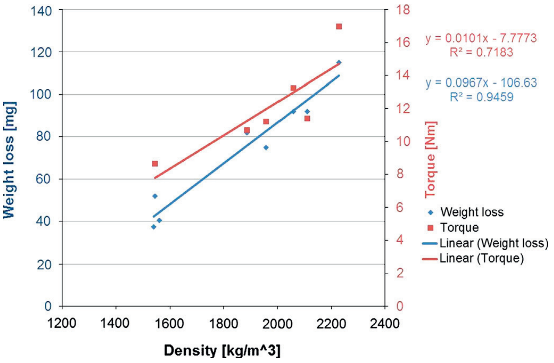

Fig. 16. Measured relation between soil compaction grade (density), abrasivity (weight loss) and average torque on one soil sample.

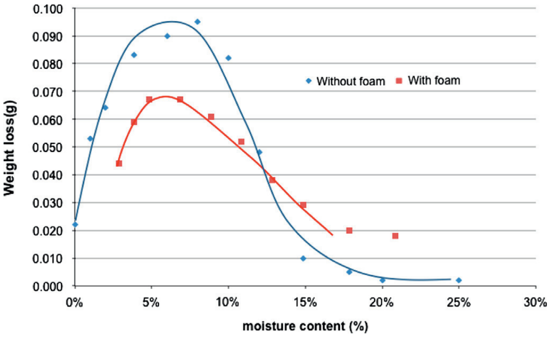

Fig. 17. Abrasivity (weight loss on the steel tool) for different moisture contents on one soil sample [16]. Soil conditioning foam clearly reduces the wear and structures the soil at higher moisture contents.

several of its in-situ conditions (e.g. water content, density/compaction, original grain size distribution) and a steel sample. The contact pressure between the soil and the steel sample is also varying as different soil grains have different hardness and mechanical properties.

The simplified tests, represented by the SAT™ test, indicate promising correlations between measured abrasivity and TBM tool life based on data collection from 9 projects. However, the use of the exponential relations between SAT™ values and recorded tool life for tool life prediction should be used with caution [14]. The SAT™ values from a specific project in Germany corresponded quite well with the trends that can be observed in Fig. 8, but for a similar project (small tunnel diameter, abrasive soil conditions and the same contractor and equipment) it did not correspond well. The main reason for this observed inconsistency can be explained by that the SAT™ value is a measurement on a cohesionless powder. This effect is expected to be prevailing for the other tests and approaches. The LCPC test, the Ball Mill test and the use of VHNR does not take in to account the mechanical properties (e.g. cohesion, strength, plasticity) of the soil.

On the other hand, the empirical relations are still quite promising. This means that further research should be done to

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include other in-situ parameters into the tool life estimate (e.g. in-situ soil density). Due to this, and the relative low amount of data in the correlation charts tunnel excavations should not be scheduled without any interventions.

The suggested NTNU/SINTEF/BASF Soft Ground Abrasion Test, makes it possible to evaluate the water content, density/compaction and utilization of soil conditioning additives on steel tool life. The initial results obtained by the suggested test indicate that denisity/compaction is highly influencing the tool wear. It is expected that such a test would have a better relation to reality, but this needs to be proven as more data from both the field and laboratory is collected.

In order to assure that the “simplified tests” and the suggested new test really represents the reality, surface analyses on the steel samples (test pieces) should be carried out. Further, the worn out micro structure of the test pieces should be compared with worn out tools from real TBM tunnelling application.

6. Conclusive remarks

There are several available methods for measuring soil abrasivity. Currently, there are no model recognized by the tunnelling industry, including contractors, project owners, consultants, TBM machine manufacturers and academia.

Generally speaking, due to the complex conditions characterising tunnelling conditions, predicting real-life wear on TBM tools from laboratory experiments is inherently complex. In this paper, we have examined the degree to which four existing laboratory approaches succeed in providing predictability.

NTNU, in close connection with SINTEF and BASF Construction Chemicals are trying to meet this demand from the tunnelling industry by (1) continuation of the existing abrasion testers used in connection with soil TBM tunnelling, and (2) continue the development of the suggested Soft Ground Abrasion Tester, which is trying to meet the demands for the tunnelling industry and criticism of the existing simplified tests and approaches.

The initial results are promising and the suggested test obtains abrasivity and torque measurements for a larger span of grain sizes than the other methods. The method is also sensitive to the water content of soft ground samples, the compaction/density of the samples as well as the use of soil conditioning additives.

Aknowlegdements

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Paper 7

Overview of Methods and Approaches used at NTNU/SINTEF to Estimate Soil Abrasivity in TBM Tunnelling

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Overview of Methods and Approaches used at NTNU/SINTEF to Estimate Soil Abrasivity in TBM Tunnelling

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Abstract

The increase of urbanization constantly demands more infrastructure, which often requires to utilize the underground. There are several methods and approaches to estimate geo-material's abrasion properties in tunnelling with Tunnel Boring Machines (TBM). The methods are mainly based on using empirical observations and experiences from completed tunnelling projects correlated with simplified laboratory test results. The simplified laboratory tests means that the soil's in-situ properties such as the cohesion, density, adhesion, water content and original grain size distribution are lacking or is disturbed. The intention of this research paper is to give a brief overview on the approaches and methods from a Norwegian perspective, the test procedures and their pros and cons. The up to date methods will be evaluated with respect to applicability from a practical view and with some general tribological experiences such as the influence of hard minerals or particles, grain shape and grain size.

Keywords: TBM Tunnelling, abrasivity, soil, rock.

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1. INTRODUCTION

Full face tunnelling with tunnel boring machines (TBMs) is a well-known and widely utilized method to excavate tunnels. Approximately 70 % of all tunnels excavated by TBMs are removing soil and soft rock material [1]. According to [2] the total amount of TBMs working to excavate soil the last 5 years is approximately 350 units.

In order to excavate the soil and soft rock, a combination of rotating disc cutters, scraper tools and ripper tools are installed on the TBMs cutterhead. Generally the disc cutters are designed to apply a high load in to rock mass, inducing tensile failures and chipping from rock, while scraper tools are designed to scrape coarse soil from the tunnel face and ripper tools are ripping cohesive soil material (clay and silt). These tools are exposed to relative high contact forces with abrasive material causing various degradation processes.

In soil tunnelling the TBMs utilize various soil conditioners. Slurry shield TBMs utilizes bentonite, which has lubricating properties and consists of a fine clay mineral. Utilizing bentonite is mainly done to stabilize the tunnel face during excavation. However, by applying the right amount of bentonite with the right pressure it can also increase the life of tools on the TBM.

Earth pressure balance shield TBMs utilizes various soil conditioning additives to reduce the torque demand on the TBMs. The addiives can also change the soil matrix in order to reduce clogging effects of clays, and to make the excavated soil more transportable through the pressurized excavation system [3.] The introduction of such additives is therefore an important part of the steel – soil interaction in soil tunnelling.

Figure 1: *EPB TBM with foam nozzles (Photo by Robbins TBM Company)*

At the time being there is not recognized standard method or approach to estimate tool life in soil TBM tunnelling. However, the tunnelling works are in most cases based on tender documents with pre-investigations of the soil or rock along the tunnel drive. Various contractors then have to assess the pre-investigation values in order to make a tender. However, there are currently numerous disputes between contractors and owners/consultants when it comes to TBM performance and tool life.

This research paper aims at presenting some of the most common methods for measuring soil abrasivity. Further, some comments on the various methods pros and cons and applicability from a practical view are presented.

2. CAUSES AND CONSEQUENCES OF WORN OUT TOOLS IN SOIL TUNNELLING

The direct consequence of tunnelling in abrasive soil conditions is an increased demand for replacement of the excavation tools (disc cutters, scrapers and rippers). The disc cutters are equipped on TBMs if the rock mass exceeds a compressive strength of 20 MPa [4]. However, disc cutters are quite often installed to cope with boulders (large rock blocks) inside a soft soil as well.

The cost of tools are varying depending on size, manufacturer-customer relations, material quality and type. In addition to the direct cost for purchasing tools, the down time of a TBM, unproductive time for workers and possible delay of the tunnelling project should be included. In a recent hard rock TBM project in Hong Kong it was stated that 1 second downtime has the cost of USD 1, meaning that one working shift's downtime can cost as much as USD 30 000 excluding the purchasing cost for the tools (further details on down time cost of TBMs is to be published in 2012).

Figure 2: *Double disc cutter and scraper tools in contact with a mixed face consisting of claystone and gypsum (Photo by Pål Drevland Jakobsen)*

In soil tunnelling the tools and cutterhead interventions are quite often subjected to hyperbaric working environments, meaning that the actual intervention and tool replacement is a diver operation. The reason for the hyperbaric environment is to stabilize and avoid a collapse of the tunnel face. By assuming an 40 meter overburden with hydrostatic water pressure the working environment for divers involve mechanical work in 4 bars pressure in a mix of soil, additives and water. Such operations are both risky with respect to health and safety for workers, and are more costly and time consuming to conduct compared with the same intervention and work in a self-stable tunnel without the need of hyperbaric stabilization of the face. In hard rock TBM tunnelling there are generally a higher consumption of tools than for soil tunnelling. However, the consequences of worn out tools in soil tunnelling are higher due to the hyperbaric operation that is needed.

3. THE LCPC ABRASIVEMETER

The LCPC abrasivemeter test procedure and apparatus is described in the French Standard P18-570 [5]. The test is based on exposing a 4.0 – 6.3 mm fraction of crushed rock or natural soil for a rotating steel impeller for 5 minutes. The rotation speed of the impeller is 4500 rpm and the steel consists of a relative soft steel alloy with Rockwell B hardness of 60 – 75. For coarse soils the 4.0 – 6,3 mm fraction can be sieved out, while for clay, silt and sand samples the LCPC Abrasivemeter standard test procedure is not suitable.

Figure 3:*The LCPC test apparatus (Photo by Filip Dahl).*

The weight loss of the steel impeller is measured after each test, and this is the measured abrasivity parameter. The LCPC abrasivity coefficient (LAC) is calculated as LAC = (m_0 – m) / M where (m_0 - m) is the weight loss of the steel impeller after a test and M is the soil or rock materials weight (0.0005 tons) [6] The soil material's brittleness properties can also be measured by the LCPC Abrasivemeter by comparing the sieve curves of the initial 4.0 – 6.3 mm sample fraction with the particle size distribution after the test.

The effect of different grain sizes outside the standard 4.0 – 6.3 mm, has extensively been studies in [6]. The study indicates higher abrasivity for larger grain sizes. Whether this is a result of grain's abrasivity properties or caused by the influence of heavier grains which has the potential to cause more damage and degradation on the test steel bit is uncertain.

In [7] the relationship between the LCPC abrasivity coefficient (LAC) and equal quartz content (EQC) is studied. The correlation is very poor with no clear trend in the current data set consisting of 22 samples from the recently completed Inntal railroad tunnel project in Austria. Further a relation between the Cerchar Abrasivity Index (CAI) and LCPC is shown based on [6] findings. The CAI value is a scratch test used to determine disc cutter tool life on hard rock TBM tunnelling (**Fig. 4 and Fig. 5**).

Figure 4: *Cerchar Abrasivity Index (CAI) apparatus (Photo by Filip Dahl).*

The use of the correlation between CAI and LCPC values did not provide a good tool life estimate (based on back calculations of the real tool life in the Inntal project) [7]. Some of the reasons for this are according to [7]:

- Soil abrasivity measured in lab does not always reflect the "soil mass abrasivity"
- Influence of TBM operational parameters is not taken into account
- Influence of face support is not taken into account

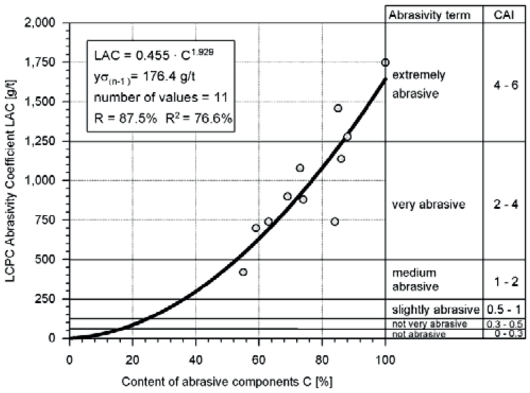

Figure 5: *LAC plotted against the content of abrasive (crystalline) components and CAI values in gravel samples. [6]*

4. NTNU/SINTEF SOIL ABRASION TEST™

The NTNU/SINTEF Soil Abrasion Test™ is a development of the existing test procedure for hard rock (AVS (Abrasion Value cutter Steel) test). Compared with the hard rock abrasivity test *AVS* some details have been changed with respect to sample preparation and steel test piece. [8] The relatively small changes has been done in order to have possibilities of comparing hard rock abrasivity measurements (test database contains around 2000 unique test values from hard rock samples) with soil abrasivity measurements (SAT™ database contains around 250 unique test values).

In order to reduce or avoid changes of the original grain shape and size, soil samples should be dried in an ventilated oven at 30°C for 2-3 days. After the drying process the following techniques should be used in order to disintegrate and separate the particles for the abrasion powder:

1. Disintegration by using a soft hammer
2. Sieving with steel balls
3. Initial disintegration in a jaw crushed if the samples contain hard lumps of cohesive material after the initial drying. Crushing of intact grains should be avoided.

The SAT™ value is calculated as the mean value of the measured weight loss in mg. In order to be accepted as a test results, weight losses of 2 – 4 parallel tests should not deviate by more than 5 units.

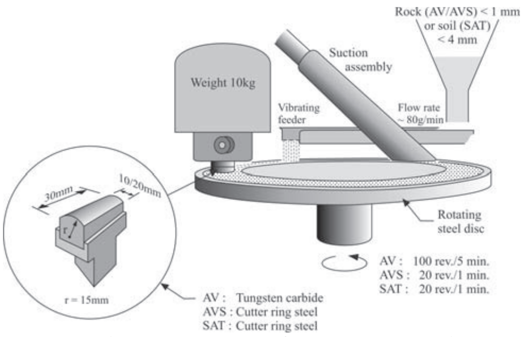

Figure 6: *Schematic overview of SAT™ test procedure [8].*

The maximum contact pressure between soil samples and the steel test piece is ranging from 200 to 370 MPa, dependent on the elastic properties of the soil material. The steel test pieces are machined from a TBM cutter disc ring, and it is a heat treatable, low alloy steel containing nickel, chromium and molybdenum. The hardness of the steel piece ranges from 54 – 56 HRC.

The relation between SAT™ values and the AVS classification system for hard rock abrasivity is shown in **(Fig. 7)** [8]. The abrasivity properties of hard rock samples are generally found to be more abrasive than the soil samples. There is no clear explanation of this, but some indications can be:

1. Soil originates from degraded rock material. “Softer rock”, (which generally is less abrasive) will be transformed into soil before “harder rocks”.
2. In the hard rock abrasivity database TBM projects with abrasivity problems is over represented in the data set.

The SAT™ value has good correlation coefficient with the soil samples’ quartz content and Vickers Hardness Number Rock [9] (VHNR). Relations between SAT™ values and “general tribological” parameters such as grain shape, grain mineralogy and grain size is to be published in 2012.

As more soil abrasivity data is gathered the distributions might converge into each other.

In order to evaluate the SAT™ procedure’s applicability to the reality some indications of SAT™ values relation to recorded tool life has been prepared **(Fig. 8)**. However, the current data s is based on few cutter changes, meaning that introduction of more data will influence both the strength of the correlation as well as the regression’s equation. The tool life has been calculated according to [10].

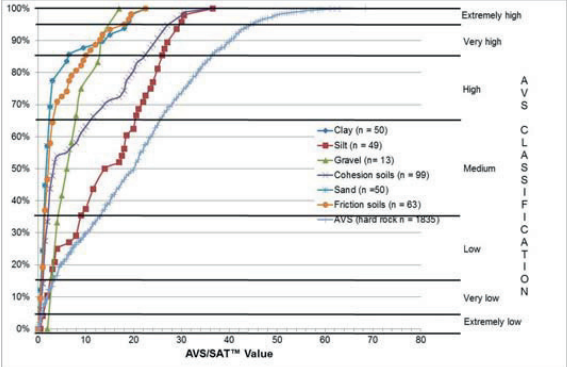

Figure 7: *Cumulative distribution of measured soil abrasion values and AVS classification.*

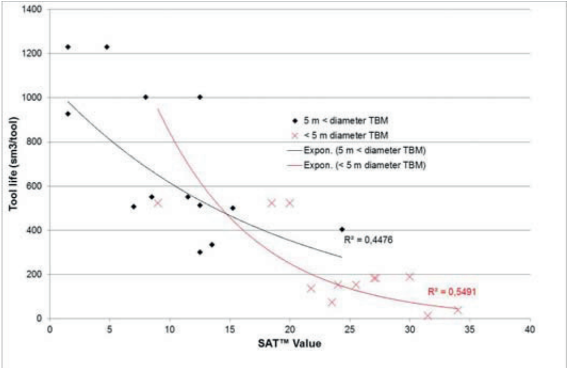

Figure 8: *Indications of SAT™ values´relation to recorded tool life (scrapers and rippers) for TBMs < 5 m diameter and TBMs > 5 m diameter.*

5. MILL TESTS

There are several mill tests available for determining soil and rocks resistance against crushing and abrasivity properties. At NTNU/SINTEF the Ball Mill Test has been used in order to determine the use of anti-abrasive soil conditioning foam´s influence on geo material´s abrasivity properties. The test procedure is easy and strait forward: A 1500 g sample consisting of grains less than 16 mm is exposed to 20 steel bits (consisting of ordinary construction steel) for 5400 revolutions which are equal to 60 minutes test duration. The weight loss of the steel bits is measured after the testing. The measured weight loss is the abrasivity value detected in the Ball Mill Test.

The influence of foam enriched soil conditioner clearly reduces the weight loss of the steel samples [11]. The test also indicates that the abrasivity of most geo material increases to a certain level of moisture content.

Figure 9: Ball Mill Test apparatus can be used to show the reduction of abrasivity by introducing foams.

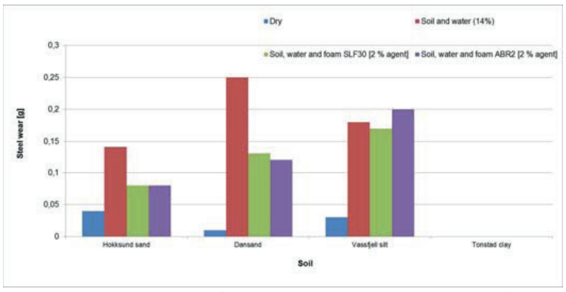

***Figure 10:** Reduction of abrasion due to introduction of soil conditioning foam. [11] and [12].*

For the clay sample in **Fig 10** no weight loss was recorded under the present testing conditions. The test results in mill tests are highly influenced by which grain size that is included in the test. The procedure can provide good indications of various soil conditioning foams and moisture contents influence on abrasive wear for specific samples with a defined grain size distribution. The contact forces between the steel and soil particles are also relatively low (by gravity and tumbling of the drum). The low contact force is not in accordance with reality where TBMs have a relative high thrust and torque ripping and scraping the soil during excavation.

6. TEST PROCEDURES ON IN-SITU LIKE SOIL AND SOFT GROUND

The last few years more advanced test approaches has been introduced in order to provide "self -explanatory" test result on soil abrasivity. The intention of such test is to rebuild an in-situ like soil, in order to do a direct test on a similar material as the TBM has to encounter. The tests allows the abrasivity measurement to be conducted on in-situ like soil meaning that water content, soil compaction and density, use of soil conditioner and influence of pressure can be modified and adjusted to simulate the real conditions in front of a TBM cutterhead [13] and [14].

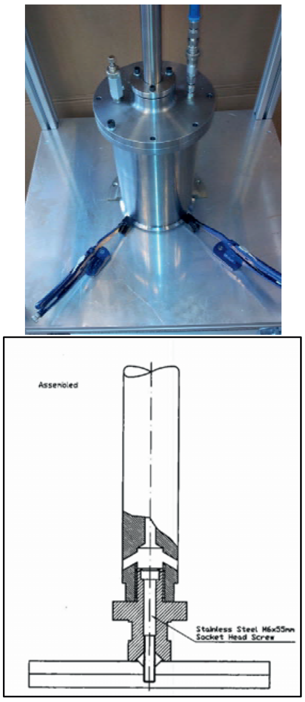

***Figure 11:** Hyperbaric test chamber for abrasivity testing on in-situ like soil(up) and drawing of drilling tool (down).*

At NTNU/SINTEF there is an ongoing work in developing such an apparatus. Some initial test results are available (**Fig. 12**) **t**hat clearly is showing the influence of moisture and soil conditioning foam on tool life. More tests are being conducted to study the influence of soil compaction, soil moisture content and other foam types. The test apparatus also monitor the required torque for drilling with specified thrust and rotation speed, which also can be a valuable parameter in estimating tool life and performance.

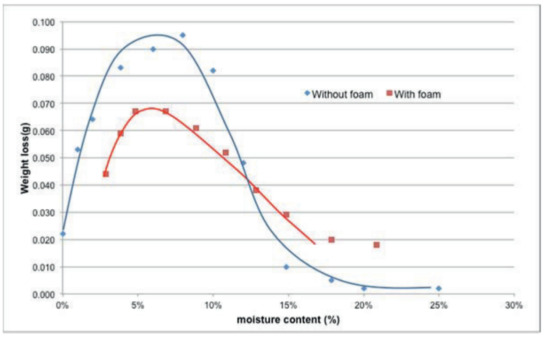

***Figure 12:** Initial abrasivity test result on one "in-situ like" soil sample.*

7. CONCLUSIVE REMARKS

The complex behavior of soil material (ranging from plastic clay to soft but brittle sandstones) confirms findings and general tribological experiences in [15]. There is a demand for numerous empirical relations between real tribological events, and simplified laboratory measurements.

A limitation prevailing for all tests mentioned in this paper is the relative limited amount of soil material tested. Excavating a 5 000 m long tunnel involves moving of 15 000 to 850 000 m^3 of soil material dependent of the tunnel diameter. In order to estimate the tool life of a TBM excavating such amount of soil demands several simplified laboratory tests, as well as adjusting the "soil abrasivity" to geotechnical parameters that may influence tool life and how the TBM is operated with respect to soil conditioning, thrust – rpm and torque ratio, scheme for cutterhead interventions.

Whether simplified "index tests" such as LCPC abrasivemeter, SAT™ and mill tests can provide a good estimation approach for TBM tool life excavating soil needs to be concluded when more data and experiences are available. However, the findings in (**Fig. 8**) is promising, meaning that simplified "index tests" should not be neglected at the moment.

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Paper 8

Predicting the abrasivity of in-situ like soils

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Langmaack, Lars
Dahl, Filip
Breivik, Torkjell

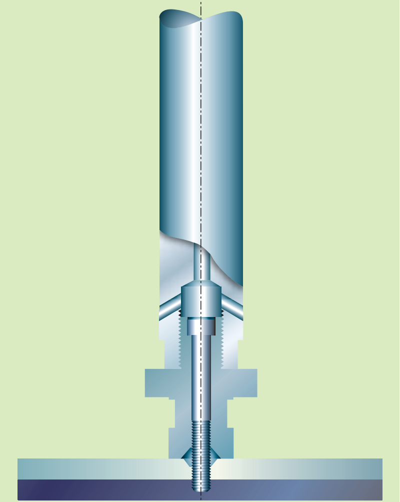
Published in Tunnels and Tunnelling International, 2012

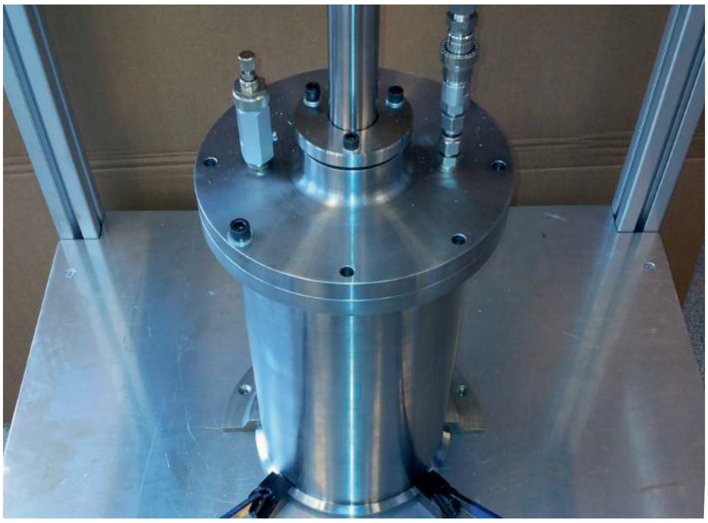
Predicting the abrasivity of in-situ like soils

Jakobsen, Langmaack, Dahl and Breivik report on further work undertaken at the Norwegian University of Science & Technology (NTNU – Trondheim) and SINTEF on better ways to study tool-soil interaction on abrasivity, particularly relevant to soft ground abrasion

Determining the abrasiveness of soil and predicting TBM tool life in shield tunnelling has become a popular research subject in the last few years. Nilsen et al (2006a, 2006b, 2006c and 2007) and Jakobsen and Dahl (2010) converted NTNU/SINTEF´s existing abrasivity measurement technique for hard rock and made it applicable for measuring soil abrasivity. Thuro et al (2007) converted the LCPC abrasivemeter, also intended for hard rock abrasivity testing, to measure soil abrasivity. Gharahbagh and Rostami (2010) and Rostami et al (2012) developed a new soil abrasivity measuring technique that takes into account in situ soil properties. Jakobsen et al (2009) and Langmaack et al (2010) presented results on the influence of anti-abrasion foams on wear by the use of the Ball Mill Test and NTNU/SINTEF abrasivity test. The main conclusions from this work were that the results showed a clear reduction of rock and soil abrasiveness by utilising polymer enriched foams. However, further evaluations are needed due to difficulties in controlling the amount of foam as well as difficulties in comparing abrasiveness results from samples with different grain sizes in the Ball Mill Test. NTNU together with SINTEF and BASF Construction Chemicals are, as a continuation of this initial work, developing a new measuring

Below, left: **Figure 1, steel-soil interaction with the current Soil Abrasion Tester;**
Below, right: **Figure 2, drilling tool for new proposed test**





Left, top: **Figure 3, hyperbaric test chamber 150 x 300 mm;** Above: **Figure 4, boring in to a compacted soil sample with soil conditioning foam under atmospheric test conditions**

Table 1: Summary of soil properties of the tested soils

	Soil 1 (from the Trondheim area)	Soil 2 (from a tunnelling project in Europe)
Quartz content measured by DTA	44 per cent	34 per cent
Cu = d60 /d10	4.66	15.5
d50	4.8 mm	4.9 mm
d25	1.5 mm	2.5 mm
Soil Abrasion Test (SAT) value	26	23.5

technique which takes several different soil properties in to account.

The reason for developing a new measuring technique is to try to study tool – soil interaction in a better way, as well as research on how various geotechnical parameters influence the steel wear due to soil abrasivity. The technique that is currently used at NTNU/SINTEF is based on testing disturbed soil material: meaning dry powder, lack of cohesion, limited grain size distribution (< 4 mm) and no influence of soil compaction. Additionally, the current technique does not allow for the testing of the possible influence of chemical additives, which are commonly used in Earth Pressure Balance (EPB) machine.

The new apparatus will be able to handle larger grain sizes (up to 12mm), different soil moisture contents, soil compaction or reproduced in-situ soil density and also the use of chemical or natural additives such as foams and bentonites.

The test is designed to take into account hyperbaric conditions, as the test chamber can be pressurised up to six bar. Additionally the required torque for drilling in the soil sample at variable rotation and thrust will be monitored, thus indicating different torque requirements in various compacted soil-additive-water matrices.

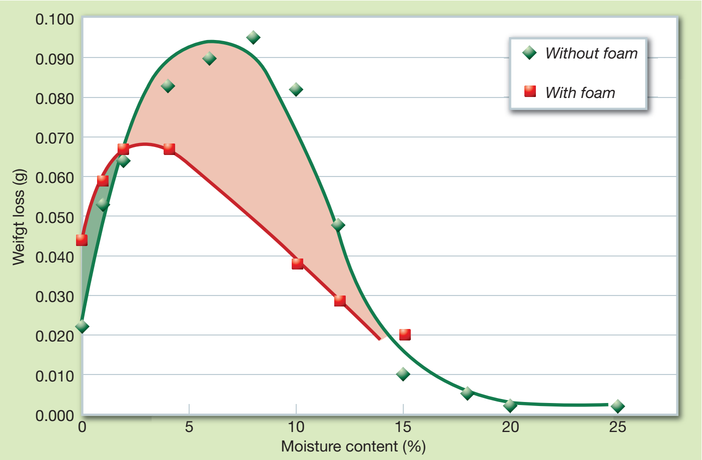
The interaction between soil and steel will be based on both rotation and penetration of the drilling tool. The drilling tool consists of four steel spokes, which drill into the soil to a depth of 200mm in each test. The steel used in the test piece has a Vickers hardness of 227.

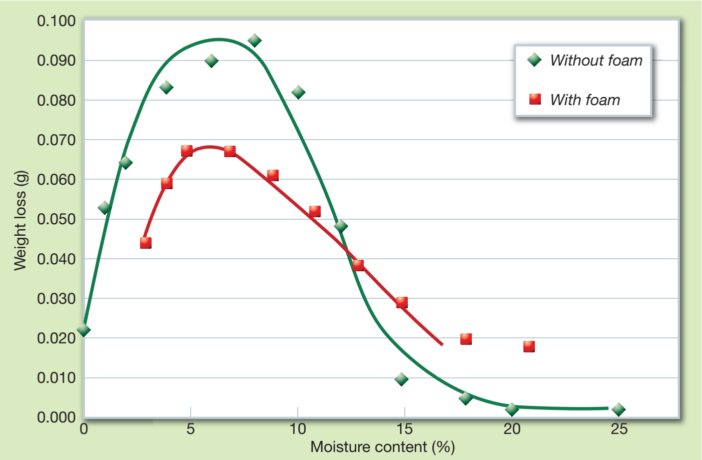
Preliminary atmospheric tests have been performed in order to evaluate the test procedure. The tests were conducted on two natural soils. One (Soil 1) is from a local source in the Trondheim area and the other (Soil 2) from site investigation of a planned European EPB TBM tunnelling project. The grain size distribution of Soil 1 ranges from 0 to 6.5mm and for Soil 2 from 0 to 30mm. Particles above 12mm were removed from the Soil 2 prior to testing.

Test procedure

The soil specimens to be tested were assembled in four layers, each compacted by ten strokes of a Proctor Hammer of 50mm diameter and 2.5kg load. The rotation speed of the drilling tool was set at 90 rev/min, and a constant penetration rate of 0.63mm/rev or 56mm/min was applied. The test was conducted by drilling stepwise to depths of 50, 100, 150 and 200mm. The reason for the stepwise drilling method was to achieve better mixing between the foam and soil.

- Dry soil application: In order to obtain a dry soil, the present soil samples were gently dried in a ventilated oven at 30°C for 48 hours.
- Humid soil application: Various amounts of water were added and mixed with the specimens to be tested in order to achieve homogeneous moist soil samples.
- Conditioned soil application: Foam with an expansion ratio FER = 10 (air/liquid ratio = 10:1) was applied on top of the compacted and humidified soil sample for the tests performed with additives. The foam injection ratio FIR = 30 per





Right, top: Figure 5, soil abrasivity development for conditioned Soil 1; Right, centre: Figure 6, Adjusted moisture content and soil abrasiveness for Soil 1; Right, bottom: Figure 7: Weight loss for varying water contents with and without foam for Soil 2

cent (foam:soil ratio = 300 litre per cubic metre) was used meaning that one litre of foam was utilised for excavating approximately 3.3 litres of soil. The foam used was BASF Meyco SLF41, which is a polymer enriched soil-conditioning additive. Generally the concept of using soil-conditioning foams is that their high surface area will confine fines in the soil matrix and subsequently reduce the friction between both soil grains and the interaction between the soil and steel tool.

As shown by Jakobsen et al (2009), and Rostami et al (2012), soil and rock abrasiveness increases up to a certain level generally expected with increasing moisture content. Subsequent to the abrasiveness' 'peak level' a general decrease of soil and rock abrasiveness occurs. A similar phenomenon is reproduced with the test apparatus described here. For Soil 1 the soil abrasiveness' peak occurs at approximately six per cent moisture content and then reduces as more water is added. The peak is assumed to be influenced by the soil's grading curve as well as general abrasion properties such as grain mineralogy and grain shape (see figure 5).

The testing performed with addition of soil conditioning foam leads to a reduction of the soil abrasivity peak (reduction shown in red shaded area in figure 5, page 43), and hence provides a good indication of the functionality of soil conditioners. However, at low moisture contents the introduction of soil conditioners in certain cases may intend to increase the abrasivity, here shown as green patterned area in figure 5. This phenomenon has also been observed at some EPB drives executed in dry soil open excavation in Switzerland and Germany where the introduction of small amounts of soil conditioners reduced the TBM cutter tool life.

The increase of soil abrasivity in low moisture contents is most likely caused by the introduction of additional moisture by using soil conditioning agents. Taking the total moisture into account, the soil-conditioning agent reduces the wear, except for the high moisture content area. The increased soil cohesion probably leads to a slower decrease of wear than just using water. The adjusted picture is shown in figure 6 (page 43).

Soil 1 and Soil 2 are quite similar with respect to the measured abrasivity properties according to the existing Soil Abrasion Test procedure, and the initial measurements by the new test. The quartz content is also in the same range. However Soil 2 has a more uniformly graded sieve curve that might cause a higher resistance, and thus higher steel wear on the excavating tools. In general a reduction of abrasive wear in the range of 25-45 per cent was observed by applying adequate soil conditioners to the soil samples.

Conclusions

The few tests conducted clearly indicate that moisture content influences the abrasive wear in a steel – soil interaction, similar to the Rostami et al (2012) findings. The introduction of soil conditioners reduces the potential abrasivity peak of the tested soil samples. However the current tests are so far only based on sandy soils, meaning that further testing on other materials is needed.

The introduction of an additional 'soil abrasion test' is, at present, not intended as a new index test. The idea of introducing this test procedure is to provide self-explanatory test results taking into account several in-situ soil properties.

Based on the promising results NTNU/SINTEF, together with BASF, intends to perform extensive testing in order to show the influence of various soil conditioners on abrasivity and TBM torque, as well as the effects of confinement pressures and soil compaction.

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Paper 9

Development of the Soft Ground Abrasion Tester (SGAT) to predict TBM tool wear, torque and thrust

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Development of the Soft Ground Abrasion Tester (SGAT) to predict TBM tool wear, torque and thrust

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ABSTRACT

The Norwegian University of Science and Technology (NTNU), SINTEF Rock Engineering and BASF Construction Chemicals have jointly developed a new test device called the *Soft Ground Abrasion Tester* (SGAT). The ambition and purpose of the design of the test and the applied test procedure is to replicate an in situ soil – TBM excavation tool contact, in a small and simplified scale. The current development is attempting to bridge a gap when it comes to estimating soft ground and soil abrasivity, as earlier research on e.g. the NTNU/SINTEF Soil Abrasion Test™ (SAT) shows that it does not catch up all driving factors for soft ground and soil abrasivity directly. The paper summarizes the development of the SGAT apparatus, and shows its capabilities to evaluate, quantify and compare how the soil mineralogy, water content, pressure, compaction, and the use of soil conditioning additives influences the wear rate on the SGAT excavation tool. During testing the required torque and thrust are monitored and logged, making it possible to measure various soil–soil conditioning matrixes requirement for operational parameters.

1. Introduction

1.1. General

Predicting soft ground TBM tool life is a complex matter. In order to study and quantify in situ soft ground abrasivity, The Norwegian University of Science and Technology (NTNU), SINTEF Rock Engineering and BASF Construction Chemicals have developed a test device called the *Soft Ground Abrasion Tester* (SGAT). The intention for developing the apparatus is to provide a reliable test method for determination of in situ like soil's abrasivity, as well as various soils and soil conditioners' torque requirement for soft ground TBM applications. The apparatus has the capability of evaluating how soil abrasivity is influenced by water content, air-pressure, compaction or soil density as well as introduction of soil conditioning additives. The developing consortium has been successful and worked in the following manner: NTNU has managed the development based on a BASF design concept. The development has been quality assured by SINTEF. Generally, the SGAT is an open source development and other suppliers, contractors, clients and TBM manufacturers are invited to run tests on the apparatus.

1.2. State of the art on soil abrasion prediction based on hard rock test methods

So far, the research on soil abrasivity and TBM tool life on soft ground tools at NTNU/SINTEF has been limited to the Soil Abrasion Test (SAT™) (Nilsen et al., 2006c,2007; Jakobsen and Becker, 2012), and the Ball Mill Test for determining the influence of soil conditioning additives and presence of water on hard rock and soil abrasivity (Jakobsen et al., 2009; Jakobsen and Lohne, in press). The initial development of the SAT™ test procedure results from a request from a contractor, which would like to evidence that a specific soil condition was highly abrasive. All these test procedures and approaches originate from NTNU/SINTEF's research on hard rock TBM tunneling performance and tool life estimates, which have been an ongoing research activity for several decades. In 2011, there has also been initiated research on the effect of tribo-corrosiveness of rock and soil in interaction with steel (Grødal et al., 2012). The intention of this present work is to achieve a further understanding of the mechanisms which are degenerating TBM excavation tools.

Similar to the development of the NTNU/SINTEF Soil Abrasion Test (SAT™), the Technical University in Munich introduced the LCPC abrasivemeter (LCPC, 1990) for determining soil abrasivity (Thuro et al., 2007). The LCPC approach has some similarities to the SAT™ procedure available at NTNU/SINTEF, as both test methods use dried soil samples in limited fractions (LCPC 4.0–6.3 mm/

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SAT™ < 4.0 mm). The sample used for the LCPC test is however exposed to a steel impeller rotating at 4500 rpm. The high speed rotation of the steel impeller is causing crushing of soil or hard rock fragments, and this interaction causes wear on the steel.

Gwildis et al. (2010) present tool wear data from the Brightwater conveyance tunnel project, which indicate that cutterhead energy consumption together with abrasivity descriptors (e.g. SAT™, quartz content or Miller Slurry Test) are the driving factors for tool wear. The simplified test approaches such as the SAT™ test and the LCPC abrasivemeter do not have the ability to directly include the soil materials' need for cutterhead energy, as the methods are based on testing the interaction between steel and loose soil particles.

Köhler et al. (2011) present experiences from the tunneling project Lower Inn valley in Austria, and conclude that there are no recognized prediction models for estimating tool wear in shield tunneling in soil. They also consider the possibility to establish correlations between small-scale laboratory index values and real-life TBM wear rates to be unlikely, if not impossible.

1.3. New developed soft ground abrasion test methods

The first approach of developing an apparatus purely intended for soil and soft ground abrasive wear prediction was performed and published by Gharahbagh et al. (2010, 2011, 2013) and Rostami et al. (2012a,b). The Penn state soil abrasion testing system consists of a rotating blade at a fixed position which is in contact with a soil sample. The apparatus has the possibilities of evaluating the influence of various water contents, rotation speeds, higher ambient pressures and various excavation tool hardness. However, the soil sample is not consolidated prior to testing according to the test suggested by Gharahbagh et al. (2010). The soil sample density/consolidation is therefore not a controllable variable. Furthermore, the rotating tool is in a fixed position during testing (not penetrating into fresh soil sample material) and soil conditioners can only be used as an already preconditioned soil sample.

A more recent approach is suggested by Barzegari et al. (2013). The test device consists of rotating steel plates in contact with soil samples or crushed rock. The soil sample can be tested under pressure, and the test device allows utilization of additives.

Due to the assessment of simplified abrasion measurements presented by Köhler et al. (2011), Gwildis et al. (2010) and Jakobsen and Becker (2012), as well as the lacking possibility to run tests on a consolidated sample in the Penn State system, a development of a more advanced prediction method is needed. The development of the new SGAT is an attempt to develop a laboratory approach that after further assessment and work, may work as a pre-investigation tool on tool life for soft ground and soil TBM tunneling.

1.4. Research questions

Jakobsen and Becker (2012) and Jakobsen et al. (2013) evaluated the SAT™ values against observed tool life for some recently completed tunneling projects with bentonite slurry face support. In this evaluation, one of the reasons for empirical outliers were identified as the influence of the soil grading. Single graded soils with high SAT™ values did not cause any reduction in excavation tool life. This effect is, as stated by Gwildis et al. (2010), explained by the relative low amount of energy the TBM needs to apply in order to excavate such soils, and thus relatively low contact pressures between the soft ground tunnel face and the TBM excavation tools.

These previously missing effects of soil and soft ground compaction, together with influence of soil conditioning additives are the main reason for developing the apparatus. If the development proves to provide valid and reliable predictions of tool life, a secondary effect of the apparatus can be to obtain laboratory data about how soil conditioning additives, compaction, water influence isolated influences tool life, and use these experiences on SAT™ values. The research questions we intend to answer in this paper are:

- To what extent does the soft ground and soil compaction influence the soft ground TBM excavation tool life?
- Is the excavation tool life influenced by the amount of energy the TBM utilizes in order to excavate the soil and soft ground?
- To what extent does the water content influence the soft ground TBM excavation tool life?
- To what extent can the use of soil conditioning additives increase the soft ground TBM excavation tool life and influences other TBM parameters like torque and thrust?

2. The New Soft Ground Abrasion Tester (SGAT)

The SGAT apparatus consists in the actual status of a drive unit (rotation and vertical movement), a shaft attached to an exchangeable cutterhead-like tool consisting of two steel bars of Vickers Hardness 227 equal to 20 HRC, a testing chamber for the soil sample with a lid which is airtight up to 6 bars pressure, and a foam pump, see Fig. 1. During testing, water, bentonite or soil conditioning additives can be added continuously and directly at the cutterhead-like tool, replicating the real TBM operation. The current steel type, which the results in this paper comprise, is a carbon steel with the chemical composition presented in Table 1.

The drilling tool consists of two steel bars attached to a holder. The tool is designed in order to achieve mixing between the soil sample and the possible used soil conditioning additives, and to achieve relatively high contact forces between the lower steel bar (Fig. 2) and the compacted soil sample during the test. The use of two separate steel bars to form the drilling tool does also provide a possibility to distinguish between primary wear, wear on the lower steel bar, and secondary wear recorded on the upper steel bar. The length of the steel bars is 13 cm, which allows large grains ($\leqslant$20 mm) to pass between the drilling tool and the periphery of the testing chamber. The inside periphery of the test vessel consist of steel. For verification issues, some tests have been run without the lid in order to see whether the soil sample rotates along with the tool, which has not been the case.

The rotation speed is variable between 0 and 100 rpm. The fixed maximum speed of 100 rpm is chosen in order to avoid erosive wear, and to reduce the possibility of high impacts between the steel and soft ground and soil fragments. Running tests on 100 rpm results in a travel speed of approximately 0.7 m/s, which is in the range of a TBM excavation tool, which typically ranges between 0.1 and 1.5 m/s dependent on the tool position.

Several techniques have been tried in order to apply soil conditioning additives, during the development of the SGAT apparatus. Fig. 4 shows the three main approaches, (a) applying the soil conditioning additive on top of the compacted soil sample prior to testing, (b) injecting foam continuously during testing and (c) pre-mix the soil and soil conditioning additive prior to testing. The by far closest to reality technique for applying soil conditioning additives is by injecting through the points shown in Fig. 2, equal to the method shown in Fig. 3b.

2.1. Preliminary test procedure

Generally, all soil samples have been dried for 48 h in a ventilated oven at 30 °C prior to testing. After the drying, grains above 10 mm are removed from the sample. The next step is to add water and properly mix water and soil. Similarly to Rostami et al.

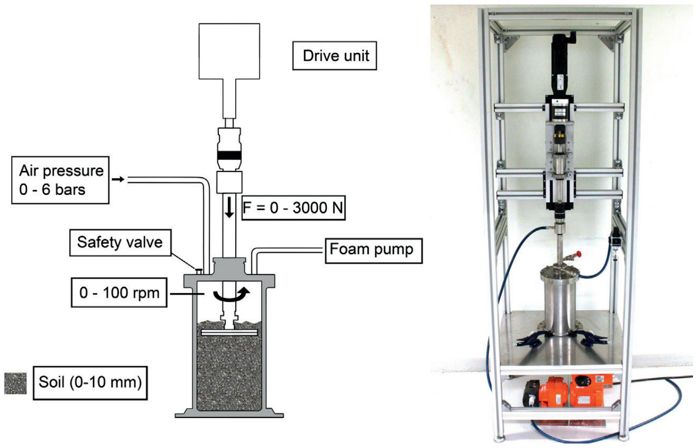

Fig. 1. Outline of the new Soft Ground Abrasion Tester (SGAT) (left) and photo of the test rig (right). The height of the test rig is 210 cm and the width is 75 cm, and the test chamber is 30 cm high and with inner diameter of 15 cm (photo by Simon Alexander Hagen).

Table 1
Chemical composition of the steel type used for the SGAT tool in the initial testing.

C	Si	Mn	Ni	P	S	Cr	Mo
0.43–0.45	Max 0.4	0.5–0.8	Max 0.4	Max 0.045	Max 0.045	Max 0.4	Max 0.1

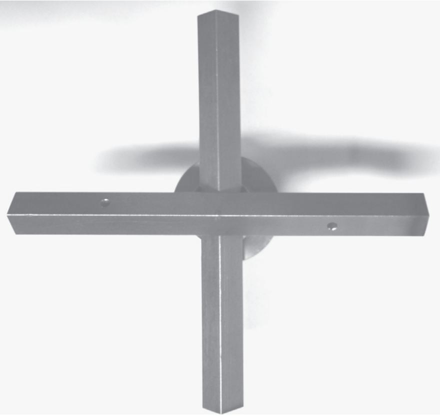

Fig. 2. The SGAT drilling tool. The test pieces have 1 × 1 cm cross-section, and the holes on the lower steel bar is the nozzles for soil conditioning additives.

(2012a,b), the mixing of water and soil were done carefully in order to ensure an uniform distribution of water. In order to avoid crushing of soil grains, thereby introducing more fines in-to the sample, the mixing were done carefully by hand[1]. For soil samples with the desired water content, testing have been conducted on the original soil sample without drying.

After finishing the sample preparation, the soil samples were assembled in four layers with different grade of compaction as shown in Table 3. Fixed volumes of soil samples have been applied to the test bucket, causing the sample weight to vary (between 6500 g and 8000 g dependent on the grain density and level of compaction). An evaluation of various compaction levels along the sample has not yet executed. The authors expect an increase of compaction towards the bottom which is backed up by increasing torque and thrust data.

The SGAT test can be run under different operational schemes. In this paper, the rotation speed and vertical penetration has been fixed, causing the torque and thrust to vary. Oppositely, it would be possible to run tests under a fixed torque with varying vertical penetration or varying rpm. The tool penetration is about 15 cm for the results presented in this paper, with a penetration rate of 40 mm/min. The apparatus has the possibility to reduce the penetration rate or even run tests without any penetration, see Table 4.

The edges on the steel bars on the drilling tool are sharp edged, prior to use. In order to avoid replacement of the steel bars after one single use, the tools need to be runned-in for 2 h in an abrasive soil sample prior to the first test.

As a standard test procedure the penetration speed and rotation speed were fixed, while the thrust force and torque varied dependent on the soil properties and possible use of soil conditioning additives. This approach is carried out in order to compare different soil samples' torque requirement, which is thought to be a good indicator of how easy or hard a soil is to excavate mechanically, as well as indicating the influence on the steel wear rate.

2.2. Data collection and software

The rotation and penetration are driven by two separate servo motors with a gear ratio. The control of the motors use standard analog IO (0–10 V) for position, rotation, penetration speed, thrust and torque. These data are together with a dedicated signal for measuring the air pressure inside the SGAT test chamber continuously logged and presented in the control software (Fig. 4). The software is written in LabVIEW 2012 and utilizes NI CompactDAQ as interface for the control of the motors.

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[1] For the soil in sample 3, lumps of sedimented clay and silt were mechanically crushed from gravel and stone size to soil <10 mm.

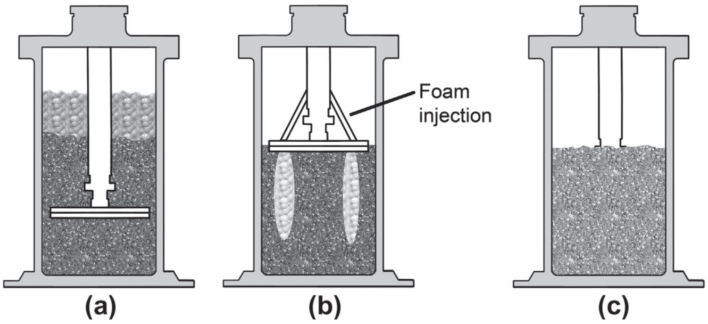
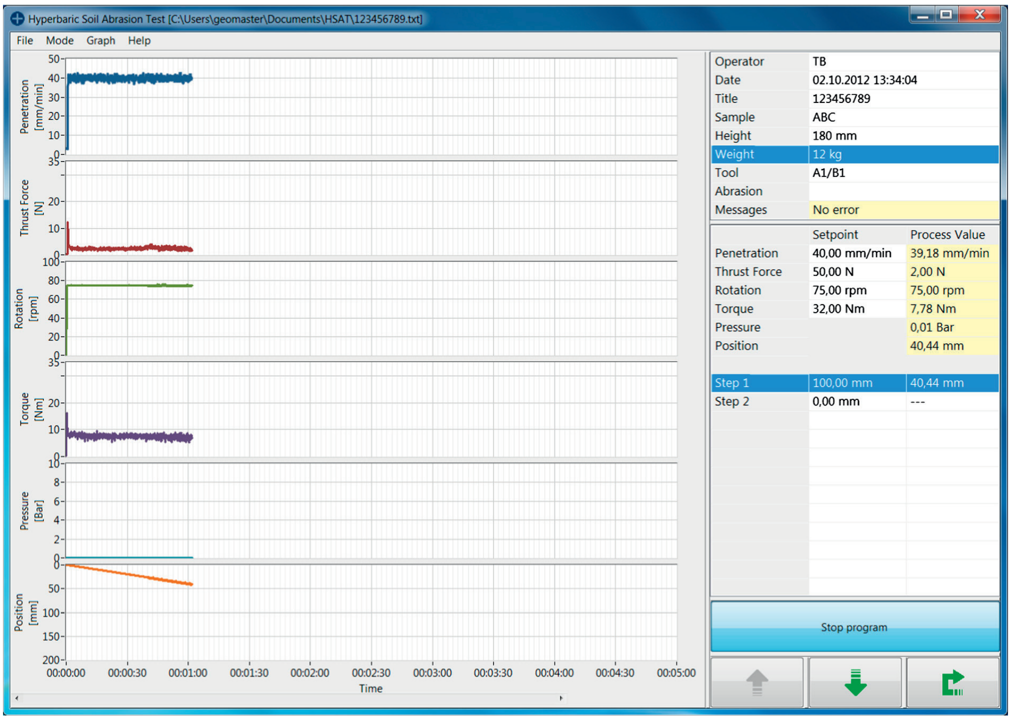


Fig. 3. Overview of possibilities to add soil conditioning additives in the SGAT apparatus. (a) Shows addition of foam on top of the soil sample, (b) shows a continuous addition of foam through nozzles, and (c) shows a premix of foam and the soil sample).



Operator	TB
Date	02.10.2012 13:34:04
Title	123456789
Sample	ABC
Height	180 mm
Weight	12 kg
Tool	A1/B1
Abrasion	
Messages	No error

	Setpoint	Process Value
Penetration	40,00 mm/min	39,18 mm/min
Thrust Force	50,00 N	2,00 N
Rotation	75,00 rpm	75,00 rpm
Torque	32,00 Nm	7,78 Nm
Pressure		0,01 Bar
Position		40,44 mm
Step 1	100,00 mm	40,44 mm
Step 2	0,00 mm	---

Fig. 4. Screen view of the SGAT operational and data collection software.

Table 2
Mineralogy of the soil sample obtained by X-ray diffraction (XRD), and measured abrasivity with the Soil Abrasion Test™.

	Soil sample 1	Soil sample 2	Soil sample 3
Quartz (%)	44	42	76
Mica (%)	18	<1	16
Plagioclase (%)	15	36	NA
Chlorite (%)	12	6	NA
Kali-feldspar (%)	5	15	NA
Amphibolite (%)	3	NA	NA
Calcite (%)	3	NA	7
Albite	NA	NA	<1
SAT™ value	26 (high)	23.5 (high)	6.5 (low)

Table 3
Example of influence of soil compaction and density on wear and torque for Soil sample 1.

Density (kg/m^3)	Compaction proc.	Wear (mg)	Avg. torque (Nm)
1544	No compaction	52	8.7
1886	5 Blows/4 layers	82	10.7
1958	10 Blows/4 layers	75	11.2
2058	15 Blows/4 layers	92	13.2
2109	20 Blows/4 layers	92	11.4
2228	30 Blows/4 layers	115	17.0

Table 4
Comparison of the new SGAT test procedure and the Penn state soil abrasion testing system.

	Soft Ground Abrasion Tester (SGAT)	Penn state soil abrasion (SAI) testing system (personal communication Jamal Rostami September 2012)
Tool design	4 Steel spokes	Propeller blade with var. pitch angle. Standard pitch angle is 10°
Tool steel	Standard construction steel. Vickers hardness 227 ≈ HRC 23 has been used so far to limit the testing time	17, 31, 43, 51 and 60 HRC
Rpm	1–100	60–180 (tested so far)
Length of penetration through the soil sample	Up to 200 mm	Fixed position, with 150 mm soil above and below the propellers
Penetration rate	0–200 mm/min	Not applicable
Thrust force	0–3000 N	Not applicable
Torque variation	0–32 Nm	Not known, but torque is measured
Ambient pressure	Atm – 6 bars (4 bars with cont. foam injection)	Atm – 10 bars
Maximum grain size	10 mm (for consistent and comparable results)	Published results include D_{50} ranging from 0.5 to 7 mm (Rostami et al., 2012a,b)
Soil compaction	Manually by proctor hammer prior to testing. Compaction as desired.	Not applicable (compaction under the propeller blade during the test)
Addition of soil conditioners	Continuous addition through the drilling tool	Premix and continuous addition through pre-installed ports

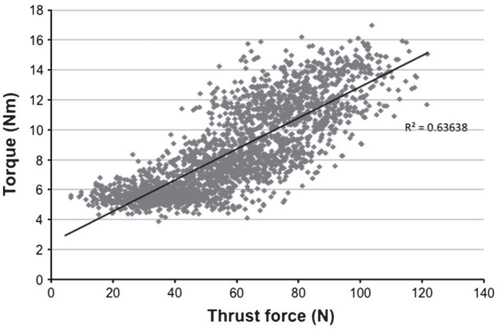


Fig. 5. Example of relation between thrust force and required torque for achieving a fixed penetration of 40 mm/min for one soil sample.

The continuous data collection enables the analyst to find how varying operation parameters influence each other. Fig. 5 shows an example of thrust force and torque correlated in the SGAT software.

3. Initial test results

The initial results are obtained by testing a soil sample with grain size between 0 and 6.4 mm (Fig. 7), a soil from an ongoing European soft ground TBM project and a soil originating from an upcoming soft ground project in Asia. As reference, Soil Abrasion Test™, mineralogy by XRD and grain size distribution analyses have been performed in addition to the SGAT values, see Table 2 for sample mineralogy and SAT™ values.

In the initial testing scheme, some SEM images have been taken, in order to show the degradation mechanisms on the steel's microstructure. Fig. 8 shows abrasive wear, and Fig. 9 shows tribo-corrosive wear, which is a synergy of abrasive wear and corrosive wear. There has been observed degradation in the micro-structure due to corrosion in short tests (Grødal et al., 2012). The SEM photos showed in Figs. 7 and 8 originates from SGAT tests with a 40 min duration. The corrosive effect has not been possible to detect quantitatively by weight loss, meaning that the SEM photos are the only evidence to show the effect (Grødal et al., 2012).

Observations and explanations on how the soil compaction/density, pressure, and introduction of soil conditioning additives influences the abrasivity and torque measurements are presented in the following.

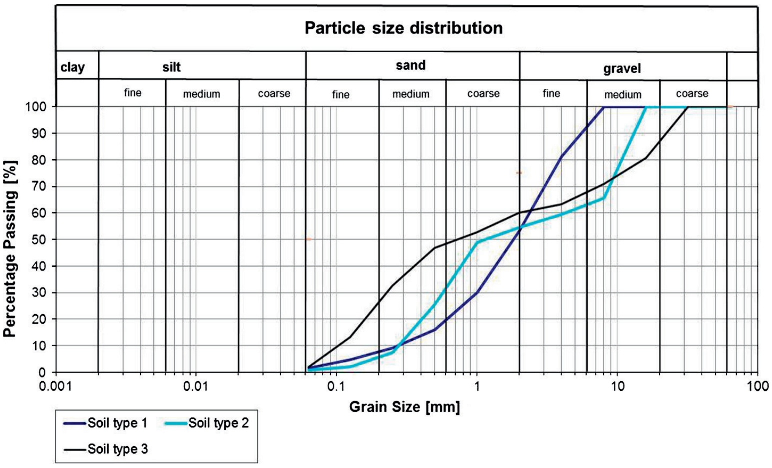


Fig. 6. The grain size distribution of Soil samples 1, 2 and 3.

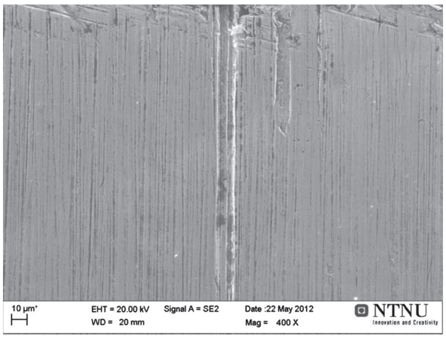


Fig. 7. SEM image showing abrasive wear on the SGAT tool steel after exposure to a dry soil sample. The photo is of the lower steel bar on the SGAT tool (photo Christian Kreyberg Grødal).

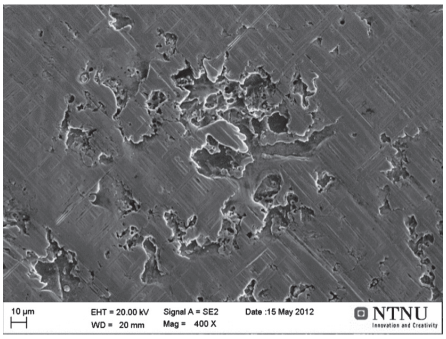


Fig. 8. SEM image showing a combination of abrasive wear and corrosion on the SGAT steel tool after exposure to a soil sample with 8 weight% water. The photo is of the lower steel bar on the SGAT tool (photo Christian Kreyberg Grødal).

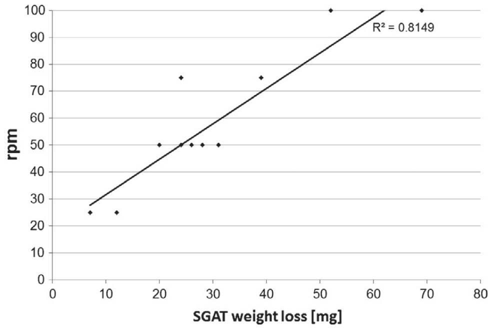


Fig. 9. Recorded influence of rpm on the SGAT weight loss for sample 3.

3.1. Influence of different soil compaction

The influence of compaction on tool life and torque has been measured on Soil sample 1. A proctor hammer has been used to compact the tested soil samples. The varying grade of compaction has been achieved by varying the number of applied blows.

The results summarized in Table 3 are based on a rotation speed of 50 rpm, a varying torque, 200 mm vertical travel length and 40 mm/min penetration rate of the drilling tool and 5 weight% water content in the soil sample.

3.2. Influence of rpm

The influence of rpm on the recorded wear by SGAT has been evaluated on Soil sample 3, see Fig. 9. The testing conditions are fixed at 40 mm/min penetration and 9% water content. The figure also illustrates the variation of test results at identical soil conditions, which seems to increase with increasing rpm.

3.3. Influence of earth pressure mode

In order to simulate the face pressure system at shielded TBMs, the test procedure allows running tests in pressurized mode. The pressurized mode utilizing air which is applied through a valve in the lid of the test chamber. A series of tests have been conducted by adding an over-pressure from atmospheric conditions to 5 bars. The rotation speed of the drilling tool was 50 rpm, with a varying torque, 400 mm total vertical travel length (200 mm downwards and 200 mm upwards) of the drilling tool, and 5-weight% water content in the soil sample. The up and down movement was performed in order to evaluate the pressure's possible influence on direction inside the test chamber.

The weight loss (wear) at different pressures is presented for the lower steel bar (test piece A in Fig. 10) and the upper steel bar (test piece B), as well as the total weight loss in Fig. 10.

The findings in Fig. 10 corresponds well with the Rostami et al. (2012a,b) findings, which conclude that the amount of additional steel wear due to increased ambient pressure is not significant. However, the findings presented in this paper only take into account a few tests on one single, relatively uncompactable soil sample. It is therefore necessary to conduct further testing to conclude, if hyperbaric pressure influences the wear rate.

The example of the face pressurés influence on the tool wear is based on the relatively single-graded soil lacking fines (sample 1 in Fig. 6). The possible effect of the support pressurés influence on the tool wear will be evaluated for a more compactable soil with water content close to the saturation point, at a later stage.

3.4. Influence of moisture and soil conditioning additives

The development of soil abrasivity for various moisture contents, when exposing the SGAT drilling tool to 1000 mm drilling, 50 rpm and 100 mm/min penetration speed, with stepwise drilling (50, 100, 150 and 200 mm) has been evaluated by Jakobsen et al. (2012). The stepwise drilling involves 50 mm drilling down, 50 mm retraction, 100 mm drilling down, 100 mm retraction, etc., until the 200 mm depth is reached and retracted. The stepwise drilling was used in 2012, in order to mix the soil conditioning additives with the soil, prior to the development of continuous conditioning (Jakobsen et al., 2012). For comparison the same development has also been evaluated for 400 mm drilling length, 50 rpm and 40 mm/min penetration speed. Fig. 11 shows the influence and importance of moisture content on the measured weight loss and torque on the SGAT.

The development of abrasiveness for varying water contents (Figs. 11 and 12) corresponds well with Rostami et al. (2012a,b) tests on the Penn state abrasion testing system. The increase of water content has previously showed a general increase of wear by using the Ball Mill Test. (Jakobsen et al., 2009) and (Klemetsrud, 2008). However, the reduction of wear after reaching a specific water content has not been observed previously with the Ball Mill test.

The Norwegian Geotechnical Institute (NGI) performed a study on soil compactibility, dependent on different moisture contents in the early 1980s in order to evaluate the tightness of rock fill dams (Damgruppen, 1983). The main conclusions of this study were that

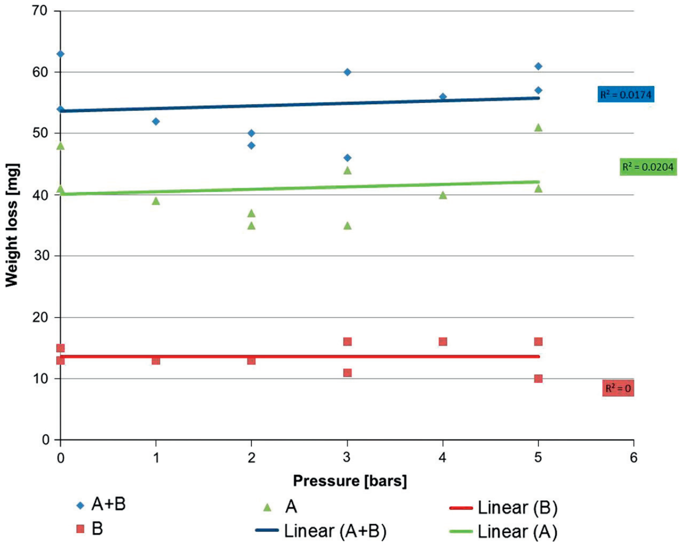


Fig. 10. Example of relation between weight loss (abrasion) and face support pressure (bars) for Soil sample 1.

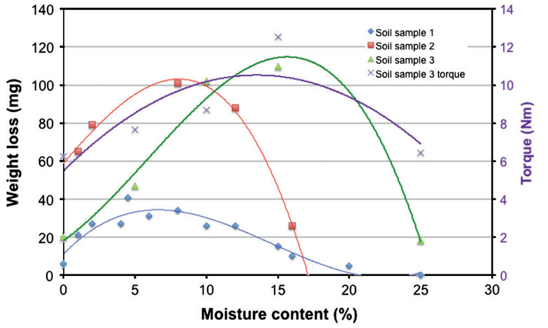


Fig. 11. Example of soil abrasivity development for various moisture contents with the same compaction procedure (5 blows with the proctor hammer in 4 layers). The graph also presents the development of torque for Soil sample 3 with different moisture contents.

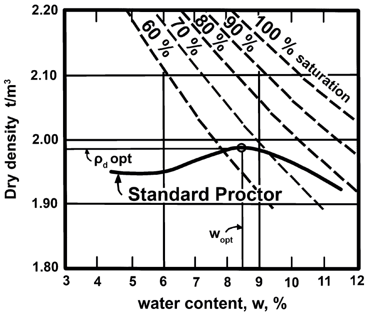


Fig. 12. Compaction curves from a natural moraine (Damgruppen, 1983).

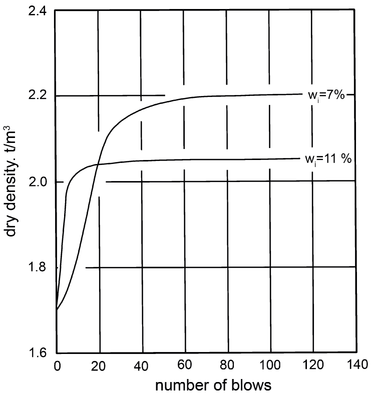


Fig. 13. Influence of the compression work on soil density. Relatively low water content gives a higher density. For higher water contents pores will be easier to close with less compression work (Damgruppen, 1983).

the dry density obtained by compaction is highly influenced on the water content in the soil sample. Single grains have a high strength if the soil is relatively dry. This makes it impossible to fill voids between the hard lumps. Thus, the dry density is relatively low. If the water content is increased, the soil gets more plastic and during the compaction the voids will be closed, resulting in a higher density (Damgruppen, 1983). This finding can explain the influence of water content on soil density, and thus the soil's potential to cause abrasive wear on an excavation tool. See Fig. 12 for density development related to water content and saturation, and Fig. 13 for the influence of compaction work on soil density.

An evaluation of the possible benefits by adding soil conditioning additives was carried out. The additives were added as (a) foam on top at the soil sample or (b) as a continuous foam injection through small foam injection nozzles 2 cm behind the drilling tool. Initially a pre-mix of soil conditioning additives and soil had been tried, but the results from this approach were discarded as the sample rheology deviated from the reality in front of a TBM.

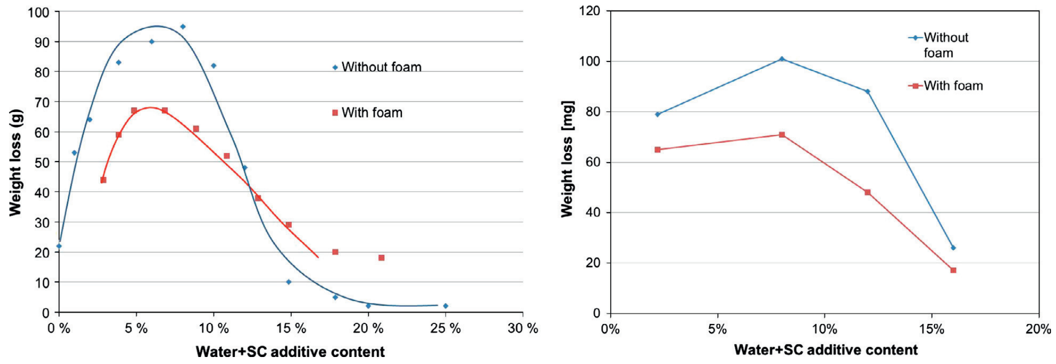


Fig. 14. Soil abrasivity development for conditioned soils. Left figure shows a soil from a natural deposit close to Trondhein, and Right shows results on a soil sample originating from a tunneling project in Europe (Jakobsen et al., 2012).

3.4.1. Tests with foam addition on the top of the sample (testing condition a)

The results presented in Fig. 14 shows that adding foam on the top of the soil sample reduces the weight loss of the drilling tool, as well as the torque. It was however discovered that the foam did not properly mix with the bottom part of the soil sample. This might indicate a too high Foam Injection Rate (FIR) in the upper part of the soil sample and a non-existing conditioning of the lower part of the soil sample. The densities of the two soils presented in Fig. 13 are approximately 2100 and 1900 kg/m^3, and the results do not have torque measurements. The tests were done in atmospheric pressure conditions with foam expansion ratio (FER) of 10 and foam injection ratio (FIR) of 30%. The results shown in Fig. 14 are obtained on moisted soil sample prior to testing.

The results obtained by foam addition on the top of the sample seem to indicate benefits of soil condition, in terms of reduced wear and torque. However, the upper part of the soil sample is likely to be over-conditioned, while the lower part remains under-conditioned to unconditioned. Quantification of varying grades of soil conditioning, subsequently the test is not done. However, in all the conducted tests, it appears that the top of the soil sample (10 cm) is over-conditioned and the lower part of the soil sample is gradually exposed to less soil conditioning additives. This effect will again not correctly indicate the effects and benefits of soil conditioning agents.

3.4.2. Continuous foam injection (test condition b)

In order to achieve a proper continuous foam injection and hence an evenly conditioned soil sample, a total of three different tool designs have been evaluated. So far, the most successful tool design is shown in Fig. 2. Prior to the design showed in Fig. 2, ejection of soil conditioning additives was tried from pipes 1 and 4 cm behind the lower steel bar. The results achieved by running tests with continuous soil conditioning are shown in Figs. 15 and 16.

Fig. 15 repeats the indication of the strong relation between moisture content and wear, and shows the high influence of soil conditioning additives injection rate. In the example showed in Fig. 16, the wear is reduced down to less than 20% of the initial value dependent on the moisture content. The torque and thrust were reduced by more than 30% for the fixed penetration rate of 40 mm/min, on Soil sample 3 with 15% water.

Several techniques have been evaluated for the continuous addition of soil conditioning additives into the soil. The first attempt was based on foam injection through two holes at the SGAT drill-shaft about 5 cm above the drilling tool. The second version used foam injection through the upper drilling tool (part B), whereas the final and currently used version (Fig. 4b) uses a foam nozzle at the level of the lower drilling tool (part A) which is in contact with the compacted soil – directly corresponding with the foam injection at the TBM cutterhead. Only this modification, by being able to apply the additives exactly at the contact zone between the drilling tool and the compacted (virgin) soil, allows SGAT test results to be directly translated to effects in EPB TBM tunneling.

In Fig. 15 the strong influence on wear by the soil's water content can be observed together with the influence of continuous foam injection. Further testing in this manner needs to be carried

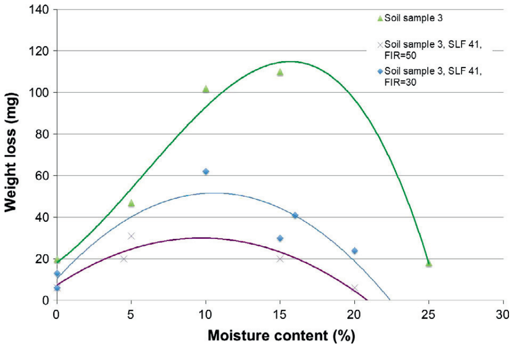


Fig. 15. Example of soil abrasivity development for Soil sample 3 for different moisture contents, and the influence of the foam injection ratio (FIR).

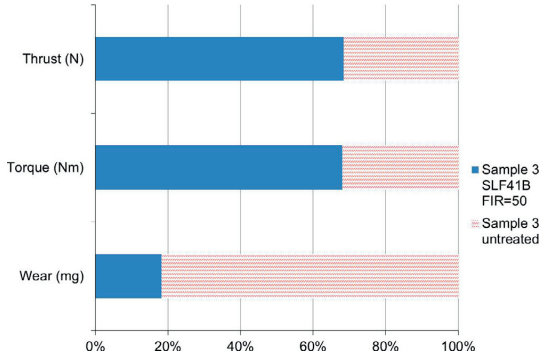


Fig. 16. Example of the influence of proper soil conditioning for Soil sample 3. The wear is reduced to approximately 1/5, and the torque and thrust to approximately 2/3 of the untreated soil.

out, in order to find “good” and “bad” soil conditioning for various soft ground samples.

3.4.3. Premix of soil and soil conditioning additive (test condition c)

In order to evaluate the possibility of premixing soil samples with soil conditioning additives some trial tests have been conducted with FER 10 and FIR of 50%. The tests were conducted with rotation speed of 50 rpm and with a total of 400 mm vertical movement of the drilling tool (200 mm downwards and 200 mm retraction upwards). A small concrete mixer was used to make the premix of soil and soil conditioning additives.

The results obtained by testing a premix of soil and soil conditioning additives do not show the reality between soft ground excavation tools and the conditioned soil, as the recorded weight loss and torque are very low, and in the same range as what is expected for dry testing. For Soil sample 1 the weight loss ranged from 5 to 7 mg and the torque from 6 to 7 Nm in premixed soil and soil conditioning additives. Therefore, the reduced torque and wear is not relevant for TBM tool life research or other phenomena taking place at the cutterhead level. However, these results can only be relevant for estimating the conditions in the EPB TBM working chamber behind the TBM cutterhead.

In order to evaluate the influence of soil conditioning additives correctly, their introduction technique is of high importance. The only way to obtain comparable results to the TBM cutterhead situation is using a continuous injection of soil conditioners at the cutterhead tool which is penetrating into a consolidated ground.

4. Discussion

4.1. General

The ambition and purpose of the design of the test and the applied test procedure is to replicate an in situ soil – TBM tool contact, in a small and simplified scale. The drilling tool was designed in a way which is causing a relative small area of initial contact between the tool and the soil.

The main differences between the SGAT and the existing Penn state soil abrasion testing system are the design of the drilling tool, the rotation speed and penetration of the tool and the possibilities to introduce soil conditioning additives (e.g. foam or bentonite) during the test. The new Soft Ground Abrasion Tester (SGAT) does in addition allow testing of soil samples with a defined compaction. Table 3 shows the similarities and differences between the SGAT and Penn state soil abrasion testing system.

The SGAT apparatus has the possibility of drilling through soil and soft ground samples, hence close to real TBM conditions in soft ground.

The limitation of the presented SGAT test procedure as compared to the real life TBM boring process consists mainly in the limit of the soils grain size. The current tool allows 10 mm large grains to be included in the soil sample. Thus, grains above 10 mm need to be removed from the soil sample material prior to testing with the current drilling tool design. The limitation will not be substantial, as the test is designed to test soft ground conditions. However, in soils containing large amount of gravels and stones, the current test may not be equally suitable.

Our analysis finds the test to be torque sensitive of the position of the drilling tool, indicating an increasing soil compaction towards the bottom. This effect is most likely induced by the layered Proctor hammer compaction procedure.

Equally, we find a clear relation between the measured tool wear and the required torque, as well as increasing tool wear by increasing rpm. As the torque increases, the contact forces between the steel tool and soil increases, causing a higher potential for degradation of the steel. The torque has also proven to show grain size variations in the soil sample quite well. A limitation in the torque measurement is an uneven compaction through the soil sample. The lowest part of the sample probably has a higher compaction than the upper part, due to the layered compaction procedure.

4.2. Test relevance and repeatability

The SGAT apparatus still lacks of a detailed test procedure intended for commercial use. The test procedure presented in this paper is preliminary, and might be changed as more data are measured and compared to real torque, thrust and tool life data from TBMs. The test apparatus is designed to evaluate several variables influence on abrasive wear and torque. Thus, the test procedure should be decided prior to testing of a new batch of sample material, based on what the test results should show or not.

In order to quantify the reliability a total of 10 tests on Soil sample 1 with 10% water content, 50 rpm and 40 mm/min penetration were carried out. The standard deviation of these tests were 6.3, which is acceptable taking into account the sources of errors present in testing of geo material with possible varying distribution of water content and compaction.

For assessing the validity of the automatic torque and thrust recording, manually measurements with a scale and torque wrench have been carried out. The findings in Fig. 17 show that there are not any inconsistency between the collected thrust and torque values in the SGAT apparatus.

A few relations between SAT™ values and SGAT values are shown in Fig. 18. The measured Soil Abrasion Test™ (SAT) values do not range in accordance with measured wear on the Soft Ground Abrasion Tester (SGAT), Soil sample 3 has the lowest SAT

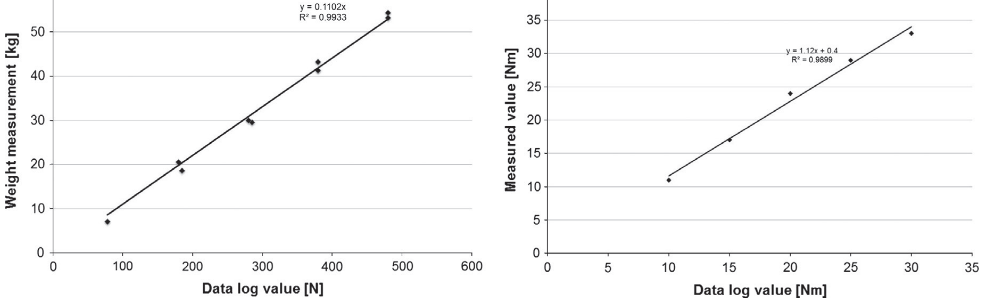


Fig. 17. Relation between data log values and measured values for torque and thrust on the SGAT apparatus.

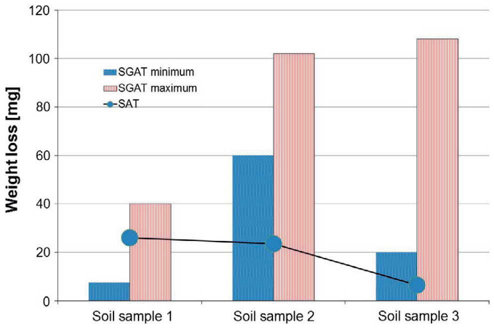


Fig. 18. Relations between SAT™ values and weight loss measured on the SGAT apparatus.

value and the highest measured SGAT wear. The main reasons for this are most likely related to the influence of compaction and soil humidity, which are not taken into account by the SAT™, as well as mineralogy of Soil sample 3, consisting of fines consisting of low-abrasive minerals mica and calcite, with coarser particles consisting of quartz. It is believed that the fines creates a cohesive paste holding the coarser abrasives, causing the high weight loss. The SGAT findings has also shown that a calculation of a more reliable wear index could be achieved by combining the measured SAT™ values with factors for in situ soft ground properties, like humidity and compaction.

4.3. Suggestions for further work

The initial testing of the SGAT apparatus and method comprises only three soil samples. In order to gain more experience and knowledge on how various soil types (clay, silt, sand and gravel) behave when they are exposed to various compaction grades, use of soil conditioning additives and pressure, there is a need for further testing.

For pressurized testing conditions, the tests presented in this paper are conducted on 5% water content. This is relatively far from reality as most pressurized TBM performances are below the ground water table. Further testing on more soil types and with water content close to the saturation point is therefore needed.

The apparatus enables a unique testing procedure being very close to the excavation conditions at a real TBM. The test results obtained with the SGAT apparatus is, however, so far not correlated or validated against any real TBM excavation. This needs to be done in order to evaluate the scaling effect between the SGAT apparatus and a real EPB TBM. Such a study will also comprise an evaluation of the necessity and relevance of distinguishing between primary and secondary wear on SGAT test pieces.

In order to evaluate the relation between SAT™ and SGAT values, more testing is needed. The authors are currently working on a SAT™ based estimate on tool life, where the SAT™ values are adjusted with other relevant geotechnical values.

In this current paper, the soil rheology is missing. Generally it should be evaluated in connection with pre-investigation and evaluations of soil conditioning additives. For the further research on the SGAT apparatus, we will therefore initiate to run flow table mortar testing according to EN 413-2 and EN 459-2 in order to check the conditioned soils rheology for EPB TBM applicability.

5. Conclusions

The set-up and design of the apparatus has the capability to evaluate how soft ground abrasivity is influenced by water content, pressure, compaction and soil density. In addition, the important influence of different types of soil conditioning additives can be evaluated.

The initial results presented and discussed in this paper are very promising for evaluating various geotechnical parameters' influence on soft ground abrasivity. The TBM operation's influence on tool wear can also be evaluated by adjusting the apparatus rpm, penetration rate, thrust and soil conditioning parameters (Foam Expansion Rate (FER) and Foam Injection Rate (FIR)).

5.1. Main findings

- Wear on steel excavating soft ground in the new SGAT apparatus is clearly influenced by
  - The nature of the soil (e.g. mineralogy, quartz content, abrasiveness, grain size distribution, compaction).
  - The moisture of the soil influences the wear (weight loss) as high as 500%.
  - Type and method of soil conditioning (soil conditioning type, FER, FIR) can reduce the wear rate down to 20% of the unconditioned sample.
- The pressure added to the test chamber did not show any significant influence on the measured soft ground abrasivity for the soil material with 5% moisture content used in this initial research.
- There is a clear correlation between the measured wear and the recorded torque, as well as rpm by the SGAT apparatus.
- The correct use of soil conditioning additives, apart from the above mentioned wear reduction, has clear effects on
  - Reduction of torque by approximately 40% in some cases.
  - Reduction of necessary SGAT penetration thrust by approximately 40% in some cases.
- Furthermore, the differences between "good or bad" soil conditioning can now be quantified, and results from the SGAT apparatus can be used to evaluate and to improve the effect of soil conditioning additives.

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Paper 10

Anti-wear and anti-dust solutions for hard rock TBMs

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World Tunnelling Congress, Vancouver 2010

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Anti-wear and anti-dust solutions for hard rock TBMs

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1. Introduction

Abrasive wear on cutter tools and high levels of dust are common processes causing problems in hard rock TBM tunneling. Wear and damage on cutter tools are mainly caused by crushed rock powder in the cutter grooves and from falling rock from the tunnel face. Wear rates on cutter tools are also observed to increase when boring without water, most likely because of high temperatures and inability to remove fines in the cutter grooves [1]. To cope with abrasive wear from fines, dust suspension and high temperatures, one approach can be utilization of chemicals. The use of water, water based agents or foam on hard rock tunnel boring machines is not new technology, and dates back to 1973 and earlier. They were or are still used, more or less successfully, in order to reduce the amount of dust and to reduce the dust-related problems.

2. State of the Art Methods

2.1. Wear Reduction

Improved performance of cutters is an area of continued research with substantial improvements made over the past fifty years. Recent research has addressed multiple facets of cutter design with cutter life being an important design objective. Some examples of areas that are evaluated with respect to cutter life are the cutterhead profile, cutter tip profile and cutter metallurgy. The number of cutters changed versus their positions is tracked, with a higher rate of wear being seen at the positions where face cutters transition to gage cutters. This reduction in cutter life in the transition region is due to an increase in both the rate of cutter ring wear and the number of blocked cutters that occur in the region. The area has been shown through the use of strain gauges to have higher loading than face cutters with a comparable spacing. Cutterhead design has evolved over time using tests and experience to refine position and mounting to extend cutter life.

A second area that has been developed to deliver performance while providing a good service life is the cutter profile. The tip width is chosen to give good penetration into the rock while still providing sufficient strength to maintain the integrity of the rings and minimize edge chipping, which is seen on the high cutter loading of modern machines. Cutter metallurgy is also used to combat this issue, with many different steels being used over time. Disc rings were historically made from bearing quality steels. Robbins cutters are made of steel with a proprietary chemistry and hardening process that has been progressively refined to provide higher hardness without the loss of fracture toughness, thereby minimizing chipping.

2.2 Dust Reduction

Dust is an inherent part of tunneling in rock. New regulations in many countries highlight the need to control airborne dust, with specific focus on quartz-containing dust. Dust is currently controlled in two different ways on a TBM. First, it is captured at point of origin to limit excessive airborne particles at the face of the tunnel. Second, water is brought to the face through a rotary union, where it is distributed to equally-spaced spray nozzles on the face of the cutterhead. As the rock is cut the water spray captures the dust and removes it through the mucking system. Water spray bars may also be installed at dust producing areas, such as conveyor transition points on the backup, and in the muck car loading area. Once the dust becomes airborne it is removed though the use of a dust scrubber. Again this is done primarily in the area of the cutterhead. Large fans pull the dust-laden air through ducting to a dust scrubber located on the back up. Fresh air is brought forward to help replace the air that is removed. The scrubber can be either a wet scrubber, which again uses a water spray to capture and remove the airborne dust, or a dry scrubber that forces the air though a series of filters. In both cases the captured dust is added back to the muck stream and removed from of the tunnel.

The following methods are of special interest [2]:
- Water sprays: wetting and airborne capture
Of the two, wetting of the broken material is far more effective. Adequate wetting is extremely important for dust control. The vast majority of dust particles created during breakage are not released into the air, but stay attached to the surface of the broken material [3]. Wetting this broken material ensures that the dust particles stay attached. As a result, adding more water can usually (but not always) be counted on to reduce dust [4,5,6].
- Water additives: foam and wetting agents
For dust control, foam works better than water. It provides dust reductions of 20% to 60% compared to water. Foam also can produce similar results at lower water use. The amount of water needed to make the foam is less than the equivalent water spray. High-expansion foam, when compared to water sprays at a belt transfer point, averaged an additional 30% dust reduction [7]. Foam released from a longwall shearer drum cut the dust an additional 50% compared to conventional water sprays on the drum [8]. Also, the system used one-half the water of the conventional sprays. The drawback of the foam was high cost. Like water, foam works best when it is mechanically mixed with the broken material. A comprehensive review of foam for dust control in mining and minerals processing has been given [9].
Wetting agents receive a disproportionate amount of attention, perhaps because they seem to offer an easy fix to dust problems. Most of the interest has been in coal mining because of the hydrophobic nature of coal. The effectiveness of wetting agents has been the subject of considerable research over the years, without much of a definitive answer on how well they work.

3. The use of Foams and Polymers

BASF has taken a fresh view on the use of foam on hard rock TBMs, believing that its use can be much more effective than the common water sprays and also more (cost) effective than described above. The effectiveness of foam strongly depends on the way the foam is generated and on how it is used – improvements can be made here. Furthermore, a possible incorporation of anti-wear-additives into the foams or the development of foamable polymers represents an interesting dual role for the new additives. The increase of dust catching effectiveness together with their new anti-wear-capacities will reduce the above mentioned high cost draw-back of the use of these additives.

3.1. Laboratory Results and Interpretation on Construction Time and Wear

Imitations of the process of hard rock drilling with TBMs have been tried by several universities and researchers. Two of the most common methodologies for imitation of hard rock TBM tunneling with respect to advance rate, cutter consumption and cost estimates are the NTNU method consisting of the Drilling Rate Index (DRI™) and Cutter Life Index (CLI™), and the Colorado School of Mine's method based on individual cutter forces to determine drilling advance[10]. In addition the Cerchar Abrasivity Index (CAI) is recognized as a quick measure on a rock's abrasivity and expected cutter consumption on TBMs.
The NTNU model is based on empirical relations between rock parameters obtained from laboratory and field, such as DRI™, CLI™, porosity, fracture class, quartz content and TBM parameters [11]. The empirical relations are established with a basis of 30 different tunnels (250 km) with respective TBM production data and wear records on cutter tools. It has been tried to use the NTNU model to check theoretically how the use of anti abrasive agents influence advance rate, cutter consumption and relative tunneling cost.

The DRI™ is based on the rock's brittleness and surface hardness, and the CLI™ is based on the surface hardness and abrasion properties of the rock type. The brittleness value is evaluated in an apparatus which is based on 20 stroking impacts on a known fraction of a rock sample. After the impacts, the percentage of the crushed down rock represents the measured brittleness value. The surface hardness measure is obtained by the Siever's J apparatus, which drills miniature holes in a rock sample. The depth of these holes is the surface hardness measure.
The final rock property needed to be established before calculation of DRI™ and CLI™ is the abrasion. The NTNU model uses an in-house built apparatus consisting of a rotating steel disc applied with crushed rock powder or soil. The soil or rock powder has to pass a cutter ring piece, which causes a measureable weight loss - the result of which is our abrasion value. The abrasion apparatus was used to measure reduction of abrasion by introducing the MEYCO ABR5 anti-abrasion agent on one rock sample from Lötschberg in Switzerland and one rock sample from the AMRII project in India. Results and classification of results are showed in Table 1. The use of additives influences the abrasion test and subsequently the CLI™, whilst brittleness values and surface hardness properties are the same with and without additives.

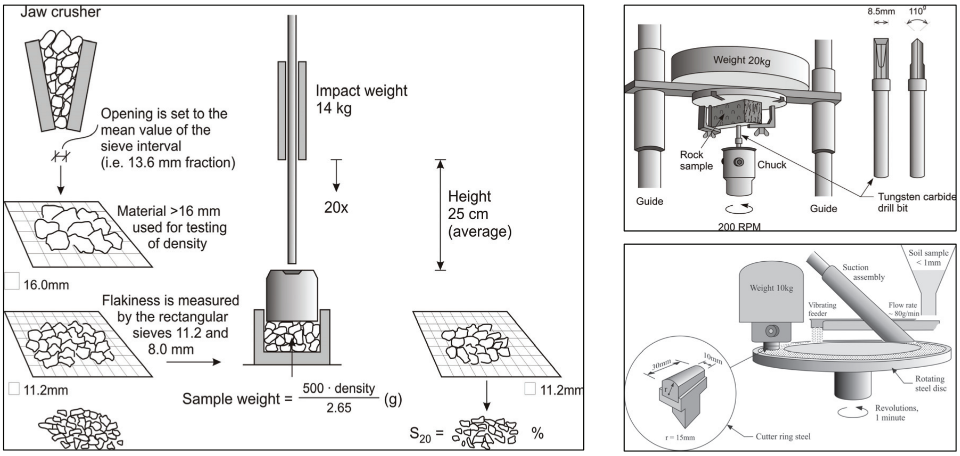
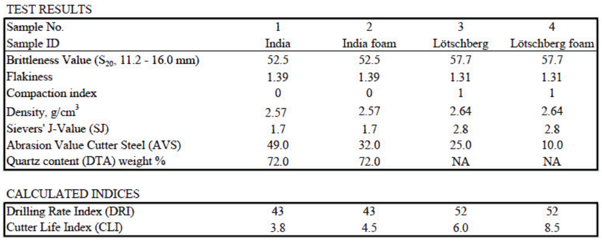


Figure 1. Schematic introduction of brittleness testing (left), Sievers J (top right) and abrasion testing (bottom right).

For further and detailed description of laboratory test procedures and pictures needed for the NTNU model please refer to http://www.drillability.com.

Table 1. Drillabillity indicies and classification for evaluated rock samples.

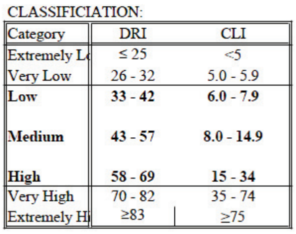


TEST RESULTS

Sample No.	1	2	3	4
Sample ID	India	India foam	Lötschberg	Lötschberg foam
Brittleness Value (S_{20}, 11.2 - 16.0 mm)	52.5	52.5	57.7	57.7
Flakiness	1.39	1.39	1.31	1.31
Compaction index	0	0	1	1
Density, g/cm^3	2.57	2.57	2.64	2.64
Sievers' J-Value (SJ)	1.7	1.7	2.8	2.8
Abrasion Value Cutter Steel (AVS)	49.0	32.0	25.0	10.0
Quartz content (DTA) weight %	72.0	72.0	NA	NA

CALCULATED INDICES

Drilling Rate Index (DRI)	43	43	52	52
Cutter Life Index (CLI)	3.8	4.5	6.0	8.5



CLASSIFICIATION:

Category	DRI	CLI
Extremely L	≤ 25	<5
Very Low	26 - 32	5.0 - 5.9
Low	**33 - 42**	**6.0 - 7.9**
Medium	**43 - 57**	**8.0 - 14.9**
High	**58 - 69**	**15 - 34**
Very High	70 - 82	35 - 74
Extremely Hi	≥83	≥75

The NTNU advance rate, cost and cutter consumption model have been used in order to go one further level in the evaluation of ABR5. The evaluation has been done with a software called fullprof which is provide quick estimates of the NTNU model [12]. The summary of the estimation is showed in Figure 2, and the estimation indicates an increase of weekly advance rates and increased cutter life.

The input parameters are drillability indices as presented in Table 1, with rock mass classification I, which is equal to average spacing of 80 cm between fissures and joint system in the rock mass. To excavate the Lötschberg rock it is assumed a hard rock gripper TBM with 51 cutters of 19 inches and average cutter thrust of 260 kN per cutter. For the excavation of India rock it is assumed a hard rock gripper TBM with 67 cutters of 19 inches and 312 kN per cutter in average thrust.

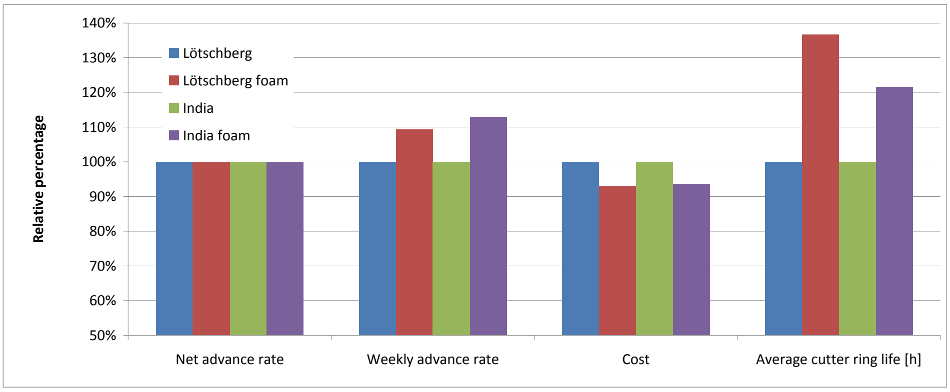


Figure 2. Relative comparison of estimated advance rate, cost and cutter ring life.

3.2. Site Example No1: Guadarrama High Speed Rail Tunnel, Spain

The Guadarrama tunnels belong to the new high speed railway link between Madrid and Oviedo. For this project the Guadarrama mountains between Madrid and Valladolid had to be crossed with a 28.400m twin tube hard rock tunnel. Totally 4 TBMs – 2 Herrenknecht and 2 Wirth – were used and finished boring in June 2005.

characteristics Wirth TBM:
diameter: 9,46m; total installed power: 5.600 kW; cutterhead torque: 27.000 kNm
characteristics Herrenknecht TBM:
diameter: 9,51m; total installed power: 5.500 kW; cutterhead torque: 20.000 kNm

3.2.1. Project description

The geology along the alignment showed 85% metamorphic and igneous rock, 10% weathered rock conditions as well as various fault zones. The 620m long Umbria fault with nearly loose ground conditions represents the longest of its kind, several others last for 10-20m only – leading to a double shield TBM concept.

Nevertheless, the intact granite sections showed UCS values of up to 280 MPa, in addition containing quartz contents of up to 80%. This resulted in measured Cerchar Abrasivity Index values between 5 and 6, classified as extremely abrasive to quartzitic.

In light of these predictions, the JV decided to consider the possibility of using anti-wear-additives and to evaluate their benefits on-site. In order to use these anti-wear-additives efficiently, the TBM needs to be adapted to their use.

3.2.2. Necessary adoption of the TBM

The MEYCO ABR 5 anti-wear-additive must be supplied to the cutter head as foam. In consequence, it requires some modifications of the TBM and additional installation:

- Foam System

A foam system is necessary in order to foam up the anti-wear-agent. Similar to the foam systems used on Earth Pressure Balance (EPB) TBMs, the following components are mandatory to be

installed: water (supplied by water booster pump), dosing pump (for the correct dilution of the anti-abrasion-agent into the water), compressed air, foam guns (which create the foam out of compressed air and the foaming solution) and a regulation system for each foam gun.
Unlike the fully computerised versions on the EPB TBMs, the system installed on the hard rock TBM was manually operated due to lower investment costs and quite steady output values.

- Foam nozzles
The foam has to be injected through special designed foam nozzles on the TBM cutterhead. The existing water sprinkler nozzles as standard equipment on the cutterhead will destroy the foam and must be replaced. In the case of the 9,5m diameter Guadarrama TBM, the above indicated 5 injection points on the cutterhead have been chosen to be changed into foam injection points in order to ensure a homogeneous and even foam distribution on the cutterhead.

- Rotary coupling (rotary swivel)
The normally installed water splitter box cannot be used for the anti-wear-additives. Only the installation of a rotary coupling ensures specific outputs per foam injection point representing a key factor for the successful use of the anti-wear-additives.

Generally, existing hard rock machines can be upgraded to the use of modern anti-dust and anti-wear-additives. Nevertheless it is strongly recommended to study especially the installation of the rotary coupling during the TBM design stage, reducing considerably the later upgrading costs without increasing the total TBM costs significantly.

3.2.3. Site test results

Altogether, some 600 tons of MEYCO ABR 5 anti-wear and anti-dust-agent were used on the Guadarrama High Speed Railway Project in Spain.
The following benefits associated with their use were reported:
- Cutter wear reduction
A wear reduction of > 15 % was achieved, resulting in 25 – 30 hours per month less down time due to less cutter changes. This downtime was then used for additional excavation. Disappearance of blocked cutters using MEYCO ABR 5.
- Clean cutter tools
The rock dust with is created during the boring process, can agglomerate on the disks as shown above when using water. This implicates a time consuming cleaning process before these disks can be changed, there may be the risk of clogging the disk window and last but not least the grinding paste formed by the stone dust & water increases wear. At Guadarrama the use of MEYCO ABR 5 prevented the stone dust from creating this paste and the tools remained clean (see figure 3).

Figure 3. dust agglomeration difference: left side water use, right side MEYCO ABR 5.

- Temperature reduction
The use of MEYCO ABR 5 resulted in a significant temperature decrease from 90 – 150°C to around 70°C, resulting in shorter down time due to less cooling and waiting time.

- Improved muck transfer and a dust free working environment (see Figure 4).

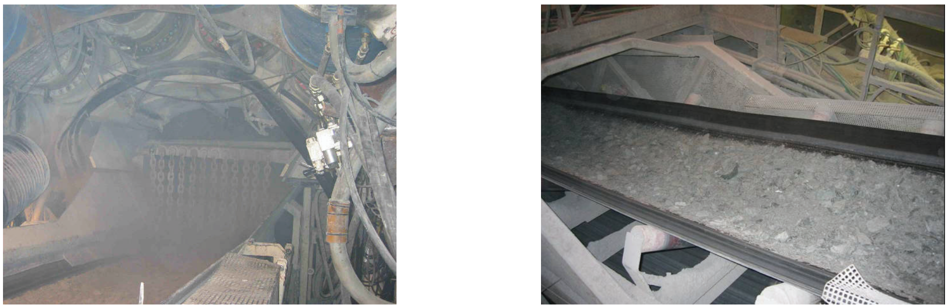


Figure 4. Dust & transport differences: left side water use, right side MEYCO ABR 5.

- Reduction of water usage and less water reclamation

When using MEYCO ABR 5, the amount of injected water was reduced from originally 310 litres/m^3 excavated rock down to 50-100 l/m^3.

Key assumptions made for the following roughly-estimated benefit calculation:
- TBM speed of around 50mm/minute
- monthly advance rate of 500m
- fixed TBM costs around 2000 €/h

With 70.000 € MEYCO ABR 5 monthly product costs it was possible to reduce the wear & maintenance in this case of more than 15%, which can be back-calculated to a reduction of maintenance and material costs higher than 50.000€.

Anti-abrasion-agents are still useful because the reduction of maintenance has not only a direct cost influence but realises also considerable time savings. The 15% of reduced downtime can directly be translated into 80-90m of extra excavation per month – turning the above calculation with an initial loss of 10-20.000€ into final savings of some 40.000€ per month.

In addition, the above quick benefit calculation does not even take into account important benefits such as a nearly dust free environment, more convenient and quicker changing of discs (due to lower temperature and clean discs), drastic reduction of sprinkling water and reduced energy consumption due to less exhausting.

Knowing that these effects do have a significant cost influence in many projects, BASF and Robbins decided to have a deeper and broader look into these parameters by launching a copious on-site test program at the Indian AMR II project.

3.3 Site Example No. 2: AMR II Water Transfer Tunnels, India

3.3.1 Project Description

The Alimineti Madhava Reddy (AMR) Project is a water project located near the city of Hyderabad in Andhra Pradesh, India and is part of a much larger water transportation scheme. The region is one of the most arid in India with only 925 mm of annual rainfall. Local water supplies to 500 area villages are contaminated with fluoride levels that far exceed guidelines. This is being addressed by a system of canals and tunnels, which contains over 100 km of canals and one of the longest TBM driven tunnels ever constructed in India.

There are two main projects emanating from a common reservoir to supply water to four districts in Andhra Pradesh, one of which is the AMR project. The main tunnel will be constructed using two Robbins 10 meter diameter double shielded machines boring from opposite ends. The main tunnel is 43.5 km long and will connect the Srisailam Reservoir to a balancing reservoir on the Dindi River for transfer during the monsoon months. A second 7.3 km long tunnel will then distribute the water to a network of canals to the plains of the Nalgonda District, where it will be used to irrigate farmland and provide potable water to 516 villages.

The geology is generally very stable, as this section of the country is part of the South Indian Peninsular Shield made up of two primary rock types: quartzites and granite. The machines will excavate in both rock types with the quartzite zones having compressive strength up to 450 MPa, and layered with shale for about 60% of the tunnel length. The granite is expected to have a range of 160 to 190 MPa (23-28 ksi) and makes up the remainder of the tunnel. The quartzite sections are of particular concern with respect to cutter cost due to significant abrasiveness and high strength. The quartzite section can also be very blocky in nature, which can increase cutter wear due to the damage caused by impact loading. The Robbins DS325-317 machine will start at the outlet of the tunnel and bore up to meet the DS325-318 machine, which will start at the reservoir at the opposite end. Both machines were delivered in 2007 and the -317 began boring in November of 2007. While the second TBM parts had been delivered, problems encountered in obtaining access to land necessary for commencing excavation of the inlet portal delayed the start of assembly of the -318 machine until June of 2009.

In early October, the assembled machine, located in the assembly portal, was flooded and covered by 10 m of water. Currently efforts are underway to repair the damage so that boring can commence (see Figure 5).

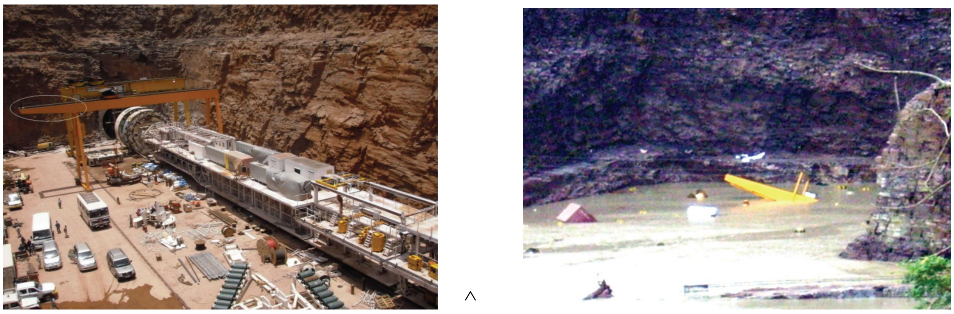

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Figure 5. AMR II Inlet portal before flood (left) and after flood (right).

3.3.2 Necessary Mechanical Changes

The delay in the ability to gain site access to the portal provided the opportunity for required modifications to be made prior to machine assembly, and new systems to be added during the assembly process. The most notable change to the machine was the addition of foam nozzles to the cutter head. Water spray nozzles cannot be used with the foam, as they damage the foam and their locations cannot be modified for use with foam, as the water alone is used as a bench mark. Engineers decided that four new locations would be provided on the cutterhead. The modification required ø200 mm holes through 100 mm of structural plate and hard plating. Mounting plates were then welded into place for the nozzle assemblies. Further modifications to the structure were required to allow for the routing of additional plumbing and the addition of a manifold. The new design provides dedicated passages for each foam location and the existing water spray system through a new five passable rotary union.

3.3.3 Necessary Foam Installation

Similar to the Guadarrama foam installation, also here a manually controlled foam system will be used. Nevertheless, a couple of new features are installed to increase the effectiveness and user friendliness:

- data measurement: the foam system is equipped with magnetic flow meters for water, anti-wear agent and compressed air. This ensures correct data logging without any need of calibration.
- Data display: in order to ensure an easy survey, the flow of water, anti-wear-agent and compressed air is displayed at the dosing unit. The specific flow values for each foam gun are displayed at the generator itself.
- Remote control: the foam system can be switched ON and OFF via remote control from the drivers cabin. If switched on again, the foam system climbs automatically back to the latest installed output quantities. Furthermore, the remote control indicates the function (or non-function) of all main dosing components in order to detect defects as early as possible.

- Foam guns: in order to increase the foam quality of the anti-wear agents, a special foam core design has been developed. The foam quality has got a high influence on the efficiency of the anti-wear agents and their lifetime. This is especially difficult for low expansion ratios.

3.3.4 Additional Data Recording

The -317 machine was provided with a data collection system that captures machine data. This includes date and time of day, cutterhead rotation speed, cutterhead power, start / stop time (i.e. propel pressure greater than X), boring stroke position, penetration rate, thrust pressure and gripper pressure, most of which is applicable in evaluating cutter performance. In addition to existing monitored parameters, additional sensors were added for the testing. To evaluate changes in water use, analog flow meters were provided with the foam generation unit, as well as flow meters to monitor compressed air usage. Additional flow meters were added to the TBM water system to monitor water flow to the cutterhead spray system. The flow meters used in combination with the added dust monitor, are then used to evaluate the effectiveness of the foam product in reducing airbone dust and possibly reducing water usage at the face. The final set of sensors added to the machine is the Robbins Cutter Instrumentation System, which supplies real time vibration data, cutter rpm, and cutter temperature. From this it is possible to infer the rock face condition and how it is affecting cutter operation, as well as the state of cutter wear, without entering the cutterhead to inspect the cutters. The cutters will also be closely measured manually during excavation.

4. Summary and Outlook

Laboratory research as well as site data illustrate the possibility to reduce the three main problems on hard rock TBMs: abrasion, temperature and dust.
This can be realized already today by traditional measurements like water sprinkling, metallurgic improvements and exhausting – but there is a chance of significant improvements by using modern foams and polymers.
In order to prove the promising laboratory data, further on-site evaluations are necessary and will be given in the near future by detailed monitoring of the above described AMR II project in India.

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Paper 11

Influence of corrosion on abrasion of cutter steels used in TBM tunnelling

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Abstract:	Abrasion on TBM cutters can be critical in terms of time and cost. Several researchers are studying degradation of cutter tools for Tunnel Boring Machines (TBM), excavating hard rock, soft ground and loose soil. So far, the research comprises mainly degradation due to abrasive wear. Abrasive wear is a highly prevailing process in TBM excavation, but keeping in mind that the environment the excavating tools are working in, corrosion might have an impact. Through this paper it is presented some methods that can be used to evaluate the influence of corrosion on abrasion on TBM excavation tools. The paper also presents the influence of corrosion on abrasive wear for some initial tests, where the steel and geomaterial have been kept constant and with varying properties of the excavation fluids (soil, anti-abrasion additives and water). The results show that the content of chloride in the water greatly influences the amount of wear proving the influence of corrosion in the abrasion of the cutting tools. The addition of conditioning additives tailor made for rock or soil conditions reduce the amount of wear however, when chloride is present in the water the additives minimize the wear rates, but they do not supress the corrosion process in the cutting tools.

Influence of corrosion on abrasion of cutter steels used in TBM tunnelling

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Abstract

Abrasion on TBM cutters can be critical in terms of time and cost. Several researchers are studying degradation of cutter tools for Tunnel Boring Machines (TBM), excavating hard rock, soft ground and loose soil. So far, the research comprises mainly degradation due to abrasive wear. Abrasive wear is a highly prevailing process in TBM excavation, but keeping in mind that the environment the excavating tools are working in, corrosion might have an impact. Through this paper it is presented some methods that can be used to evaluate the influence of corrosion on abrasion on TBM excavation tools. The paper also presents the influence of corrosion on abrasive wear for some initial tests, where the steel and geomaterial have been kept constant and with varying properties of the excavation fluids (soil, anti-abrasion additives and water). The results show that the content of chloride in the water greatly influences the amount of wear proving the influence of corrosion in the abrasion of the cutting tools. The addition of conditioning additives tailor made for rock or soil conditions reduce the amount of wear however, when chloride is present in the water the additives minimize the wear rates, but they do not supress the corrosion process in the cutting tools.

Keywords: TBM, tunnel boring, abrasion, cutter steel, corrosion, tribocorrosion.

1. Introduction

Determining the abrasiveness for soil and hard rock has become a commonly used pre-investigation method for tunnelling projects. Wear and tool life estimates on Tunnel Boring Machines (TBMs) based on simplified methods have been done since the mid 70´s for hard rock projects [1]. For tool life estimation on hard rock TBM, the most common approaches are the NTNU model including the Cutter Life Index™ (CLI), and the Cerchar Abrasivity Index (CAI) utilized by the Colorado School of Mines prognosis model for TBM performance. The CLI and CAI estimation approaches are all based on testing steel interaction against a dry rock sample. In the last 5 years there has been an increased focus on estimation of tool life for TBMs excavating soil and soft rock conditions [2]. Gharanbagh et al. [3] have suggested a method for testing in-situ like soils including a wide grain size range (0 – 12 mm), introduction of soil conditioning additives and tests on moist soil samples. At NTNU and SINTEF a similar approach is done [4] in order to study the effect of corrosion on the abrasion process of cutting tools used in tunnel boring machines, including the compaction of the soil.

In the present work, tests combining abrasion in corrosive media referred to as tribocorrosion have been conducted. The testing comprises a steel sample used in TBM excavation tools exposed to one hard rock sample and one soil sample. In addition the corrosive effect of soil conditioning additives and anti-abrasion additives has been evaluated and compared with the use of water.

1.1. Concept definitions for tunnel boring: tribology and tribocorrosion

Tribology was defined in 1966 as the science and technology of interacting surfaces in relative motion [5]. This is a multidisciplinary subject where many different disciplines of science interact for covering the study of lubrication, friction and wear of materials. Among others, abrasion is one of the four main wear mechanisms recognized in the tribology literature [6-8]. Abrasion is a form of wear caused when solid materials are loaded against particles having equal or higher hardness [8]. This is commonly experienced in TBM applications. In tribology, two main modes of abrasive wear are defined: two-body abrasion and three-body abrasion. Two-body abrasion occurs when the harder particles or firmly held grits act like a cutting tool over a solid material. Three-body abrasion occurs when the abrasive particles are free to roll and slide over the surfaces of two solid materials. For linking two- and three-body abrasion to TBM tunnelling, an example of three-body abrasion would be soil excavation, and two-body abrasion can be considered as hard rock excavation (**Figure 1**). The term *abrasive wear,* which is commonly used in tunnelling does not necessarily describe the different wear mechanisms involved in the tribological system for hard rock and soil TBM excavation. The mechanisms depend on the system conditions (speed, hardness of the interacting materials, environment: corrosive or non-corrosive environment, loads, etc). Identifying the wear mechanisms is a way of gathering information about wear rates and the failure mechanisms among others. However no general formalism for predicting wear is available, although more than hundred wear laws can be found in the literature [9]. Thus testing the materials and/or investigating the micro-mechanisms of degradation are the only ways of improving the efficiency of systems operating in abrasive environments.

An important topic in tribology is the interaction between the mechanical damage and the chemical degradation occurring in systems exposed to aqueous or hot aggressive environments [8, 10]. The effect of the mechanical action on the chemical degradation of materials and vice versa, the effect of the chemical action on the mechanical response of materials, has become an interesting topic in tribology in the last years. This has led to the expansion of a new research area in the field of tribology called *tribocorrosion.* Tribocorrosion uses tribology, corrosion science and engineering methods for investigating the degradation of materials by this mechanism. Materials properties, surface transformations and electrochemical reactions are the main aspects to be investigated in tribocorrosion since the combination of mechanical and chemical parameters often leads to unusual behaviour of materials. In the last twenty years, tribocorrosion research has been proven very relevant in passive metals (such as stainless steels), however the effect on active metals (such as steel used in excavation tools) is still a field to be investigated in more detail [10].

1.2. Why tribocorrosion in TBM applications

Verhoef [11] describes the tribological system for cutter dredging of soft rocks and soil consisting of cutting tools, soft rock/soil, rock debris and the surrounding environment is often consists of seawater. In addition to the components of the dredging tribological system a TBM can encounter all types of geology and mineralogy/chemistry, from soft clays, slits, sands etc., to soft rock and extremely hard rock, as can be seen in **Figure 1**. In tunnelling, the combined action of abrasion on the cutters rolling against the rock and the mineralogy/chemistry of the rocks might generate a tribocorrosion scenario, which might become even worse if humidity, water, oxygen and conditioning additives are involved in the process. To determine the tribocorrosion importance in TBM applications, it is not possible to look at the corrosion and abrasion processes separately and then sum the contributions, as the overall process abrasion/wear will be affected by corrosion, and corrosion will be influenced by abrasion/wear. The synergy of corrosion and abrasion can enhance the material removal rates, and can be a source of additional defects that might influence the mechanical properties of the excavation tools [10].

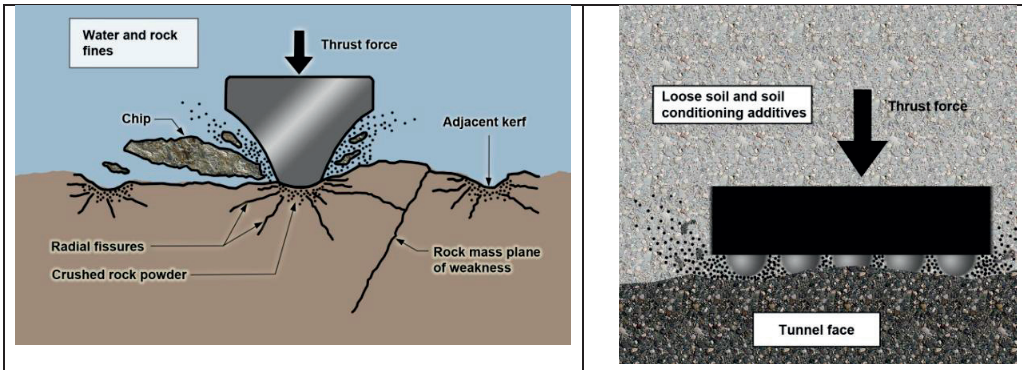
The synergy in tribocorrosion can be defined in a very simple way with the following equation already proposed in the early 80s for the abrasion-corrosion processes found in mining equipment [10, 12]:

$$T = W + C + S \qquad \text{(eq.1)}$$

Where T is the total wear arising from the two contributions, W is the wear in the absence of corrosive media, C is the material loss in absence of mechanical wear (abrasion) and S is the synergistic term. All terms can be determined in individual tests, except S that can only be estimated by isolating it from equation 1. The synergistic term can be further split in two contributions according to the following equation:

$$S = W_c + C_w \qquad \text{(eq. 2)}$$

Where W_c is the change in wear rate due to corrosion (corrosion-accelerated wear) and C_w is the change in corrosion rate due to wear (wear-accelerated corrosion). Usually C_w is the term contributing in larger amount to the synergy of the tribocorrosion process specially in stainless steels [10]. The methodologies for determining C_w and W_c are rather complex and have some limitations. In addition there are other tribocorrosion models that could be considered for quantifying the wear-accelerated corrosion in a tribocorrosion system [10]. However, an exact quantification of tribocorrosion is out of the scope of this paper and therefore a discussion of these mechanisms will not be considered here.



(a) (b)

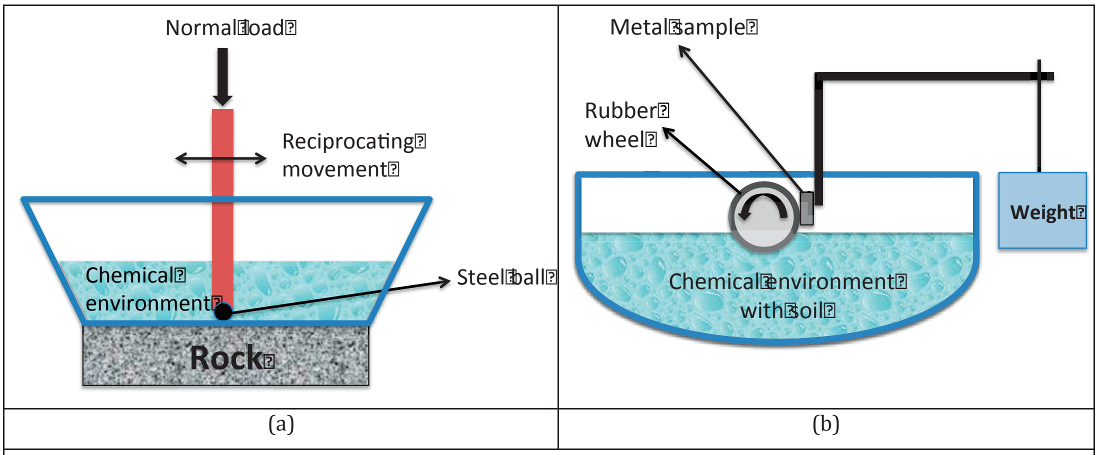
Figure 1. Simplified tribo-systems of TBM tools: (a) Hard rock cutter (After Bruland 1998 [1]) and (b) Soil cutter.

2. Experimental set-up and materials

The aim of this work is two fold, on one hand the goal is to show the relevance and the influence of corrosion on the abrasion process of cutter tools used in TBMs. On the other hand the goal is to find a lab test protocol that allows for a fast and relatively easy way to test wear conditioning additives used in tunnel boring operations. These conditioning additives aim at improving the lifetime of the cutter tools and therefore lower the costs of the tunnel boring operations [13].

2.1. Tribocorrosion tests applicable for geological materials

Two different tribocorrosion test set-ups were used in this work to evaluate the abrasion-corrosion performance of the cutter steels exposed to different chemical and geological media: (1) Reciprocating ball-on-plate (sliding wear) for the hard rock systems and (2) wet rubber wheel test (abrasion-corrosion) for the soil system. **Figure 2** shows a sketch of the two set-ups. The duration of the ball-on-plate tests was 1 hour and for the rubber wheel tests was 40 min. The tests were performed at least twice for checking the repeatability. In sections 2.2 and 2.3 an overview of the materials tested in the two rigs will be given.



(a) (b)

Figure 2. Tribocorrosion test set-ups (a) reciprocating ball-on-plate and (b) wet rubber wheel.

2.1.1. Reciprocating ball-on-plate

In this apparatus, the tests are performed by sliding back and forth a steel ball of 6 mm in diameter (in the present work made of a real cutter steel disc) with a stroke length of 10 mm, a normal load of 5 N and a reciprocating frequency of 1 Hz against the rock material (**Figure 2a**). The normal load for the tests was chosen considering a common stress indentation in a cutter disc of a TBM in hard rock of 400 MPa. According to Hertz's theory of contact, this corresponds to a normal load of 5 N using the geometry proposed in this work [8]. During the tests performed in this work the rock material has been exposed to different environments: dry conditions, water obtained from the same site as the rock, distilled water and a foam made with 3% concentration in water of tunnel boring conditioning additives (more details in sections 2.2 and 2.3). For each test the friction coefficient between the rock and steel ball was recorded.

2.1.2. Rubber Wheel

To test the influence of the chemical environment in the abrasivity of the soil, a Rubber Wheel test rig modified to be used in wet environment was employed (**Figure 2b**). The tests are performed by applying a force of 220 N between the rubber wheel and the specimen and rotating the rubber wheel at about 200 rpm, which gives a linear speed of about 2 m/s (i.e. within the range of what a cutter disc may be exposed to during boring). The experiments were performed in different chemical environments: water obtained from two field sites and foam made with 3% concentration in water of two conditioning additives tunnel boring (more details in sections 2.2 and 2.3). The soil used was a reference highly abrasive sand with a very homogeneous particle size distribution and shape.

2.2. Tests with field materials in field chemical environment

As mentioned in the previous section, materials obtained from field sites were tested in the two different tribocorrosion set-ups applicable for geological materials. The cutter tool steel tested has been a hard rock type H13 tool steel. The field abrasive materials for testing the steel have been samples obtained from two different geological sites (one soil and one hard rock). The soil sample originates from a recently finished project in the Middle East (hereafter referred as ME) and the hard rock sample originates from a recently finished project at a Scandinavian jobsite (hereafter referred as SC). In addition to the samples gathered at the sites, a purchasable cast-in sand has been used as a reference soil. **Table 1** shows a summary of all field materials used and the corresponding tests and measurements performed.

In this first group of experiments, the tests were conducted in dry and wet conditions with water collected from the same site as the soil and rock (ME and SC respectively). In these tunnel projects the water is expected to have different chemical content among which chloride is the most relevant for tribocorrosion since the chloride content of water is what provides with the corrosion rate in metals (in this case the cutter disc steel). The highest corrosion rate in air-saturated water is achieved at a concentration of 3.4 wt.% chloride, which is the concentration in seawater [14]. In addition, real tunnel boring projects occasionally utilise soil conditioners or anti-wear additives for improving the life of the cutter tools. Therefore tests with two different additive types from BASF Construction Chemicals have been performed: (1) ABR 5 – designed for hard rock [15] and (2) SLF41 – designed for soft ground soils [16]. The concentration of the conditioning additives and the physical state have been chosen according to the real use in field, this is in foam state and with a concentration in the liquid media (water or seawater) of 3 vol.%.

The tests performed with field samples have been done to set-up the base line for the test protocol in controlled laboratory conditions (see section 2.3).

Table 1. Summary of the materials used in the field tests.

Material	**Steel**	**Soil**	**Rock**	**Water 1**	**Water 2**	**Conditioning additives**
Nomenclature	H13	Reference soil	Scandinavian jobsite	Middle East	Scandinavian jobsite	ABR5 and SLF41
Abrasiveness (AVS/SAT™)	n.a	Yes	Yes	n.a	n.a	n.a
Hardness	Yes	Yes	Yes	n.a	n.a	n.a
Composition	Yes	Yes	Yes	Yes	Yes	Yes
pH	n.a	n.a	n.a	Yes	Yes	Yes
Tribocorrosion (sliding)	Yes	n.a	Yes	n.a	n.a	n.a
Abrasion-corrosion (rubber wheel)	Yes	Yes	Yes	n.a	n.a	n.a

2.3. Tests in laboratory controlled conditions

Tests in controlled laboratory conditions have been designed due to the complexity of controlling the chemical composition of the water coming from the field (ME and SC). For this reason, tests in distilled water and distilled water containing salt (3.4 wt% NaCl, hereafter called seawater) were performed.

Tests in environments containing conditioning additives prepared in distilled water and seawater were also performed in order to check the influence of chloride (Cl^-) content in the wear performance of the cutter steel. The conditioning additives used were: (1) ABR 5 – designed for hard rock [15] and (2) SLF41 – designed for soft ground soils [16]. The concentration of the conditioning additives and the physical state have been chosen according to the real use in field, this is in foam state and with a concentration in water of 3 vol.%.

In this second group of tests, the samples were the hard rock type cutter tool steel H13 tool steel and the geological material chosen has been a granite from Iddefjord (Norway) due to its well-known and documented properties, high abrasivity, and due to its homogenous behaviour, which is important for test reproducibility [17].

Table 2 shows a summary of the controlled chemical environments used for testing and the properties/measurements performed on them.

Table 2. Summary of the materials used in the controlled laboratory tests.

Material	**Steel**	**Rock**	**Distilled water**	**3.4 wt.% NaCl**	**Conditioning additives**	**Conditioning additives + 3.4% NaCl**
Nomenclature	H13	Iddefjord granite	Distilled water	seawater	ABR5 and SLF41	ABR5 and SLF41 + seawater
Abrasiveness (AVS)	n.a	Yes	n.a	n.a	n.a	n.a
Hardness	Yes	Yes	n.a	n.a	n.a	n.a
Composition before testing	Yes	Yes	Yes	Yes	Yes	Yes
Composition after testing	n.a	n.a	Yes	Yes	Yes	Yes
pH	n.a	n.a	Yes	Yes	Yes	Yes
Viscosity	n.a	n.a	Yes	Yes	Yes	Yes
Tribocorrosion (sliding)	Yes	Yes	n.a	n.a	n.a	n.a

2.4. Materials characterization tests and chemical analysis

For characterizing all materials used in this work, different experimental techniques were employed. All tests were performed at least twice for confirming the repeatability of the results.

2.4.1. Steel

The metal composition of the steel was measured by XRF (X-Ray Fluorescence, Thermo Scientific, Niton XL3t), the microstructural characterization was done by metallographical preparation (grinding with SiC paper, polishing with diamond paste up to mirror finish and etching with nital to reveal the grain structure), the hardness was measured using microvickers hardness test (MicroWiZhard, Mitutoyo) and SEM (Scanning Electron Microscopy, Hitachi S-3400) was used to study the microstructure of the steel and the topography of the worn surfaces of the materials after testing.

2.4.2. Soil/rock

The geology mineral composition of the soil and rock materials was investigated using XRD (X-Ray Diffraction, Bruker D8 ADVANCE), the hardness of the soil and rock materials was estimated by Vickers Hardness Number Rock (VHNR), described by Bruland [1] and the topography of the worn surfaces after testing was examined using SEM (Scanning Electron Microscopy, Hitachi S-3400).

2.4.3. Liquid media

The chloride content of the water collected from the field sites was measured by titration (precipitation chemical process), the metal content of all the solutions before and after the tribocorrosion tests was measured using ICP-MS (Inductively Coupled Plasma Mass Spectrometry, Finnigan ELEMENT 2).

The pH of all liquid media (water and conditioning additives) was measured using a PHM210 standard pH meter from MeterLab.

Finally, the viscosity of the liquids was evaluated by using a Hakee III Rheomter. The liquid media were put in a sample holder and the viscosity was measured with a rotational device. In this work the viscosity was measured by a constant increase in the rotational speed for 180 seconds. After this the rotational speed was kept constant at 500 RPS for 15 seconds, and then it was slowly decreased for 180 seconds until it stopped. The viscosity measurements from the region of constant speed were used as the viscosity values. The measured viscosity was the dynamic viscosity (Pa s) of the fluid and all measurements were performed at room temperature (25 ^{o}C).

3. Test results and discussion

3.1. Steel and geological samples characterization

In this work, the cutter steel tested has been the reference steel used in hard rock tunnel boring machines, H13 tool steel, having a measured (by XRF) average composition taken from three different positions in the cross section of the cutter disc: 90.8 wt.% Fe, 0.6 wt.% C, 4.8

wt.% Cr, 1.3 wt.% Mo, 0.9 wt.% Si, 0.9 wt.% V, 0.3 wt.% Mn, 0.1 wt.% Cu, 0.1 wt.% Ni. **Figure 3** shows the microstructure of the steel after metallographical preparation. In the figure a typical tempered martensite microstructure is observed in the H13 steel cross-section with some areas of retained austenite (light areas). The steel has been die forged and heat treated to increase the hardness, which was ca. 639 Vickers Hardness. Comparing this hardness value with the typical value of a H13 steel (600 Vickers Hardness or 54 Hard Rockwell C [18]) it is possible to assume that the steel was air cooled from a high temperature of about 1000 ^{o}C and then tempered at a temperature of about 500 – 550 ^{o}C, however, this is an assumption based only on the steel hardness measured and not on real data obtained from the steel producer.

The chromium (Cr) content of the steel may allow for some corrosion protection, but it would not be as high as it is for stainless steels (> 11 wt% Cr). The steel also contains some molybdenum (Mo), which protects against chloride penetration (pitting) and increases the hardenability of the steel. There is also some vanadium (V) and nickel (Ni) present, which increase both the strength and hardness of the steel and its resistance to impact. The carbon (C), silicon (Si) and manganese (Mn) will make the steel harder, but less ductile. Considering the heat treatment and the alloying elements, the H13 steel should have a good balance between hardness and ductility/toughness. It should also exhibit some degree of protection against corrosion.

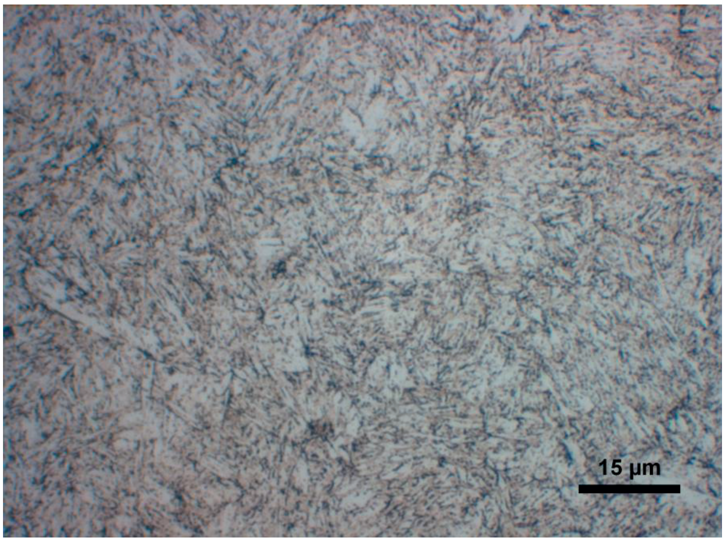


Figure 3. Microstructure for the cutter steel disc (H13 tool steel) tested in this work.

The mineral composition of the rock and soil samples found using XRD is shown in **Table 3**. In addition, the hardness of the samples estimated by VHNR according to Bruland [1] is also shown in the table. As can be seen, the geological materials contain mostly hard abrasive compositions (Quartz and Feldspar) therefore their abrasivity is expected to be very high (see section 3.2.1).

Table 3. Overview of mineralogy in the geological samples measured by XRD and calculated Vickers Hardness Number Rock (VHNR) according to Bruland [1]

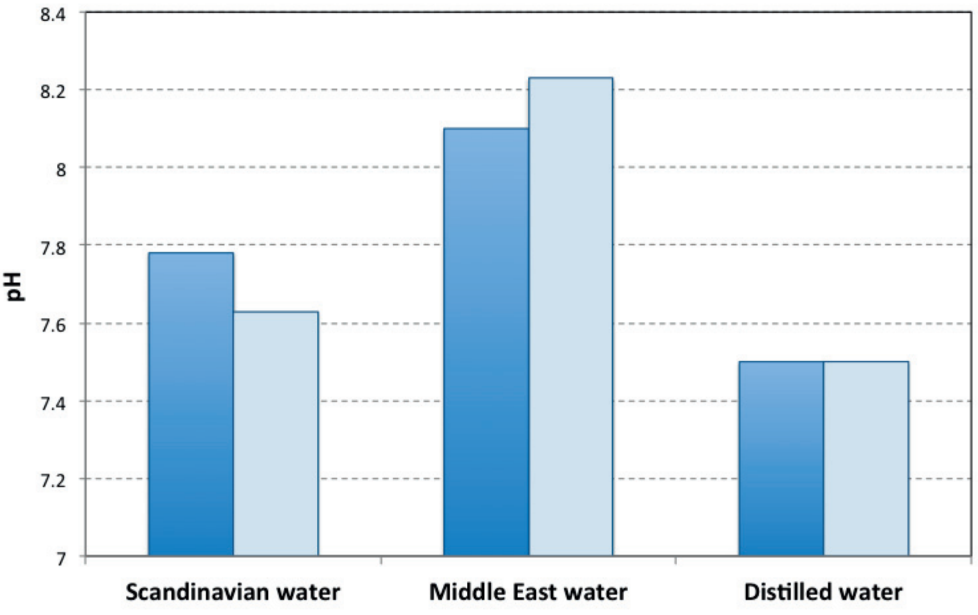
Soil/rock name	Quartz	Feldspar		Clino-pyroxene	Magnetite	Calcite	Actinolite	Muscovite	Albite	Magnesia	Microline	Mica	VHNR
		Plagio-clase	K-feldspar										
Abrasive reference soil	73%	-	-	-	-	-	-	2%	12%	1%	12%	-	893
Scandinavian jobsite	3%	79%	4%	12%	2%	-	-	-	-	-	-	-	798
Iddefjord granite	25%	32%	35%	-	-	-	-	-	-	-	-	8%	785

3.2. Chemical analysis and pH of the liquid media

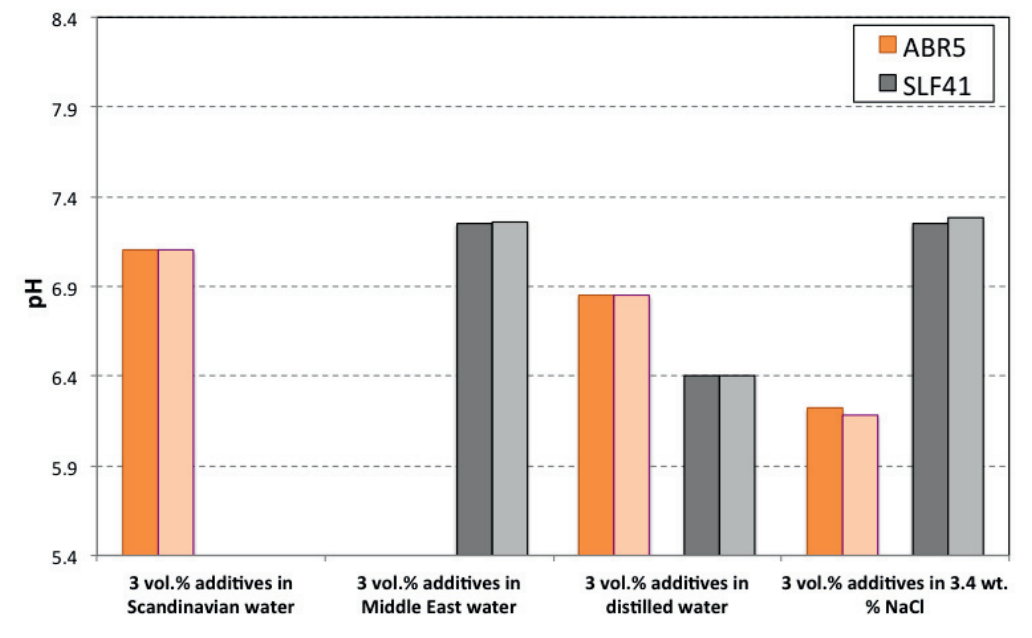
The pH is an important value to take into account in the corrosion resistance of steels. In pure or soft waters, too low pH values (< 4) lead to rapid corrosion and pitting (due to the dissolution of iron oxide film) of steels. Between pH values of 4 and 10, the corrosion rate is kept constant and it decreases rapidly at pH values above 10 (due to the formation of a protective iron hydroxide film) [19]. In hard waters, those with a high content in Calcium Carbonate ($CaCO_3$) that deposits on the surface of the steel and protects it against the diffusion of oxygen. The formation of this carbonate layer depends, among others, on the pH of the water and the amount of $CaCO_3$ in the water. To know if a hard water can protect the steel against corrosion, the saturation index (SI) of the water and the concentration of $CaCO_3$ should be known. If the SI is positive, then the steel is protected against corrosion [19].

In the present work, three different types of water were used. Two obtained from the field (SC and ME) and distilled water. The hardness of all the waters was tested by performing a strip test (i.e. strips for measuring the amount of $CaCO_3$ in the water). In the case of the distilled water and SC water the content of $CaCO_3$ was between 40-70 mg/l, which corresponds to soft water and in the case of the water from ME the $CaCO_3$ content was > 375 mg/l, which corresponds to a very hard water. The SI value for the ME water was calculated for the water with and without conditioning additives. The values obtained were 1.3 and -3.5 respectively, therefore the surface of the steel is protected against corrosion when it is exposed only to the water, but it is not protected when the conditioning additive is added. Therefore in this work, the measurement of pH will be used as an orientation to the expected degree of corrosion in the steel.

The pH values of all the liquid media used in this work were measured using a pH meter and are presented in the column graphs of **Figure 4**. This figure shows the results of two independent pH measurements. **Figure 4a** shows the pH values of the waters taken from field (SC and ME) and the distilled water. In all cases the pH is above 7, therefore they are expected to provide with a constant corrosion rate to the steel. However, it could be expected some degree of passivation (corrosion protection) of the steel for the ME water, since its pH is close to the minimum required pH for passivating iron (Fe) [19]. **Figure 4b** shows the pH values of the water/conditioning additives mixtures. In this figure it is clearly seen how the additive mixtures present lower pH values than the waters alone. The lowest pH values are found for SLF41 in distilled water and ABR5 in 3.4 wt.%, which could lead to higher corrosion rates.



(a)



(b)

Figure 4. pH values of all the liquid media used in this work: (a) field and distilled waters and (b) conditioning additives and conditioning additives in different waters. The figure shows the results of two independent tests performed for each condition.

As mentioned earlier, chloride (salt) is an element with a large influence on the corrosion rate of steel in air-saturated water. The corrosion rate increases with chloride concentration up to ca. 3.4 wt.% and then decreases to values below distilled water when the concentration of salt is around 26 wt.% [19]. This is due to the oxygen solubility in water, which decreases with increase chloride concentration. The initial increase in corrosion rate (up to 3.4 wt.% chloride) is related to the nature of the protecting film formed on the surface. When the concentration of chloride is well below 3.4 wt.% the formation of a protective hydroxide film is favoured and as chloride concentration reaches the value of 3.4 wt.% the formation of soluble iron chloride ($FeCl_2$) is favoured and a continuous dissolution of iron is observed [19]. Therefore, the amount of chloride in the water used in this work is an important value to take into account.

The amount of chloride in the field waters has been measured by titration with silver nitriate ($AgNO_3$) solution. $AgNO_3$ reacts with NaCl to form a white precipitate of silver chloride (AgCl). By measuring the volume of $AgNO_3$ necessary to form the first precipitate of AgCl and using some chemical equations it is possible to know the amount of chloride contained in the water.

The amount of chloride in SC and ME waters was 0.02 and 1.43 wt.% respectively. The lowest concentration of chloride is for the SC and distilled water, which will result in very low corrosion rates. The highest concentration is for the water taken from the tunnel project in the ME, which will result in high corrosion rates (close to those for seawater [19]). For this reason, the solutions chosen for the laboratory tests were distilled water and artificial seawater.

3.3. Viscosity of the conditioning additives and their mixtures

Viscosity is an important parameter in lubrication. High values of viscosity normally lead to good lubrication performance and therefore reduced wear rates. In order to assess if the viscosity of the conditioning additives and their mixtures used in this work could have an influence in the wear observed after tribocorrosion testing, dynamic viscosity measurements were performed. As can be seen in **Table 4,** SLF41 conditioning additive has higher dynamic viscosity than ABR5, which could indicate a higher content in polymer. However, when the conditioning additives are mixed in distilled water and artificial seawater the values decrease drastically and are only slightly higher than pure water (i.e. 0.8 x 10^{-3} Pa s at room temperature [8]).

Table 4. Summary of the dynamic viscosity of the conditioning additives and their mixtures in water and seawater.

	ABR5	SLF41	3 vol.% ABR5 in distilled water	3 vol.% ABR5 in 3.4 wt.% NaCl	3 vol.% SLF41 in distilled water	3 vol.% SLF41 in 3.4 wt.% NaCl
Dynamic viscosity Pa s [10^{-3}]	29.14	45.82	1.47	1.49	1.80	1.68

3.4. Abrasive wear of the steel in dry and wet conditions

3.4.1. Abrasion ranking in dry conditions (AVS and SAT tests)

As mentioned in section 3.1, the geological materials contained minerals such as quartz and feldspar, with very high hardness. In order to quantify the abrasivity of these materials, the Abrasion Value Cutter Steel (AVS) for the SC rock and the Iddefjord granite and the Soil Abrasion Test™ (SAT) for the reference soil were performed and the abrasion values of the materials are shown in **Figure 5.** As can be seen in **Figure 5** the hard rock abrasion values are classified as medium (Scandinavian jobsite) and very high (Iddefjord granite and reference soil) according to Dahl et al. [20].

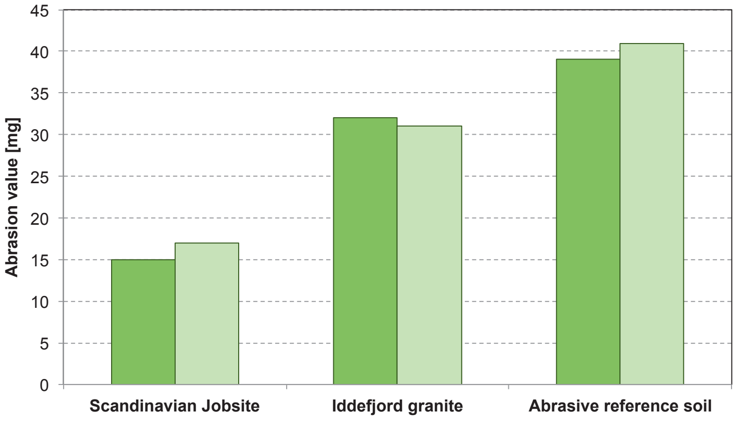


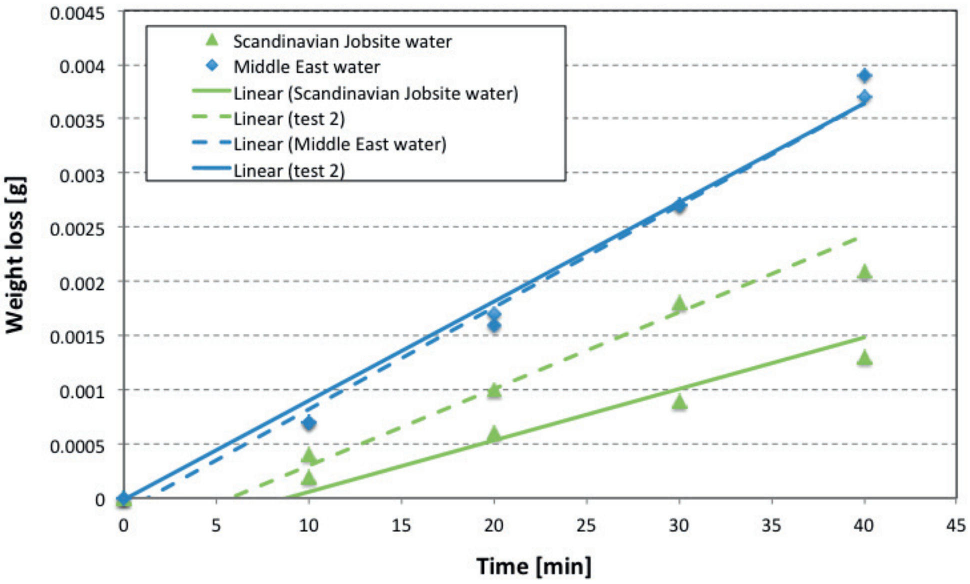
Figure 5. Abrasiveness ranking for the geological materials.

The main elements in the geological materials are much harder than the steel (**Table 3**) thus, the wear on the steel will be more severe. According to the theory of abrasion the hardness of the steel should be 1.3 times the hardness of the rock to efficiently reduce the wear of the steel [8]. However, this would make the steel too brittle to withstand fracture in tunnel boring applications. Because the rock is harder than the steel, this will cause more wear on the steel preventing unwanted fracture failure of the tools and therefore warrantying the cracking of the rock at high enough pressures.

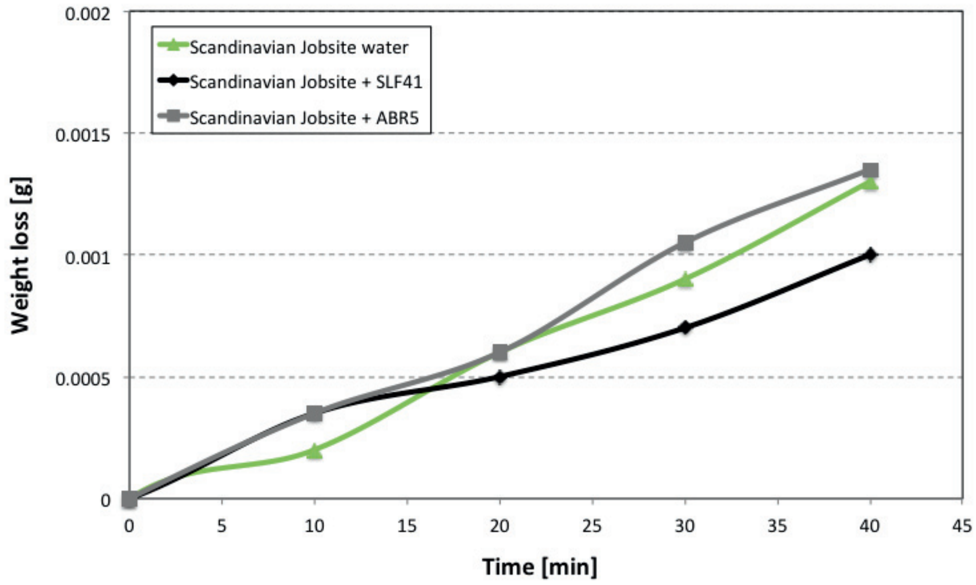
3.4.2. Abrasion in wet conditions: Rubber Wheel

As mentioned section 2.2, the rubber wheel tests were performed in wet conditions to simulate the abrasion-corrosion situations in soil tunnel boring systems. Two different types of tests were performed: (1) with field water (SC and ME) to test the effect of the chloride content (corrosiveness) and (2) with field water containing 3 vol.% of conditioning additives SLF41 (designed for soil tunnel boring) and ABR5 (designed for hard rock tunnel boring) to test the effect of the foam. **Figure 6** shows the weight loss results of the tests performed. As can be seen, the effect of chloride content in the weight loss is quite pronounced indeed, after 40 min test the weight loss in the tests performed with the ME water is two times higher than in the tests performed with SC water (**Figure 6a**).

When investigating the effect of the conditioning additive in the abrasion rate (**Figure 6b** and **6c**), the results show that the use of the conditioning additives decreases the abrasion rate of the H13 steel, in both waters (SC and ME). However the effect is more pronounced in the case of the ME water where indeed both additives work positively. In the case of .the SC water the effect of the additives is not as pronounced as in the ME water however, it the additive designed for soil conditions provides with lower abrasion rate.



(a)



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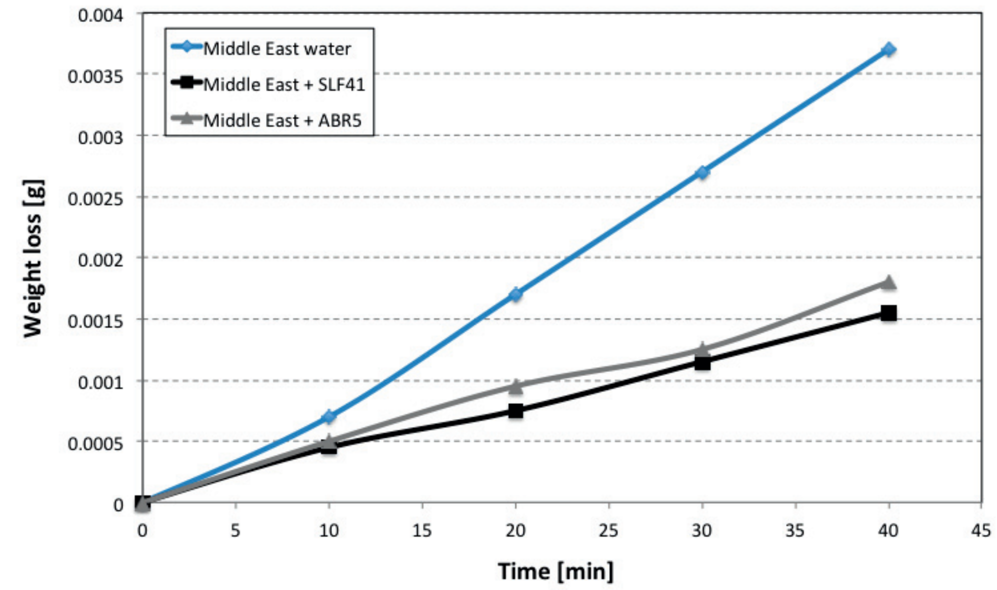


(c)

Figure 6. Weight loss evolution with time for the H13 steel tested with reference sand in: (a) SC and ME water and (b) ME water with and without conditioning additives and (c) SC water with and without conditioning additives. In (a) two tests performed with the same testing conditions are shown for repeatability purposes, in (b) and (c) only one test of each testing condition is shown since the repeatability in (a) was good.

Figure 7 shows the wear topography of the H13 steel after rubber wheel testing. As was expected from the tests performed in SC and ME water to check the effect of chloride in the abrasion rate, more abrasion marks and some corrosion marks (pitting) are observed in the test performed with ME water (**Figure 7b**). This is in accordance with the larger abrasion rate recorded in **Figure 6**. Therefore, it is possible to conclude that the amount of chloride has a negative effect on the abrasion rate of the steel and therefore a premature failure of the steel should be expected (i.e. higher abrasion rates due to tribocorrosion effect). When the conditioning additives are used in both cases the wear rate decreases having the SLF41 the best performance. This is not surprising since this additive is specially designed for soil conditions. The decrease in the abrasion rate when using the additives can be due to the increase in viscosity of the liquids (**Table 4**). The lower abrasion rates are confirmed by looking at the SEM images (**Figures 7c** to **7f**) where almost no abrasion marks are found. However, pitting is observed on the surface of the steel after testing in ME water mixed with conditioning additives (**Figures 7e** and **7f**). This shows that the additives are designed to decrease wear, but on the other hand the corrosion protection is not fully optimized for corrosive waters. In addition, the SLF41 additive seems to create more pitting due to its lower pH values however the differences between SLF41 and ABR5 in the pitting of the steel are not as large as could be expected.

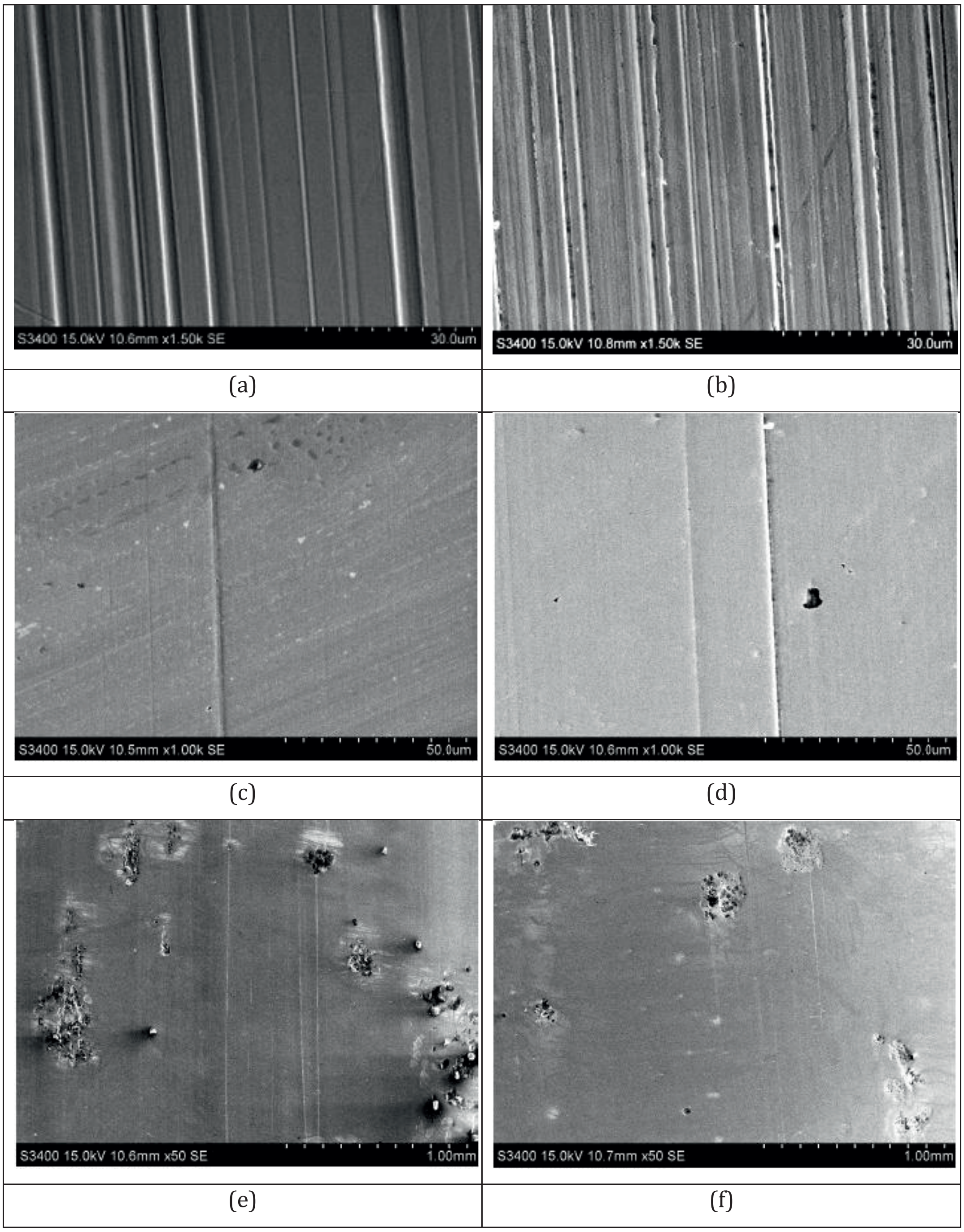


Figure 7. H13 steel wear topography after rubber wheel testing: (a) Scandinavian jobsite water (0.02 wt.% chloride), (b) Middle East water (1.4 wt.% chloride), (c) SC water with SLF41, (d) SC water with ABR5, (e) ME water with SLF41 and (f) ME water with ABR5.

3.4.3. Sliding tribocorrosion: Reciprocating ball-on-plate

Figure 8 shows the Coefficient of Friction (CoF) during rubbing in the different conditions tested for the field and laboratory controlled conditions. The CoFs for the dry tests and the tests performed only with water (field and distilled) and seawater are very high (in some cases above 1), this is typically found in those systems suffering from severe wear and it is actually expected when using bad lubricants as water [8]. The wear topography of the steel balls after testing is shown in **Figure 9a, 9b, 9d** and **9e** where the large wear marks and wear debris are observed. This shows the very close rock-steel ball interaction leading to abrasive wear. Interesting to note, is the pitting marks and corrosion products on the steel ball due to the corrosion effect of the seawater (**Figure 9f**).

A drastic decrease in friction when the conditioning additive ABR5 is prepared in water (**Figure 8a** and **8c**) is observed. The friction reached is below 0.2, which can considered to be almost in the hydrodynamic lubrication regime (i.e. full separation of the surfaces in contact leading to low wear and friction) [8]. This can be due to the lubricant action of the foam, which actually seems to be an efficient lubricant as opposed to water. The viscosity of the lubricant plays an important role here since it helps to separate the ball from the rock surface and thus decreases friction. Indeed, the dynamic viscosity of the conditioning additives prepared in water and seawater was larger than the dynamic viscosity of only water (**Table 4**) therefore this effect of lower friction should not be surprising. However, interesting to note is the large friction values when the sliding tests are performed with the conditioning additive SLF41, which is actually not designed for hard rock tunnel operations. In this case, the values are closer to what was obtained in the tests performed only with water or seawater. Also, an increase in friction is observed when ABR5 is mixed in seawater. These results show that the corrosiveness of the liquid media used plays a very important role in friction since more corrosion was observed on the surface of the steel after testing in seawater and SLF41 (water and seawater) and ABR5 (seawater) as shown in **Figure 9**.

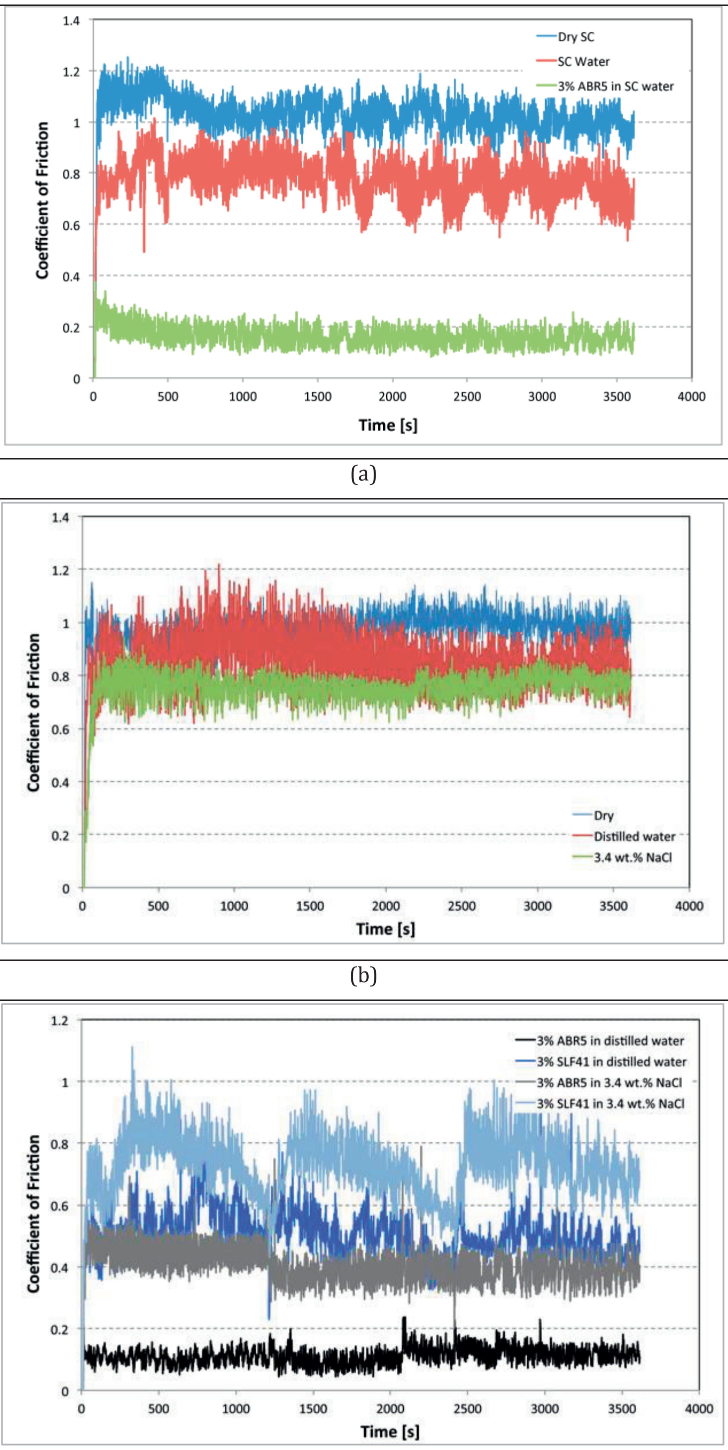
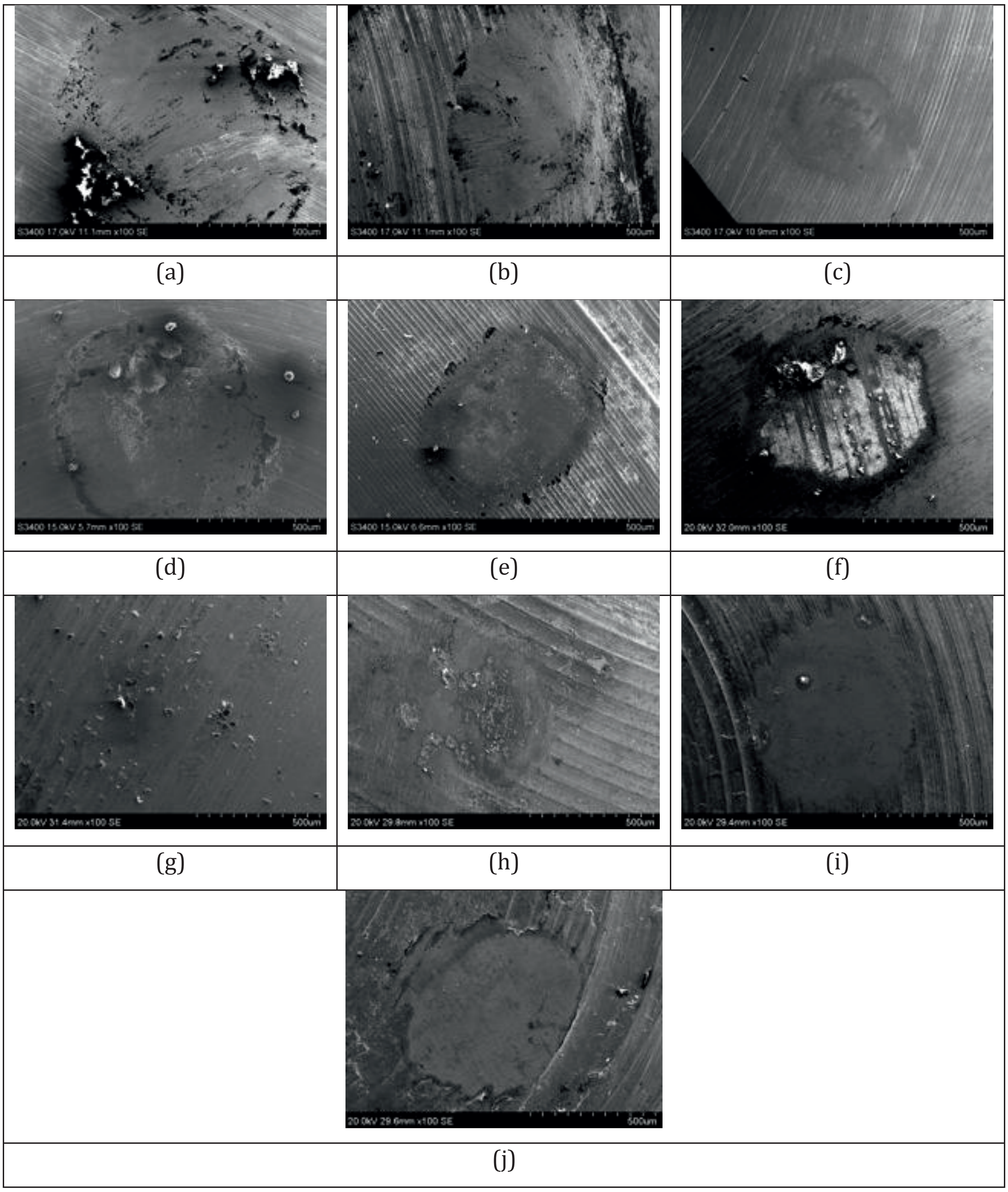


Figure 8. Coefficient of Friction vs. time after ball-on-plate test in (a) field test conditions, (b) laboratory controlled conditions in distilled water and 3.4 wt.% NaCl and (c) laboratory controlled conditions with conditioning additives in distilled water and 3.4 wt.% NaCl. Only one curve per test is shown since the repetition gave the same result.


(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

(j)

Figure 9. Wear topography of the steel balls after sliding testsing: (a) Dry test with Scandinavian jobsite rock, (b) wet test with Scandinavian jobsite rock and water, (c) wet test with Scandinavian jobsite rock and 3 vol.% ABR5 in Scandinavian jobsite water, (d) Dry test with Iddefjord granite rock, (e) wet test with Iddefjord granite rock and distilled water, (f) wet test with Iddefjord granite rock and seawater, (g) wet test with Iddefjord granite rock and 3 vol.% ABR5 in distilled water, (h) wet test with Iddefjord granite rock and 3 vol.% ABR5 in seawater, (i) wet test with Iddefjord granite rock and 3 vol.% SLF41 in distilled water, (j) wet test with Iddefjord granite rock and 3 vol.% SLF41 in seawater.

3.1.1. Tribocorrosion of cutter disc steel used in TBM

As already discussed and shown in previous sections, the corrosion process occurring in the steel is greatly influenced by the presence of seawater and the type of additive. In order to measure how much the steel is corroding in the different environments, ICP tests of the liquids after testing were conducted. The ICP tests were conducted to measure the amount of metal ions released to the environment during testing. These measurements show the degree of wear-corrosion interaction.

For the Rubber Wheel testing the use of ME water increased the wear rates and pitting marks were observed on the wear topography (see section 3.4.2). This is confirmed with the ICP tests where it can be seen the larger content of metal ions in the liquid media after testing with ME water with and without conditioning additives (**Table 5**). When using ABR5, the metal ions concentration also increases, as expected from the pitting corrosion observed in the steel after testing with this solution (**Figure 7**).

For the ball-on-plate tests, a similar result as for the Ruber Wheel is observed. The largest metal ion release is observed when the additives are used. However, the additives seem to work more positively in the presence of seawater, especially in the case of ABR5 where both less wear and lower metal ion released are observed.

Table 5. Metal ion content of the liquid solutions after Rubber wheel testing.

	Fe [μg/mL]	**Cr [μg/mL]**	**Ni [μg/mL]**	**Cu [μg/mL]**
Reference soil – SC water	0.029	-	0.003	0.003
Reference soil – ME water	0.160	0.003	0.013	0.006
SC water & SLF41	0.710	0.011	0.008	0.027
SC water & ABR5	0.492	0.003	0.004	0.019
ME water & SLF41	1.594	0.011	0.020	0.093
ME water & ABR5	8.169	0.341	0.214	0.374

Table 6. Metal ion content of the liquid solutions after ball-on-plate testing.

	Fe [μg/mL]	Cr [μg/mL]	Ni [μg/mL]	Cu [μg/mL]
100% SC water	0.002	-	0.003	0.005
3% ABR5 – SC water	1.230	0.047	0.072	0.037
100% distilled water	0.067	0.003	0.013	0.006
3.4 wt.% NaCl	0.792	0.043	0.013	0.011
3% ABR5 – distilled water	1.787	0.089	0.035	0.173
3% SLF41 – distilled water	2.493	0.101	0.050	0.278
3% ABR5 – 3.4 wt.% NaCl	0.511	0.028	0.019	0.235
3% SLF41 – 3.4 wt.% NaCl	2.820	0.131	0.091	0.573

4. Conclusive remarks

In the present work, the influence of corrosion on abrasive wear on TBM cutter tool steel in interaction with excavation fluids (soil conditioners, anti-abrasion additives and water) has been evaluated. The results clearly show the influence of corrosion on the abrasion rates for both soil and rock conditions. The following conclusions can be drawn:

- The conditioning additives led to lower the abrasion rate of the H13 steel when this was tested in two different waters (low and high chloride content).
- In the case of the hard rock tunnel process, the wear marks were also smaller when the additives were used indicating the beneficial effect of the additives in the abrasion process.
- Corrosion was observed in the steel in the presence of seawater and additives, which could be measured via the chemical analysis of the liquid environment and the microstructural analysis of the steel.
- This work shows the possibility of using this methodology in the study of other tools related to tunnelling excavation exposed to both degradation mechanisms, wear and corrosion (i.e. drill bits for drill and blast tunnelling).

5. Acknowledgements

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Paper 12

TBM Cutter Steel – a challenge for Norwegian steel suppliers

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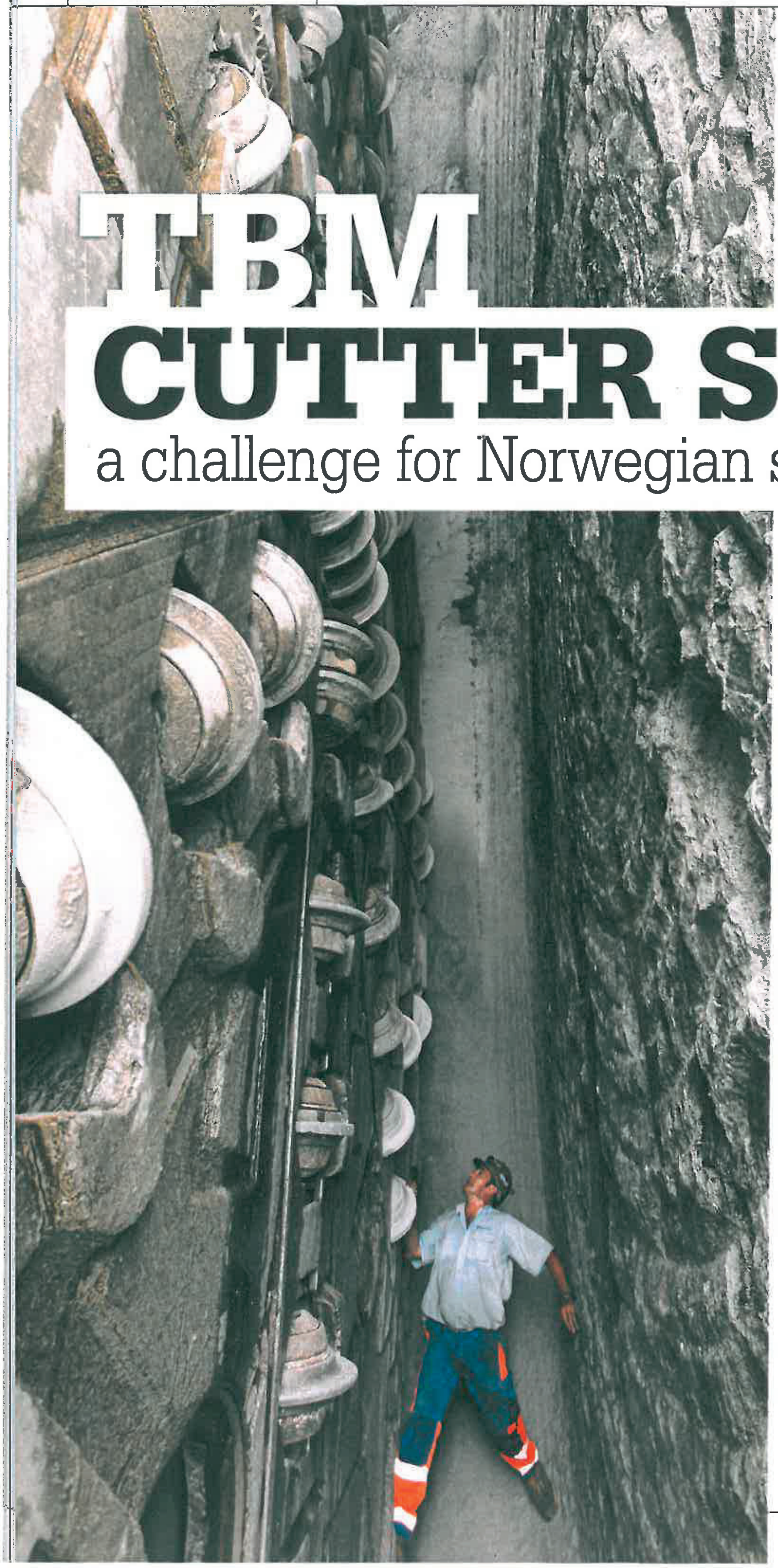


Industry experts give Tunnelling Journal an insight into the current state of Norwegian based research into the use of disc cutters on hard rock TBMs

TBM CUTTER STEEL

a challenge for Norwegian steel suppliers

EIVIND GRØV, chief scientist at SINTEF Building and infrastructure, part of the largest independent research organisation in Scandinavia, and professor at the Norwegian University of Science and Technology (NTNU) sees the use of rolling disc cutters on TBMs in hard rock as a crucial issue. A cross-disciplined approach is needed to really improve the boring performance. "In order to assist the improvement of steel alloys used for disc cutters, we need to understand not only the behaviour of the cutter itself, but also the behaviour of the rock and tool-rock interaction. It is clear that the key to overcoming this challenge is a strong collaboration and a complementary interaction between SINTEF institutes and NTNU," he believes. Within this context Norway's Future Advanced Steel Technology for Tunnelling (FAST-Tunn) research project has been initiated and is managed by Prof. Grøv. The project is a collaboration of academics, Scana Steel Stavanger and BMS (steel manufacturers), the Norwegian government, BASF and Robbins (industrial partners) with the objective of improving the efficiency of new cutters to 25% increased durability. The ultimate aim is to produce steel quality for cutters that produces a significant increased resistance to cutter wear and thus prolonged cutter life time.

What makes NTNU-SINTEF unique?
Laboratory facilities - "An optimal cutter will depend on the wear and fracture resistance of the designed material for TBM application. This will strongly be related to the selected alloying steel elements and the process for cutter production. The project's laboratory and large scale facilities are a great advantage for assessing the metallurgical and mechanical properties of the cutter tool," says Grøv.

Pål Drevland Jakobsen, PhD candidate at NTNU, emphasizes that, "we have also the

possibility to study both steel alloys and rock, with and without the influence of their interaction through the tribo-corrosion-drillability and rock engineering laboratory at NTNU/SINTEF. Simplified rock mass models can be estimated from the laboratory test results, which is used to document and advise on optimal cutter use conditions."

In hard rock TBM tunnelling there are several recognized experimental methods for assessing the rock mass potential to cause abrasive wear: 1) The Cerchar Abrasivity Index (CAI), which utilises a pin scratching a rock surface; 2) the NTNU/SINTEF Abrasion Tester, which exposes a steel sample to crushed rock powder under given contact pressure and flow speed; 3) the LCPC abrasive meter, which exposes a steel impeller to a crushed rock sample. The tests have provided valuable results in terms of estimation of abrasive wear on TBM disc cutters. However, these simplified tests do not take into account "synergetic wear", which can occur as a combination of abrasion, impact, fatigue and corrosion.

"In terms of evaluating new steel alloys for TBM tunnelling, simple tests like the CAI, the

Above: The focus for the FAST-Tunn project, disc cutters for hard rock TBM-tunnelling

Right and top right: Test equipment used at NTNU/SINTEF to determine Abrasion Value (AV) and Abrasion Value Cutter Steel (AVS).

Top left: Eivind Grøv

Opposite page: Double shield Robbins TBM working at a hard rock tunnel face in AMR in India

NTNU abrasion tester and the LCPC abrasive meter will give quick indications of the steel's abrasive wear resistance. In order to get the full picture of the suitability of proposed disc cutter steel, further steel/rock material understanding and assessment of the combined effect of abrasive wear, fatigue, impact and corrosion resistance are required," confirms Jakobsen.

***Material and interface steel-rock understanding* -** When used in disc cutters, it is believed that the alloy will retain its inherent ductility to avoid cleavage fracture, and provide excellent wear resistance due to its strong hardening characteristics. The hardening process will continue as the top surface layer wears off and exposes more of the ductile bulk material. When designing cutters, it is essential that this behavior is well understood. Several challenges remain, however, to capture and predict the physical mechanisms involved during the rock breaking process. During this process high loads, strain, and elevated temperatures are expected at the cutter/rock interface due to impact and friction. "Valuable input to tunnelling performance models and cutter design/layout will depend on our capacity to provide qualitative and quantitative information on the combined effect of local environment/temperature/contact and the local material (rock/steel) response at the rock steel interaction,"says Jakobsen.


Above: Measuring wear and contact behaviour

An experimental program has been established through the project FAST-Tunn to investigate the cutters' steel behavior under cycle fatigue and monotonic loading at room and elevated temperatures. Moreover, tribology tests are used to characterize the wear behavior of the chosen alloy and the friction between cutter and rock. The sliding tests are performed for different thrust force levels, at different temperatures, different velocities and different steels. The wear mechanism of the investigated specimens is then studied at the microstructure level and compared with those of the disc cutter in real industrial processes.

The testing program is also dedicated to the rock mass and mechanical response under a multi-axial state of loading. "The rock strength dependency with the level of axial loading and confining pressure is a key parameter to understand. Simplified representative tests (as indenter tests) of true loading conditions while drilling with a TBM are evaluated and further developed. The proposed development will integrate the results of in-field observations and collected specimens of rock fracturing," clarifies Grøv.

***Numerical modelling capability* -** Alexandre Kane, research scientist at SINTEF Material and Chemistry, underlines that numerical models are complimentarily used with the tests in order to support the material understanding and design process.

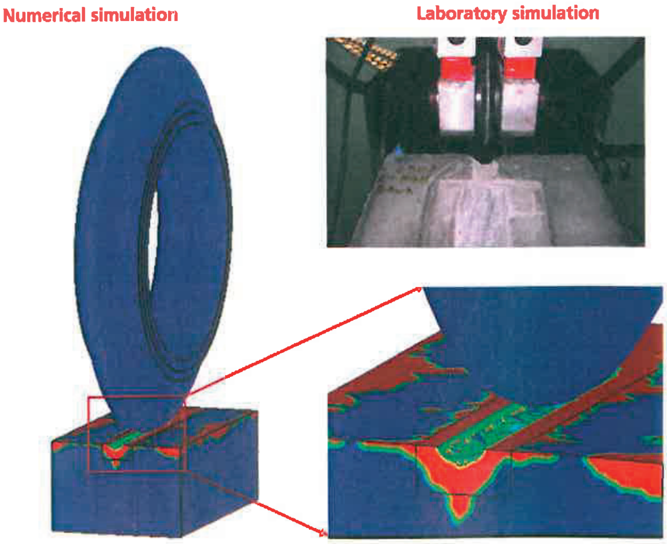
An example is the numerical simulation of a linear cutter test (LCT) of a rock sample. "LCT is a well-established laboratory test for the TBM tunnelling community. It provides important output data to study the tool/rock interaction behaviour, namely rock fragmentation, cutting force evolution, and cutting efficiency. The disc cutter can also be instrumented in order to have access to the temperature evolution at the tool/rock interface," says Kane. "The influence of different testing parameters, e.g., rock type, cutter shape, penetration depths, and cutter spacing (distance between two consecutive cuts) can also be investigated. The test results will support decision making of appropriate TBM parameters in order to minimize the operation energy and to have an optimum rate of penetration. However, the laboratory simulation of the rock cutting process is time consuming and expensive. Numerical simulation is thus used as an effective alternative," adds Hieu Hoang research scientist at SINTEF Material and Chemistry.

Virtual testing provides a significant flexibility to study the influence of the cutter geometry and material on the rock breaking efficiency and the tool degradation process. "An added value of numerical modelling is that we can look into not only the global behavior of the cutting process - as for instance the thrust and rotation speed - but also local information such as stress-strain and temperature evolution within the cutter. This will give the necessary input to define the expected material properties for the development of new tools," comments Hieu Hoang.

"Cutter design can be strongly supported by the development of robust simulations able to account for the strong coupling between the evolution of cutter material properties and cutter geometry while boring. Continuous research is required to reduce the gap between the model and the uncertainty of real operating conditions. The success of the optimization process will increase with our ability to strengthen the dialogue between numerical and experimental analyses," adds Kane.

***Empirical Prognosis model* -** An optimal design for advanced cutters, should also evaluate the proposed cutters according to

3D finite element analysis (FEA) of a linear cutter test, including rock material failure process by using explicit finite element method.



the entire package of influencing factors for TBM performance.

Different prediction models have been developed to estimate consumption of time, costs and cutter wear. Some of the well-known models are the NTNU-model (Bruland, 1998), the model from the Colorado School of Mines (Rostami & Ozdemir, 1993) , (Rostami, 1997) and the Q_{TBM}-model (Barton, 2000). The NTNU prediction model is an empirical method based on the historical field data of more than 250km of tunnels excavated with TBMs and the laboratory tests developed at NTNU/SINTEF drillability laboratory (Dahl, Bruland, Jakobsen, Nilsen, & Grøv, 2012). The parameters used by the NTNU model are rock mass properties: Geology (density and orientation of fracture systems), the Drilling Rate Index (DRI)™, the Cutter Life Index (CLI)™ and quartz content, as well as machine parameters: Cutter thrust, cutterhead RPM, cutter spacing and installed power. The step by step model estimates: Net penetration rate (m/h), cutter life (h/cutter, sm^3/cutter), machine utilization (%), weekly advance rate (m/week) and excavation costs (NOK/m). There is a simulation tool (FULPROF) with which it is easy and fast to make calculations and do risk assessments.

While the laboratory tests, the Drilling Rate Index (DRI)™ and the Cutter Life Index (CLI)™, are continuously being developed and there is a large amount of data, the empirical models are based on past data and the machine technology and capabilities have to be updated frequently. A higher knowledge of the boring and wear process requires regular updates. A further extension of use, greater knowledge of the boring and wear process, technology and capacity at the current level, together with the intervention of the new parameters in the process, would make the NTNU prediction model more applicable and have more accuracy.

Complementary competence - Two PhD-students have been recruited through the project FAST-Tunn and are currently working at NTNU. Prof. Grøv, who supervises the first PhD working at the Dep. of Engineering Geology and Mineral (IGB) and co-supervises the second working at the Dep. of Civil Transport and Infrastructure (IBAT) states that complementary interactions have been defined between the PhDs themselves and also between PhDs and the different partners of the project. "These PhDs will provide fundamental bases to better understand the rock fracturing process and improve the capabilities of the NTNU model for performance prediction of tunnelling operations in Norway," says Grøv.

Strengthen with industrial partners

The Robbins Company helped develop hard rock TBM tunnelling in the 1950s and is the industry forerunner in mechanized hard rock tunnelling. As a TBM manufacturer, Robbins is also well aware of the need to optimize disc cutters for a wide spectrum of conditions. "We are involved in R&D projects on everything from soft ground tool design, to EPB-specific disc cutters, to lubricants that may increase cutter life," said Steve Smading, Product Manager for the Robbins Cutters Department (Tunnelling Journal Oct/Nov 2011).

Robbins will provide experience and knowledge in TBM operation and cutter ring performance evaluation in the-full scale tests. Robbins has several ongoing TBM projects; this provides opportunities for full scale data and case study validation of the new cutters proposed in FAST-Tunn. A field study has already been done, at The Alimineti Madhava Reddy (AMR) Project in India. The field study was done by PhD students collecting core samples from the tunnel face for studies on rock properties and fracture mechanism, and by to Master students following up the use of anti-abrasion foam for hard rock TBM tunnelling.

> **"We are involved in R&D projects on everything from soft ground tool design, to EPB-specific disc cutters, to lubricants that may increase cutter life"**

"Robbins primary interest is in the practical and cost effective application of advanced technologies to our everyday products. The admittedly ambitious goal of a 25% increase in cutter disc life in hard and abrasive ground will greatly benefit our customers if it can be achieved," says Smading. Such an increase in disc life will significantly reduce the cost of tunnelling by increasing the amount of time available for boring.

Smading also noted that cutter disc steels have not changed appreciably for more than twenty years. This is not for lack of effort, but rather it is a testament to the suitability of the steels developed in the 90s and still in common use. "However, we are optimistic that by applying numerical methods, chemistry, and materials science, coupled with laboratory and field testing, that cutter disc steels can be further improved upon."

The benefit of anti-wear products

BASF Construction Chemicals is one of the worldwide leading suppliers of specialty chemicals for underground construction – including TBM tunnelling. "We truly believe that the use of anti-wear agents have a significant effect on the cutter tool lifetime but there is still a lack of in-depth knowledge when it comes to detailed wear and corrosion mechanisms," said Lars Langmaack, technical manager TBM. "There is a need to better determine the individual importance of the identified key influencing factors like temperature effect, corrosion mechanisms, moisture content, choice of lubrication agents and choice of steel protection agents." Additional benefits of the anti-wear products are their dust catching capabilities, another strong argument to improve working conditions and to create a healthier working environment.

BASF contributes to the consortium with extensive chemical background knowledge, foam systems for hard rock TBMs and testing material. Langmaack points out the importance of the composition of the consortium and its common interest. "This project will bring us a considerable step ahead for the precise development of anti-wear products. What is particularly interesting for us is the close link between university research, numerical modelling, metallurgical background as well as the site focused application provided by the industrial partners which makes this project quite unique and hopefully likewise successful."

Future members of the consortium

The project has been looking for additional members to be included to complement its value chain. At present one Norwegian contractor has been approached to become a member of the project. TBM tunnelling appears to have once again become popular in Norway after 20 years of absence and the first contractor to resume TBM tunnelling is LNS (Leonard Nilsen & Sons). LNS will do about 10km of tunnels for the hydroelectric power scheme called Røssåga. Having a contractor in the consortium enables vast possibilities for the project to perform tests at a tunnel site close to the University campus in Trondheim. In being part of the hands-on development of future cutter technology, the contractor also adds to his understanding of the entire process of TBM-tunnelling: A win-win for all parties involved.

An important part of the scientific work to be done during the research project is developing a dedicated system to store, systemize and analyze data to create correlations and diagnostic indicators. Having such tools installed does not, however, diminish the need for manual observations, recordings and monitoring. The project is currently discussing with Babendererde Engineers to become a partner by supplying automatic TBM operation and performance recording tools.

Importance of strong ties between industry, projects, and academia

The Norwegian National Rail Administration (NNRA) has several upcoming tunnel projects in its extensive investments program aimed at achieving higher speed and capacity. Many include long tunnels according to Trine Bye Sagen at their office for technology development in Trondheim. One such project is the Follobanen which is 2x20km of tunnelling with TBMs as the Owners preference.

Norwegian rock consists of mainly Precambrian gneisses, commonly referred to as hard rock. Boring operations in hard rock are typically associated with low penetration rates, high tool wear and frequent cutter ring changes, which influence the project costs. The NNRA wants increased flexibility regarding choice of excavation method, and hopefully the FAST-Tunn project will give us better steel quality which in turn will reduce costs and increased predictability says Trine.

BMS Steel and Scana Steel Stavanger, both suppliers of products in wear resistant cast steel, have joined this project with the ambition to increase the use of wear resistant cast steel, and to find new products and new areas of use. The goal is to utilize the unique possibilities of material structures, e.g. hard particles in a ductile matrix for wear resistance, in components made by net shape castings.

"We are working closely with Norwegian steel companies in the design process of new steel alloys. It is a great benefit for the project since Scana Steel Stavanger has a melt shop with foundry and forging capabilities to produce high quality steel and BMS Steel uses sand and shell casting techniques to manufacture the desired prototype components," says Rune Østhus, research scientist at SINTEF Raufoss Manufacturing.

"Within this project, we have identified world-class laboratory facilities and middle scale investigations of the steel against various rock types as the added values recommended for steel companies before manufacturing final products in large quantities," says Østhus.

The success of the complementary research activities at SINTEF institutes and NTNU relies on the close dialogue established with the companies to support the development of the technology.

"FAST-Tunn offers Scana Steel Stavanger a unique opportunity to find new areas of applications for our steel alloys and possibly the development of a new steel alloy. It is also a huge benefit to be able to perform this in close cooperation with the research facilities and end-users participating in this project," says Håkon Jørgensen, metallurgist at Scana Steel Stavanger.

Conclusion

The two main objectives of this project are: 1) to develop more efficient systems for the excavation of hard rock using cutter rings for TBMs, and 2) to improve the capabilities of the NTNU model for performance prediction of tunnelling operations in Norway. To reach this a cross disciplinary approach must be taken involving theory, laboratory testing, numerical modeling and full scale testing. Empirically the prognosis model will follow-up the results of this and reflect the innovation in terms of constituting a tool for better predictability on cost and time.

The aim of creating longer lasting cutter wheels will also have a beneficial environmental influence, since the production, refinement and heat treatment of steel is an energy demanding process. Current technology development in chemicals that provide a smoother rock – tool interaction will add to these savings and improvements, and as such it constitutes an important part of the TBM-technology development.

These are the goals we are aiming concludes Prof. Grøv, managing a project which combines research and academia closely with suppliers, manufacturers and end-users. A first step in what we hope can be a continued research effort in the future.