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Use of excavated rock material from TBM tunnelling for concrete proportioning

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SUMMARY:

This thesis studies the possibilities to utilize excavated rock material from tunnel boring machines (TBM) for concrete proportioning. Available alluvial sand deposits are becoming scarce on a global scale and crushed rock are normally the replacement. Tunnel boring machines (TBM) grinds the rock when excavating and produces a granular material which has potential as concrete aggregates. Utilizing this material has proven to be a viable alternative to the natural sand, additionally influencing the environmental and economic interests.

A list of earlier TBM projects where spoil has been utilized into concrete aggregate are listed. Particle size distributions (PSD) from earlier TBM projects are investigated with focus on the filler content. Impurities in concrete aggregate and chemical reactions such as Alkali-silica reaction, mica and sulphur are obstacles in terms of utilization. High filler content in TBM spoil (10-20%) can be utilized with the knowledge of its effect on concrete and using a newly developed micro proportioning principle.

Introductory an overview of TBMs and the boring process are presented and the parameters influencing the PSD are described. Concrete aggregate requirements and proportioning with Alkali reactive aggregates. Different material processing methods are presented, including potential crushing, screening and classification machinery for processing of spoil. Field research has been done at TBM projects Follo line and Ulriken in 2016/2017. Collected spoil was investigated in terms of utilization into concrete aggregates. The choice of sieve mechanism in (wet or dry) <0.125 mm fraction impacts the accuracy. Further experiments include the TBM filler composition and behavior in a cement paste to evaluate rheology.

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Bruk av bergmateriale fra TBM drift for betongproporsjonering

UTFØRT AV:

Torjus Berdal

SAMMENDRAG:
Denne oppgaven tar for seg mulighetene for å utnytte bergmateriale fra tunnelboremaskiner (TBM) i betongproosjonering. Tilgjengeligeheten av alluviale avsetninger er blitt redusert på global skala og knust stein /maskin sand er normalt erstatningen. TBM knuser fjellet ved inndrift og produserer et granulært materiale som har potensiale som betongtilslag. Utnyttelse av dette materialet har vist seg å være et levedyktig alternativ til den naturlige sanden, og samtidig ha innvirkning på de miljømessige og økonomiske interessene.

Tidligere TBM-prosjekter der spoil har blitt utnyttet til betongtilslag vill bli gjennomgått. Partikkelstørrelsesfordelinger (PSD) fra tidligere TBM-prosjekter blir undersøkt med fokus på filler mengden. Urenheter i betongtilslaget og kjemiske reaksjoner som Alkali reaktivt tilslag, glimmer og svovel er hindringer når det kommer til utnyttelse. Høyt fillerinnhold i TBM-spoil (10-20%) kan utnyttes med kunnskap om virkningen på betong og ved hjelp av et nyutviklet mikroprosesseringsprinsipp.

Først vil en oversikt over TBMer og selve boreprosessen presenteres og parametrene som påvirker PSD blir beskrevet. Standardiserte tilslagskrav og proposjonering med Alkali-reaktive tilslag. Ulike materialbehandlingsmetoder presenteres, inkludert knusere, screeners og klassifiseringsmaskiner for å kunne utnytte massene. Feltarbeid er utført ved TBM-prosjektet Follobanen og Ulriken i 2016/2017. Innsamlet bergmateriale ble undersøkt med hensyn til utnyttelse som betongtilslag. Valget av siktmekanisme (vått eller tørt) påvirker <0.125 mm fraksjonens nøyaktigheten. Ytterligere eksperimenter inkluderer TBM fillerens sammensetning og oppførsel i en sementpasta med fokus på reologi.

FAGLÆRER: Professor Stefan Jacobsen

VEILEDER: Førsteamanuensis Pål Drevland Jakobsen

UTFØRT VED: Institutt for konstruksjonsteknikk, NTNU

Preface

This Masers thesis is the result of the work carried out in the spring 2017, marking the end of the Master's degree program in Structural Engineering at the Norwegian University of Technology (NTNU), Trondheim, Norway. The work has been carried out at the Department for Structural Engineering, together with one trip to Arna outside of Bergen and another to Åsland outside of Oslo. Each trip was in coordination with Bane Nor.

I would like to thank my main supervisor Professor Stefan Jacobsen(NTNU) and co-supervisor Associate Professor Pål Drevland Jakobsen(NTNU). I'm grateful for the friendly cooperation but most of all your insight and knowledge. With the help of your network it's been possible to arrange the trips to Ulriken and the Follo line and introduce me to engineers with knowledge on the field. Additionally, do I want to thank certain people:
-Post-doctor Rolands Cepuritis for sharing a part of his materials and important documents concerning micro proportioning.
-Site manager Vegard Løwø at Arna Quarry(NCC) for guided tour at the quarry and being helpful in the collection of TBM spoil.
-Concrete technologist Silje Ytterdal and Espen Rudberg at the Follo line project for an interesting meeting and sharing of data.
-Arnulf M. Hansen for sharing well preserved grading curves from the Madamfelle TBM.
-Construction manager Leon Eide (Bane Nor) at Arna for generosity and cooperation while staying at the Ulriken project for four days.
-Professor Børge Wigum(NTNU/Norcem) for the knowledge in aggregate production and sharing different issues on the topic
In addition, was my summer job in 2016 at the concrete batching plant Norbetong, Trondheim. This gave me insight from an industry perspective and additional possibilities in concrete proportioning.

Trondheim, 11st of June 2017

Torjus Berdal

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Table of content

Glossary of abbreviations and terms

Abbreviation/term	Meaning
ASTM	American Society for Testing and Materials
ISRM	International society for rock mechanics
EN	European standard
NS	Norwegian standard
PSD	Particle size distribution
NB	Norwegian concrete association
LA	Los Angeles test
GBT	Gotthard Base Tunnel
WTC	World Tunnelling Congress
JV	Joint Venture
CIP	Cast in Place(In-situ)
EMPA	Swiss Federal Laboratories for Materials Science and Technology
SCC	Self-compacting concrete
CEN	Comité Européen de Normalisation (European Committee for Standardization)

1. Introduction and background

1.1 Background

Urbanization is a global trend rapidly increasing and requiring cities to adapt to the forthcoming changes. Predictions state that 70% of the world's population will live in cities by 2050 [3]. Action is already taking place as Crossrail in London will result in 42 km of new rail tunnels below the city, this is accomplished using eight TBMs [4]. In Stockholm 18 km of road tunnel is created below the city, taking approximately 10 years to finish [5]. In Oslo, 20 km high speed rail link is excavated as part of the Oslo InterCity project, connecting Oslo and Ski. 21 TBMs are being used for tunnelling 111 km below Doha, the capital of Qatar [6]. The increasing demand for effective logistics and infrastructure is evident, either below cities or between them. Tunnelling in or between urban areas requires gentle tunnelling avoiding already existing underground constructions , this can be solved by use of TBM's which has seen a massive technology leap the past 20 years, earlier limitations as depth and groundwater influx are now possible to overcome [7, 8].The underground volumes creates millions of tons of excavated material normally ending up in surrounding landfill and deposits. This results in extensive transport throughout the project, transporting the excavated material long distances and simultaneously emitting greenhouse gases. The tunnel is normally covered by concrete in the lining and portal. If the TBM spoil was to be utilized as concrete aggregate it would be beneficial both economically and environmentally. It would be more value generating compared to use the spoil as new agricultural or filling up old quarries. Additionally, would the need to transport be significantly reduced as the utilization of the TBM spoil could be placed at the tunnel portal with a processing facility and a concrete bathing plant. The investment cost of this facility would be repaid as the project could potentially be self-supplied on concrete.

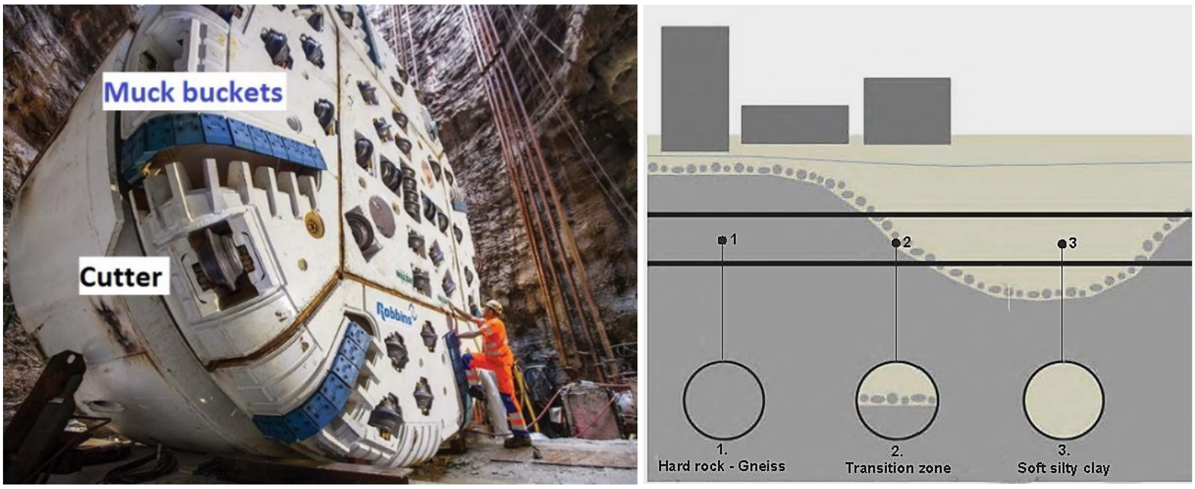


Figure 1-1: Left: Double shield TBM with 7m diameter in Ohio, USA [9]. Right: Potential geological conditions for underground tunnelling, a key parameter if the spoil is to be utilized as concrete aggregate [10].

Concrete is one of the most widely used material in the world and it contains 60-70% aggregates [11, 12]. The aggregate normally originates from quarries and natural sand deposits. Aggregates can be divided into natural or crushed. The natural sand originates from river deltas dating back to the late ice age. Natural sand edible for concrete has naturally been formed by bedrock being transported to the river outlet and naturally sediment and sorted. For countries with these naturally deposits of sand there has never been any interest or need to use the finer fractions of the crushed aggregates for concrete. But the naturally sand deposits are limited and is gradually being emptied [13]. It appears clearly that measures must be made to develop methods to produce concrete aggregates that's not depended on natural sand deposits. Countries with few natural sand deposits has already met the reality of emptying their deposits. In certain countries its evolved into black markets and stealing from sandy beaches [14].

A noticeable source of a less used sand and gravel are reviling itself using tunnel boring machines (TBM). The TBM is a type of mechanized tunnelling technology which is an alternative to the widely-used drill and blast method. Instead of using explosives, the TBM is a large-scale drill which shatters the rock. The result is a much finer excavation material with a distinctive flaky shape. The spoil (excavated material) has potential to be utilized into valuable gravel and sand, though often used as landfill or sold to a third parties due to not being applicable in the project. Uncertainties on petrography, impurities and filler is unwanted in concrete aggregates [15]. Figure 1-2 illustrates different particle size distributions (PSDs) from raw granular sources, most interesting is the hard rock TBM spoils close resemblance to concrete aggregates. The PSD is reviling excessive filler amounts and to coarse gravel content, creating a dense granular material. If only unprocessed TBM spoil was used in as concrete mix alone it would most likely result in a water demanding concrete, and risk of weakening the structural properties due impurities and the flaky and elongated shape.

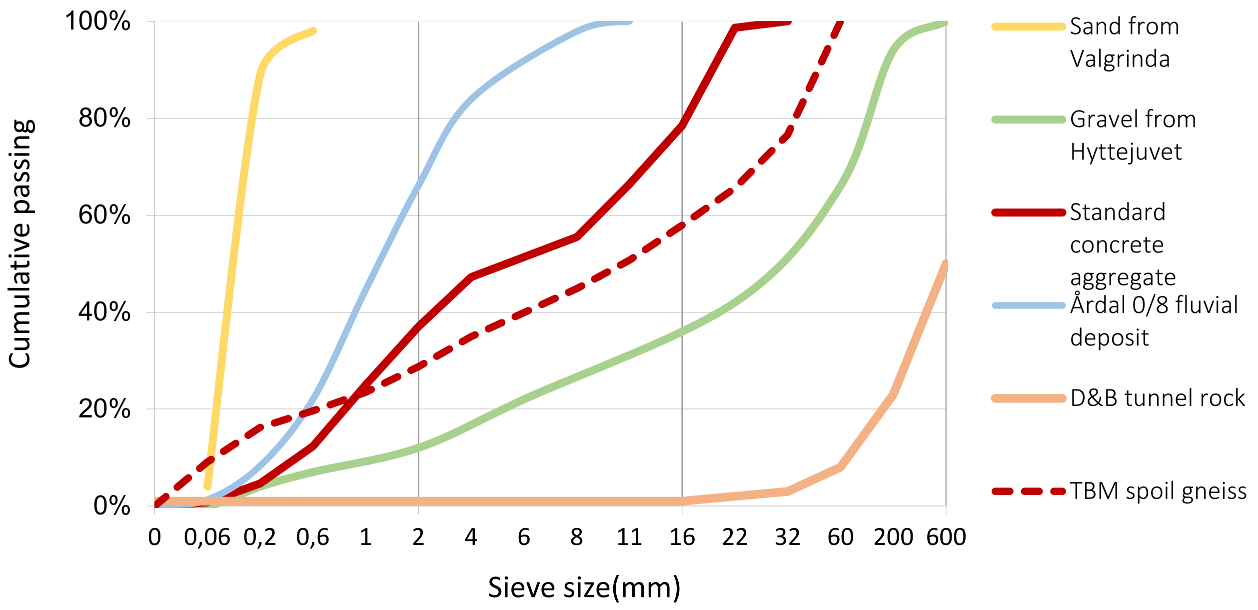


Figure 1-2: The PSDs illustrates the TBM spoils close resemblance to concrete aggregates in comparison to other granular sources.

Considering the spoil as a crushed granular material makes it possible to apply newly developed concrete proportioning techniques to utilize the spoil in concrete. Initiatives has been made to increase the use of crushed sand with PhD published by Rolands Cepuritis at NTNU. The PhD investigates the methods of processing crushed sand with a micro proportioning method. The term micro proportioning involves determining detailed parameters of sand on micro scale, emphasizing on the fraction below 0.5 mm as this is greatly determining the concrete workability. With this knowledge it is possible to engineer different PSDs for a desirable fresh concrete behavior [16]. The PhD is a strong contributor in the transition into increased use of crushed sand for a more value-generated use. Driving forces for the transition will relate to the gradually depletion of natural aggregate deposits.

The material processing industry plays a key role in the comminution of utilizing TBM spoil into quality concrete aggregates. As the hard rock TBM spoil has a characteristic flaky shape, the use of impact crushers reduces the flaky shape and creates more cubical particles suited for concrete aggregates. This technology has already been successfully applied at TBM projects in Europe since 1995 [17-20]. Figure 1-3 Illustrates how a VSI (Vertical shaft impactor) has processed flaky crushed aggregates into a more cubical granular material.

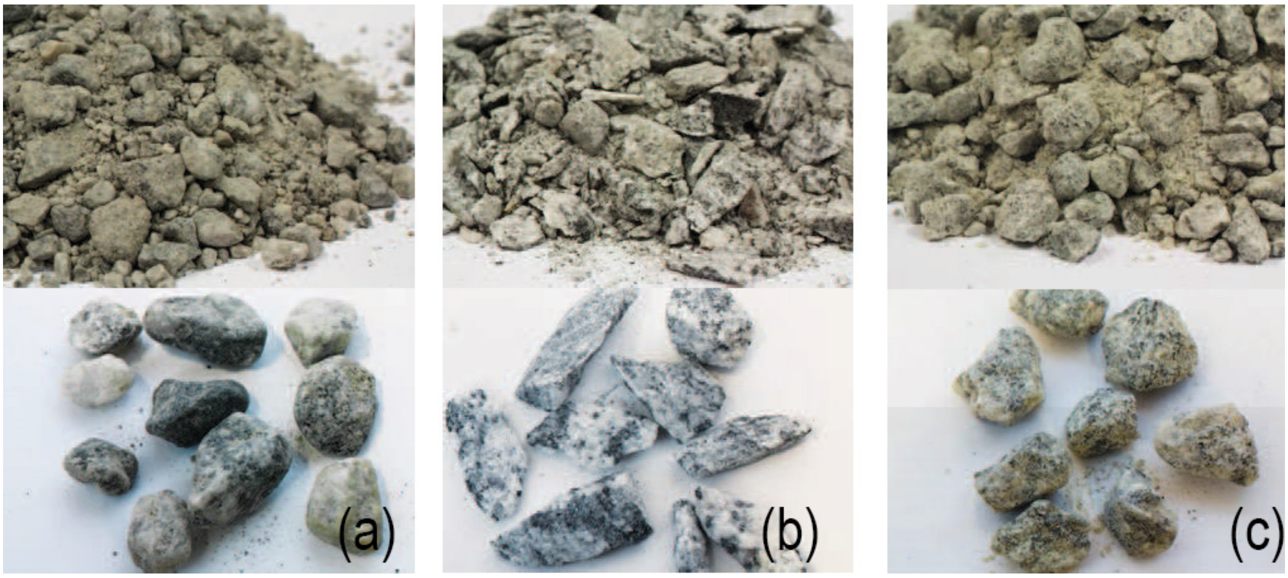


Figure 1-3: Three different 0/8 fractions from Norway. (a) The most wanted: glacifluvial originated sand, (b) low quality crushed aggregates. (c) Crushed aggregates processed through a VSI, producing a product in close resemblance to the glacifluvial sand

1.2 Current state in utilization of TBM spoil

As of 2017 there are only a few countries who can confirm utilization of spoil from hard rock TBM projects, these are Switzerland (5 projects), Austria (1) and Norway (2), France (1). Project details can be found in the result chapter.

Earlier Swiss tunnel projects(AlpTransit) has already been processing tunnel spoil into high quality concrete aggregates in several large scale TBM projects the last 15 years, two of these projects are Gotthard base tunnel and Lötschberg tunnel, both finished before 2016 [21-23]. In light of these projects it was developed concrete admixtures especially suited to handle the processed spoil and simultaneously producing high quality concrete. The concrete requirements which must be emphasized, breaks down to resistance to alkali-silica reactive aggregates, aggregates containing sulfates, water intrusion, aggregate angularity and fire resistance. Another obstacle in material processing is high mica content, also solved by the Swizz. This has been done by developing floating technique, with confirmed removal of 50% mica in a 0/1 mm crushed sand. In combination with other machinery like cubifiers and gravity sand-sizing, the Swizz processing facilities has demonstrated concrete mixing with use of 100% crushed aggregates [17].

Relevant literature on material handling of TBM spoil have been written, this includes Cedric Thalmann's doctoral thesis from 1996 submitted at the Swiss Federal Institute of Technology in Zurich(ETH), with the title: *Assessment and possibilities for re-utilizing muck from mechanical tunnelling as concrete aggregate.* Additionally, did Cedric Thalmann have the title expert site manager for materials and concrete at the Gotthard base tunnel(GBT).

Additionally, are there a so-called Dragon report from the EU with headquarters at University of Leoben. This report proposed a method to optimize the potential of TBM spoil with automation and massively upgrading the TBM. Adding analyzing machinery connected to the conveyer belt and disc cutter monitor system. This is done to increase the efficiency to determine the spoils potential and application areas. Further described in chapter 2.7 [24].

Other publication in the field of utilizing with computer simulation:

- Stefan Ritter Master thesis 2009, University of Leoben:
  Tunnel Excavation Material Handling Using Decision Analysis
- Markus Scheffer, Tobias Rahm, Ph.D. candidates, Ruhr-University Bochum(RUB), paper released 2016: *Simulation-Based Analysis of Integrated Production and Jobsite Logistics in Mechanized Tunnelling.*

The industry working with excavated tunnel material from TBM's are using different terminologies to describe the excavated material. Table 1-1 lists the established terms which are used including the accompanying description. During this thesis, the term spoil will be used. All mentioning of <u>hard rock</u> TBM tunnelling will from here on be referred just as TBM tunnelling.

Table 1-1: Terminology describing the excavated tunnel material produced by a TBM.

Term	Description	Used in this refrence
Spoil	Raw excavated tunnel material, normally transported on a conveyor belt. This term will be most used throughout this theis.	[17, 18, 25, 26]
Muck	A term for exavated tunnel material, from a point of view describing the material as a waste.	[1, 25, 27-31]
Chips	Describing the larger sized spoil, excavated by the TBM	[32, 33]
Cuttings	Describing the minor sand particles of the spoil excavated by the TBM.	[22, 27, 32, 34, 35]
Breakout material	Synonym to spoil	[36]
Cut material	Synonym to spoil	[33]

1.3 Objectives and limitations

The scope of this report is to introduce the reader to the tools and parameters used in concrete proportioning and give a brief introduction to TBM tunnelling. Literature in the field of utilizing TBM spoil has been gathered to give the reader an understanding of what's already accomplished. TBM spoil is more than a waste material. Though the measures to start utilizing is a demanding, and the actual utilized material may be less than foreseen due to unknown geology conditions through the tunnel. The use of TBM spoil is to be investigated, emphasizing on the filler fraction. Investigating the filler, concerning its behavior in fresh concrete. This involves clarifying impurities in the spoil which could influence concrete either in fresh state or in the long term (100 years). The alternative in this case is the third-party aggregate which always would be quality assured and delivered with a fixed price from regional suppliers.

Filler is heavily responsible for the slump value of fresh concrete. With this knowledge, the spoil can be measured in accordance to the FlowCyl apparatus method. The FlowCyl will give important data concerning the flow resistance of the matrix. Using three engineered limestone fillers with known PSD on micro scale, the limestone filler can be mixed to mimic the TBM filler. The work of Rolands Cepuritis and the micro proportioning of concrete legitimizes the use of crushed fines and eventually TBM filler in concrete proportioning [37].

Objectives

- Investigate PSDs from hard rock TBM tunnelling projects.
- What are a characteristic PSD TBMs, and which parameters decides the PSD produced by a TBM.
- What are the used measurements and apparatuses to characterize TBM spoil.
- How can TBMs produce more suitable concrete aggregates.
- How do TBM filler behave in a flowing cement paste compared to a reference limestone filler.
- How do the TBM filler correlate to blasted rock from Norwegian quarries, when PSD are compared (<0.125 mm)
- Regard all spoil as Alkali reactive and adapt the concrete recipe accordingly

Limitations

- Soft rock tunnelling will not be discussed due to the properties of the output material. The thesis will not discuss the blasted rock or the comminution of these. The author is acquainted with already utilized blasted tunnel rock used as concrete aggregates.
- Economical evaluation in terms of investment in a processing facilities in a tunnel project. This is a key factor for utilization of the spoil at site. This subject is highly relevant, though will not be discussed due to lack of literature and minor cooperativeness from the industry.
- Material processing will mostly be discussed on a general level and technical aspects will be to comprehensive to include in this thesis.

2. TBM, spoil characteristics, material processing and concrete proportioning

2.1 The boring process

The machine was invented to increase the efficiency in the mining and excavation industry compared to the drill and blast method back in 1952 [38]. The TBM is powered by electrical engines, together with its propulsion system which is normally powered by hydraulic compressed arms to either the tunnel lining or invert concrete segments, or both. The first TBM project completed in Norway was a 1.0 m diameter tunnel for Tokke hydroelectric plant in 1967 [39]. This was followed by around 50 other TBM projects mostly in connection with hydroelectric plants. This TBM period lasted to 1992 ending with the Meråker project, also a hydroelectric plant [39].
Only a few of the projects did utilize spoil and most ended up as landfill [28]. Norwegian Water Resource and Energy Directorate (NVE) did research concerning erosion and fertility. Confirming successful growth of trees, grass, potato and raps with TBM spoil [40].

China has completed several large-scale tunnel projects the last years using mechanized tunnelling, though using EPB or mixshield will naturally be a response to excavating through different cohesive soils and consequently being less suitable as construction aggregates[41].

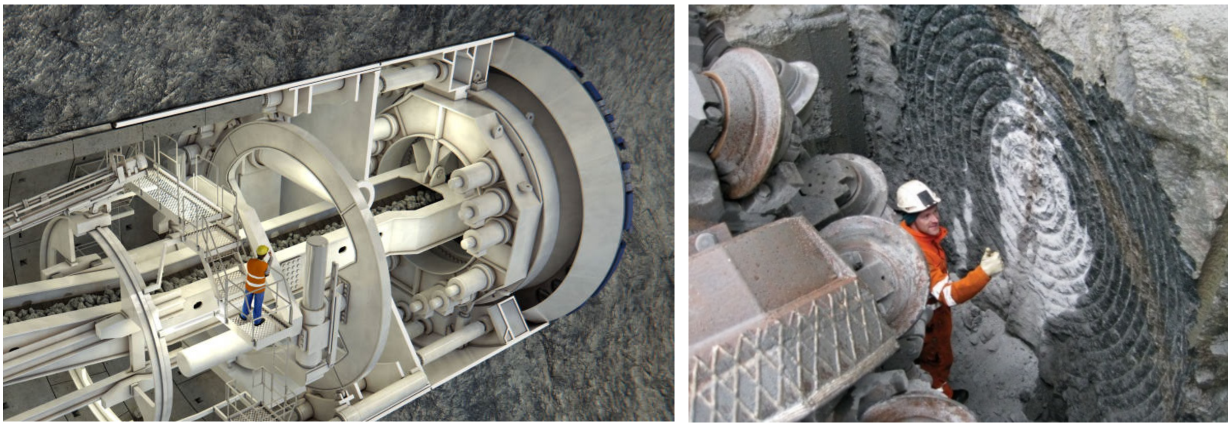


Figure 2-1 Left: Illustration of a double shield TBM[42]. Right: An engineer is inspecting the tunnel at a project at Faroe Island in 2010. The spacing and penetration is visible in the rock face [43].

Different TBMs are developed for every possible geology and soil conditions. and are here divided into 6 diverse types. Each type has been custom made to overcome a type of rock condition or soil conditions.

Table 2-1 General description of the different TBM types

Type	Geology	Technology
Gripper /Open TBM	Medium to high rock strength	Hydraulic arms gripping on to the tunnel wall and with thrust pushing the TBM forward, no protection from rock fall if not manually secured with bolts and/or reinforcement mesh and shotcrete.
Double Shield TBM	Hard/ medium rock	Has a protective second layer underneath the outer edge which protects the lining until concrete segments are in place. Thrust is generated either grippers or/and axial pressure on concrete segments.
Single Shield TBM	Medium/soft rock, above groundwater level	Has no gripper possibilities, progresses with axial pressure on concrete segments.
Mix shield/dual mode/crossover TBM	Mixed soils with rock	Uses technologies from other TBM types to cope with both cohesive soil and hard rock
Earth pressure balance machine (EPB)	Soft and cohesive soils and loose sedimentary deposits below groundwater levels	Completely sealed, and water tight excavation with pressurized cutterhead chamber and slurry transport of spoil.

During the excavation with TBM, the cutter discs are freely rotating around their shaft, while the cutterhead is thrusted forward with a rotating motion. The rotational movement is normally generated by electric motors. Thrust is generated by hydraulic arms. Wear are gradually occurring, reducing the work efficiency of the TBM[44]. The disc spacing and thrust is largely effecting cracks formation and amount of chips, cuttings and dust produced. The TBM has possibilities to adjust both rotation speed, thrust and angle. It's proved that an increased thrust normally generates more cubic and larger chips, but it may not be effective in the terms of advance rate [39]. Real time monitoring of every cutter disc is possible, measuring factors as thrust, cutter wear and cutter temperature. Possible failures can also occur as a cutter stops turning because the seal is filled with rock debris or clay. At Gotthard base tunnel(GBT) there was confirmed grain sizes of up to 800 mm, this was crushed in back-up installation of the TBM, e.g. a roll-crusher at GBT and a jaw crusher at Koralm TBM project, crushing down to grain sizes with Dmax 150 mm [45]. To add a crusher to the back-up system is an optional choice for the entrepreneur.

Figure 2-2: Left: Jaw or roll crusher can be installed behind the TBM shield to guarantee maximum spoil size on conveyer belts. Right: Double Shield TBM spoil transported on a conveyer belt at Alimineti Madhava Reddy Project in India [46, 47].

Development into higher thrust of the TBM is limited to the maximum thrust capacity of the cutter discs(ring steel)[39, 48]. Table 2-2 shows how increasing disc diameter, spacing and thrust results in increased penetration rate. Calculating penetration rate of the TBM with i_0 (measures penetration for each revolution of the cutterhead). The normalized penetration is calculated by regression [49].

$$i_0 = (\frac{M_B}{M_1})^b \ \ (mm/rev) \tag{1}$$

i_0 = TBM penetration per revolution(mm/rev)
M_B = gross average thrust per cutter (kN/cutter)
M_1 = critical thrust to achieve a penetration of 1 mm/rev (kN/cutter)
b = penetration coefficient

M_1 and b are factors which includes factors as wear of cutters, and normalization of job site data. Efficient cutting process can be indicated by the frequency of larger/thicker chips generated between two kerfs. As this is difficult to actually measure behind the cutterhead the use of the particle size distribution(PSD) can give a guiding indication of the boring efficiency [49].

Table 2-2: Example of various parameters and resulting penetration rate [39].

	TBM specifications 1	TBM specifications 2
Disc cutter diameter(mm)	42.5	50
Disc cutter spacing (mm)	65	70
Average thrust, (kN/cutter)	230	320
Penetration rate (m/h)	3.45	5.25

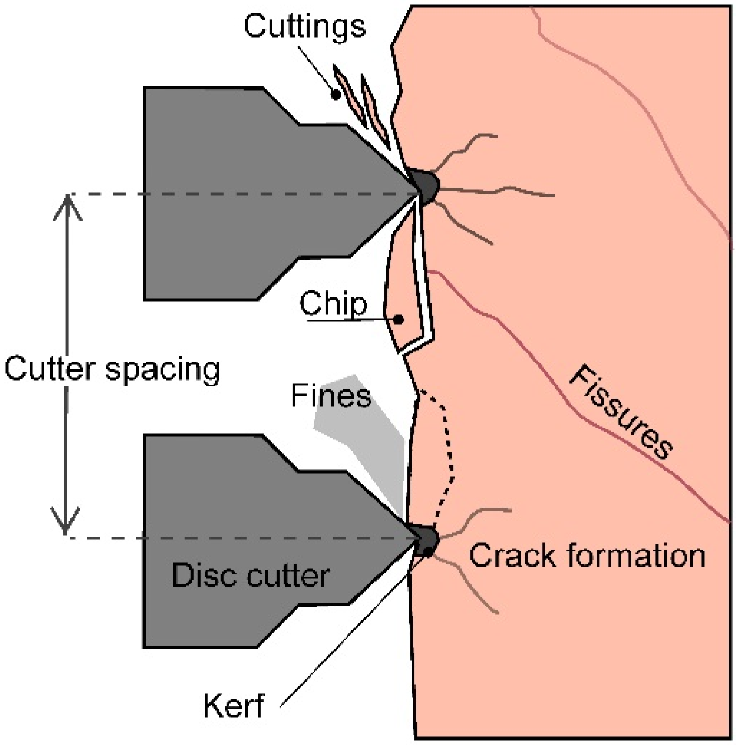


Figure 2-3: Schematic of the excavation mechanisms at the TBMs cutterhead [50].

Figure 2-3 are showing the factors involved for creation of the particle size distribution from a TBM [51].

- Fines, evolving from contact zone between cutterhead and rock
- Cuttings created by cutter alone and fracturing of minor rock fragments
- Chips created in between two kerfs
- Random sized fragments or blocks created in combination of crack formation by the disc cutter and already established fissures in the rock

The cutters discs are part of two different processes when rotating. The first is the crushing process which is the result of the cutter disc penetrated into the rock and creating the kerf, see Figure 2-3. This fragmentation or crushing is the main reason for the high number of fines produced by the TBM. Secondly comes the cracks produced for each turn the disc cutter passes the same face. Each turn lengthens the cracks, which may after the third or fourth turn connects to the neighboring crack created by the adjacent kerf. The connection releases larger pieces called chips, this is a wanted effect as it leads to a more effective excavation (chipping frequency). Cracks created by the cutter discs can also connect to already established fissures in the rock. Larger cutter disc spacing has proven to create coarser PSD's, but may negatively affect the penetration rate, see figure Figure 2-5 [28, 49].

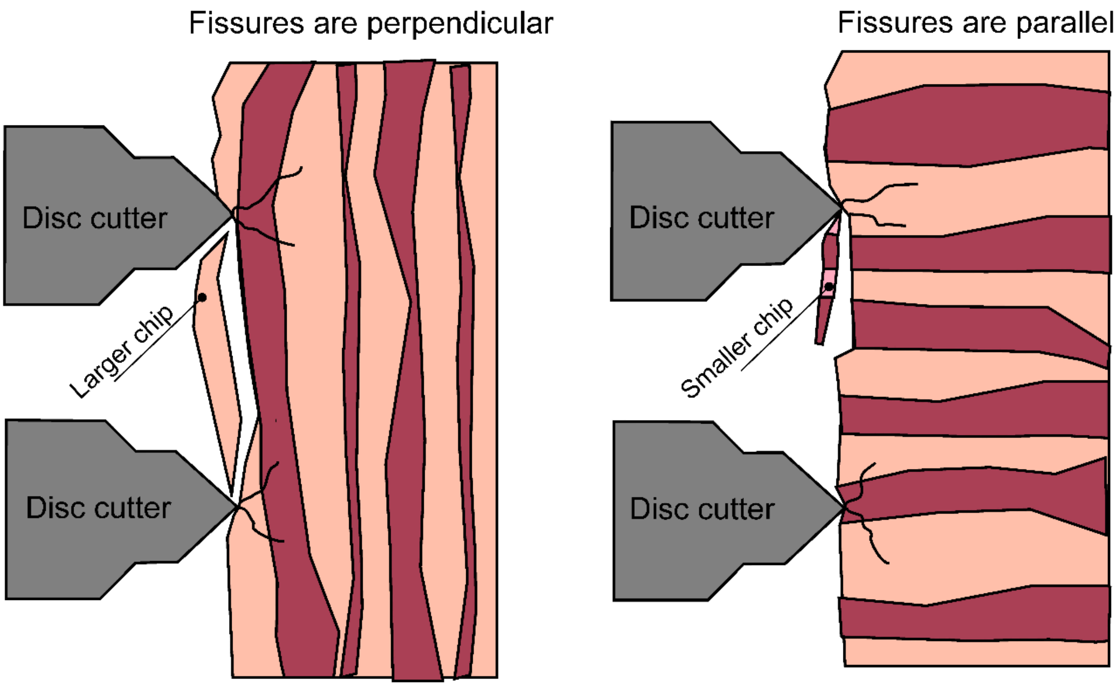


Figure 2-4: Anisotropy in relation to the cutter face angle will impact the spoil properties. Tunnelling perpendicular to the direction of fissure direction tends to generate larger and more elongated chips [28].

The Anisotropy in the rock will influence the chip formation as seen in Figure 2-4. The layering structure will possibly result in the chip being "cut off" when the disc cutter is more parallel to the rock. When the rock layers are more perpendicular to the disc cutter, the formation of chips will not be stopped and the chips has potential to grow larger between to kerfs.

When the chips, cuttings and fines are loosened from the rock, it falls down and are picked up by the muck buckets. Transport of the spoil out of the tunnel are normally done by conveyer belts or trains. The use of conveyer belt will require adaptable length to compensate for the moving TBM [10].

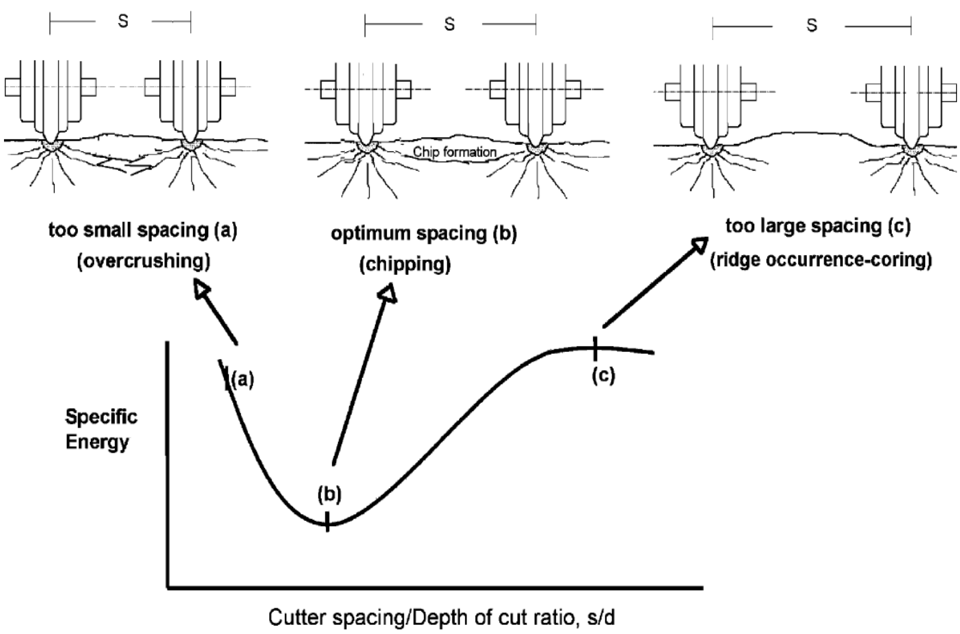


Figure 2-5. Right: The optimum cutting efficiency is closely related to the cutter spacing/penetration ratio and specific energy [27].

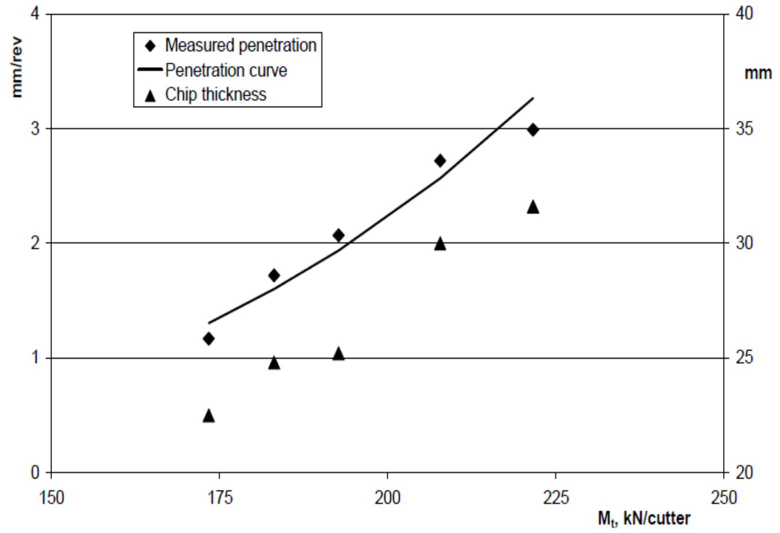


Figure 2-6: Increasing chip thickness with increasing penetration in a mica gneiss [49].

Research has been done on the cutterheads effectiveness and wearing, this have resulted in a general interpretation of the different rock parameters. Rock mass is a heterogeneous material, meaning its rock type can vary through a tunnel resulting in variation in anisotropy, geotechnical conditions, rock stresses and weakness zones. The TBM is relying on the rock itself to fragment chips but it will require increased thrust as the stress confinement grows with higher overburdens, increasing the wear of the cutterheads [52]. Focusing on the chips, it's confirmed that the mentioned parameters have an impact on the resulting aggregate. The chips will undergo a pressure relief as they are removed from the confinement of the massive and could later result in micro cracks and spalling and/or caving of the chips. In-situ rock strengths versus compressive strength of chips tested afterwards do confirm the differences [33].

A 5 m diameter double shield TBM tunnel named Tuzla–Dragos in Istanbul, Turkey have been investigated regarding rock cutting efficiency and noted an optimum ratio for efficiency between specific energy, depth of cut and spacing. The minimum s/d ratio in Figure 2-3b used a cutter spacing of 75mm. This is close to the similar choice for spacing at the Follo line and Ulriken TBM project which uses approximately 70 mm.

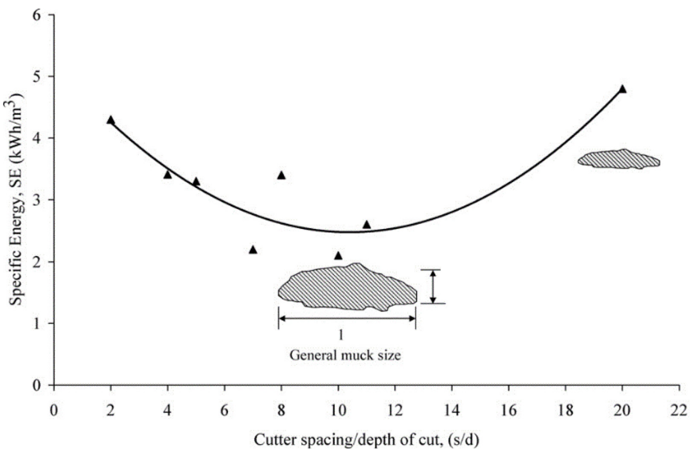


Figure 2-7: Left From the muck buckets the spoil is carried on to the conveyer system by closed gutters. Wetting of the conveyer belt is also used to lower the dust development inside the tunnel[53].
Right: Relationship between specific energy of the TBM cutter head versus spacing/cutter depth ratio. Largest PSD was obtained with a cutter spacing of 75 mm[27].

The radial distance(spacing) of disc cutter has proven to closely relate to the produced spoil, this can be seen Figure 2-8. Tests done on granodiorite with a normal spacing of 90 mm did show a doubling in the amount of >32 mm fraction when the spacing increased to 130mm[31]. This effect in increased spacing result does not take into account the possible reduction in penetration rate, which is of foremost importance in a tunnelling project. The PSD's from different type of rock material collected in Switzerland do also seem to have impact as seen in Figure 2-9. For spoil utilization it would be of importance to acquire enough coarse spoil to produce sufficient amounts of the coarsest fraction which normally is 32 mm in size [28].

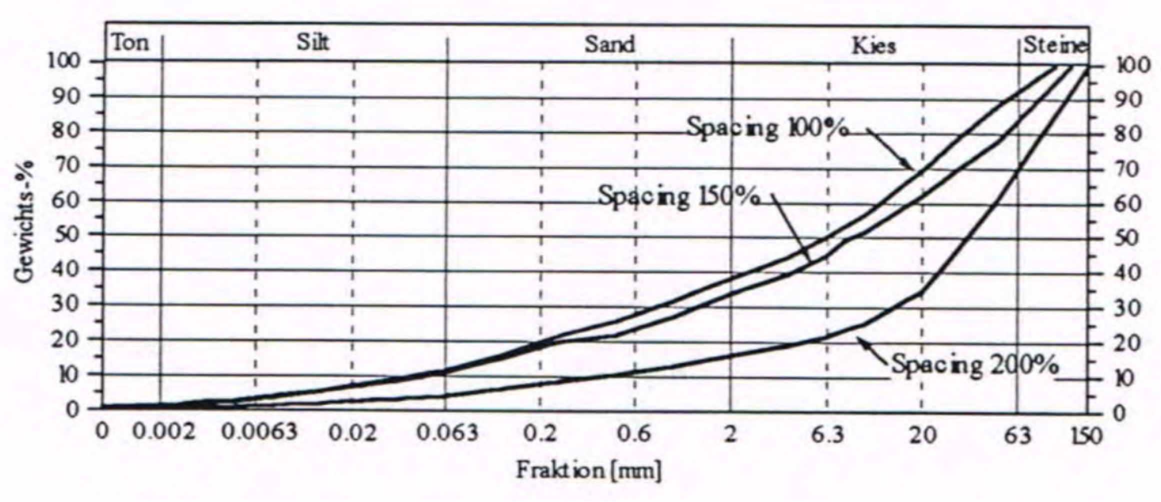


Figure 2-8:Increasing spacing between disc cutters results in a coarser PSD [53].

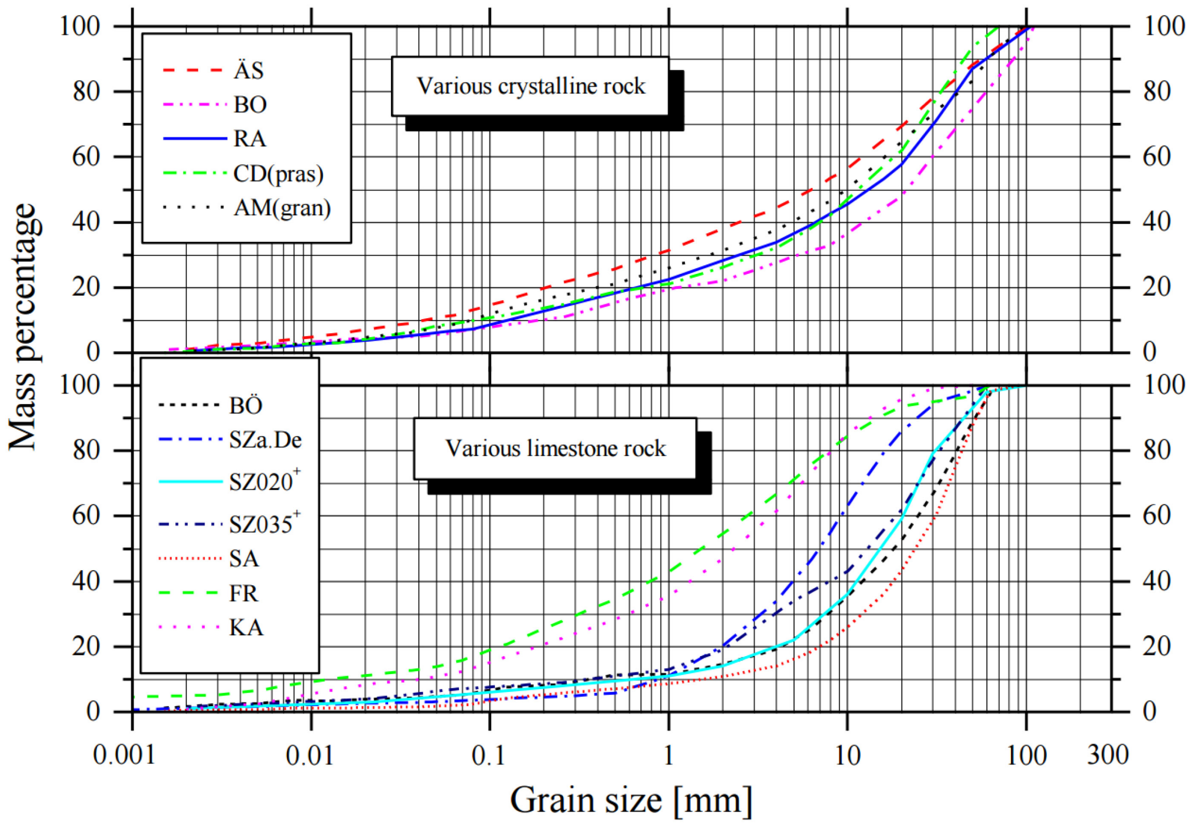


Figure 2-9: PSDs from different TBM spoils in Switzerland, sorted by crystalline or various limestone rocks [38].

2.2 Aggregate production and processing

There is minor experience in utilization of Norwegian TBM spoil. Out of 49 TBM projects between 1972-92, only one project did utilization the material in concrete [54]. Though with the renewed faith in TBMs comes longer projects lasting several years and producing millions of tons of spoil material[4, 55, 56]. As the TBM material is naturally unfit for concrete aggregate in both in particle size distribution and shape, it is the processing plant task to transform the material into useful concrete aggregates. As of today, there a range of mineral processing machinery to select from. Some are capable of handling high amounts of fines, others to transform elongated chips to more cubical. Low packing grade are experienced with TBM spoil , due to its elongated chips[28]

Crushing stages can be divided into four, the first stage is the primary crusher. Compared to blasted rock which can produce boulders of up to 2000 mm, the TBM spoil have much finer grading with Dmax 800 mm. This will affect the plant setup and max feed size of the primary crusher.

1. Primary – Reducing boulders and large rocks down to 300 – 400 mm
2. Secondary – reducing further to 40 - 60 mm
3. Tertiary- A large variety of reduction in this stage, ending in different fractions
4. Quaternary- reprocessing fractions with stricter requirements to e.g. fines, impurities or water content

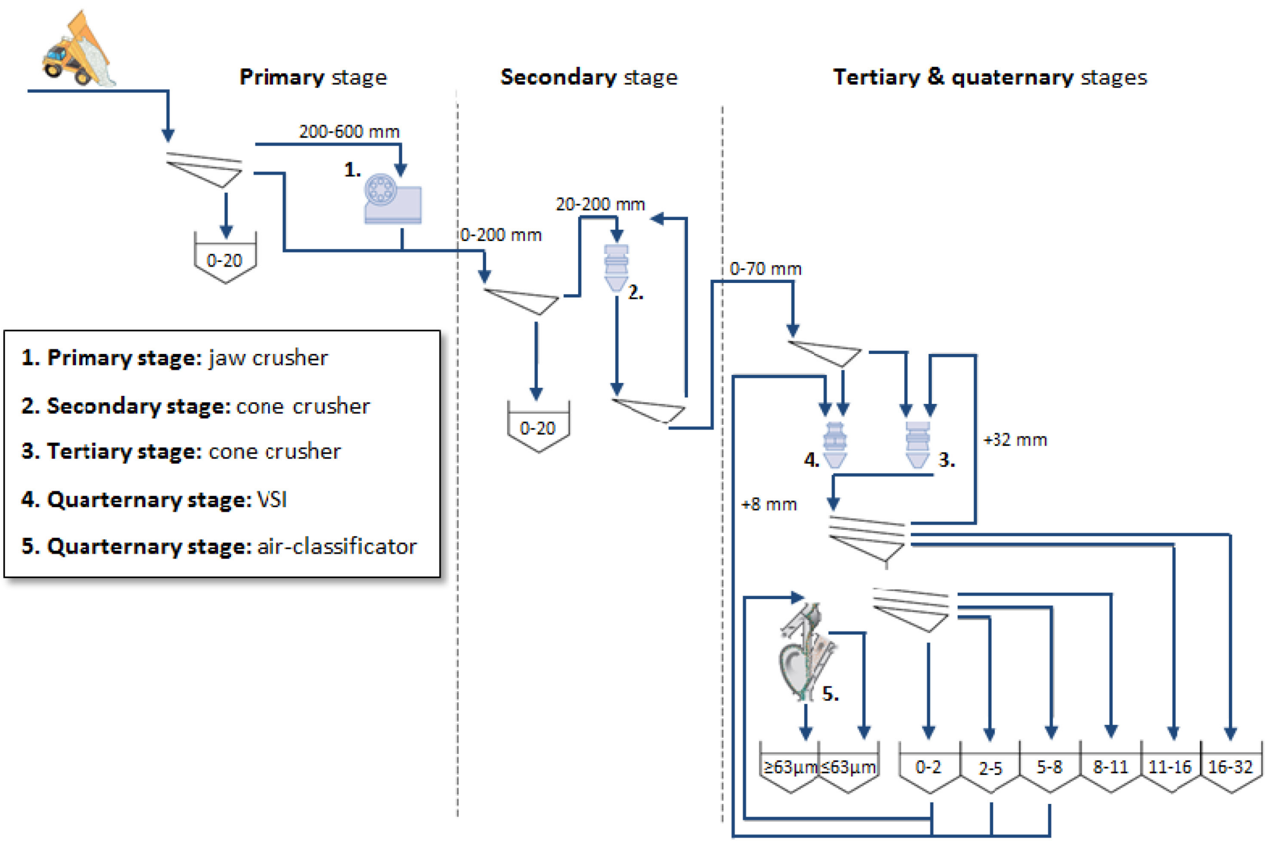


Figure 2-10: Processing of crushed sand, the quaternary stage is illustrated with a dry process , though wet processing is also possible [13].

2.2.1 Crushing and screening

Crushing is divided into two methods based on compression or impact resulting in different type of fragmentation of the material. Crushers are used in the aggregate and mineral industry and can also be divided into stationary and mobile plants. Setup of the crushers, feed sizes and speeds plays a major role in production of high quality construction aggregates.[57] At a certain stage in the comminution, the rock material fragments down to free minerals grains as e.g. free mica or quartz minerals. In Figure 2-11 are the different crusher types listed.

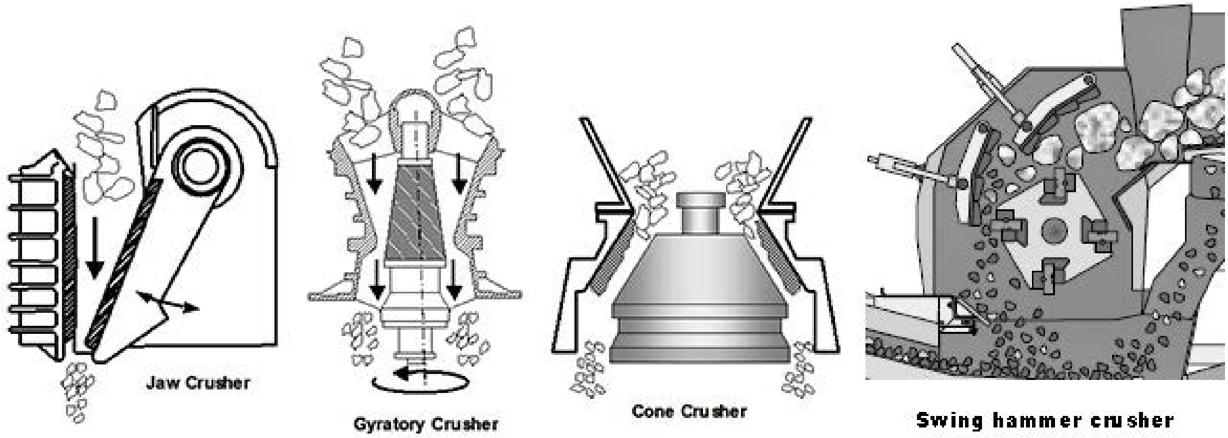


Figure 2-11: Illustration of crusher types which potentially be used in processing TBM spoil [34].

Table 2-3: Listing well established crusher types

CRUSHING			
Type	Model	stage	Reported use
Compression crushers	Jaw crusher	1	Large quarries. Part of the back-up on TBMs at Koralm [1].
	Gyrator crusher (cone crusher)	1,2, 2,3,4	Large quarries, Used in koralm and follo processing plant [22]
	Roll crusher	1	Quarries, part of the back-up on TBMs at GBT [45].
Impact crushers	Swing-hammer crusher	2,3	Recycling concrete for aggregate utilization. Used at the Linthal project
	Vertical shaft impactor (VSI)	3,4	Quarries, Used at the Koralm and Follo line project
Mills	Impact mills	4	Mineral processing
	Tumbling mills	4	Mineral processing
	Roller mill	4	Mineral processing (cement production)

Impact crushers relies on the rock itself to fracture along its natural cleavage planes, resulting in what is called a good quality product in the industry. For crushing of TBM material one should focus on reducing the amount of “over crushing” as minimal production of crusher fines are wanted when crushing chips [33].

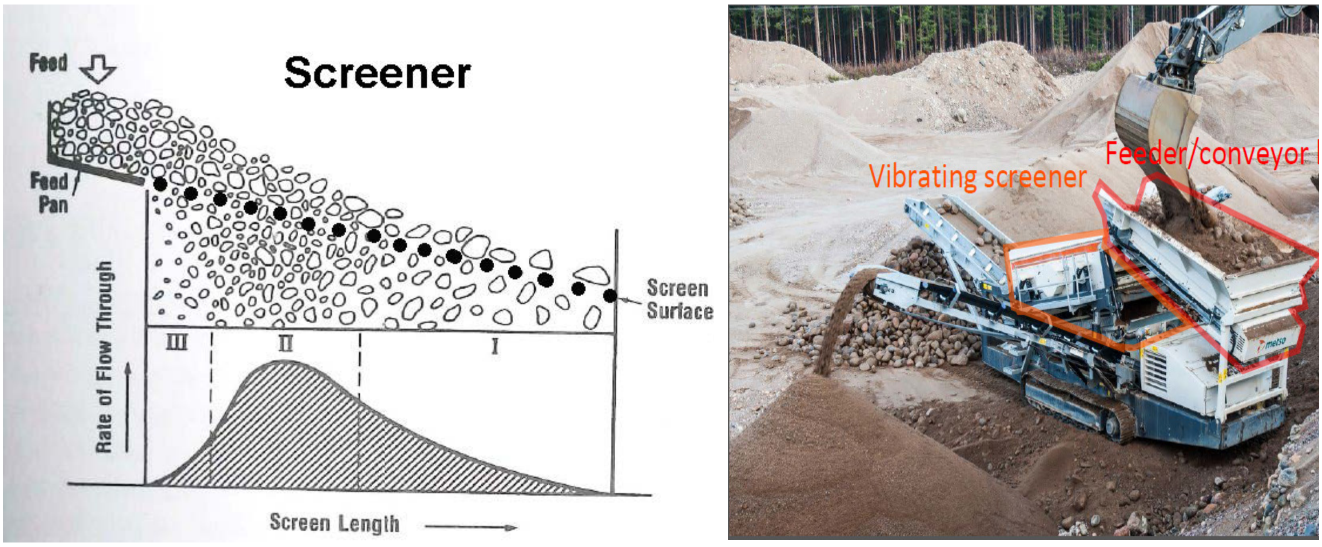


Figure 2-12: Left: Basic concept of screening through stratification and separating the feed into three fractions with a rapid separation of fines. Right, Showing Metso Scalping vibrating screener separating material into 3 different fractions [58].

Screeners are placed in the process combined with other screeners or crushers to separate rock material. Screeners transports material through gravity commonly with the help of inclined positioned vibration. Reduced accuracy if large areas of the steel mesh are blocked.

Table 2-4: Listing several used screeners [57].

<table>
<tr><th colspan="3">SCREENING</th></tr>
<tr><th colspan="2">Type</th><th>Note</th></tr>
<tr><td colspan="2">Fixed screen</td><td>No moving parts. Used in Follo line project for removing 0-20mm</td></tr>
<tr><td colspan="2">Rotary/trommel screen</td><td>Low production rate, and risk of blockage</td></tr>
<tr><td colspan="2">Screw classifier</td><td>Dewatering</td></tr>
<tr><td rowspan="11">Vibrating screen</td><td>Inclined two-bearing screen</td><td>Basic screener, widely used</td></tr>
<tr><td>Inclined four-bearing screen</td><td>Basic screener, widely used</td></tr>
<tr><td>Variable – ellipse screen</td><td>The vibration source placed above the screener, creating elliptic rotation</td></tr>
<tr><td>Banana/multi slope screen</td><td>Inclined curve at starting point</td></tr>
<tr><td>Electromagnetic screen</td><td>Limited fines separation</td></tr>
<tr><td>Probability screen</td><td>Up to six screening decks</td></tr>
<tr><td>Centrifugal screen</td><td>Specialized in handling fines</td></tr>
<tr><td>Live-deck screen</td><td>Specialized in handling materials with high moisture content</td></tr>
<tr><td>Dewatering screen/wheel</td><td>Reduces moisture content</td></tr>
<tr><td>Flip-flop screen</td><td>Soft screening medium with bending properties</td></tr>
<tr><td colspan="2">Air separation</td><td>Requires dried mass. Can separate in range of 15-250 microns</td></tr>
</table>

When designing the processing plants which shall treat the TBM material, it must be planned concerning a variety of factors as throughput tonnage required (tph), maximum size of feed (mm) entering the system, end product requirements and type of material (e.g. moisture content, flakiness, PSD). For processing TBM material a facility must be adaptable for the spoil entering may originate from a weakness zones or unfit spoil for utilization into concrete aggregates. The projects reviewed have all divided spoil into classes of two or more as part of the decision making.

An interesting project Is the Linthal hydroelectric plant which did not have a road or rail connection. All equipment had to be transported by cable. Luckily tunnels and caverns lied within a favorable limestone massive, which enabled excessive amounts of utilization of spoil to the tunnel lining and the massive dam construction. Both a dry and a wet processing facility was assembled for the project. Though dry processing could only be carried out in the summer months[59, 60]. More about the project can be found in 2.7.

Figure 2-13: A 38 ton mobile impact crusher(swing-hammer) combined with a screening unit are being transported to the tunnel site(2500 ASL) at the Linthal-Limmern power station for the purpose of dry processing TBM spoil [61].

2.2.2 Classification and dewatering

Classification covers the size control of particles < 1mm. Conventional screeners and crushers are not applicable below this size [34]. A range of methods can be used for classification, though all builds on certain fundamentals. These are utilizing the natural gravitational force and the particles corresponding behavior to separate the particles into fractions or dividing a liquid from particles (dewatering/clarifying). Classification accuracy will be of relevance as concrete aggregates do have boundary limits according to PSDs on fillers in the sand fraction [34]. Particles in this size range do also tend to cluster together. These phenomena are called agglomeration and is unfortunate in terms of concrete batching. Figure 2-14 illustrates some of the classifiers on the marked, both dry and wet methods.

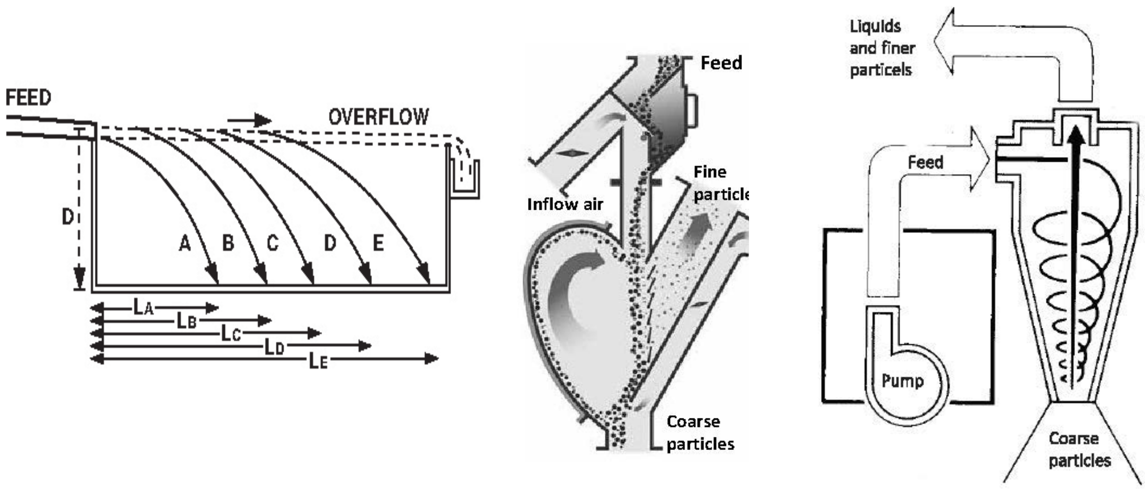


Figure 2-14: Left: Showing horizontal traveling path of falling sand particles in a classifier tank[57]. Middle: Particle path in gravitational inertial classifier[34]. Right: Creating a vortex to separate particles in a Hydrocyclone classifier [34].

Sedimentation is used both for cleansing contaminated water and as a separation of fine particles (classifier tanks). Example of usage is in sewage cleansing and concrete batching plants. The technology used relies on the relative buoyancies and particles differences in settling rate. The settling rate will be affected by either specific gravity or the particle size, see Figure 2-16. The sedimentation slurry will increase in density and viscosity as a result of the increased presence of particles launched into to container, this is called hindered movement and are applicable for gravity ad centrifugal classification.

Table 2-5: Typical classification machinery for screening, dewatering or clarifying purposes

CLASSIFICATION (<1 mm)			
Type	*Type*	*Note*	*Approximate operating fraction*
Dry	Gravitational inertial classifier	Separation by air stream.	150µm/1.4 mm
	Centrifugal classifiers	Separation by air stream.	15/100 µm
	Gravitational inertial classifier	Separation by air stream.	63/300 µm
	Cyclonic ultrafine	Creating airstream formed as a vortex to separate	10/50 µm
	Gyrotors/ Delta-sizers	Dynamic air classifier	45/500 µm
	Multi-stage fluid bed coolers	Using cooling in combination with a drop of pressure, lets finer particles together with moisture be separated from the granular material	50/1000 µm
Wet	Hydrocyclone /cyclone	Creating a vortex in a water container and separates the coarse from the fine particles. The minor particles gather in the center. Can also be used for dewatering	150/840 µm
	Spiral classifier	Rotating spiral in a sloped setting half emerged in slam water. Separates coarse particles from fine. Used in separation of slam water from concrete, see Figure 2-15	150 µm/32mm
	Filter press/VPA	The Vertical plate pressure filter(VPA) or chamber filter press. Used on fines and capable of removing 90% of the water. Creating disposable mud cakes, often connected to a clarifier.	1 µm/100 µm

Wet processing could require dewatering to reduce moisture content of the product. Machinery to dewater can be applied on coarse material using machinery like a spiral classifier or a dewatering wheel. Dewatering of fines or water treatment is the removal of fines from a liquid, possible to achieve using a VPA (Vertical Plate Pressure Filter) or lamella clarifier. The machinery allows for utilization of residues from blasted rock and potentially producing crushed sands qualified for concrete production, in addition also applied at the Follo line project for production of 0/8 mm crushed and washed TBM spoil, see Figure 2-15 and Figure 2-16.

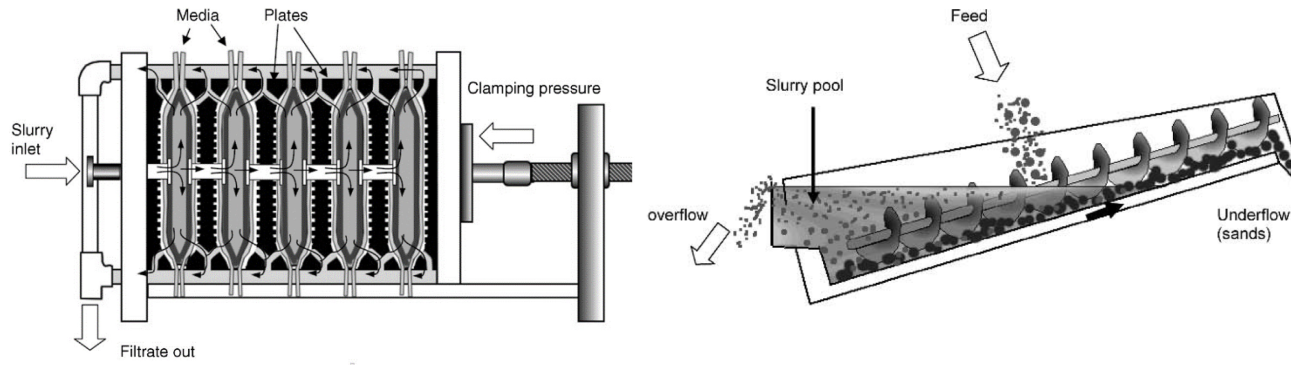


Figure 2-15: Left: dewatering of mud water with filter press(VPA) for removal of fines [62]. Right: Dewatering of coarser particles with a bottom spiral classifier [62].

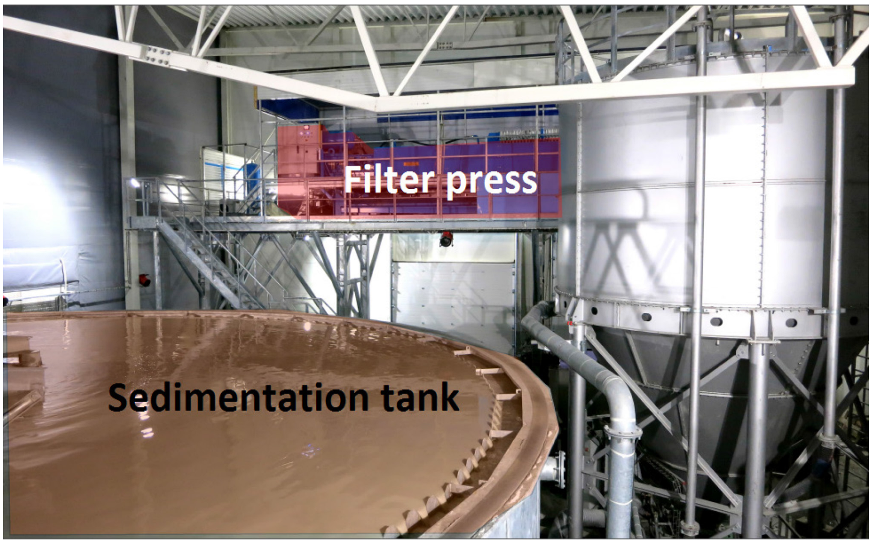


Figure 2-16: At the Follo line project(figure) and AlpTransit projects the cleansing of sludge from the wet processing of TBM spoil was done by a clarifier (sedimentation tank) and a VPA (filter press) creating filter cakes of mud for the landfill. The partially cleansed water can be used back in the wet processing.

Flotation is a separation process dating back to 1905 and used in mineral processing to extract valuable minerals from a slurry. It's the most used processing operation for hard rock and coal separation [62]. Used in extraction of materials as copper, lead-zinc, iron and phosphate. The principle is based on making the selected mineral(s) hydrophobic while the gangue mineral (worthless mineral) hydrophilic. The hydrophobic mineral attaches to an air bubbles and rise to the surface(Figure2-19). Removal of two or more minerals is referred to as bulk flotation and removal of one mineral is referred to a selective flotation. Chemicals used in flotation differ as their effect on minerals vary. In the AlpTransit projects Froth flotation was used to extract the mica in the TBM spoil and dewater the remaining spoil and use it as concrete aggregate. In that case the gangue mineral was the free mica particles, removed when surfacing [62].

Figure 2-17: Large scale flotation was applied at the AlpTransit projects, removing the mica content in the TBM spoil fractions 63/125 µm and 125/250 µm[53].

Figure 2-18: Laboratory setup for the froth flotation. The picture shows a laboratorist adding a "frother" to reduce the tension of the pulp(bubbels) and collecting the wanted/unwanted minerals at the surface [63].

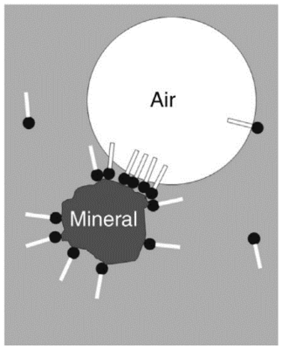


Figure2-19:Illustrating how and air bubble ascends to the surface and attaches to the hydrophobic mineral along the way (e.g. mica)[62].

2.3 Spoil impurities and classification

2.3.1 Impurities

Aggregates has major impact on concrete properties as it consists of approximately 70% of the finished concrete product. The aggregates in a mix will most importantly impact the water demand and cement need.[15] A pricy high quality aggregate could potentially be economic in the sense of reduced cement need because the certain aggregate has a low water demand. Aggregates must withstand a set of influences and material properties mostly set my CEN and ASTM though some values are set by national guides through empirical investigation which can differentiate between countries.

Frost resistance is determined by NS-EN 12620 , where all aggregates with less than 1% water absorption can be classified as frost resistant, though high amounts of mica or schistose structure has shown to reduce the frost resistance [64]. Increased void content has also proven to increase frost resistance. 4-6% is regarded as valid values to accomplish frost resistance to a certain extent.[65]

Chlorides has potential of corrode the re-bars in the concrete, greatly impacting the concrete strength. Will normally occur through surface intrusion from road salt or sea salt. Aggregates washed with saltwater or salt captured in the aggregates which later is to be used as concrete aggregate must be prevented[12].

Acid soluble Sulphur content in concrete aggregate has the potential of expanding product which could potentially result in expansion, cracks and a precipitation of rust products from the concrete surface. The presence of iron sulfurs has been found in rock types like hornfel, mica schist, phyllite, and granitic gneiss. The deleterious effects could reduce strength and faster deterioration though minerals like Pyrite has been reported to just cause discoloration due to rust products[15, 64]. EN 12620 has set limits for Sulphur in concrete aggregates, see Table 2-6. If Sulphur values are found to be above 0.1%, the type of mineral must be determined. The Sulphur minerals react with the help of oxygen and water. The degradation mechanisms are split in two. First the unstable aggregate could produce rust product (Sulphuric acid) containing of iron oxide/hydroxide/oxyhydroxide. Secondary the oxides could potentially react internally and produce gypsum, etteringite and thaumasite if the internal conditions are right, resulting in expansion or crack formations [66].

Table 2-6: Showing varying max values for Sulphur content by volume percentage in different minerals. Gathered from NS-EN 12620, 6.3.2.

Mineral containing Sulphur	Chemical description	Maximum percentage in concrete aggregate, set by EN 12620
Pyrrhotite	FeS_2	0,1%
Pyrite Marcasite others	FeS	1%

Humus, originating from dead plant or animal remnants. Can be found in fine particles in the aggregate composition, effecting the curing time and development of compressive strength. Methods to determine humus can be found in NS-EN 1744-1 [15].

Clay minerals has been encountered in hard rock TBM tunnelling in Norway and Switzerland and are not suitable for concrete aggregates[39, 55]. If a gneiss contained 30% or more of phyllosilicate (clay minerals), schistose, flaky or broken rock at the GBT it was determined as the borderline between A and B material, for more info about the GBT see chapter 2.7.

Mica minerals in coarse fractions has little or no potential danger, though free mica minerals in the fine sand fractions could have negative effects on concrete. Mica is a schistose structured mineral with layers of thin flaky minerals reducing the concrete flowability due to the increased specific surface. Can also affect compressive strength, just has humus. No determined values are set by NS-EN 12620. Though the industry does control the mica content in the fraction 0.125-0.250 mm and 10-15 % is known to be high amounts and should be avoided. Free mica in the fraction (< 0.125 mm) has shown positive effects on both slump value and compressive strength[33]. The Mica content is investigated on the sand fraction with microscope analysis and is extensive work. Only investigating the 0.125/0.5 mm fraction has proven to be representative for the 0/4 mm fraction, see Figure 2-20. Total mica content is calculated based on the total aggregate composition used for the concrete mix.

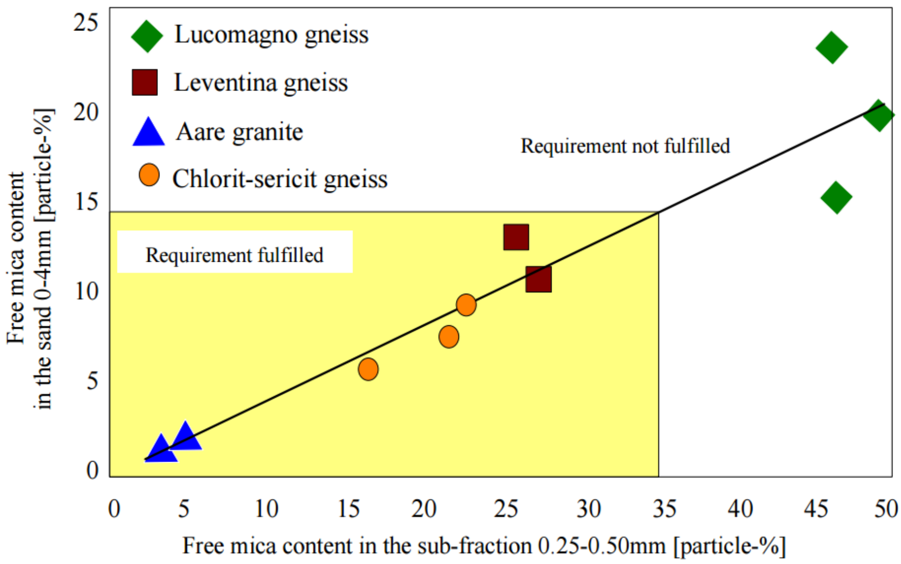


Figure 2-20: Correlation between free mica content in 0/4 mm and 0.25/0.5 mm fraction. Yellow zone represents a sand which have fulfilled B30/40 concrete [33].

Alkali-Silica Reaction(ASR) describes a reaction between certain aggregate types and the pore water in the concrete. Three parameters must be present for the ASR to propagate: Alkali reactive aggregates, certain degree of moisture and internally and high alkali values in the matrix [15]. The reaction product is an expanding gel which subsequently could swell and produce a distinctive expansion and map cracking. In chapter 2.4.6 concrete mixes suitable for any alkali reactive aggregates has been proven according to NB21.

2.3.2 Classification

The coefficient uniformity(Cu) defined by US standard ASTM D-653, also described by the Norwegian road authorities in "Håndbok 18" The coefficient is extracted from a sieve test and will give an indication on the compaction levels and stability. Most commonly used are the parameters D_{60}/D_{10}, in special cases the D_{75}/D_{25} boundaries can be used [67, 68]. For a more detailed description of soil classification, refer to EN 14688: Identification and classification of soil, part 1. The coefficient of uniformity will give a value to describe how well graded a sieve test is. This is done by dividing size(mm) at 60% on the size at 10%. The coefficient is also used by Norwegian road authorities, though they have set their own boundary values for the granular material as a load bearing mass for road and potential frost heaving.

$$Cu = \frac{D_{60}}{D_{10}}$$

Table 2-7: Coefficient of uniformity values and corresponding requirement or description by Svv and ASTM.

	Classification	Value	Defined grading
ASTM D 2487	Gravel	Cu ≥ 4	Densely graded
		Cu < 4	Open graded
	Sand	Cu ≥ 6	Densely graded
		Cu < 6	Open graded
Statens vegvesen(Svv)	Gravel	Cu ≥ 15	Required value
	Sand	Cu ≥ 15	Required value

2.3.3 Spoil test methods

C. Thalmann proposes daily tests of TBM spoil to indicate the crushability(CR) or grindability when utilized as concrete aggregate. The Los Angeles Index should serve as a reference method. The CR is standardized with The French standard NF P18-579 [33]. The method is also applicable to blasted rock. Abrasivity index (ABR) can also be determined alongside the test [69]. The test requires 500g of air-dried granular material in the fraction 4/6.3 mm and is poured into the white container seen in Figure 2-21. The test requires 1-2 hours. Point load index is another test method according to IS-8764 and determines the unconfined compressive strength of a granular material on bore cores or chips. A decission tool which includes these apparatuses can be can be found in Appendix C.

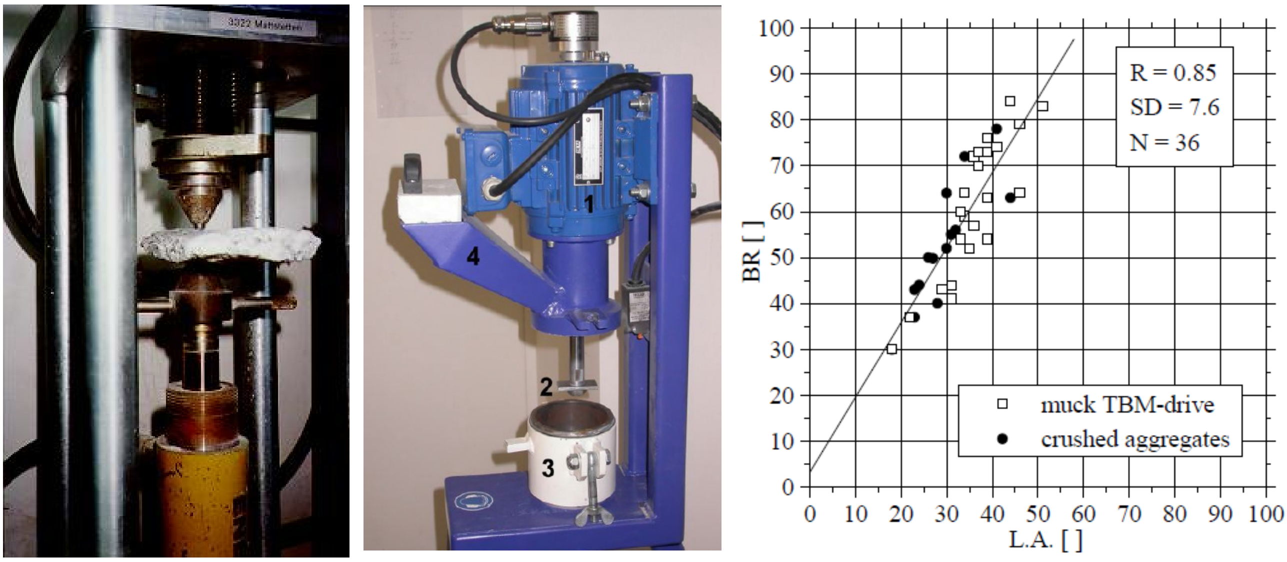


Figure 2-21: Left: Point load apparatus[33]. Middle: The LCPC apparatus measuring crushability(CR). Right: The CR correlates to the LA test on both crushed aggregates and spoil [50, 69].

2.4 Aggregates requirements for concrete

2.4.1 Standardized characterization

Aggregates designed for concrete has strict property requirements. Transport of high quality aggregates either by boat or ship is not unusual, even though local aggregates are present. The normal weight density varies between 2-300 kg/m^3. Several aggregate manufactures are now also capable to split aggregates into shorter fractions such as 0/4, 4/8, 8/11. The use of shorter fractions breaks down earlier limitations when mixing. Short fractions give the batching plants possibilities to combine in new ways to serve different concrete purposes [15].

EN 12620 is taking into account the variety of concrete recipes used in the industry with setting a maximum value of fines below 0,063 mm. Table 2-8 describes the pre qualifyed values for different fractions. Though higher fine content can be allowed, but EN 12620 states this has to be "declared" . For further relevant concrete aggregate requirements, see Appendix A.

Table 2-8 Prequalified maximum values of fines content in concrete aggregate (EN 12620).

Fraction	Maximum content of fines (<0,063 mm)	Category class
0/4 mm	22%	f_{22}
0/8 mm (Naturally graded)	16%	f_{16}
Combined fractions	11%	f_{11}

LA test is a valuable test method used to determine a fragmentation of construction aggregates. The LA test has can be used in concern to the E modulus of cured concrete as it correlates with the LA value [70]. This confirms aggregates prominent impact on concrete. A high LA value indicates a weak aggregate with low resistance to abrasion. Norwegian road authorities have set a maximum value on concrete aggregate at LA 35 when mixing SV 40 concrete (SV 40 = MF40 concrete with detailed values of silica fume). Thalmann advices setting minimum rock strength of TBM chips to 75 N/mm^2[50].

2.4.2 Natural and crushed sand

Natural originates from fluvial sources, has often natural fitted size distribution and shape for concrete use. Requires little or no processing resulting in ease access and low cost. Does vary in moisture content and could contain impurities as clay minerals. The most wanted sand for Norwegian concrete batching plants[15]. Crushed sand has a normally a more angular shape, resulting in lower slump values. Originates from quarries crushing larger boulders and screening out different fractions for different commercial products, the sand does normally contain too much fines, restricting its application areas and usefulness. If washed or air-classified, the sand will have potential as concrete aggregate as the fines can be engineered or removed. Additionally, has crushed aggregates shown increased compressive strength in concrete. Believed to be caused by its higher surface friction. The same effect has also been experienced from utilized spoil at the GBT [15, 33].

2.4.3 Particle size distribution

The PSD is the main aggregate parameter for concrete proportioning. PSDs are usually combined with other fractions which together makes up the total aggregate content in a concrete mix. According to recommended values , the amount of filler should be maximum 10% when natural 0/8 is used[71]. Though with the use of the particle matrix method, filler is defined as <0.125mm. This contrasts with NS12620 which define filler as <0.063mm.Possibilities and combination of PSD gives different effects in fresh concrete mentioned below. [72].

-Water consumption

-Workability

-Compaction

-Separation/Bleeding

-Air content

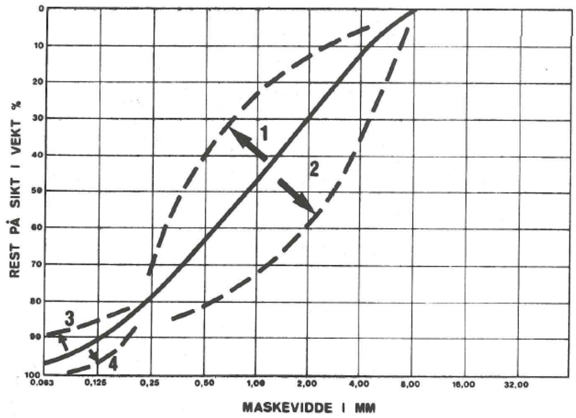


Figure 2-22: possible changes to a PSD 0-8 mm fraction[72].

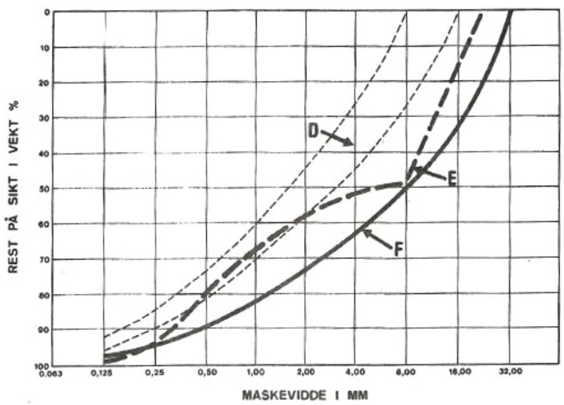


Figure 2-23: Suited PSD for different types of concrete, 0-8 mm fraction [72].

1: Will result in reduced packing grade, and bleeding

2: Higher packing grade, lower workability

3: increases stability, less workability

4: Better workability, chance of bleeding

D: Between dotted lines: PSD suited for shotcrete

E: Gap grading, with low filler content, containing equal amounts of 0-4mm and 8-16mm fraction

F: “Fuller curve” method to give maximum possible packing grade

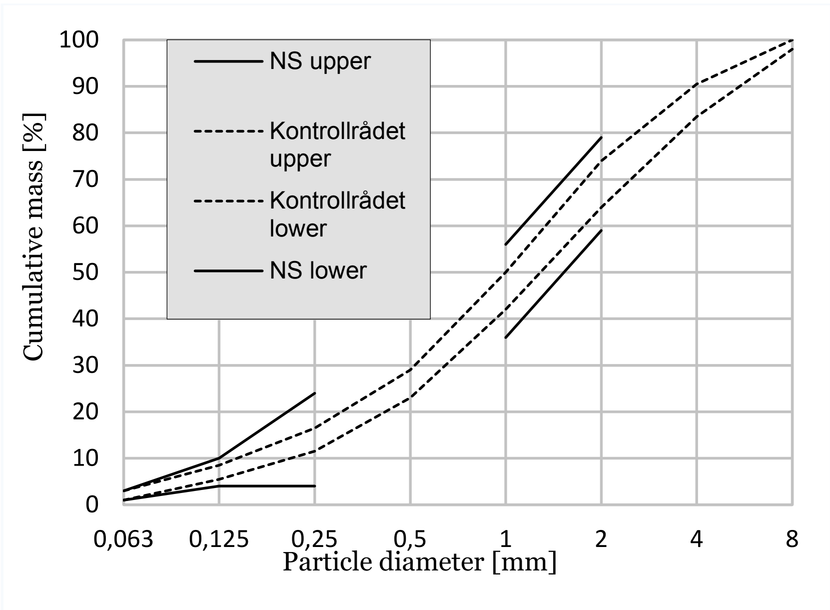


Figure 2-24: boundary conditions set for 0/8 mm natural sand.

2.4.4 Shape

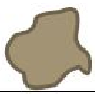
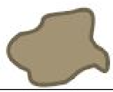
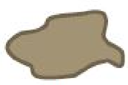
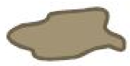
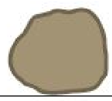
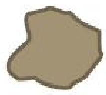
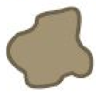
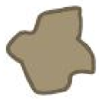
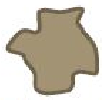
Determined by NS 933-3 the method to determine flakiness index(FI) is described. Though dependent on ordinary cubic sieving described in NS 933-1. Flakiness index is only usable between 4-100mm fractions. This is the general formula for Flakiness index:

$$FI = \frac{M_2}{M_1} * 100 \tag{1}$$

M_2=Bar sieve: Total weight of all the particles through each passing.
M_1=Cubic sieve: Total weight of all the particles through each passing.

Norwegian natural sand and gravel has normally a FI value of 2-3% while crushed rock in the range of 5-8%[13]. The shape of a particle can be classified by shape and angularity. The shape will vary in length and width, but the angularity will describe the surface of the particle in terms of how rough or how cornered it is. The particle with no angularity would theoretically be a sphere, See Table 2-9.

Table 2-9: A proposed index for describing shape and angularity in concrete mixing, taken from Ph.D. by Erik P. Koehler [73].

	Visual Shape and Angularity Rating ($R_{S\text{-}A}$) Well-Shaped, Well Rounded ← → Poorly Shaped, Highly Angular				
	1	2	3	4	5
Shape	most particles near equidimensional 	modest deviation from equidimensional 	most particles not equidimensional but also not flat or elongated 	some flat and/or elongated particles 	few particles equidimensional; abundance of flat and/or elongated particles 
Angularity	well-rounded 	rounded 	sub-angular or sub-rounded 	angular 	highly angular 
Examples	most river/glacial gravels and sands	partially crushed river/glacial gravels or some very well-shaped manufactured sands	well-shaped crushed coarse aggregate or manufactured sand with most corners > 90°	crushed coarse aggregate or manufactured sand with some corners ≤90°	crushed coarse aggregate or manufactured sand with many corners ≤90° and large convex areas

2.4.5 Aggregate packing

Creating a workable concrete will be influenced by the aggregates degree of compaction or packing. The matrix fills the voids in the aggregate composition in order to create a workable concrete. The PSD, moisture content and shape will be of importance. As a normal Norwegian aggregate composition will contain 25% voids. This will result in 250 liters of voids per m^3. To obtain a workable concrete the matrix must first fill these voids and additional matrix must be added to create the flowable concrete, called an aggregate-matrix void saturation, see Figure 2-26.

$$p = 1 - \frac{p_b}{p_p} \tag{2}$$

P = Porosity
P_b= bulk density (kg/m^3)
P_b= particle density (kg/m^3)

Determining the aggregate packing of a polydisperse material will give valuable information on the void space left in a naturally packed volume of aggregates. Either determined with fraction of solid material in a known volume container (C) or the opposite void content (1-C). The packing will have impact on the accompanying matrix need (cement paste). Different packing grades have shown to influence the cost/Mpa and cost/mm (slump, flow diameter) when the aggregate-matrix void saturation has been kept constant[74].

The source for a certain packing (bulk density) relies on a variety of several factors, some factors are activated when small particles pack together and other factors will be more prominent on larger particles. Listing below is some factors described [74].

- Shape
- Gravitational forces, impacts the layering structure
- Interaction of particles,
- Surface forces, concerns the smallest particles such as silica fume
- Impact forces between particles in motion
- Interlocking, concerns angular and longitudinal shaped particles
- Wall-effect is a term used describing the extra void space required when smaller particles are packed against larger ones

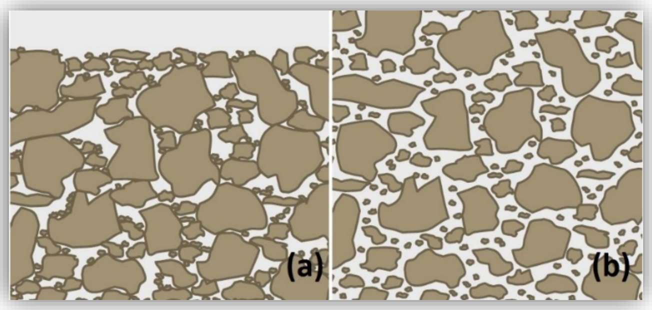


Figure 2-25: (a) Aggregates packing with no interference. (b) Aggregates dispersed and lubricated by the matrix[73].

2.4.6 Alkali-silica reaction

To assure no alkali silica reaction(AAR) in concrete produced with the TBM spoil, a proportioned concrete mix must withstand the possible reactive aggregates, this can be assured according to Norsk Betongforening(NB) publication 21. NB 21 states a protection against deleterious AAR with a matrix consisting of $\leq$ 3kg Na_2Oeq/m^3 , regardless of aggregate amount or type.[75] Though cements containing slag, fly ash or silica has a higher tolerances for alkali content in the matrix ($\leq$ 4-7kg Na_2Oeq/m^3) Limit values can be found in NB21 table C1. These values are valid for Norwegian used cement products and aggregates.

In accordance with NB 21 an industry concrete is proportioned in Table 2-10 to show the constituents and amounts. The mix is proportioned using the Particle matrix model which is explained in next chapter.

Exposure class: XS3 (Risk of rebar corrosion due to chlorides from seawater)
Durability class: M40
w/c= 0.40
Filler content = 40% of cement volume

Table 2-10 Proportioning with particle matrix method and in accordance with NB21

Phase	Material	Kg/m^3	Density(kg/m^3)	Volume(l/m^3)	Total Volume(l/m^3)
Matrix	CEM II/A-V 42.5 N*	360	3020	119.21	314.7
	Water	144	1000	144	
	SP(Dynamon SR-N)*	3.96	1050	3.77	
	Filler of 0/8(fi/c=0.40)	128.7	2700	47.7	
Particle	0/8mm 60%	1077.78	2700	393.08	685.3 (665.3+20)
	8/16mm 40%	718.52	2700	262.05	
	Water absorption(1%)	1.79	1000	0	
	Air			20	
					1000

*Containing alkalis

The constituents which contains alkalis are summed up and compared to values set by NB21, see table below.

Table 2-11: Calculation alkali content of the constituents which contains alkalis

Constituent in matrix	Amount · $Na_2Oeq/m3$	Equivalent alkali content
CEM II/A-V 42.5 N	360 kg/m^3 · 0.6%	2.16 kg/m^3
SP (Dynamon SR-N)	3.96 kg/m^3 · 2%	0.0792kg/m^3
Safety factor (1.10%)		1.10 %
Total alkali-content (eq. Na_2O)		2.463 kg/m^3
Certified against NB21		**2.463 < 3.0** kg Na_2Oeq/m^3

2.5 Concrete proportioning

The Particle-Matrix method is commonly applied in Norway for concrete proportioning. The method is an effective tool to engineer the effect on workability of concrete [76]. With the use of the method the filler amount can be determined as a part of the matrix together with water, cement, pozzolans, and additives (all liquids and constituents below 0.125 mm).

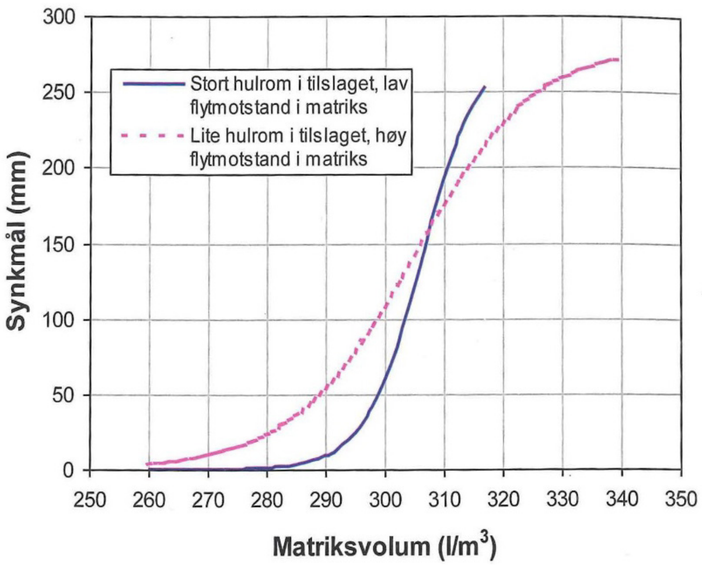


Figure 2-26: The correlation between slump value and matrix volume. Until slump values of 150 mm the most efficient slump is achieved with the so-called particle dominated mix. Slump values above 150 mm will be ruled by the matrix as it's volume is large enough to increase the spacing between aggregates [77].

2.5.1 Filler in fresh concrete

Fillers in a concrete mix will typically originate from the 0/2, 0/4 or 0/8 mm fractions. Though the cement will also act like a filler, and has been reported as a very good filler[77]. The filler content is either determined as the content below 0.063 mm or 0.125 mm.

With the use of different laboratory methods, it is possible to understand the behavior of filler to a greater extent. As of today, there is different technologies to measure the size distribution of particles below <250 µm. To determine the PSD of filler fraction Ph.D. student Rolands Cepuritis applied the different measuring methods on the same filler specimens to evaluate their precision and uncertainty. As a result, the X-ray sedimentation method gave the minimum uncertainty and the most precise results. Stokes law is implemented with the use of a SediGraph, measuring the difference of sinking speed in accordance with the known particle density. With an assumption of harmonic spherical specimens it is also possible to extract specific surface from the PSD of the filler fraction [78].

Four filler properties will impact the fresh concrete; specific surface, PSD, particle shape and mineralogy[77]. An increase in spesific surface would require increased amounts of water or water reducing admixtures to maintain the original flowability. The matrix role is luqifying the surface area of the aggregates and dispering them, though 80-90% of the surface area in concrete originates from the filler[77]. This is why the filler in the sand fractions are closely observed by technologists at concrete batching plants as they do routinely measure the particle size distribution of the sand fraction.

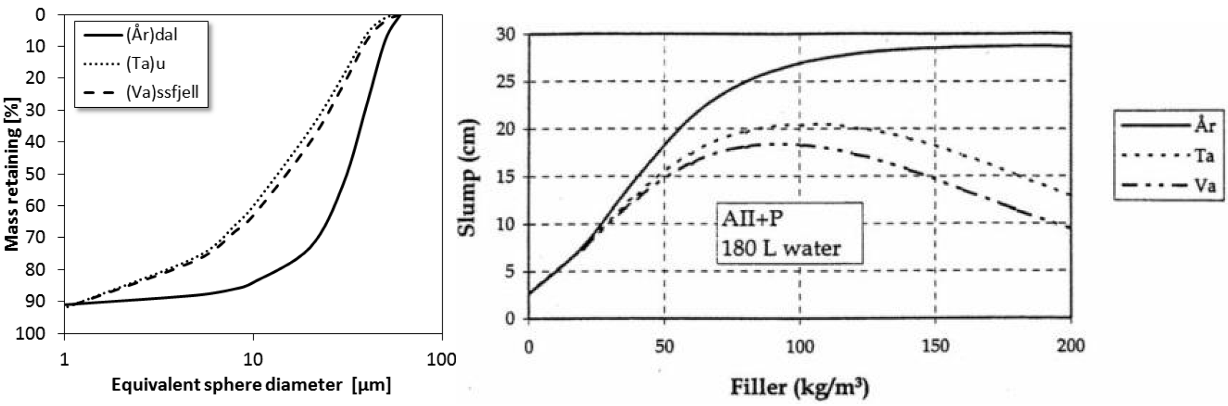


Figure 2-27: Crushed sands (Ta and Va) and natural sand (År) show increased flowability when filler amount is increased in the matrix until 100 kg/m^3. Increasing the amounts above this limit reduces flowability of those concrete mixes, though the natural sand upholds a good flowability regardless. An explanation to the differences are seen in the differences in PSD in the filler fraction (<0.063 mm) [79].

2.5.2 Micro proportioning

The Research project COIN (concrete innovation center) has produced several journals and a several PhD s between 2007-2015 concerning innovation in the field of concrete. It's been developed principles to micro proportionate concrete with the PhD of Rolands Cepuritis. This is among other things is possible due to the access of PSD down to micro scale. Figure 2-28 can confirm impact on slump value due to changes in the PSD on micro scale (≤125-250 µm). It's been confirmed that the particle shape <4 mm fraction is of great importance to concrete workability[80]. This has resulted in development of the Micro Flakiness Index (µFI) which is a method capable of measuring the flakiness of aggregate down to 1.25mm. With the use of VSI on crushed rocks the Flakiness index can been reduced regardless of initial particle shape or crushability. This was proven using 10 different crushed rock samples from different Norwegian Quarries[81].

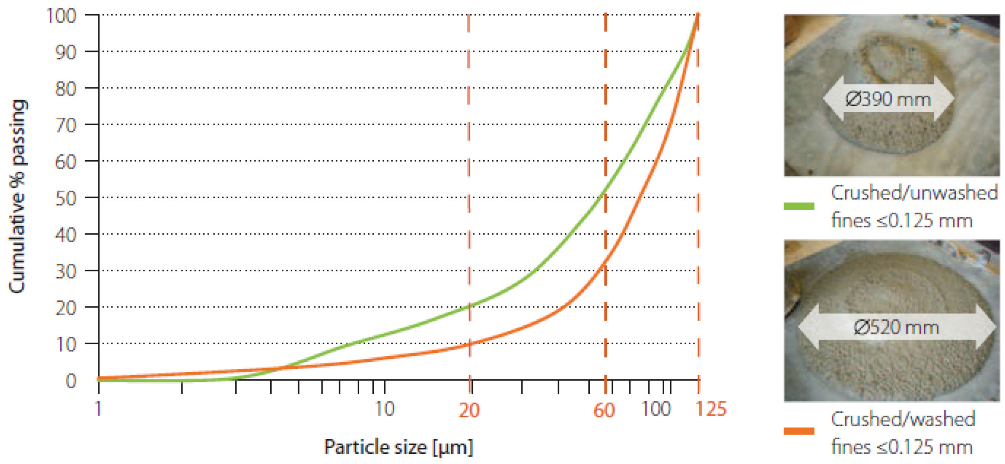


Figure 2-28: Two similar concrete recipes with w/c=0.5. Green line is unwashed filler and orange is washed filler. The differences in PSD in the filler fraction is seen to have significant impact on slump value in the fresh state. [37]

Assuming spherical particles in the PSD makes it possible to calculate the specific surface of the matrix. Through Coin project report 63[82], Velde and Skanska has proven how the specific surface of the filler is possibly the single factor which needs to be controlled concerning workability, similar results was also achieved by Cepuritis. Using different crushed fillers or filler/cement ratio naturally impacts the specific surface. The effects these changes does to the fresh state is proposed to be governed by change in specific surface. This could be utilized at concrete batching plants to indicate the behavior of a certain filler type, see Figure 2-29.

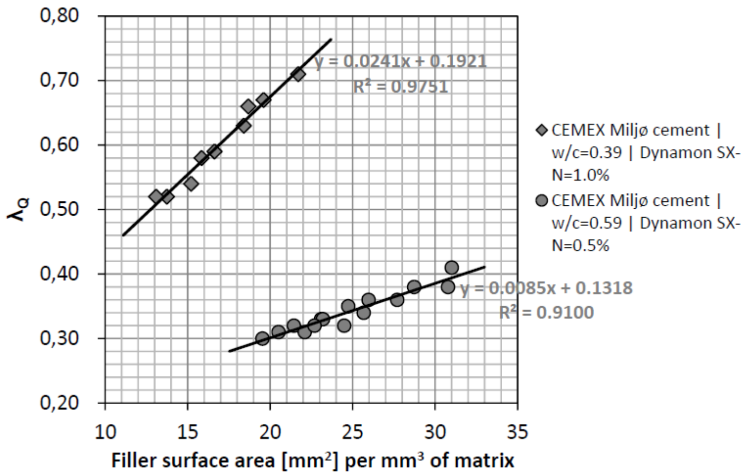


Figure 2-29: Two concrete receipts with w/c=0.39 and w/c=0.59. Both mixes have been altered with varying fillers and varying filler/cement ratio. The prominent flow impactor is nonetheless the surface area of the filler. [82]

The journal “Possibilities of improving crushed sand performance in fresh concrete by washing: a case study” Investigating aggregates PSD in the 0-63 µm spectrum. As seen in Figure 2-30 the c-0/8-u (crushed unwashed) has a higher fines content. Though hard washed and normal washed achieve the same PSD as the natural. This was achieved using a classifier tank, dewatering wheel, lamella clarifier and a hydrocyclone. For general material processing see chapter 2.2[83].

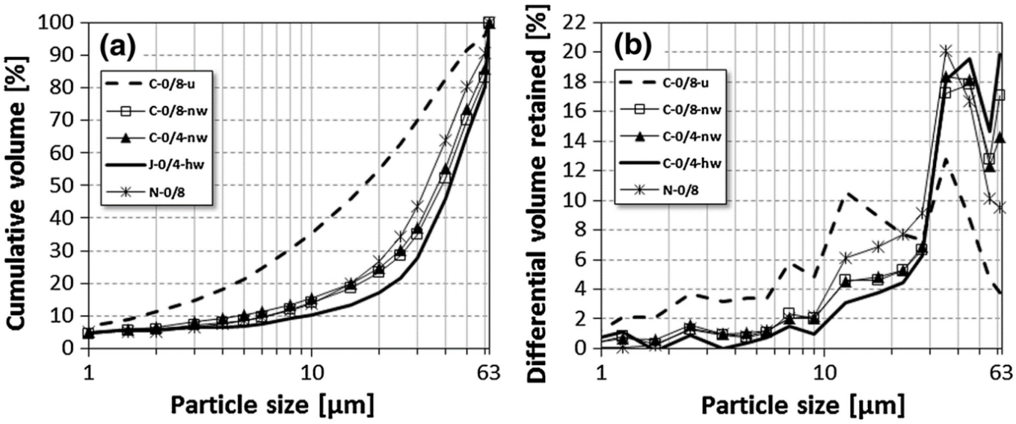


Figure 2-30: (a) PSD measurements with X-ray sedimentation method. (b) presented by difference in volume [83] C-0/8-u = crushed unwashed
C-0/8-nw = crushed normal wash
C-0/8-hw =crushed hard wash
N-0/8 = Natural

There are obstacles in using micro proportioning in the concrete industry. One of the main problems using crushed aggregates is creating economical mixes with suitable workability, due to uncertainties concerning the filler fraction in crushed aggregates, below are some important finds done by Rolands Cepuritis concerning crushed fines in concrete proportioning [82].

- For a 0/8 mm fraction the shape of the 0.125/2 mm and properties of <0.125 mm are the dominant factors concerning concrete workability.
- Crushed fine aggregate has proven to increase the tensile strength of concrete, due to the increased interlocking and friction between particles and the cement paste.
- Increasing use of SCC will promote the use of crushed fine aggregates, due to the considerable amounts of fillers required in a SCC receipt.
- Shape, surface texture and mineralogy of ≤ 0.125 mm could impact the fresh concrete in the same range as different PSD could.
- X-ray sedimentation is the most accurate method to create a PSD of the concrete aggregates <0.125 mm

2.5.3 FlowCyl

The FlowCyl is a type of viscometer used to measure the flow resistance of a liquid paste. The output measurement is the parameter λ_Q. The method is developed in the PhD of Ernst Mørtsell in 1996. The method is a modification of the Mars Cone test apparatus. The liquid paste is pouring through a cylinder with an output nozzle of 8 mm in diameter, see Figure 2-31. The weight is continuously measured in a bowl below the cylinder and at what time (sampling rate 2 sec). The flow resistance is measured and compared to an ideal fluid with zero flow resistance. For typical fluids with measured λ_Q, see Table 2-12, The expression for λ_Q:

$$\lambda_Q = \frac{F_t}{F_i}$$

F_t = flow rate of the tested matrix
F_i= flow rate of an "ideal" fluid

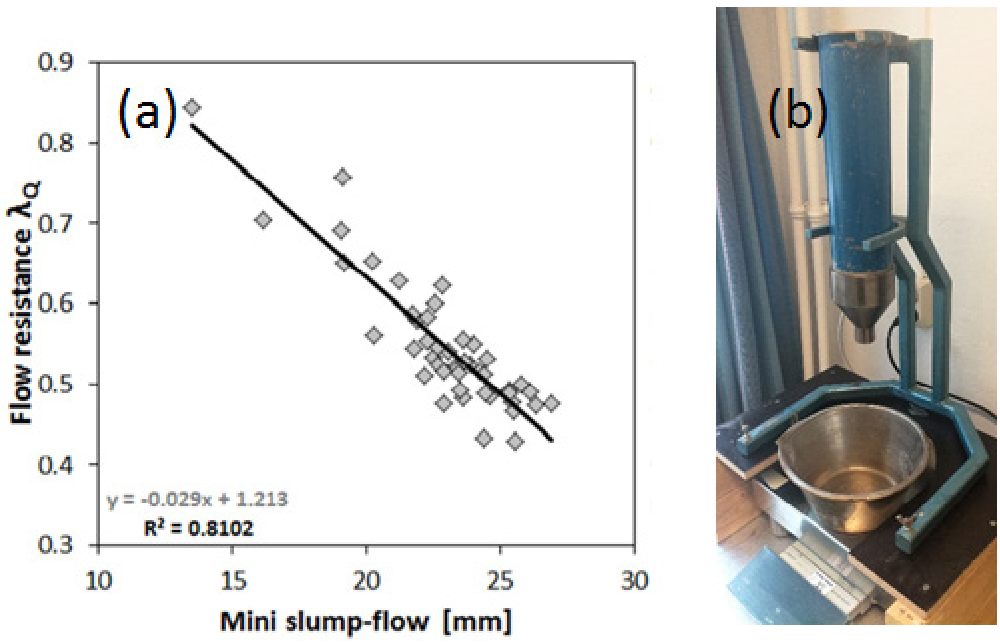


Figure 2-31: (a) The correlation between mini slump-flow and the flow resistance measurement λ_Q [84].
(b) The FlowCyl apparatus, the weight measurement frequency is set to 2/sec.

Table 2-12: Typical values for the flow resistance λ_Q [12].

Material	λ_Q
Water	0.10
Matrix w/b= 0.6	0.35
Matrix w/b= 0.45	0.55
Matrix SCC	0.65

2.6 Project references

The utilization of spoil for concrete is solved with different approaches and given varying assets due to factors such as project leadership, budget and contract obligations[85]. Four hard rock TBM projects where three has successfully utilized spoil as concrete aggregates back into concrete lining either as shotcrete or segments are presented.

2.6.1 *Ulriken tunnel*

There is already a tunnel for the railway between Bergen and Arna station, but the capacity is maxed out and another tunnel besides the old is now gently being excavated with a Grippper TBM. Containing mostly diverse types of gneisses, the rock is suitable to be utilized as concrete aggregate, though this is not the case. The tunnel spoil is transported to a variety of deposits in the region and to cover a polluted seabed at the Bergen harbor. Though one of the gravel works which do receive tunnel material have invested in a clarifier and VPA which do have been able to produce a high-quality sand fraction by processing the blasted rock from the Ulriken project. Sieve tests of the TBM spoil has also been conducted to look at the materials potential as stabilizing mass for road works. Though it was concluded to contain excessive amounts of fines.

Table 2-13: General project details

Period	2016-2021
Length	7.8 km
Type	1x Herrenknecht gripper TBM
Number of concrete plants	0
Entrepreneur	Skanska Strabag JV
Max speed	160 km/h (130 km/h freight)
Connecting	Arna – Bergen
Owner	Bane Nor
Concrete	Shotcrete, B35 M45 E700 Average 8 cm thickness
Prominent geology	Augen gneiss, banded gneiss, Transformed migmatite gneiss, Granitic gneiss
Petrography data	60-280 Mpa Average 140 Mpa

Figure 2-32: In a weakness zone. Securing the tunnel lining before shotcrete are applied in the new Ulriken tunnel

2.6.2 *Koralm base tunnel*

Koralm base tunnel was divided into three contracts. Only contract KAT 2 involved two double shield TBMs, the rest would be tunneled by D&B. Already 3 years before project start preliminary tests was conducted to verify performance against frost resistance and alkali reactivity [1]. Unfortunately, there was discovered mica content of up to 35%. Though this would be solved by large intermediate storages of the 16/150 mm spoil. Mixing low mica content spoil with high mica content would reduce the total mica content and possible to utilize, see Appendix E and F. Strict governmental regulations in Austria requested thorough determination of the TBM spoil and tipping, for instance chemical composition and quality assurance. This also included reporting if the discharge point of TBM spoil was in the groundwater variation range or outside of it as this could possibly risk the spreading of unwanted substances [1, 85, 86].

Table 2-14: General project details

Period	2010-2019
Length	21 km
Type	2 Aker Wirth Double shield TBM’s
Number of concrete plants	2
Entrepreneur	Aker Wirth Strabag AG Rowna Tunnelling Logistics BMTI
Max speed	250 km/h
Connecting	Leibenfeld – Paierdorf, Austria
Owner	OBB infra
Concrete	Segments: C35/45 Inner lining: C25/30 CEM II
Prominent geology	Schistose gneiss Amphibolites marble varieties eklogites pegmatitic and quartzitic rocks.
Petrography data	50-150 Mpa LA test = 25-40

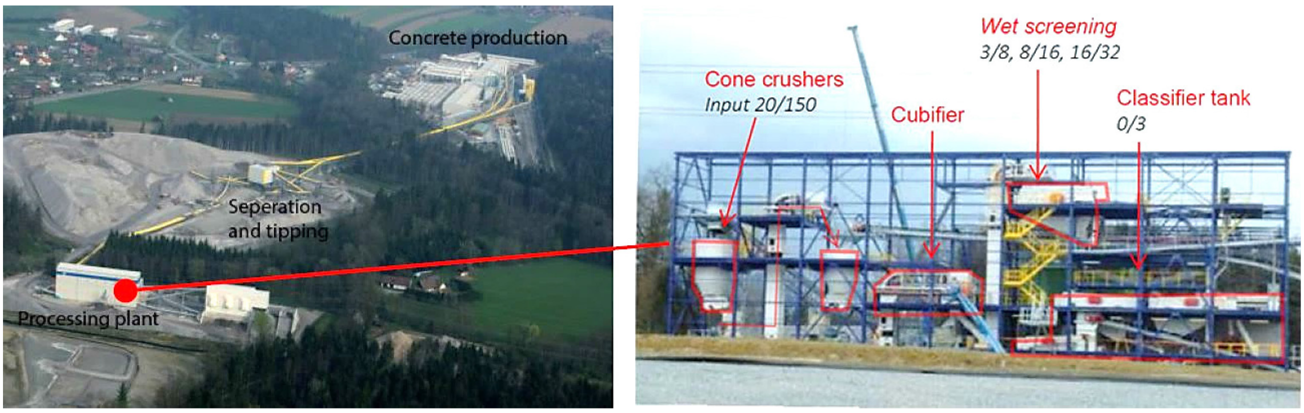


Figure 2-33: Left: Overview over Koralm KAT2. Showing the concrete production at tunnel portal. Secondly, separation and tipping of spoil (0/16 and 16/150). At last processing of spoil and storage. All connected by a conveyer system[22]. Right: The building of the processing plant and installing of the machinery.

2.6.3 *Follo line tunnel*

A Spanish and an Italian entrepreneur has cooperated to complete Norwegians longest railway tunnel ever built. Using an EPC contract, 9 million tons of tunnel mass is expected. Predicted utilization to concrete aggregates are just 10%. Complicated petrography is problematic for the utilization and only coarse spoil >20 mm is processed which leaves 60-70% of the spoil to tipping. Potential spoil between 20-150 mm are to be crushed, screened, washed and used as concrete aggregate. Creating the fractions 0/8,8/11 and 11/22. In addition are these fractions also purchased from regional suppliers and 0/8 natural are also if necessary mixed with the crushed 0/8. The result is large use oftrucks doing shuttle traffic between nearby quarries to supply the aggregate needs. For flow diagram for the processing plant of Follow line can be found in Appendix D.

Table 2-15: General project details

Period	2015-2021
Length	20 km
Type	4 Herrenknecht Double shield TBM's
Number of concrete plants	3
Entrepreneur	Acciona Ghella JV
Max speed	250 km/h
Connecting	Oslo – Ski
Owner	Bane Nor
Concrete	Segments: MF40(SV40), CEM II/A-V. w/c = 0.35
Prominent geology	Amphibolite Granitic gneiss/dark gneiss Pegmatite
Petrography data	Average: 142 Mpa[87] Max: 300 Mpa LA test: 30-40

Figure 2-34 Overview of the main site, Åsland. 10 km from both Ski and Oslo.

The entrepreneur approaches the utilization task with an experience based approach and by January 2017 has not yet decided a defined processing strategy. Though a set of mobile crushers and a screener are in place. Clarifier tanks and filter press are also in place to re-use mud water for wet screening.

One of the main difficulties was the water content of the 0/8 cw combined with short intermediate storage. This resulted in uncertainties to the batching plants as they would need to adjust free water added, changing the original recipe. There was a general agreement by concrete technologist and process site manager that an extra storage of the 0/8 cw, would make a buffer from output processing plant, to input aggregate silos. This could lower the water content variation and also allow removal by drainage and heating of the silo. As of 2017 the water content could reach 10%. The so called buffer in storage are also mentioned in the evaluation of GBT and Koralm KAT 2[88].

2.6.4 Gotthard base tunnel

17 years of tunnelling has finally ended and the Gotthard Base tunnel opened in 2016. With a 57 km tunnel, it was necessary with 3 access tunnels. The most complicated obstacle was the 1 km vertical addict which was necessary for the middle access. With early invitation to tender (1993), the cement and additive suppliers was put in teams and went through a largescale pre-qualification. With testing of the concrete performance for each team, the selected entrepreneurs were chosen for the projects lifetime (17 years). With impressive planning. As the project only did in situ concrete, special constructed concrete trains consisting of 23 wagons was used throughout the whole project for the concrete lining, the front wagon (pumping wagon) can be seen in Figure 2-36 [89]. The fresh concrete could also be transported for more than 3 hours into the designated area. A specially developed retarder was also created for the GBT to be able to retain workability even when exposed to high temperatures and in combination with water reducers and accelerators [90]. At Erstfeld and Amsteg the material handling included rail connection to the local train station Erstfeld SSB.

Table 2-16: General project details

Period	1999-2016
Length	57.1 km
Type	4 Herrenknecht Gripper TBM’s
Number of concrete plants	~Batching trains: 5
Entrepreneur	AlpTransit (joint venture consisting of government and private sector)
Max speed	250 km/h (160 km/h freight)
Connecting	Erstfeld- Bodio
Owner	Swiss Federal Railways (SFR)
Concrete	Shotcrete(<20cm) In situ concrete lining(<30cm) CEM III/B 32,5 N C40/30 w/b= <0.50 Dmax 32[91]. XA2
Prominent geology	Leventina gneisses, Lukmanier, chlorite-sericite schist, magmatic biotitt gneisses, Aare granite,
Petrography data	Amphibolite, pegmatite, aplite, gneiss, Schistose gneiss, schist, phyllite, talc schist

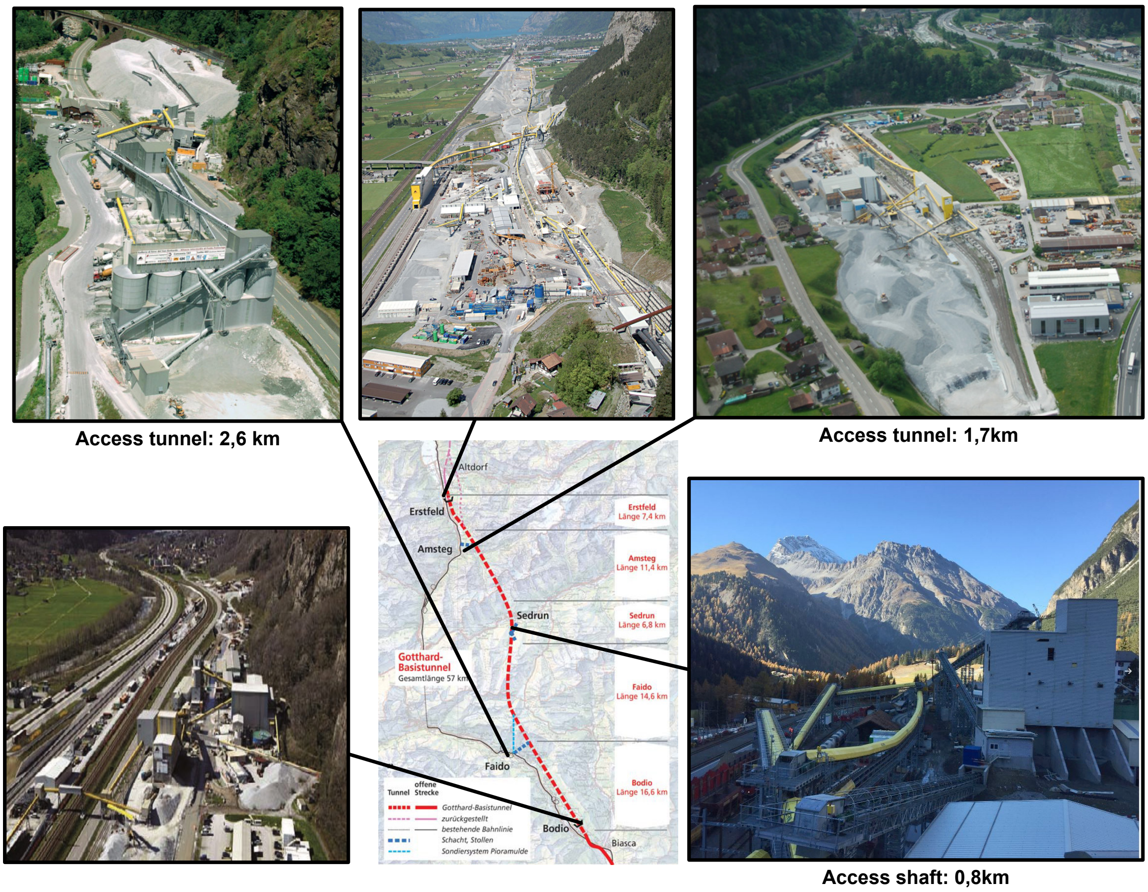


Figure 2-35: The Gotthard tunnel illustrating the three intermediate access tunnels and two portals. Erstfeld, Amsteg, Sedrun, Faido and Bodio. Actual aggregate processing happened at Amsteg and Bodio [55].

Figure 2-36: (a) The concrete batching plant train[92]. (b) Aggregate silos for the concrete train at Amsteg, (c) Inspecting aggregate quality at Amsteg aggregate plant [93].

2.7 Utilization strategies and experience

Dragon report

A proposed solution for efficient utilization of the TBM spoil, are placing a screener inside the tunnel with an adjusted process facility adapted to the tunnel diameter. The proposed design is not yet been applied to an actual project. The decision and evaluation of the spoil before it reaches the screener is done with microwave moisture measurement and X-ray elemental analysis. In addition, PSD is supposedly extracted with a photo-optical analysis. Extracting spoil from the main conveyer belt will be done with a so called hammer-sampler[24]. This upgraded TBM would add another 70 meter to the TBM on the so called TBM-backup. It would also allow for a single-track rail for access, see Figure 2-37 and Appendix B.

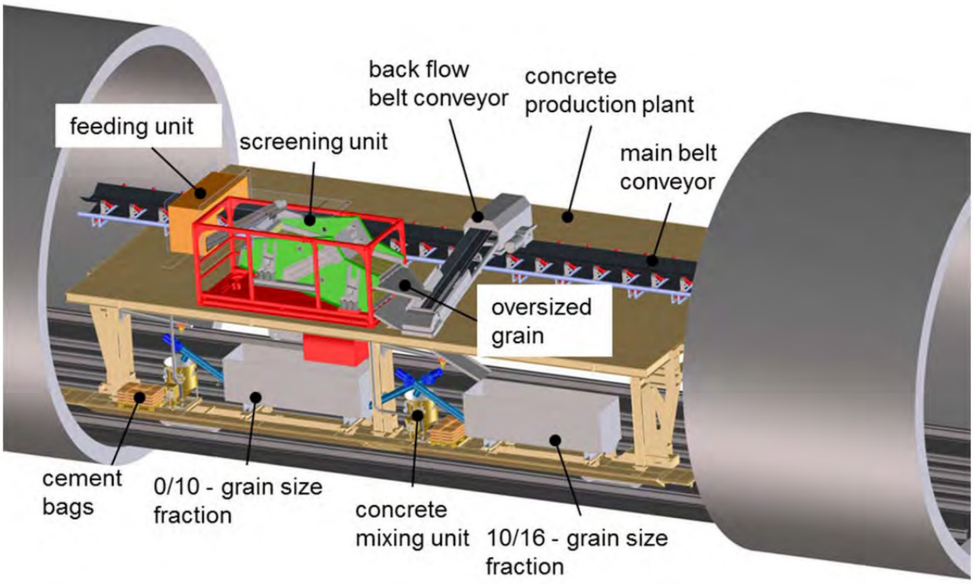


Figure 2-37: Illustrating the concept of processing TBM spoil in the "back-up" for CIP concrete. Aggregate storage, cement storage and mixing plant is not seen in the illustration.[53]

The choice of tunnel lining will impact the possibilities of a processing plant. Shotcrete and CIP (Cast in place) concrete is both applied fresh inside the tunnel and would be able to directly utilize the spoil screened in the back-up. As an example, the back-up should be able to store up to four days of shotcrete consumption to ensure continuous supply through geological fault zones. Four 60m^3 storage bins is expected to be sufficient for a 12m diameter TBM and 20 hour working days. Storage of cement additives and fiber is also needed. All the constituents would be mixed in the back-up and delivered by piston pump to the application area, seen in Figure 2-38. As the TBM runs through fault zones the change in material quality can change rapidly. The transition into another zone is not often perpendicular to the tunnel course and could result in a period of high grade and low grade rock material mixed within the same cross-section, this material would possibly not has potential as concrete aggregates [33].

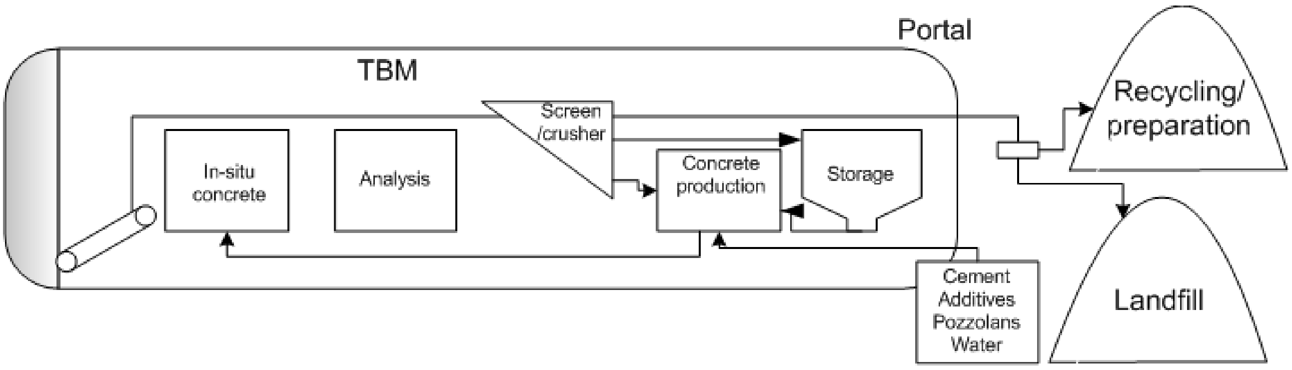


Figure 2-38: Illustrating the main procedures in the strategic plan for an automation of spoil processing [53].

Figure 2-39: Three used tunnel lining methods. Left: Shotcrete (2-20 mm) reinforced[94]. Middle: CIP concrete lining [95]. Right: Concrete segments(30-50mm) [96]. A tunnel lining can also include both shotcrete and CIP.

Table 2-17: The different choice of concrete lining and correlating aggregate size limitation. A back-up plant can dry process the spoil and serve directly as aggregate for only shotcrete and CIP.

Lining	D max	Back-up processing plant
Shotcrete	8mm	Yes
Cast in place concrete(CIP)	16mm	Yes
Segments	32/22mm	no

The choice of tunnel lining will be chosen based on several factors, to be able to piston pump the concrete its normally done with aggregate fraction up to Dmax 16 mm to assure no stoppage. If the tunnel is to be covered with concrete segments the aggregate processing is placed at the portal. Figure 2-40 is a simplified schematic of the general process of the spoil to create concrete aggregates and management of other spoil application areas.

The percentage to obtain self-supply will vary due to the type of concrete lining chosen and tunnel diameter. For a 12 m diameter TBM segment lining its predicted to need 40 cm thick segments, 20 cm to fill void behind segments and at last invert filling. These three needs for aggregate is calculated to only require 17.2% utilization of the spoil to be processed into concrete aggregate. It's important to mention this number do not include concrete demands for the portal, launching tunnel or cross passages. In addition, would the utilization requirement increase when diameter is reduced. With the similar tunnel lining setup as the 12 m tunnel, a 5m diameter tunnel would require 27% utilization. This is due to the different ratio between lining thickness and tunnel diameter [97].

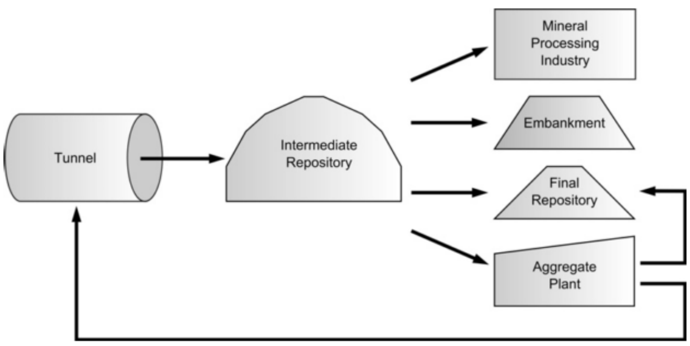


Figure 2-40:Left: general flow chart for an Swiss made approach of excavated material called TEMH(Tunnelling excavation material handling) 2012 [23, 33].

Test frequency
Laboratory tests can be divided in two. The extensive, time consuming tests should be conducted in the pre-investigatory face of the tunnel project. Normally extracted from a pilot tunnel, surface, drill cores, etc. The second tests conducted are the ones conducted daily at the on-site laboratory if necessary. The measurements must be economically acceptable and possible to carry out within 1-2 hours, see Table 2-18 [33].

Table 2-18: A guideline to utilize the TBM spoil as concrete aggregates and at what time in the project tests should be conducted.

Testing properties of spoil	
Before TBM excavation (time consuming, pre-investigatory)	During TBM excavation (Completed in 1-2 hours)
• Frost degradation • Thaw behavior • Chloride • Sulphate • Mica • Radioactivity	• Crushability(CR) and abrasiveness(ABR) with the LCPC apparatus • Unconfined compressive strength (point load index) • Macroscopic description • Sufficient control of petrography (e.g. mica or sulphur)

Petrography of a potential tunnel is often investigated by pilot tunnels, bore cores or from the surface. The rock conditions will be in direct link to the usability for concrete aggregate. Impurities can be discovered and forecast the spoils potential, helping the project team to make choices concerning wet or dry plant, crusher type, screener type. Based on this knowledge the project can predict an approximate a utilization percentage even before project start [88]. See Appendix A for maximum values on mica content in TBM spoil.

Experience from AlpTransit
Certain rock types have proven to be more suitable for material processing and concrete aggregates. Throughout the GBT project the spoil was divided into A and B classes, “A” material was suitable for applications such as concrete aggregate, “B” did not has potential and was instead used as landfill. If a gneiss contained 30% or more of phyllosilicate (clay minerals), schistose, flaky or broken rock it was determined as the borderline between A and B material. The tunnelling would use lengthy periods thrusting past massifs of different petrography consequently classifying them as “A” or “B”. In the spirit of increased utilization of material and wanting to reduce the landfill volumes, material was classified as “A” despite having too high phyllosilicate or mica content [17, 55].

AAR was of importance for spoil utilization at the GBT as it was conducted preliminary concrete tests with crushed rock to detect the extent of possible AAR. Extracting 43 rock samples, it was indicated that 50% of the rock samples had some sort of AAR [55] (tested after French standard ANFOR P18 588 and 589) [55].

Through the AlpTransit projects experience in utilizing TBM spoil has grown. These include certain factors when using spoil as concrete aggregate [33].

- 5-20% increased cement need
- Up to 50% reduction in E-modulus
- Possible to create mixes with w/c < 0.5
- Compressive strength stays normal or may even be higher
- Increased shrinkage, but without cracks due to the low E-module
- Extra attention to workability
- Minimum cement content of 450 kg/m^3 in shotcrete

Table 2-19: GBT's classifying of the spoil material at the GBT according to petrographic description.

Material class	Petrographic description
A material, suitable for recycling	Amphibolite, pegmatite, aplite, gneiss
B material, suitable for deposit	Schistose gneiss, schist, phyllite, talc schist

Table 2-20: The total material balance in the GBT project [55].

Material volume	Classification	Use	Percentage
28.7 million t	"A" grade material	Aggregates for production of concrete	23.0%
		Disposal to third parties	3.2%
		Preparation losses	2.8%
		Sludge and slurries from preparation	4.3%
	"B" grade material	Internal use for dam construction	16.0%
		Depositing and cultivation	44.3%
		Back filling material for third parties	5.7%
	Sludge and slurries for	Bioreactor landfill/use in cement plant	0.7%

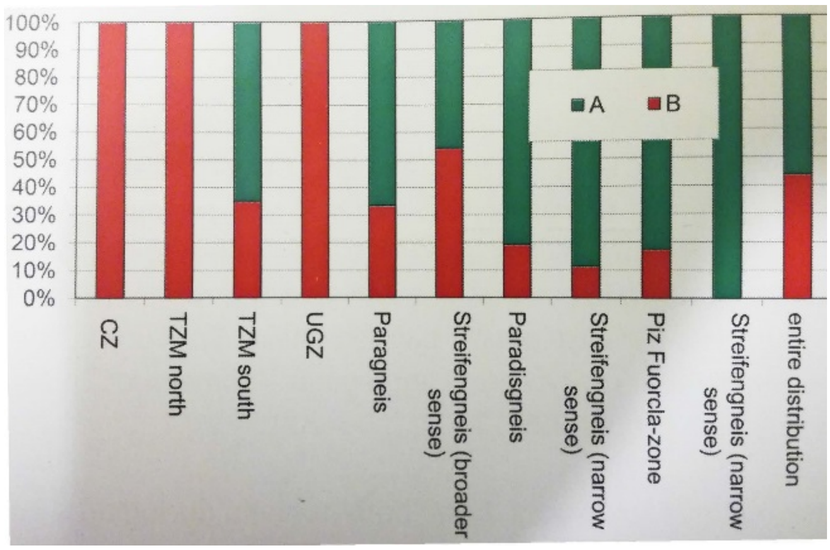


Figure 2-41: Displays the ratio of A and B material, excavated from GBT sorted in zones excavated. CZ(Clavaniev zone), TZM(Tavetsch intermediate massiv), UGZ(Urseren-Garvera zone) [55].

Experience from Linthal

The hydroelectric plant in the Swiss Alps was carried out between 2009-2016. The Linthal project was pioneer work in terms of utilizing TBM spoil and blasted rock for concrete purposes. This was possible with both dry and wet processing. At the intake, dry processed was used to dam concrete and at the outlet wet processed rock was pumped in and used for inner lining and turbine cavern. Luckily the massive malm limestone excavated had no quartz content and neglectable amounts of mica. AAR reactions could also be ruled out. The in-closed wet processing facility was also designed to produce aggregates in outside temperatures of -20 °C. In the planning stage product quality was assured with testing of crushability, abrasiveness and point load index described in 2.3.3. Additionally, during processing, specifications on pumped concrete involved boundary limits on PSD, flakiness and LA test. PSDs from both the dry and wet processed material can be found in Appendix H.

Table 2-21: Obstacles and how they wore solved during the processing of spoil and blasted rock from the Linthal hydro-electric project [20].

Problem	Solution
Dry processed material fluctuated daily on PSD and created problems for the concrete mix. (Sudden negative changes in concrete workability)	Daily moisture measurement and PSD of the 5 fractions produced (0/4, 4/8, 8/16, 16/32, 32/63). Additionally, adapting the concrete mix daily based on the amounts of fines in the 0/4 and 4/8 fraction resulted in successful concrete mixes. Predictions were also necessary.
Concrete for cavern and inner lining had to be pumped 500 m.	A filler fraction was created from residues from 4/8 and 8/16 mm wet processed material to assure good pumpability and lubricating of the pipeline.

Figure 2-42: Wet processed aggregates used at the Linthal hydro-electric project. For both the Y-branch construction(SCC) and inflow and outflow portals.

Experience from Zugwald 1998

Experience from the utilization of spoil for concrete involves continuous monitoring of TBM spoil due to changes in the rock and geology as the dependent factor. The projects processing plant involved an impact crusher, washing facility with a clarifier (sedimentation tank) and VPA to create mud cakes for the landfill. From experience, its listed suitable and unsuitable petrographic of the spoil in Table 2-22. If the spoil only contained 5% of the soft rocks the material was regarded as suitable [19]. Continuing samples was taken daily, including PSD and petrographic description [36].

Table 2-22: Suitable and unsuitable spoil for concrete aggregates.

Suitable	
1	Hard: Fine homogenous crystal rock. Well solidified quartz rich sandstones.
2	Medium: Lime, dolomite
3	Medium: Coarse crystalline rocks, mica-rich gneiss
Unsuitable	
4	Soft: Coarse-crystalline Limestone spars, Marl Limestone, soft molasses sandstones, brittle components, Gypsum, Anhydrite, Pyrite.
5	Soft: Mica flakes, Chlorite, Lime, Clay slate, and Marl Shale
6	Wood, glass, slag, coal

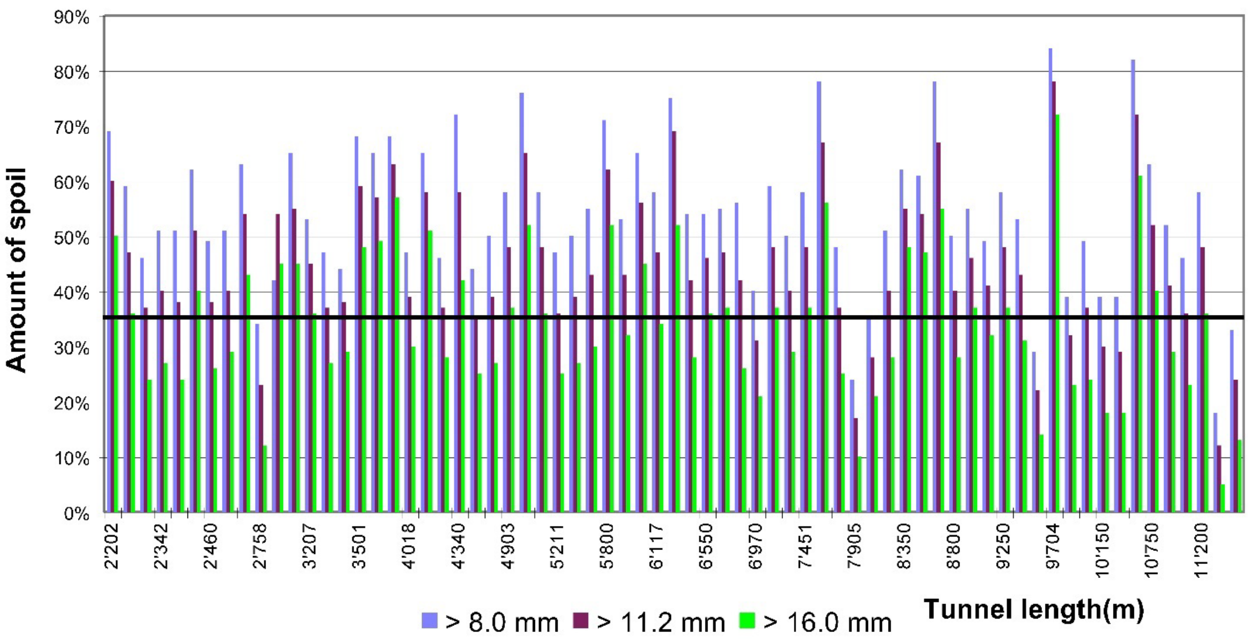


Figure 2-43: The TBM spoil excavated over a period of 9,5 km in the Zugwald tunnel. The black horizontal line are the average of >16 mm , which was 34 % [36].

Experience from Koralm

290, 000 t of concrete aggregates originated from utilization of spoil by 2015 at the Koralm KAT 2. The aggregates have been able to result in concrete segments for tunnel lining concrete C35/45. Special segment parts with C50/60 requirements has not been produced with utilized spoil and external sources has been used. Crushability measured with LA test and compressive strength with point load index. The project has experienced extreme amounts of mica in the gneisses, though simple solutions has been used to solve the problem, see Table 2-23. Experiencing increased problems with muscovite compared to biotite and chlorite minerals [1, 15]. Concrete recipes have also been adapted, based on the lithology. Point load index shows higher compressive strength on gneiss versus mica schist. This results in 30 kg/m^3 reduction of required cement in the recipe. Still achieving the same concrete strength, see Appendix F. The most crucial factor affecting the PSD are concluded to be the disc cutter number and spacing. For the processing stage the influencing factors are mineralogical composition, shape, strength, moisture content. An attentive crew stab are also required for proper decision making[98].

Table 2-23: Obstacles and how they wore solved during the processing of spoil and blasted rock from the Koralm KAT 2 [98].

Problem	Solution
TBM spoil contains too high moisture content for proper preliminary screening	Discharged and tipped before screening stage. Let too dry before the dried spoil is re-entered into the screening with a wheel loader
No fluctuations in moisture is unavoidable. It is still creating problems for the concrete batching plant.	Workability measurements on the fresh concrete
Free mica content of up to 40% in the 0.125-0.250 mm fraction of the 0/3 mm produced concrete aggregate Same problem was experienced with high carbonate content of up to 50%.	Mix two storages of TBM spoil. The first source would have low content of the impurity and the second source would have exceeding values. This lowers the overall percentage and the aggregate requirements was approved
Limited amounts of spoil for the 16/32 mm fraction	Changing mix design to aggregate Dmax 16 mm

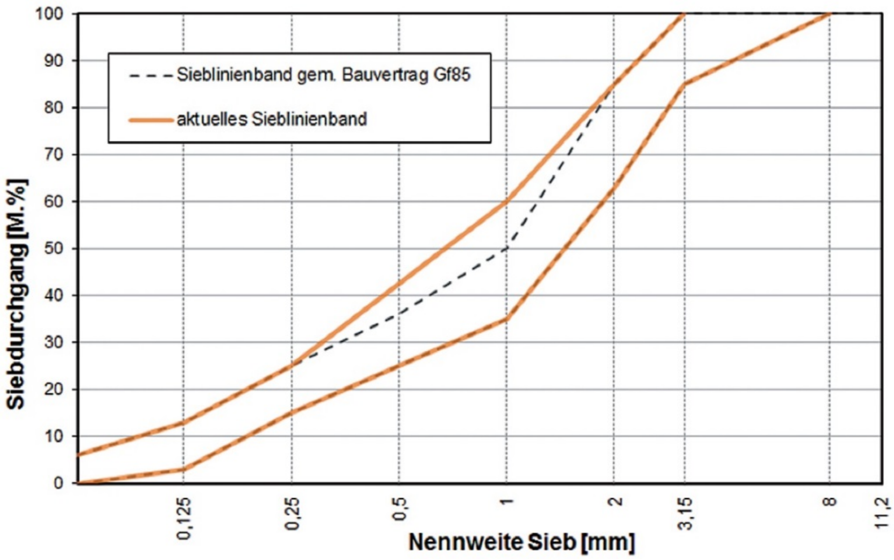


Figure 2-44: Boundary lines for the 0/8 mm fraction. The boundaries allow for high amounts below 0.125 mm [98].

Simulation tools

Total self-supply of concrete aggregates is not realistic as the initial period would require concrete before sufficient spoil is produced. Using a computer based tool(TEMH) to simulate and input uncertainties in material handling it's possible to predict the amounts of spoil which can be reused into concrete aggregates. Various input parameters can be set such as geology, loosening factor, water inflow, overburden and transport speed/capacity (trucks, conveyor systems or muck trucks), storage facilities, advance rate, processing advance rate. Several simulations are done with the same parameters to evaluate uncertainties. Total volume of self-supplied concrete aggregates is presented in correlation to excavated material by time. Figure 2-45 are showing how the self-produced concrete aggregate are sufficient after a certain delay in the project timeline, the mean value predicts 37.6% self-supply of concrete aggregates, where the remaining 62.4 % must be bought from regional suppliers [23]. The Java based simulation program was used to aid the project administration at Brenner Base tunnel (D&B) in Austria/Italy [99].

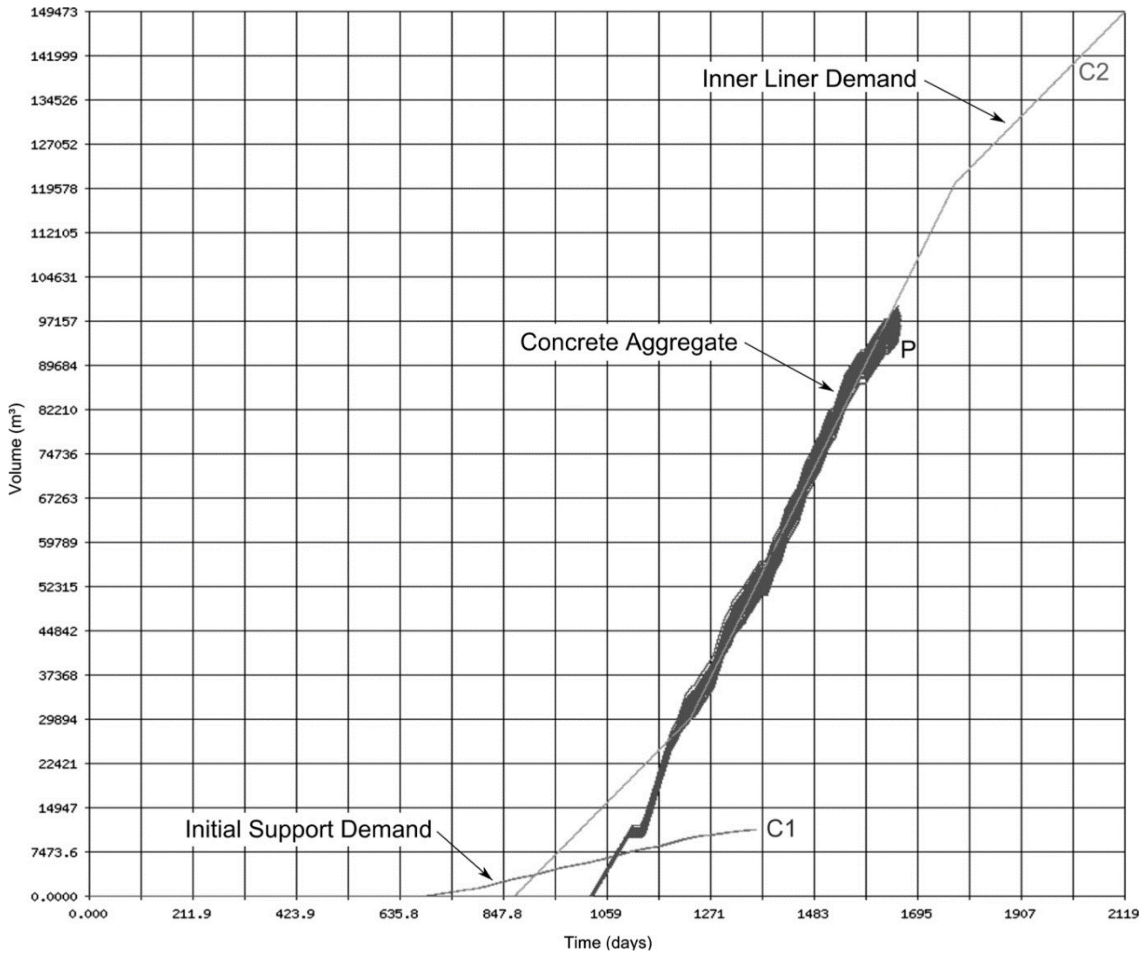


Figure 2-45: Concrete aggregate consumption through a four-year tunnel project versus the self-produced concrete aggregate. Grey area represents 100 different simulations which are based on uncertainties as evading geological conditions [23]. Self-supply of concrete aggregates is obtained 424 days after concrete consumption starts.

3. Field and laboratory research

3.1 Field research

3.1.1 Ulriken TBM project

Between 26.10-29.10.2017 field research was done at Arna, closest train station to Bergen. Living at the barracks and working at the site office (Bane Nor) to learn about the project, at the time the TBM was in a weakness zone. Daily routines included concrete trucks arriving with shotcrete which was poured into the shotcrete trains and transported into the tunnel. A wheel loader was used at the tipping point for the conveyer belt (Figure 3-1a) to lift spoil into transport trucks doing shuttle traffic between Arna and a close by landfill. The distance between the shotcrete trains and tipping point of conveyer belt was approximately 30 meters. During the stay, a close by quarry was visited which was receiving a substantial amount of spoil from the TBM, seen in Figure 3-3c. The quarry was in the process of approving a 0/4 mm fractions originating from D&B, but was not processing the TBM spoil because it was supposed to be used as a layer on the seabed in the Bergen harbor. The wet processing facility, newly installed at the quarry was done with a clarifier combined with a VPA, exactly as the Follo line process facility, see 2.2.2 for more. In total was three spoil samples extracted during the stay and sent back to the concrete laboratory at NTNU.

Figure 3-1: (a,b) Spoil from the TBM transported by conveyer belt, trucks would arrive based on the drilling rate that given day. (c,d) On top of one of the “mountains” of TBM spoil at NCC Ytre Arna gravel works, collecting a sample.

3.1.2 Follo line TBM project

25.01.2017 field research was done at main project site at Åsland outside of Oslo. The site was constantly receiving a vast amount of spoil from 4 Double TBMs. The spoil could end up in 4 different storage units, based on its quality. The highest quality spoil was poured out to process facility area and transported by wheel loader to the scalping screen (>20 mm), seen in the background of Figure 3-2c. The process is further described in Appendix D. The produced fractions 0/8, 8/11 and 11/22 was stored under roof and combined with the exact same fractions from regional suppliers, which was delivered daily. One additional storage for only external aggregate 0/8 mm fraction was needed. The external 0/8 mm fraction would also be mixed with the self-produced 0/8 mm fraction to normalize properties of the self-produced sand, based on concrete mixing experiences at site. The aggregate storages were connected to the concrete plants aggregate silos with conveyer belts. The conveyer belts started from below ground as it couldn’t intervene with the truck delivery of the external aggregates. Experience with fluctuating moisture content of the self-produced sand was discussed to be solved with larger storage capabilities as this would create a buffer before it ended up in the concrete mixer.

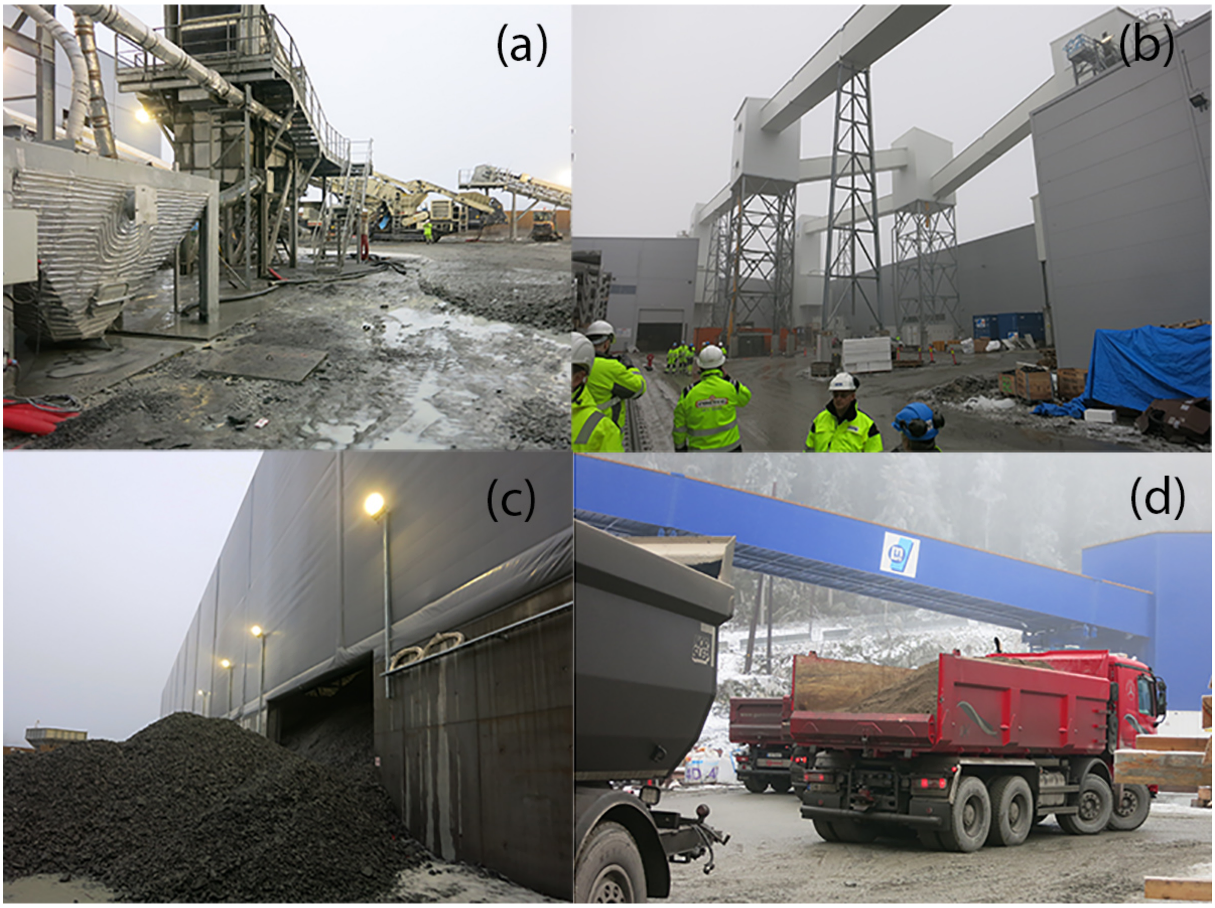


Figure 3-2: (a) Processing facility at the follo line project, dewatering cyclone can be seen in front, in the back a mobile screener combined with a cone crusher. (b) Conveyer system, concrete batching plants and segment production. (c) High quality spoil, this would be transported by wheel loader into the scalping screen and material processing. (d) Constant delivery of third party aggregates for concrete production.

3.2 Laboratory preparations

3.2.1 Sampling, splitting and aggregate packing

Several measurements have been done on the spoil from the Follo line project and Ulriken. The spoil has been collected mostly from stock piles and may be affected by segregation. This is a variable and could impact the sieve tests. Larger and heavier particles will generate higher velocity and end up further away from the pile. In addition, would rainfall potentially transport dust particles away from the pile. When extracting from such a pile in Figure 3-3, gathering should be selected from different heights of the pile, resulting in a more accurate sampling. TBM spoil can also be gathered directly from the conveyer belt.

The gathered material originates from three sources:

1. Commercial limestone filler from Tromsdalen Quarry (T0)
2. TBM spoil gathered at portal (T1-T4)
3. TBM spoil processed at follo line processing facility (T5)

Table 3-1: The material used in the various laboratory tests.

Test No	Source	Tunnel profile (meters from Oslo)	Geology	Density	Dmax [mm]	Origin
T0*	Limestone filler Tromsdalen Quarry	-	Limestone (97% $CaCO_3$)	2.74	0.125	PhD Rolands Cepuritis
T1	Ulriken	465.646	Quartz rich mica gneiss	2.60	90	From tip
T2	Ulriken	465.618	Granitic gneiss, with biotite mica	2.54	90	From tip
T3	Ulriken	465.185	Augen gneiss, banded gneiss, transformed migmatite gneiss	2.61	90	From conveyer belt
T4	Follo line	10.483-12.460	Dark gneiss with amphibolite/pegmatite dykes	2.68	90	From tip
T5	Follo line material processing	-	Dark gneiss with amphibolite/pegmatite dykes	2.76	8	(0/8 mm) From process facility

*Combined of: 15% coarse, 38% medium, 47% fine filler. Done to mimic the spoil fillers PSD T1-T4.

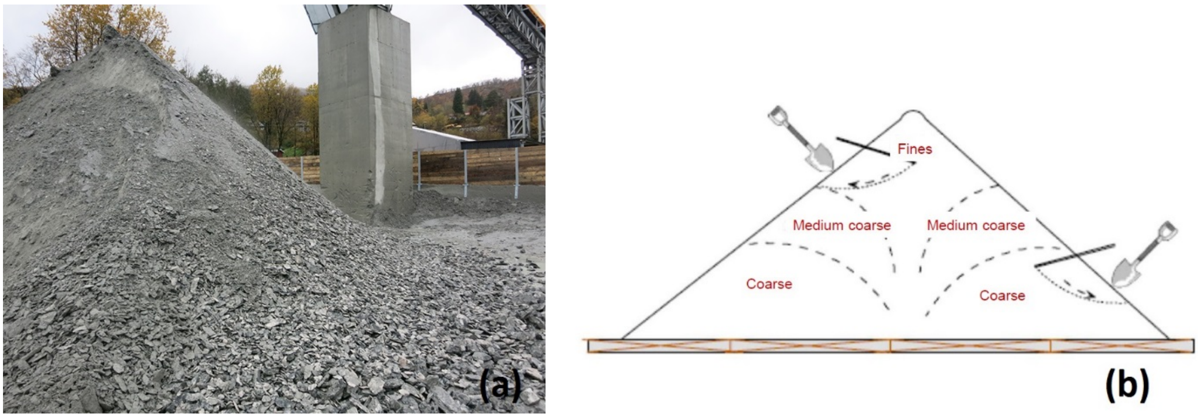


Figure 3-3: (a): Showing stock pile at Ulriken tunnel project, sample 2 was taken from this pile. (b): the normal segregation generated when piles are created from conveyer belts.

NS-EN 932-1 and 2 are used to extract samples and split them. Methods to extract a sample from a granular material which may vary in properties if not the sampled with the knowledge of segregation. The goal is to split and collect representative data of a given granular material to produce legitimate test results. Sampling and splitting of spoil was needed and additionally splitting of filler (<0.125 mm). In Figure 3-4b the sampling reduction of TBM spoil is captured. Density of spoil are measured with the use of a water filled cylinder and gravel which displaces the water and increases the water level (Archimedes principle). The measurement was done with a set of 1-3 mm gravels from each sample. Each set of gravels was submerged three times and height and weight registered. Water height was measured at the minimum point of the meniscus.

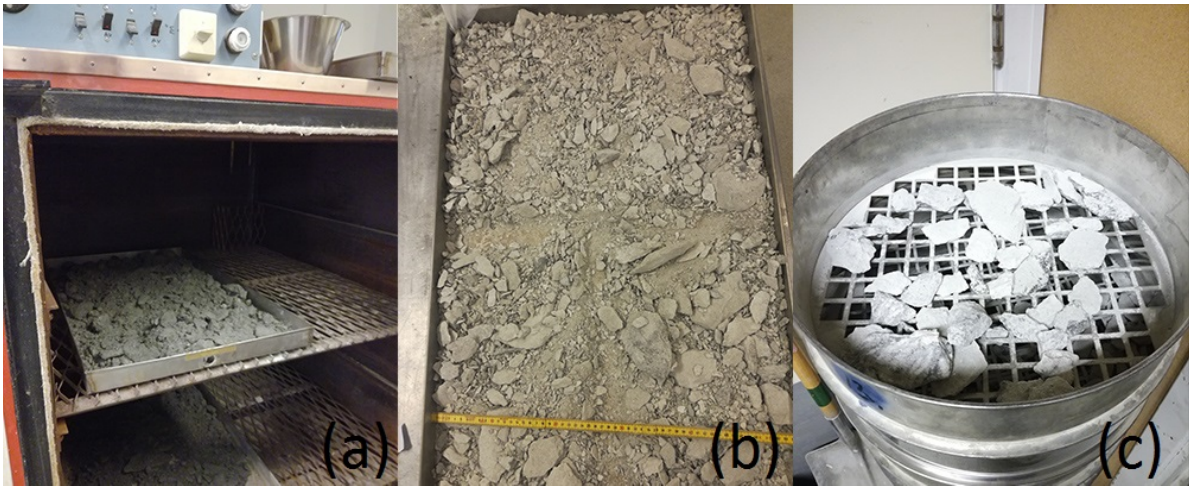


Figure 3-4: (a) Drying TBM spoil at 105 ºC. (b) Reducing sample by quartering for further dry sieving. (c) Dry sieving of TBM spoil.

Dry sieving	**Wet sieving**
Carried out at the Department of Structural Engineering, NTNU. Repeated once. Procedure based on EN 933-1. ISO standard sieves from 0.063 – 32 mm 1. Sample placed on the 32 mm sieve and vibrated for 15 min. Weight retained on each sieve measured	Carried out at the Department of Geoscience and Petroleum, NTNU. Not repeated. Procedure based on EN 933-1. 1. Washing the sample of fines, cleansing the coarse (>16 mm). 2. Dry sieving of the >16 mm 3. Sludge below 16 mm was placed to dry in an oven/drying room. 4. Wet sieving of the oven dried <16 mm fraction.

Aggregate packing

Using the density measurement already collected, the loose packing grade was measured. The procedure would involve a container formed as a cylinder, height: 163 mm, diameter: 100 mm. The test was evading from the container requirements in NS-EN 1097-3. The standard states a minimum cylinder capacity of 5 liters when working with D=16 mm particles. The actual container had a capacity of 1,28 liters. The deviation was discussed and the consequences could result in slight reduction in the accuracy of the measurement, results are found in 4.2.2.

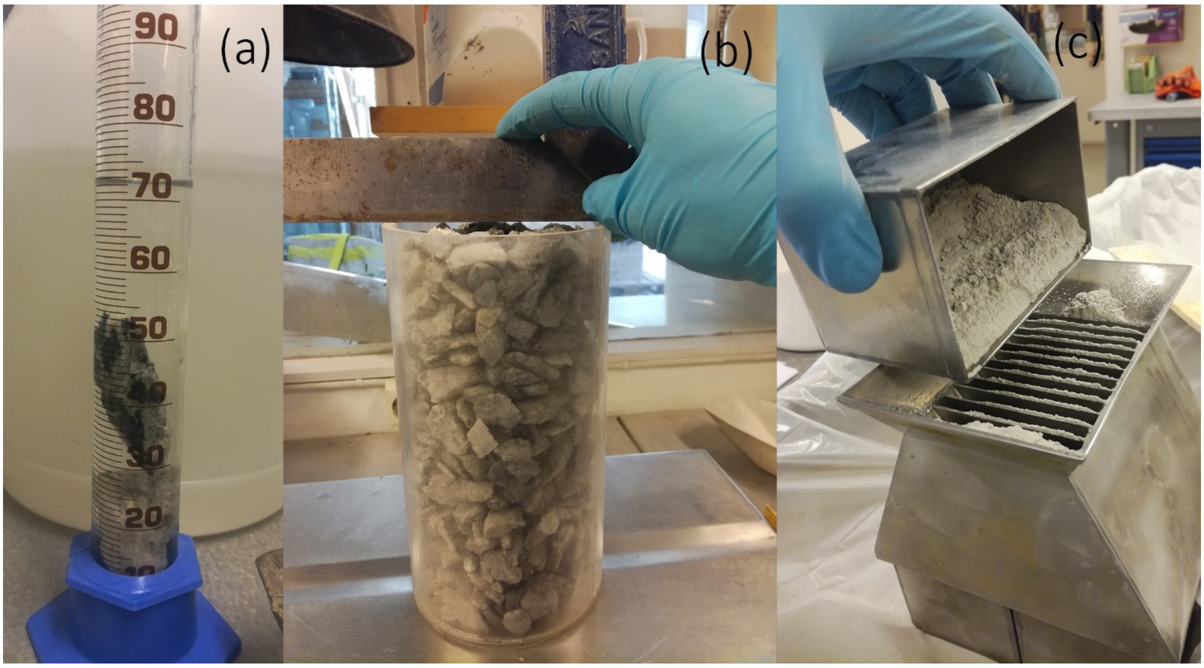


Figure 3-5: (a) Density measurement of cuttings by submerging in water. (b) Packing grade measurement. (c) Splitting of filler in preparation for the SediGraph.

3.2.2 X-ray sedimentation

The TBM spoil has been investigated on micro level. PSDs in the 1-0.125 µm fraction has been investigated to evaluate the properties of the TBM filler and look for unwanted properties such as clay minerals. All tests were performed with the SediGraph III PLUS under the exact same circumstances. Dispersing liquid used was A-12 at 30°C which corresponds to a viscosity of 3.93 mPa s and density of 0.808 g/mL. Measurement was done in the size range 1-125 µm and resulted in approximately 30 minute tests. A baseline and a trial test was acquired before each real test to confirm the X-ray counts and to measure the exact mass(g) needed for real test. To acquire the most accurate results the filler and dispersing liquid was mixed prior to the SediGraph and placed in an ultra-sonic bath for 15 seconds before it was poured into the mixing chamber of the SediGraph. A reduction in X-ray counts of 30-31% was normal values during the test. 8-15 grams of filler was required for preparation tests and real test. The results can be found in Figure 4-9.

3.2.3 Rheological properties

The matrix is proportioned to represent a typical industry concrete(B45M40) and is scaled down from a mix design with a 360 kg/m^3 cement content. This mix is meant to be in close similarity with the matrixes used in concrete recipes for large scale infrastructure projects. The matrix is designed to withstand any type of Alkali-silica reactive aggregates in accordance with NB 21. The matrix is sufficient to for special aggressive environments as its edible for exposure class XSA[12]. The matrix was mixed in a stiff rubber container, the detailed procedure can be found in Table 3-3. More about the FlowCyl can be found in 2.5.1. Rheological test on the TBM fillers has been replicated with an engineered limestone filler and curve modelling has been applied to copy the PSD of the TBM fillers which was measured with the SediGraph. To accomplish this the limestone fractions 0/20, 20/60 and 40/250 µm has been combined in different ratios, see Figure 3-6. Afterwards FlowCyl and mini-slump measurements was conducted.

Table 3-2: Matrix composition used with TBM fillers and limestone filler.

Constituents	kg	density(kg/m3)	volume(l/m3)
CEM II/A-V	2.288	3020	0.758
Water	0.915	1000	0.915
SP 0.9 %	0.021	1050	0.020
Filler(T1-T4)	0.818	2700	0.303
Sum	4.05	-	1.999
Density	2.027		

Limestone filler T0 (µm)	%	m(kg)
0/20 µm	47 %	0.385
20/60 µm	38 %	0.311
40/250 µm	15 %	0.123
sum	100 %	0.818

w/p	0.30
w/c	0.40
fi/c (vol)	0.40
fi/c (weight)	0.36
powder/vol ratio	0.53

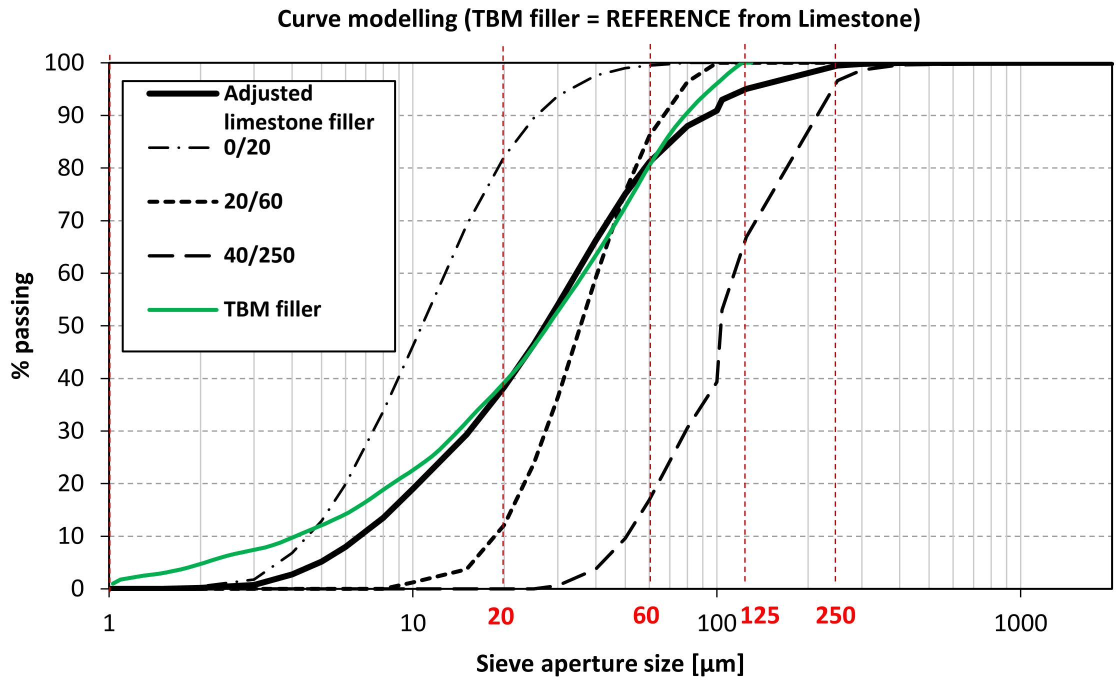


Figure 3-6: Curve modelling of limestone filler to mimic the TBM fillers. The curve "Adjusted" is a combination of 0/20, 20/60 and 40/250 µm in the ratio 47, 38, 15% respectfully.

Mini-slump cone test is a downscaled slump test similar to standardized slump cone test used for concrete[100, 101]. The cone used had these dimensions: bottom diameter = 89 mm, top diameter = 39 mm, height = 70 mm. The measurement was performed on a transparent plexiglass and resulted in no leakages between matrix and cone. The top was leveled to assure the same amount of matrix in each measurement.

Table 3-3: Matrix mixing procedure followed by FlowCone and mini-slump cone measurement.

Time line		Action
Total[min]	Step[min]	Preparation
2	2	Dry preparation: filler and cement mixed in a Hobart mixer with flat blade at low speed (140 RPM)
4	2	Wet preparation: water and SP is poured into the mixing cylinder (2 liter).
		Mixing
5	1	Dry mix is added into the mixing cylinder
7	2	Mixed with handheld drill with a steel beater, high speed (1850 RPM)
9	2	Rest
11	2	Mixed at low speed (1000 RPM)
12	1	Poured into FlowCyl apparatus
15	3-5	FlowCyl and Mini-slump cone test

4. Results

The results are divided in two.

4.1: The findings from real TBM projects where spoil has been utilized as concrete aggregate.
4.2: Laboratory measurements on TBM spoil conducted by the undersigned.

4.1 Review of PSDs from hard rock TBMs

As of 2017 there are only a few countries who can confirm utilization of spoil from hard rock TBM projects, these are Switzerland (5 projects), Austria (1) and Norway (2), France (1). All projects are either railway or hydro-electric plants. The Swizz entrepreneur Marti Technik and the Swizz concrete technology consultant B + G have large involvement in nearly all Swizz and Austrian TBM projects listed. All projects do normally include some sort of conventional tunnelling. This is due to excavating the launching tunnel for TBM, crossovers between parallel tunnels or caverns for the turbine in hydro-electric plants. The “Dmin” column in Table 4-1 describes the minimum fraction of TBM spoil utilized into concrete aggregate, this results in a fraction above either > 10, 16 or 20 mm. Other projects have in certain good quality rock conditions, been able to utilize the whole spectrum of spoil down to 0 mm. Different spoil management plans have been used in the different projects. Important experiences and obstacles on both concrete proportioning and material processing has been mentioned in *2.7 Utilization strategies and experience*.

Table 4-1: TBM projects with confirmed utilization of spoil in concrete.

Project	Country	Year	TBM	Km	D(m)	Million tons	Utilization [%]	Dmin (mm)	Referene
Zugwald (R)	CHE	NA-1998	1xGripper	9.5	7.65	1.2	16%	>16	[36]] [19]
Gotthard base tunnel (R)	CHE	1999-2016	4x Gripper	57.1	9.58	28.7	23%	>0	[55]
Koralm KAT2 (R)	AUT	2013-2023	2x Double shield	21	9.93	8.6	17%	>16	[1] [102]
Follo line (R)	NOR	2016-2021	4x Double shield	19.5	9.96	9	10%*	>20	[92]
Breheimen (H)	NOR	1986-1989	Atlas copco Foro 1500	5.5	4.5	NA	NA	>10	[28]
Lötschberg (R)	CHE	1999-2007	2x Gripper	34.6	9.43	16	29.1%	>0	[103]
Linthal (H)	CHE	2010-2015	1x Gripper	3.7	5.2	1	100%	>0	[20]
Nant de Drance(H)	CHE	2008-2016	1x Gripper	5.5	9.5	1.14	25%	>0	[104]
Lyon-Turin Mont Cenis base tunnel (R)	FRA/ ITA	2002-2025	4x Hard rock 2x dual mod 2x mixed shield	57	10.5	NA	25%*	NA	[105, 106]

CHE - Switzerland, NOR – Norway, AUT – Austria, FRA/ITA – France, Italy
R = Railway tunnel, H= Hydro tunnel,
*Predicted values, project not finished.

From what's possible to collect of PSDs from earlier projects Figure 4-1 presents a three considerable new TBM projects in hard rock. Ulriken and Gotthard was done with Gripper TBMs, Follo line are excavated with double shield TBMs. Ulriken and Gotthard are similar though it is expected that Ulriken would generate a wider specter of PSD's if more samples was collected. Gotthard PSDs are most likely done with dry sieving and may explain the lower filler content compared to Ulriken which are wet sieve tests of approximately 50 kg. GBT has a cutter spacing of 90 mm and diameter of 432 mm while the Norwegian TBMs has 70 mm and 475 mm respectfully. This may explain the coarser sieve curve from GBT. Sieve tests conducted at Follo line are for some unknown reason not conducting sieving below 1 mm. Interpolating are performed and predictions are shown with dotted lines which reveals high filler amounts. All the original PSDs can be found in the Appendix K, L, and M.

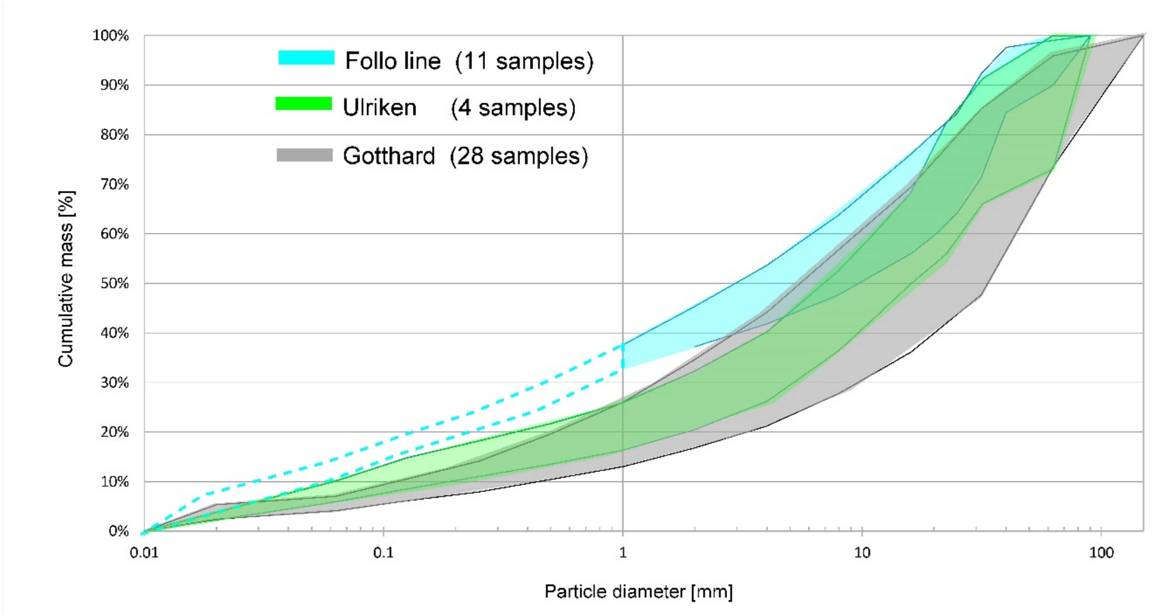


Figure 4-1: Follo line, Ulriken and Gotthard compared on its normalized PSDs, the extremes are removed. Follo line: Predicted content below 1 mm is marked with dotted lines due to missing data.

Comparing PSD of old and new TBM projects is presented in Table 4-2. The minimum and maximum values to fluctuate and Gotthard do fluctuate the most, but do also have the most recorded PSDs.

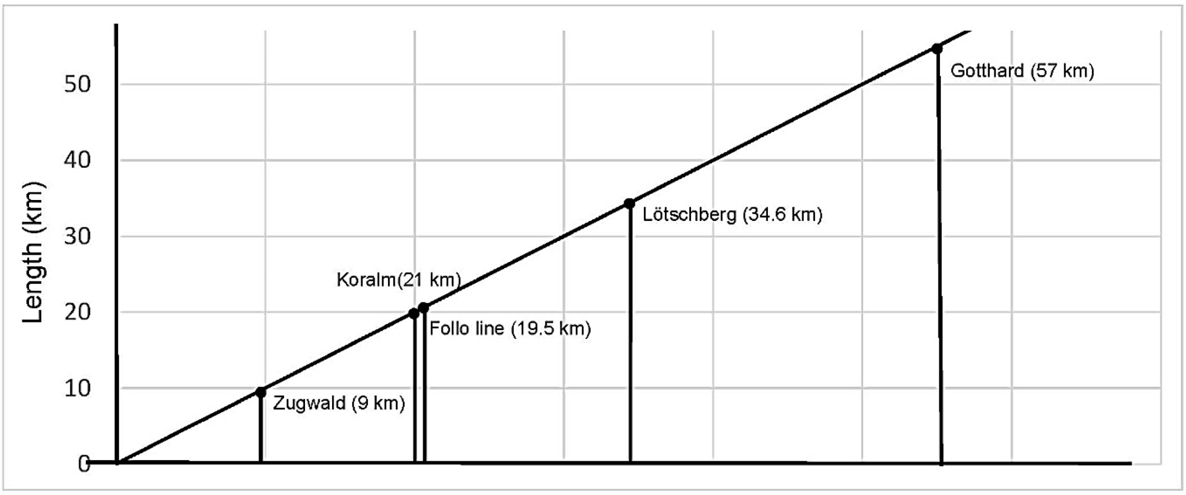


Figure 4-2: The railway tunnels from Table 4-1 which utilized TBM spoil into concrete aggregate has a minimum 10 km length, All tunnels are double barrel, except Zugwald.

The table below are six sources of PSDs from TBM projects. The <0.125 mm content are compared (mean values).

Table 4-2: Average filler content in different spoil from hard rock TBM projects.

TBM projects	No of PSD's	Dmax [mm]	0.125 mm content [%]	0.125 mm Min-Max [%]	Appendix
Ulriken, Bergen 2016	4	90	12.9	8.5-15.6	L
Fløyfjell, Bergen 1988	11	63	9.6	6-16	N
Mix of earlier Norwegian (1977-1983)	4	63	18	12-26	J
Mix of earlier Swizz (<1998)	5	63	10	5-16	I
Follo line, Åsland 2016	1	63	14.7	13-19	K
Gotthard Base tunnel(Amsteg)	28	156	9.50	3.6-19.7	M

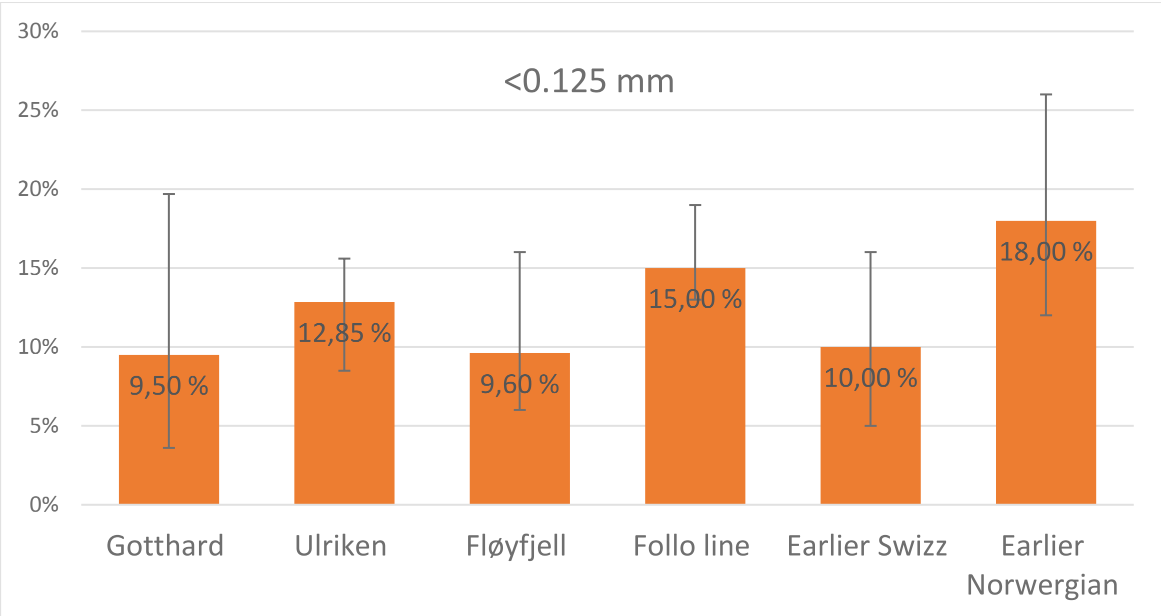


Figure 4-3: PSDs from various TBM projects and their average content of what is below the 0.125 mm sieve. The average is 11.8%.

Fløyfjell and Ulriken are two projects 30 years apart but both in contact with the same gneiss and hornblende slate close to Bergen. Surprisingly do TBM used in Ulriken produce a finer PSD. This could be the result of more accurate wet sieving applied on the TBM spoil from Ulriken. Another factor could be the angle the TBM are attacking the mountain, which could result in reduced chipping frequency or block formation.

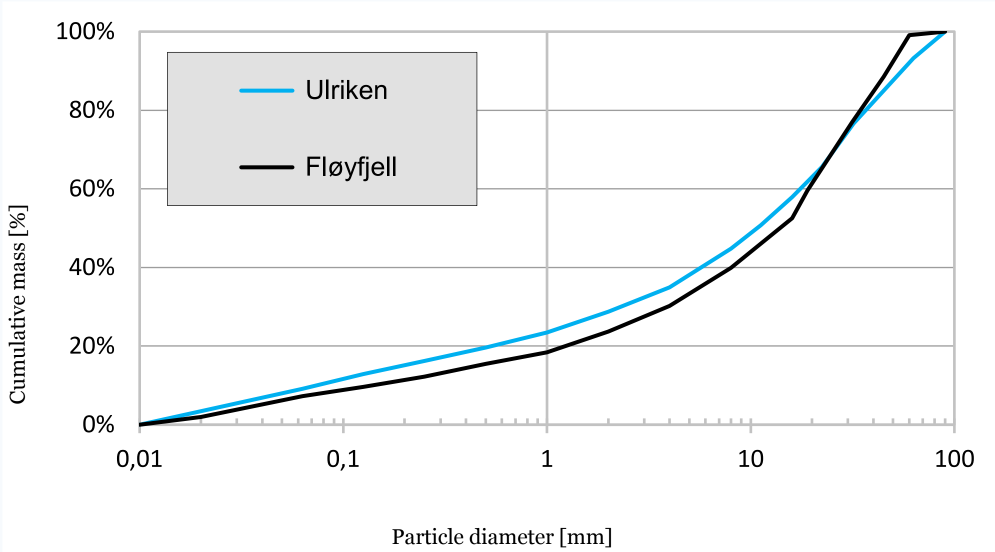


Figure 4-4: Comparing the average of PSDs from TBM projects Ulriken and Fløyfjell.

4.2 Laboratory experiments

4.2.1 Microscopy

During the investigations of the TBM spoil at the laboratory, wet sieved was needed as fines was spotted covering larger particle of the spoil and resulting in inaccurate PSDs. This is confirmed with a microscopic analysis done using a microscope of type Bach & Lomb, Stereozoom 7. The pictures where taken with a normal digital camera placed above the microscope. Wet sieving is proving itself as the qualitative and the most detailed approach if a PSD measurement is carried out. The 0/0.063 mm fraction have a strong cohesive bond and seen as layer on larger particles. Even oven dried spoil (105 °C) and intensive vibration carried during a dry sieve has proven to not be able to remove these fines. It’s unknown if these filler particles will fall off during a fresh concrete batch. If this wore to happen it would probably be a combination of wetting by the matrix and scraping and interaction of the aggregate particles. If these fillers would stay layered on the aggregates particles through the concrete hardened state it would most certainty reduce the bond between matrix and aggregate and could negatively affect the concrete strength. A wet sieve is a more demanding task compared to a dry sieve and dry sieves do correlate to a wet sieve in the coarser fractions, see Figure 4-6.

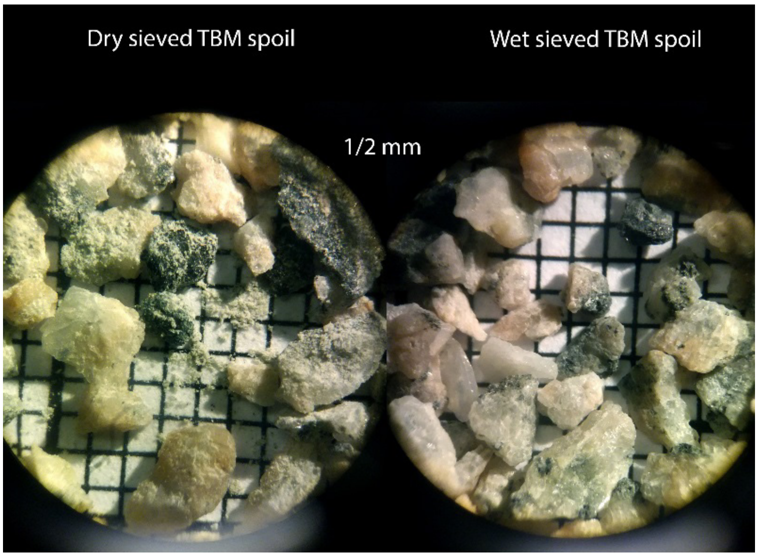


Figure 4-5: Fines have a cohesive binding to particles which stick to the dry sieved spoil. Light scraping on the dry sieved 1/2 mm fraction and finer particles fell off. Squares are 1 mm.

4.2.2 Sieving and aggregate packing

Samples used in laboratory experiments are listed in Table 4-3

Table 4-3: Samples for laboratory experiments

Sample	Type	Origin
T0	Limestone filler	Tromsdalen Quarry
T1	TBM spoil	Ulriken
T2	TBM spoil	Ulriken
T3	TBM spoil	Ulriken
T4	TBM spoil	Follo line
T5	0/8 crushed washed TBM spoil	Follo line material processing

T1-T4 has been sieve tested with both dry and wet method at NTNU (1 kg tests). Parts of the T3 sample had earlier been sent to NCC labs (50 kg) for wet sieving. Additional spoil not used by NCC was collected by undersigned. The undersigned has compared results to this sieve curve in Figure 4-6. The results are proving inaccuracy between wet and dry sieving technique and the difference in amount(kg).

The gap between curves in Figure 4-6a is due to the larger chips of the PSD which has drastic impact on smaller sieve tests. E.g. one chip measured to weigh 300 grams, which is close to a third of the total weight of 1 kg. In the 50 kg wet sieve test several chips are included, and normalizes the test as it includes more large chips.

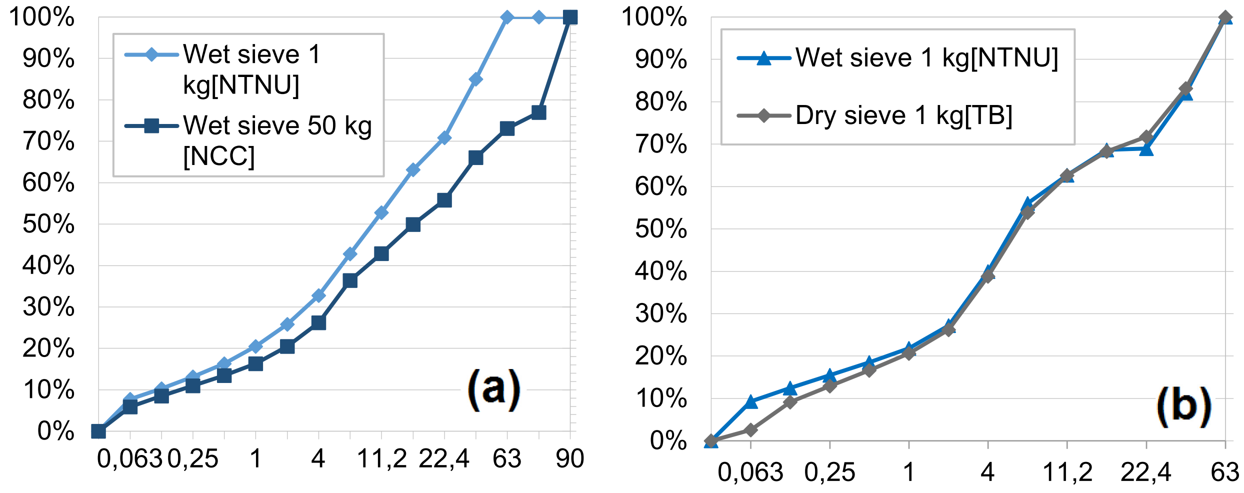


Figure 4-6: Proving differences in the use of wet and dry sieving technique and the amount used (kg) Left: T3, Right: T1.

Figure 4-6 b shows increased amount below 0.250 mm when wet sieved are applied to the 1 kg tests. This is due to minor particles stuck to coarser particles in dry sieved samples. In wet sieving these are detached and more correctly sieved.

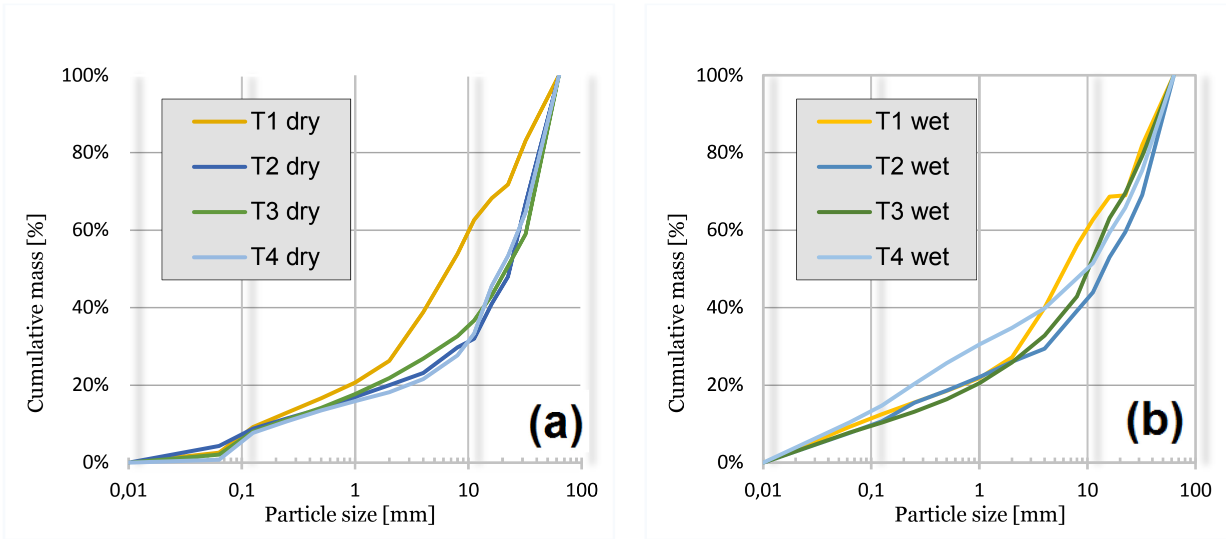
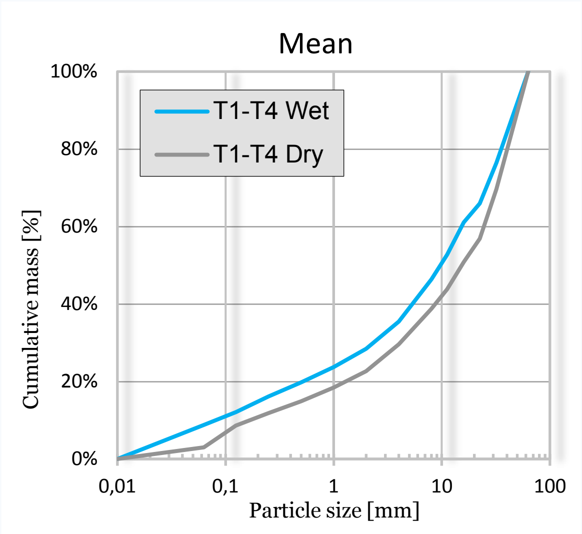


Figure 4-7: 1 kg PSD measurements of the TBM spoil, wet and dry sieved technique applied.

Comparing T1-T4 dry versus T1-T4 wet shows differences possibly due to the amount used for each test sieve (1 kg) allows for a sampling error. The sudden dump down occurring below 0.1 mm on dry sieve is due to adhered fillers retaining on coarser sieves as already explained. Average values of T1-T4 show 2.46% increase on the 0.125 mm sieve when wet sieved. And 5.79% on the 0.063 mm sieve.



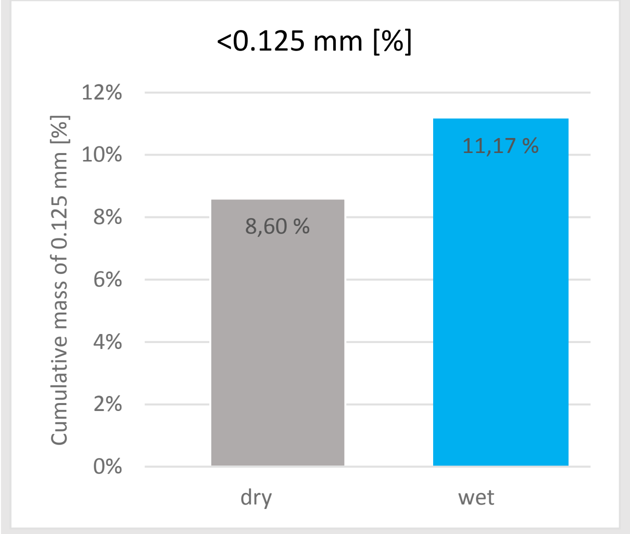


Figure 4-8: Left: Wet sieve always creates a finer PSD when compared to dry sieve. Right: T1-T4 compared on the 0.125 mm sieve

Aggregate packing

The solid fraction content of packed 8/16 mm spoil fraction is on average 47.35 %. This is a low solid content but would increase if mixed with a sand fraction.

Table 4-4: Solid fraction of the four samples measured with a 1.28 liter container and 8/16 mm spoil fractions after NS-EN 1097-3.

No.	Packing grade (solid content) [%]
T1	0.452
T2	0.491
T3	0.474
T4	0.477

4.2.3 *Micro PSD*

Figure 4-9 are showing minor differences between the TBM fillers. The only difference seen is the single Follo line filler (T4) which has higher content of fines below 20 µm compared to T1-T3.

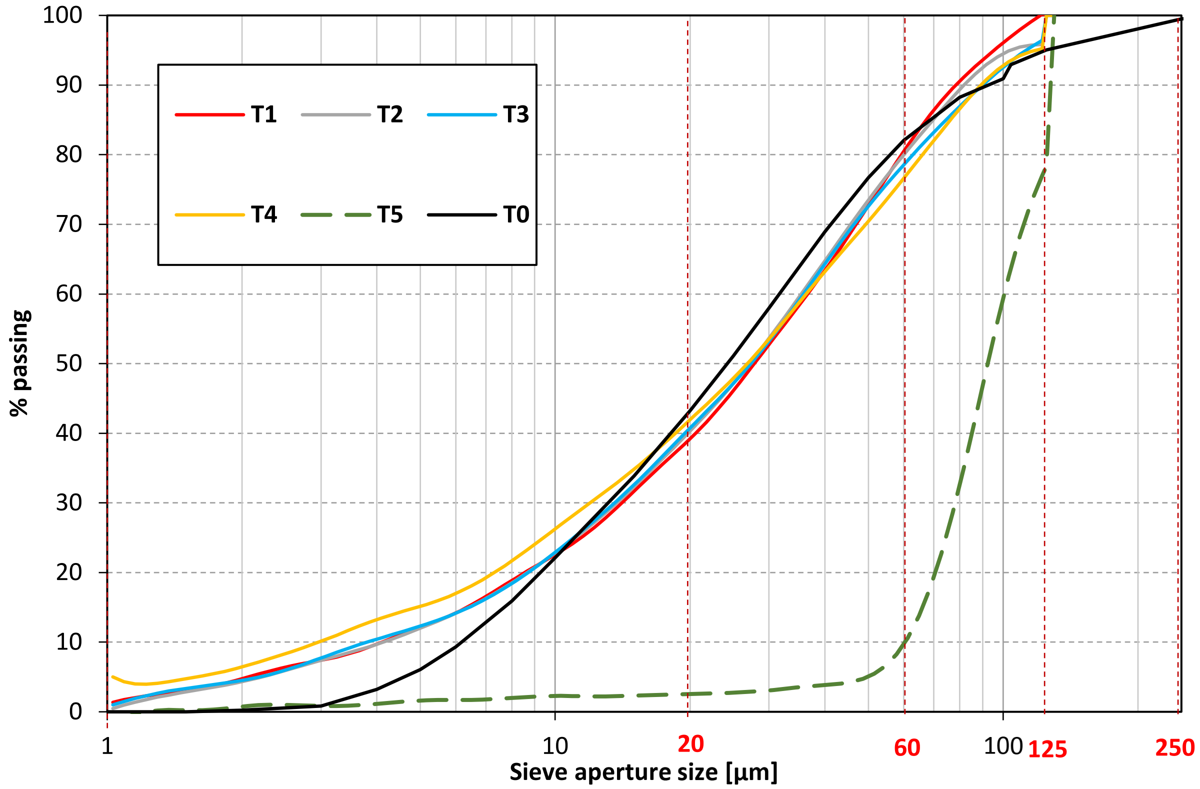


Figure 4-9: PSD of the TBM fillers from Ulriken and Follo line. The raw unprocessed TBM spoil show minor differences. It was not possible to create an identical PSD to the TBM spoil

From the results, its seems the TBM material is not fluctuating much in the PSD(<0.125mm) regardless of which part of the tunnel it's excavated from. The filler PSD originates from varying factors such as wear of cutter discs, TBM thrust, RPM and disc spacing. These factors are minor compared to the fragmentation mechanisms of the rock material itself. All spoils are of the granitic type which is concluded to be the prominent factor and the reason for the nearly identical PSDs. The limestone filler (T0) did not have enough particles in the fine fraction to create an exact replica of the TBM fillers. The limestone filler deviates from the TBM filler below 10 µm and do have particles up to 250 µm as seen in Figure 4-9. This deviation was a compromise that was necessary to proceed with the other laboratory measures (FlowCyl and Mini-slump).

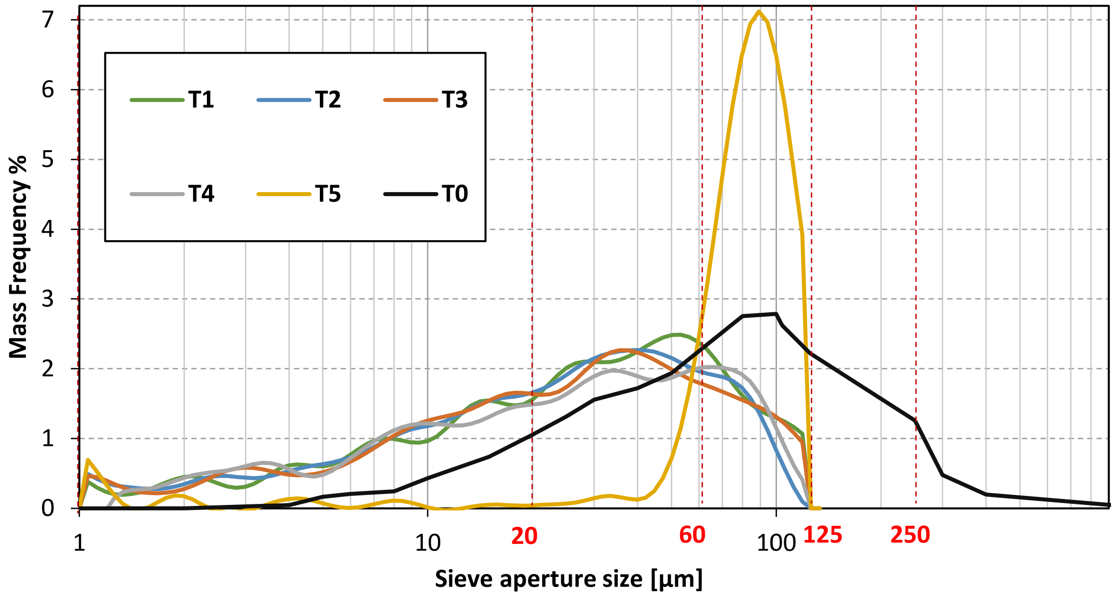


Figure 4-10: The mass frequency of the different TBM materials. Minor variation in the frequency of the 4 TBM spoils. The processed 0/8 mm follo line aggregate(T5) do show high occurrence between 60-125 µm. This can be explained by the reduction of fines with the cyclone placed at Åsland.

Figure 4-5 illustrates how the dry sieved sample includes unwanted filler particles in the 1/2 mm fraction. The wet sieve removed these fines and transported them to their representative screen. Analyzing the PSD on both sources in the <0.125 mm fraction indicates that fillers attached to the larger particles are not of a particular size, but rather a representative sample of the dry sieve PSD, see Figure 4-11.

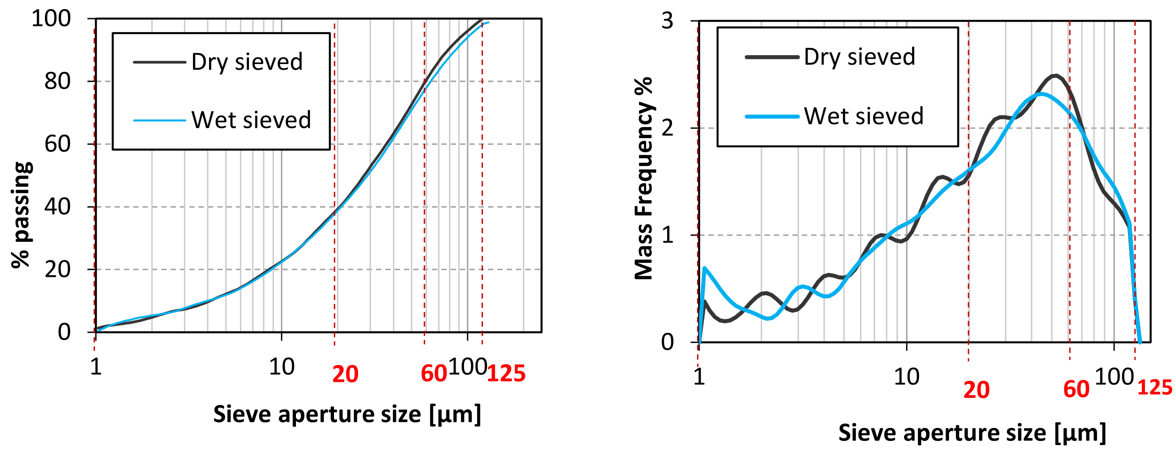


Figure 4-11: TBM spoil(T1) has been dry sieved and wet sieved. Afterwards has both samples has been extracted on the fraction <0.125 mm and been analyzed with the X-ray sedimentation. Minor differences in the PSD is noticeable.

To measure the effect of different fillers on the flow resistance (λ_Q) of the matrix, a reference filler has been engineered from a limestone filler from the PhD work of Rolands Cepuritis. The filler was already dry sieved into coarse, medium and fine fraction in the 0-125 µm spectrum with air classification. Through FlowCyl measurements with consistent mix design and varying filler, the difference in flow resistance can only originate from the filler.

Comparing filler type

Comparing three fillers to the TBM filler reveals close similarity to the crushed sand (Tau and Hokksund, see Figure 4-12. Fillers from a cone crusher/VSI or TBM does not seem to influence the PSD in the 0-125 µm fraction. The processed material is similar, even though the TBM filler originates from an alternative impact crushing process. Comparing TBM filler with quarry filler shows the filler content below 10 µm is less in the TBM filler. It must be mentioned that the total amount of filler would normally be much higher in a TBM PSD.

Table 4-5: Four fillers originating from various sources and three of them from a type of crushing mechanism[107].

Source	Usage	Crushing	Reduction mechanism	Rock type
(T1) Ulriken	Deposit and landfill	Compression	Cutter discs (TBM)	Granitic gneiss
Tau	Commercial product	Impact	80% VSI, 20% cone	Mylonitic quartz diorite
Hokksund	Commercial product	Impact	Cone	Gneiss diorite
Årdal	Commercial product	-	No crushing glaciofluvial and moraine deposit	Granite/gneiss

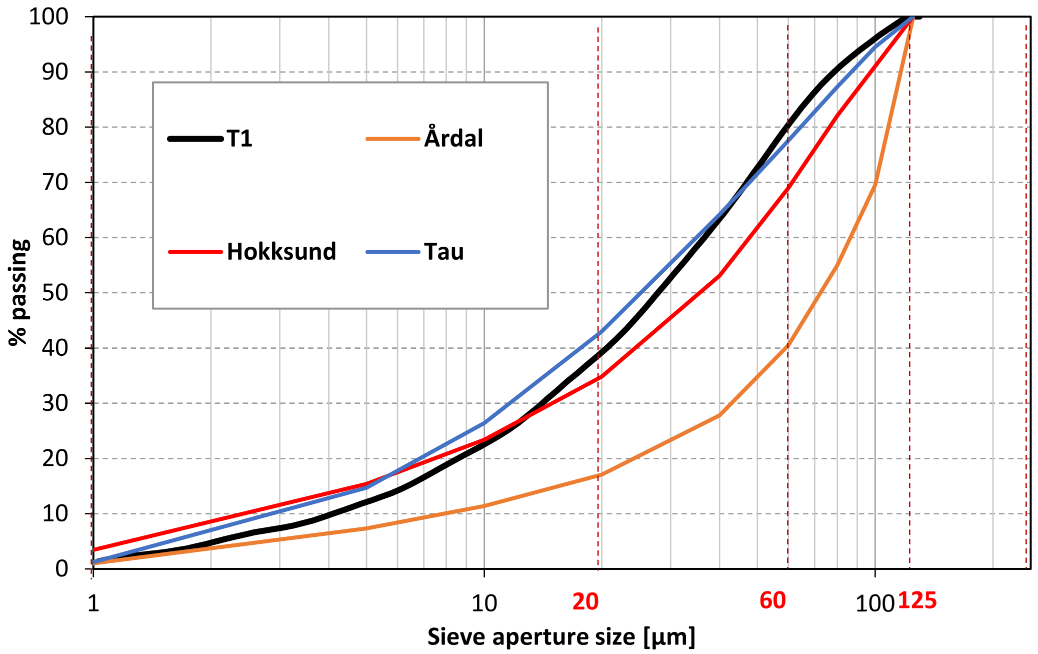


Figure 4-12: The crushed rock by either cone crusher, VSI or TBM cutter head shows similar PSD below 0.125 mm. The natural Årdal shows a coarser PSD.

4.2.4 FlowCyl and Mini-slump

For sufficient accuracy, each matrix with a different filler was repeated two times. The filler has steady results in both λ_Q and mini-slump measurements. The Follo line produced 0/8 mm fraction (T5) was not used in the FlowCyl or mini-slump measurements as there was not enough material available. Compering the engineered limestone filler(T0) to the TBM filler(T1-T4) does show higher viscosity and lower workability on the TBM filler. This could be the result of minor differences in the PSD, see Figure 4-9.

Table 4-6: FlowCyl and Mini-slump measurements

No.	Source	λ_Q (1)	λ_Q (2)	Mini-slump (1) [mm]	Mini-slump (2) [mm]
T0	Limestone filler	0.726	0.764	26.5	27.5
T1	TBM filler	0.816	0.798	23.2	23.6
T2	TBM filler	0.811	0.804	22.7	22.8
T3	TBM filler	0.801	0.810	21.3	21.2
T4	TBM filler	0.814	0.819	21.2	21.3

(1) First measurement
(2) Second measurement

Table 4-7: λ_Q and Mini-slump results

Mean result		
No	λ_Q	Mini-slump[mm]
T0	0.745	27.2
T1	0.807	23.4
T2	0.808	22.8
T3	0.806	21.3
T4	0.817	21.3

T1 filler have positive impact on rheological values compared to the other TBM fillers. In the macroscopic description of the fillers, it I described containing mica. As discussed in 2.3.1 the mica content below 125 µm has proven to have positive effects on the concrete in the fresh state and increase the flowability, this is possibly the reason for its higher slump and lower.

The TBM filler had a higher percentage of filler below 10 µm compared to the limestone. Differences in petrography or shape may also have influence.

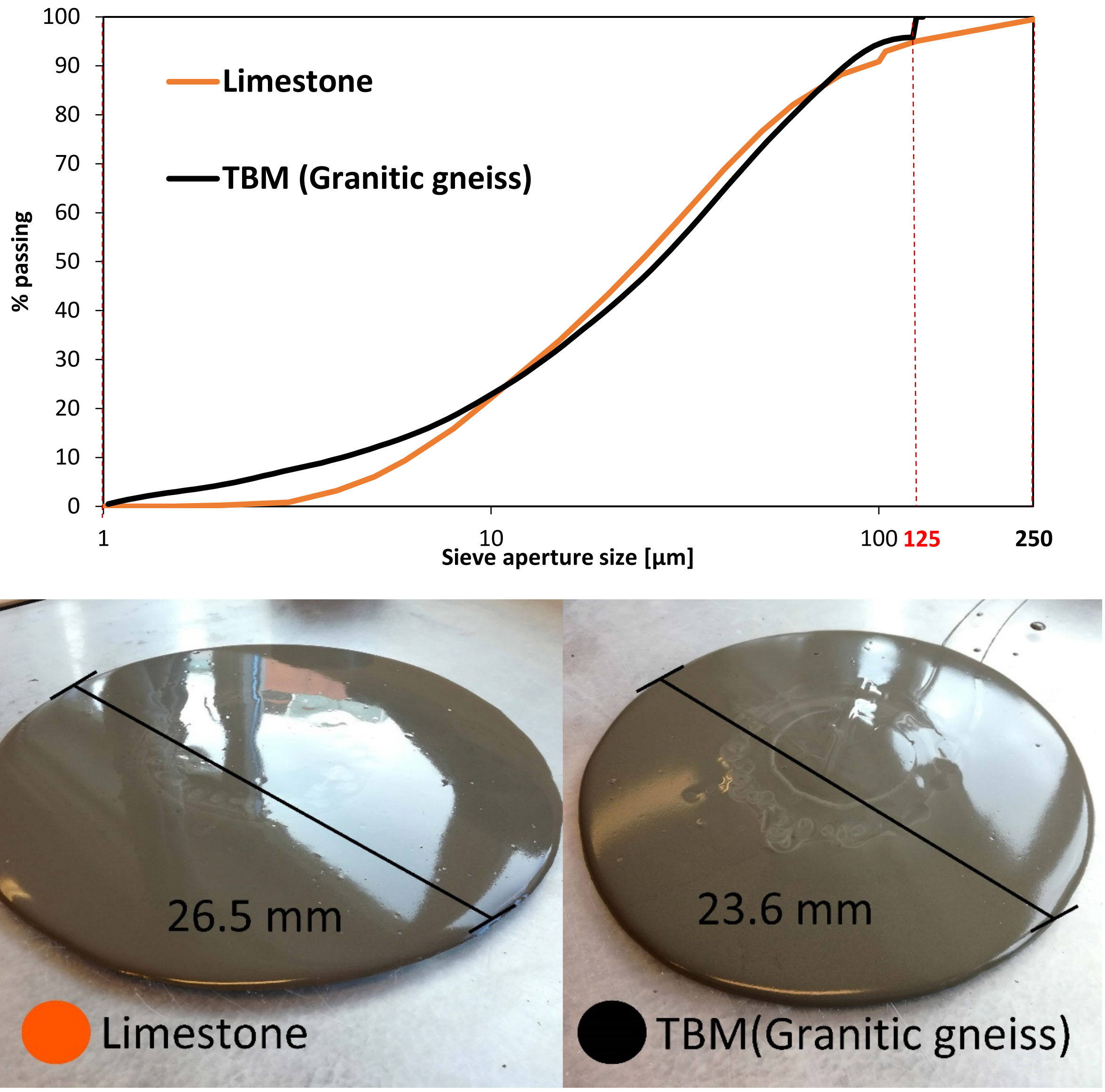


Figure 4-13: Comparing the most similar mini-slump values between the limestone and the TBM filler (T0 vs T1).

5. Discussion

The aim for this thesis was to investigate the hard rock TBM spoil and its potential as concrete aggregate. This included collection PSDs from Switzerland and Norway. In addition, was TBM spoil from two ongoing TBM projects in Norway taken to the laboratory at NTNU. Laboratory testing on the TBM spoil investigated the particle size distribution in the 0/0.125 mm fraction and its behavior in fresh cement paste. A limestone filler was used as a reference.

5.1 Particle size distributions

Most off the projects with known processing procedure are removing the fines from the spoil or from the crushed spoil above 10, 16 or 20 mm, which results in approximately 50% of all the spoil being disregarded. Coarse chips are not the obstacle and easily crushed down from 150 mm to 22, 32 or 63 mm. Use of impact crushers (VSI or swing hammer) to create more cubical shaped particles is well established knowledge. All the fines are in contrast problematic to process and some are adhered to the coarser particles as well. Additionally, are extra fines produced through the crushing stages of the chips. Wet processing is the most used technology to remove these fines. If TBM spoil is to be utilized directly it would be best suited for low strength concrete as a high w/c ratio would tolerate a higher filler content.

All projects are either railway or hydroelectric plants. Hydroelectric plants with an isolated location would largely benefit from utilizing the spoil for concrete as transport would become a substantial expense. The concrete for a hydroelectric plant could be applied in the tunnel lining, turbine rooms or dam construction. Linthal is a perfect example of this with 100% utilization of spoil into concrete aggregates.

5.2 Filler properties

Reason for differences on PSDs between wet and dry do not only originate from wet sieves more accurate method, but could also originate from sampling error and using only samples of 1 kg. The reason for 1 kg tests originates from too excessive amounts retained on the sieves below 0.5 mm if larger samples wore to be used, >1 kg, in accordance with NS-EN 933-1, chapter 7.2.

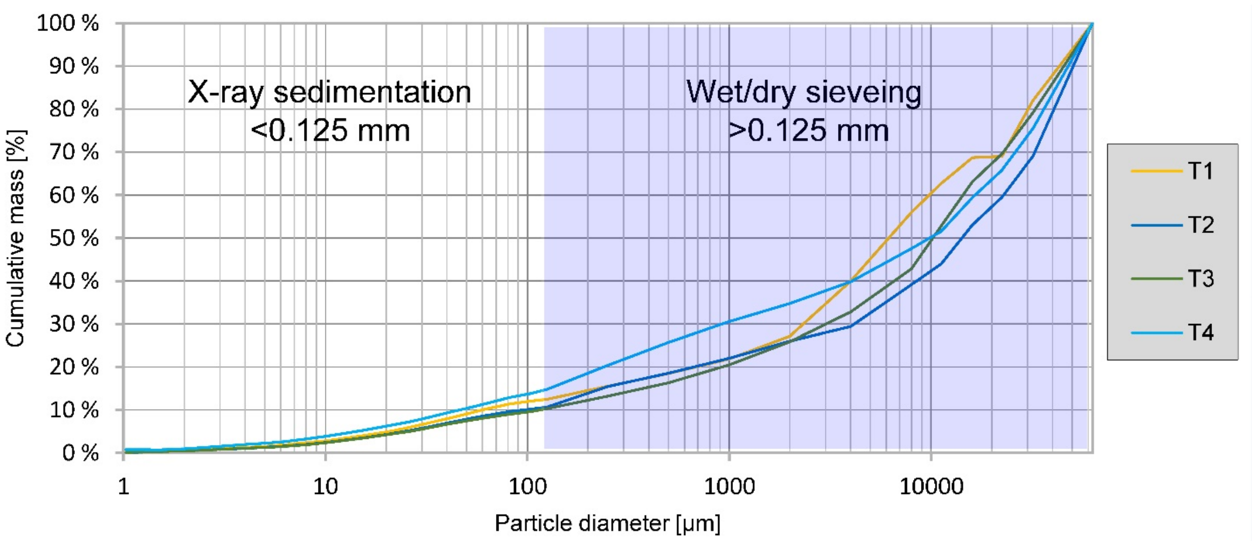


Figure 5-1: The PSDs produced can be combined. The X-ray sedimentation PSDs are not easy to differentiate at this scale.

Optimizing the utilization of TBM spoil do have potential impact on the regional quarries as a major TBM project could put surrounding quarries on “pause”. The spoil could be processed into valuable commercial products and not necessary just concrete aggregates. This is an environmental friendly approach to the often enormous amounts of spoil [108].

5.3 TBM specifications

For the most effective penetration rates in a certain rock condition, TBM specifications are decided based on factors as disc cutter spacing and thrust. Less prioritized are the produced spoil. Though the most effective penetration rates favor a high chipping frequency. This is also favorable for spoil utilization as it produces more coarse particles and may also produce less fines. It will be more realistic with larger disc cutter spacings on more fractured and lower strength rock. Larger cutter spacings do also have the potential of reducing the fines. Well used disc cutter spacing in Norway are approximately 70 mm, compared to 90 mm which are reported used at GBT in Switzerland [55]. So theoretically the Norwegian TBMs produce a finer PSDs due to a lower disc cutter spacing, though on the contrary the compressive strength would be higher. A Norwegian TBM project would therefore be more abundant in fines spoil of high strength which potentially would result in a high strength concrete. The fresh state of the concrete with high filler content would eventually be the problem as it would increase the flow resistance.

The TBM material will most probably always produce excessive amounts of fines for concrete aggregate use. It’s therefore the concrete recipe which should be adapted to the aggregate composition if TBM spoil is to be further utilized. Follo line TBM project utilizes its spoil for concrete aggregate and Ulriken TBM project does not. Ironically do the Ulriken project produce more suited spoil for concrete aggregates than the Follo project, based on PSD. As the scale of the two projects are of big differences, it should still be of interest for further small TBM projects to early investigate the rock conditions and its potential as concrete aggregates. For hydro-electric projects with TBM use for the water inlet/outlet and D&B for the turbine cavern it’s possible to combine the excavated material for utilization purposes [20].

5.4 Material processing

The investment of a facility to process the TBM spoil into concrete aggregates would require a high investment cost at project start. It's a one-time investment and will in addition require sufficient quality spoil to be profitable in the long term. This is an uncertainty in long tunnels where geological conditions could be unknown. Below is a list of important factors determining if a project would agree in investing in a processing plant for the spoil material[17].

- Economic gain: Transport and dumping cost, versus an on-site processing plant with a feasible Utilization percentage of rock mass
- Environmental thrive from the project owner
- Concrete consumption in project and at which time
- Total required landfill through the project
- Surrounding topography for sufficient storing capacities and industry plant
- Contract processing and specifications
- Paradoxical legislations

Self-supply of concrete could potentially be achieved after a certain period of tunnelling and last to project end. Though special high concrete requirements have required external aggregates as experienced at the Koralm project, mentioned in chapter 2.7.
Figure 5-2 is a simplification of the investment of a process facility and its economic potential after a certain time. The x-axis could alternatively to time also be described with; "Amount of spoil". The intersection between the two curves would be affected by the factors such as:
-Amount of potential spoil in the rock mass
-External aggregate price
-Price for tipping

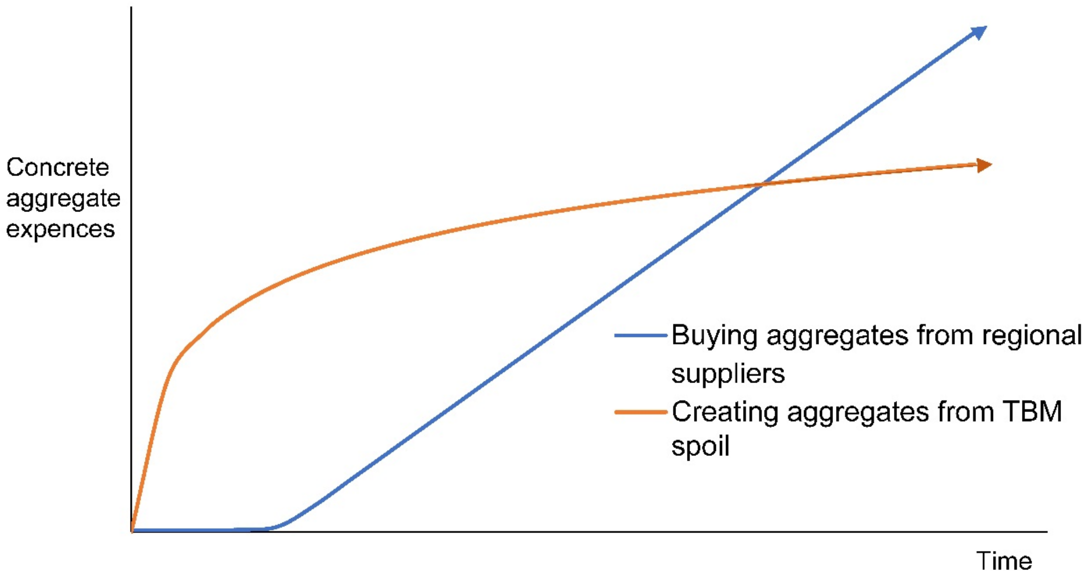


Figure 5-2: Concrete aggregate expenses in a TBM project. Illustrating the economic potential of investing in a processing facility for spoil utilization. After a certain period, the investment cost of the facility will pay off in terms of reduced need for external aggregates. The initial growth by the orange curve are illustrating the investment of a processing facility[18].

5.5 Further work

Future work on the field of utilization of TBM rock will govern several fields of expertise, these include geology and petrography, concrete technology and material processing. In addition, would future automation require adapted computer tools. Below are additionally bullet points.

-Further work into a cost estimation to evaluate the economic potential for investment of a processing facility. Including the factors as amount of potential spoil, transport distances, pricing.

-Utilized TBM spoil from crystalline rock normally contains quartz. Establishing water reducing admixtures that reacts with quartz filler in synergy with already established superplastizers. This would allow for increased filler use.

- Validating the use of TBM spoil in low strength SCC with high w/b ratio for lower strength concrete.

-TBM tunnelling do have potential in further automation. As the TBM is always in “touch” with the rock, the rock strength can be monitored based on the pressure on the cutter discs. More effective analyzing methods are possibly wanted in future large scale TBM. What remains are the uncertainties on requirements for concrete aggregates. This must be investigated and updated to boundary values which are realistic for the TBM spoil. This could include adapted cement content in a concrete recipe based on point load and crushability of the spoil.

-Comparison of crushed fines from blasted rock (tunnelling or quarries), versus filler from hard rock TBM in terms of fresh concrete properties.

6. Concluding remarks

Hard rock TBM spoil is high quality construction aggregate with the wrong shape and excessive filler amount. Most of the investigated TBM projects discard spoil below 10,16 or 20 mm. This is often 50-60% of the total amount of spoil. The PSDs average filler content is 11.8 % (<0.125 mm). Crystalline rock can contain sulphur, mica or alkali reactive aggregates which normally has negative effects on the concrete. The technology to create concrete with these impurities inherent do exist. Froth flotation to remove free mica, sulphur-resistant cement, concrete mix design with low alkali content. From the different impurities are free mica and ASR the most registered problem in utilization. Wet processing of spoil creates the most accurate PSDs and are the most used processing method.

PSD from hard rock TBM is mainly governed by cutter disc spacing, thrust, and petrography. Utilization of spoil must not intervene or disturb the tunnelling as this is the main priority. The disc cutter spacing and thrust will be decided based on the performance and penetration rates. The geological condition, anisotropy and fissures in the rock are also affecting the produced PSDs. Crystalline rocks as gneiss and granite create mostly similar PSDs, but drastic fluctuations can't be ruled out.

Test methods on TBM spoil is most effectively done with an LCPC device which gives indication of the crushability and abrasiveness(ABR). The LA test can be used as a reference method as it has a linear connection to the LCPC. Point load index and disc cutter loading system is used to measure unconfined compressive strength and confined compressive strength, respectively. The crushability measurement are to be conducted daily, proposed by Thalmann [33].

When 1 kg wet sieving are conducted it shows 5.79% higher mass of particles below 0.063 mm sieve, compared to dry. Dry processing has shown to create inaccurate PSDs, though adapting the concrete mix accordingly do solve this problem to a certain extent. Wet processing requires more infrastructure in the form of a mud water treatment facility.

TBM filler (<0.125 mm) added in a cement paste (fi/c = 36%) reduces the workability on mini-slump values with an average of 5 cm (27.2 -> 22.2 mm) when compared to a limestone filler with the same recipe and similar micro PSD. Same trend is seen when λ_Q values are compared. Use of TBM spoil results in average $\lambda_Q = 0.809$, where using limestone resulted in $\lambda_Q = 0.745$. This is a difference of only 0.064 which indicates a similar flow resistance. The TBM filler investigated can be applied in large scale concrete mixes when filler content or filler properties are known.

7. Literature

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8. Appendices

A. Concrete aggregate requirements

Table 8-1: Proposed values in order to validate the TBM spoil, based on the Dragon report: Automation Strategies for solid rock and soft ground processing.

Test	Norm	Requirements
Macroscopic petrography of the tunnel face	visual assessment (SN 670 115)	petrographic unsuitable layers: ≤ 10 [%]
Petrographically inappropriate Components (excl. phyllosilicates) in the excavated material: fractions 1/4 mm (microscopic); 4/22, 22/128 mm (macroscopic)	Based on SN 670115 und SIA 162 /1	≤ 10 [weight-%]
Layer silicates in the rock mass (hand pieces)	Thalmann, 1996	≤ 20 [Vol-%]
Free phyllosilicates in the crushed sand (fraction 0.25/0.50 mm)	Def. EMPA (1993)	≤ 35 [piece-%] (EMPA, 1999)

Table 8-2: Measurements to characterize concrete aggregate

Field	Test/Parameter	Description	Reference
Particle size distribution (PSD)	-Mechanical sieving (dry and wet) -Laser diffraction -X-ray sedimentation -DIA method	The particle size distribution will give a clear measurement of the amount in each fraction by weight. The most important parameter.[78] Different methods for sand and filler	NS-EN 12620 NS-EN 933-1
Water	Moisture content	Determine the water content of aggregates	NS-EN 1097-5
	Water absorption	Determine the aggregates capacity to absorb water.	NS-EN 1097-6
Density and surface	BET specific surface	Specific surface by gas adsorption	Ph. Eu.2.9.26 Method II
	Dry particle density Dry bulk density	With the use of a helium pycnometer for filler density Use of cylinder container for bulk density	NS-EN 1097-7 1097-3
	<0.063 mm	Sedimentation test in cylinder filled with water. Measuring "mud" height at various time intervals with the help of dispersion liquids.	Håndbok R210 (132)[67] NS-EN 1744-1
Exterior	Shape	-Flakiness index: Determines the flakiness of the aggregates which has a great impact on fresh concrete behavior. Only applicable on >4mm	NS-EN 933-3
	Mechanical	-Compressive strength -Resistance to Fragmentation(LA) -Resistance to wear(micro-Deval) -Compressive strength (Point load index) -Crushability(LCPC) -Abrasivity (LCPC)	NS-EN 206-1 EN 1097-2 EN 1097-1 IS-8764 NF P18-579 NF P18-579
Impurities	Chemical	Sulphur content, chlorides	NS-EN 12620 NS-EN 1744-1
	Petrography	-Mica schist content -Disintegration durability due to frost -Expansion due to water/temperature -Abrasion durability -Reduced adhesion	NS-EN 932-3
	Reactivity	Alkali silica reaction: Measuring the aggregates to determine if it will react with alkalis in the matrix	NB 21

B. Design concept for in-situ concrete production installed as one of the TBM backup systems[53]

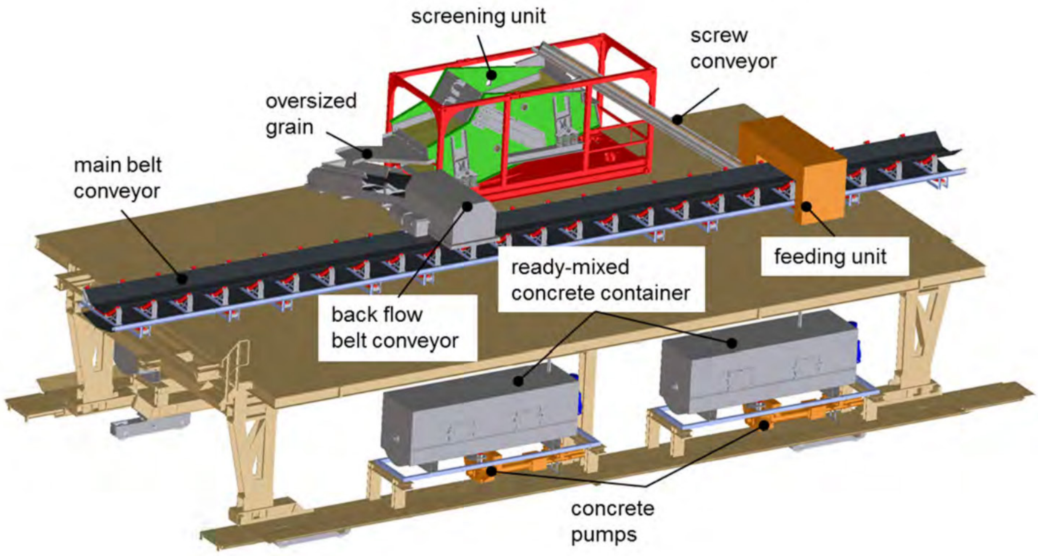


Figure 8-1: Opposite view of, now showing ready-mix concrete containers and pumps.

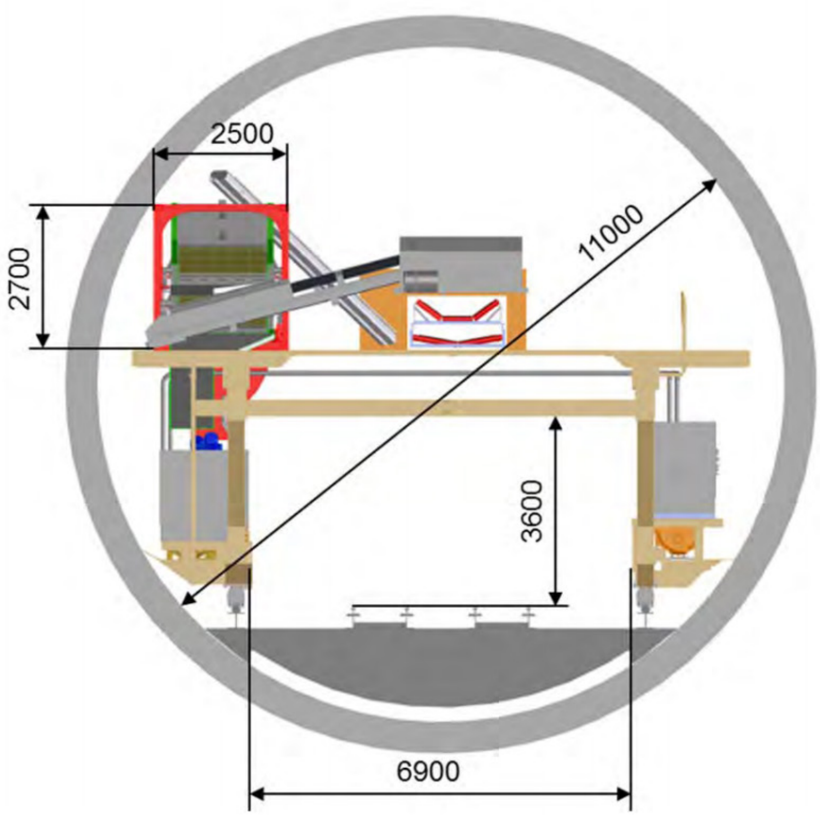
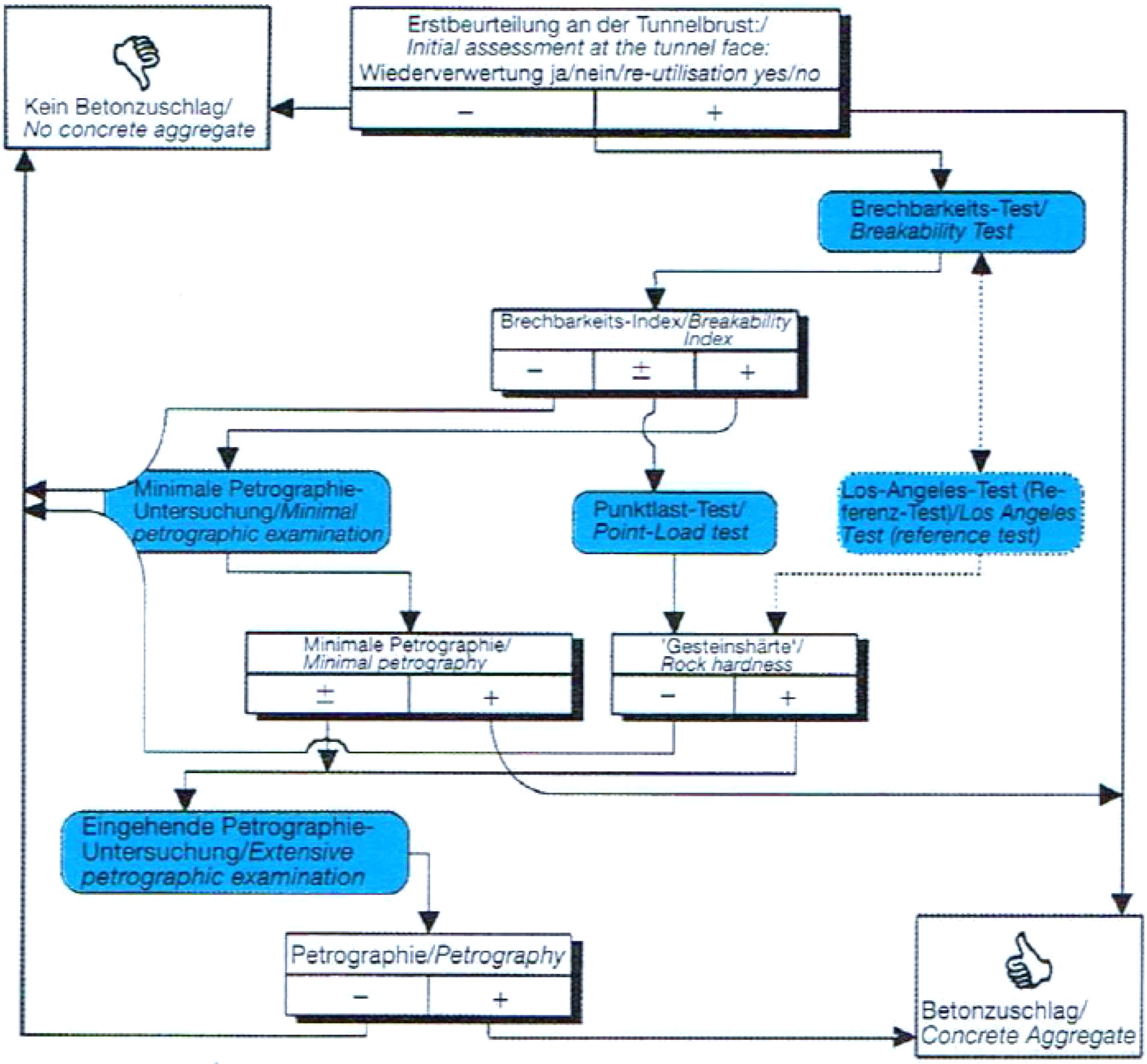


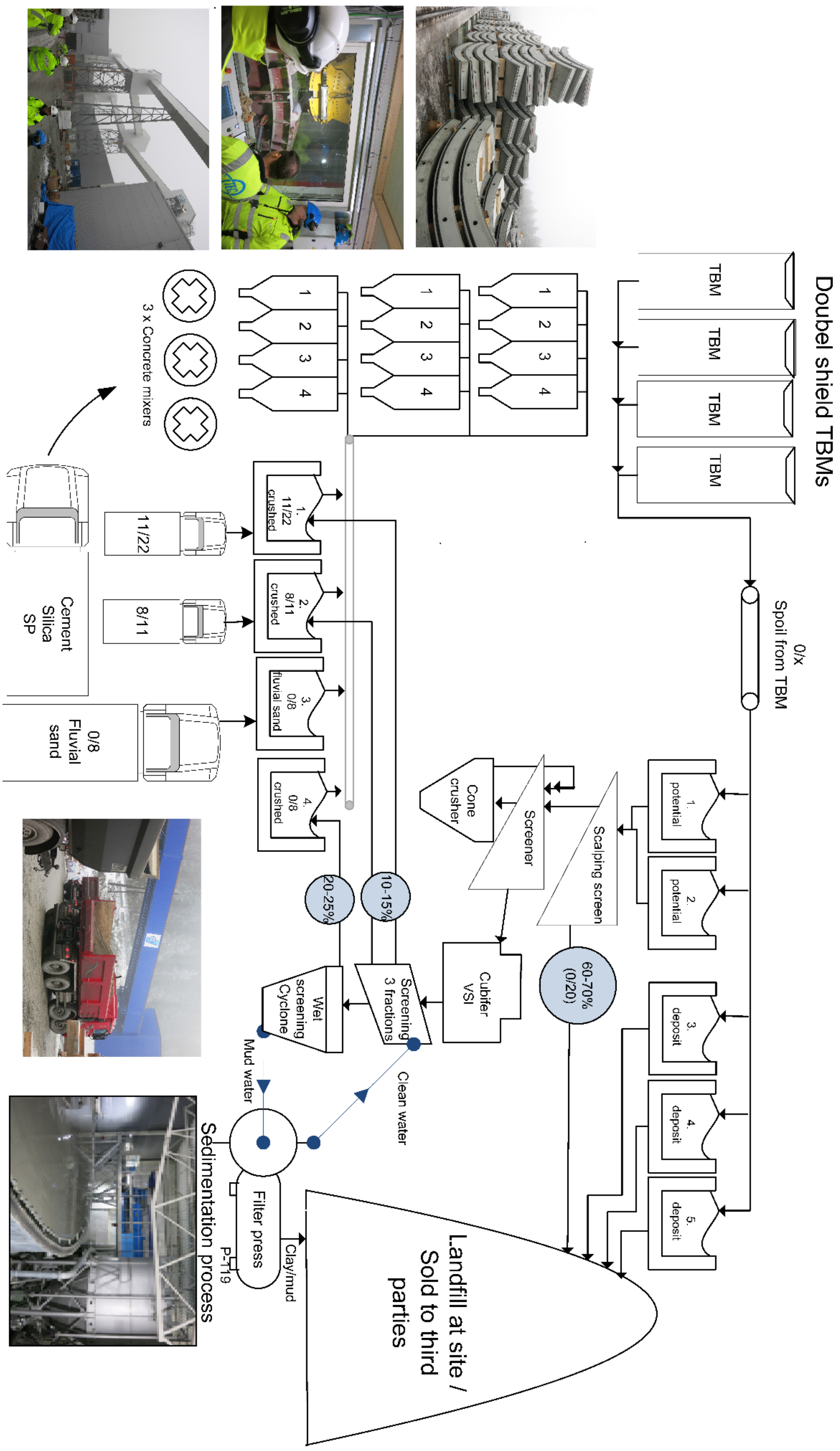
Figure 8-2:Cross-sectional view of screening unit placed inside the tunnel connected to the main conveyer belt.

C. Flow diagram for utilization of TBM spoil into concrete aggregate

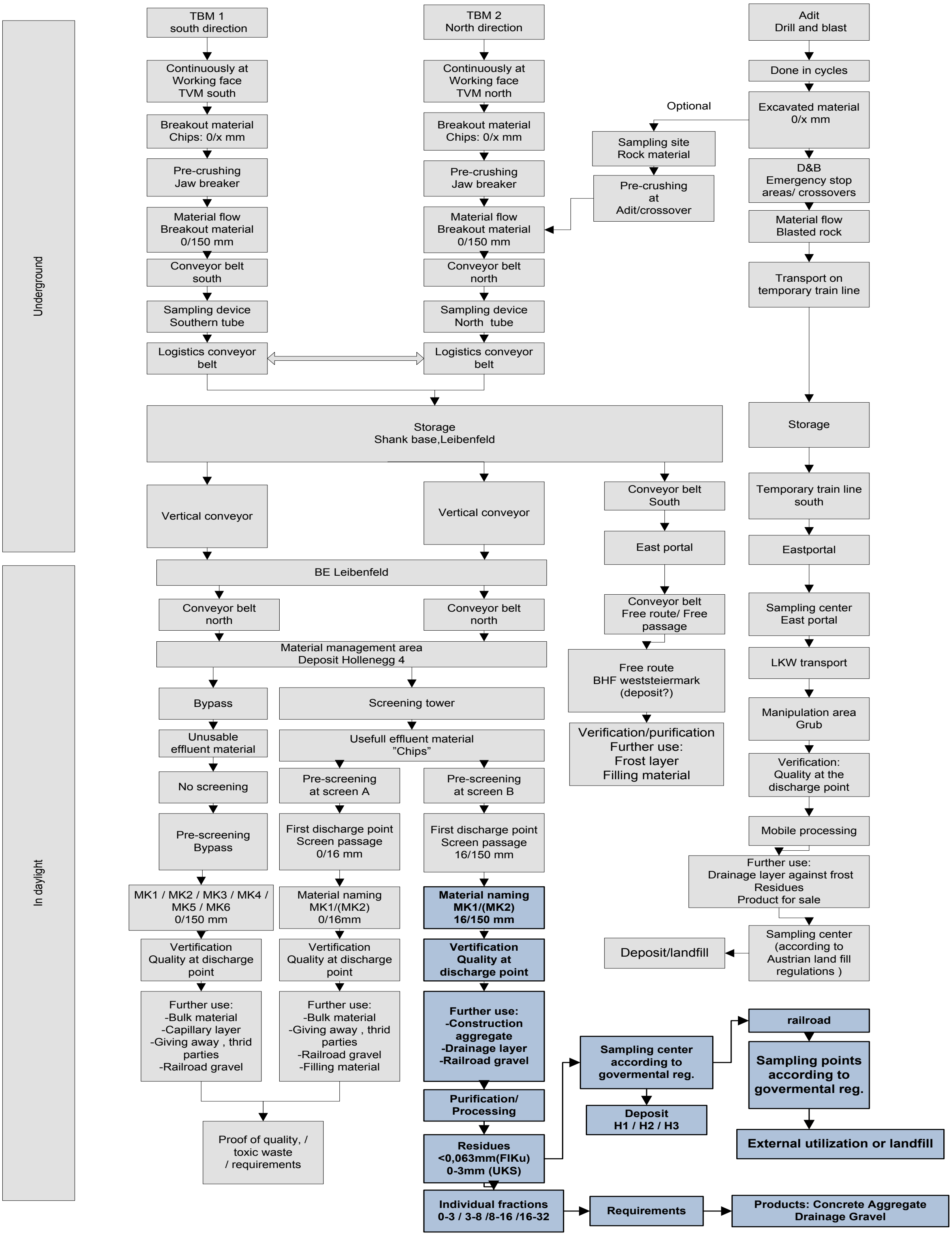
The flow diagram is a decision tool to determine if the TBM spoil can be utilized as concrete aggregate. If the spoil is determined to have potential from the first visual inspection it can be accepted as concrete aggregate straight away or go through a set of tests as (crushability test, point-load test, LA-test and/or petrographic description) [50].



D. Flow diagram of the Follo line project



E. Flow sheet of material flow at koralm base tunnel



F. Koralm base tunnel Flow diagram and spoil properties

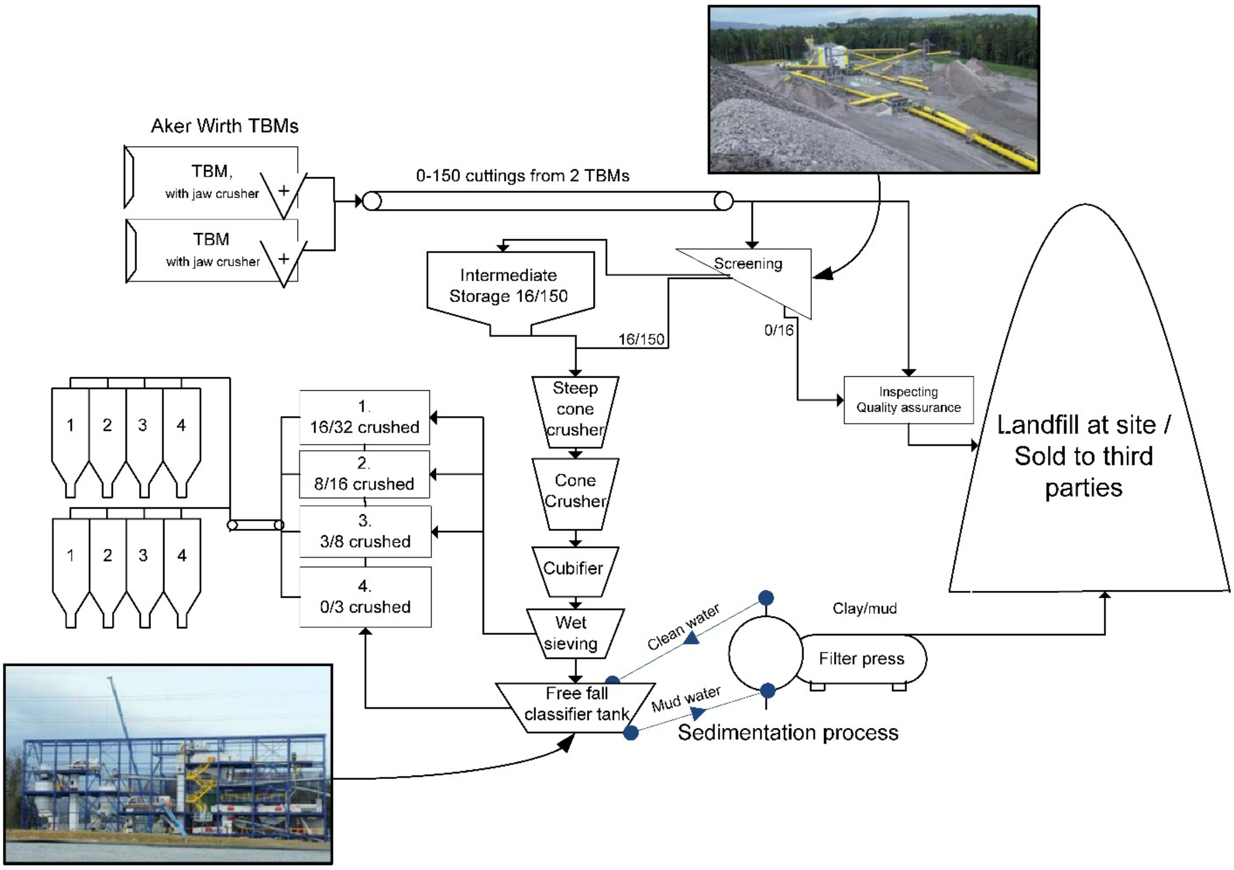


Figure 8-3: Flow diagram is based on report: *Use of recycled material for segments and inner lining – first experience of on-site processing on KAT 2* [1].

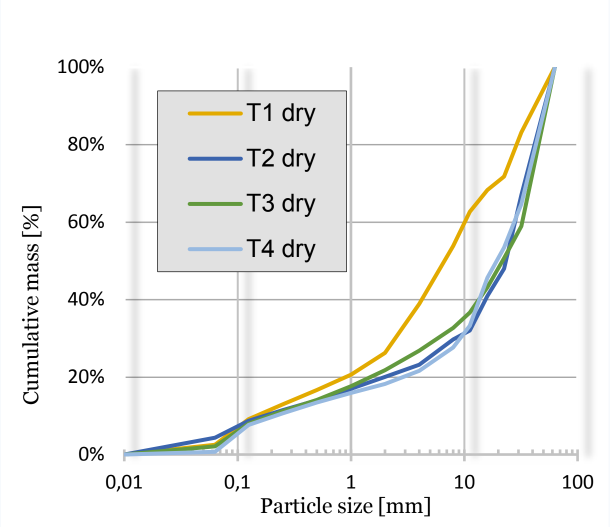
Table 8-3: Processed TBM spoil has been tested with several test methods. Different rock qualities as compressive strength results in adaptations in the concrete recipe, e.g. Gneiss requires only 370 kg/m^3 cement.

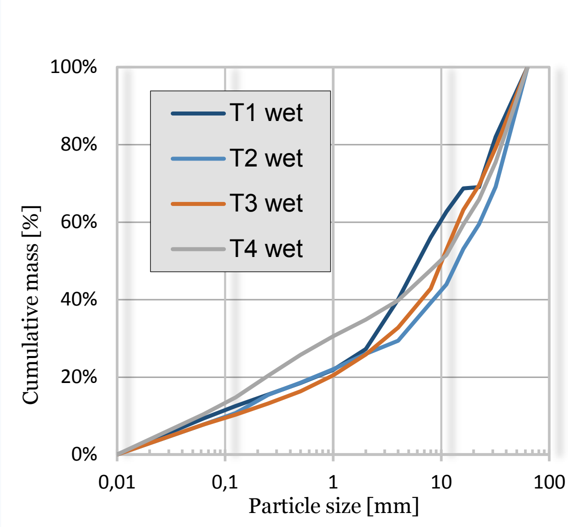
	Lithology / Gesteinsarten	Glimmerschiefer – Schiefergneis / Schist				Gneis (Platten-, Feinkorngneis) / Gneiss			
Processed aggregates / Aufbereitete Gesteinskörnung	Grain-size fraction / Kornfraktion [mm]	0/3	3/8	8/16	16/32	0/3	3/8	8/16	16/32
	Grain shape / Kornform Si (MW / Mean; min – max)		9 (3-17)	7 (2-16)	10 (2/17)		5 (2-8)	5 (3-7)	8 (2-12)
	„Mica content" / Glimmergehalt" 0,125 – 0,250 mm (MW/Mean; min - max) [%] (Bestimmung der blättrigen Minerale mittels FFT)	28 (16 – 32)				24 (13 – 37)			
	Los Angeles Test / LA-Koeffizient (MW / Mean; min – max)			27 (15 –37)				20 (17 –24)	
	Compressive Strength derived from Point Load Strength Tests / Druckfestigkeit aus Punktlastversuchen (Raw material size / Rohmaterial 16/150 mm) [MPa]			97				181	
	Content of carbonate / Karbonatgehalt (Loss-on-ignition method / Glühverlust) [%] (MW / Mean; min – max)	16 (4 – 30)				6 (3 -11)			
Concrete / Beton	Concrete grade for segments/ Tübbingbetonsorte	C35/45/XC4/XA1L				C35/45/XC4/XA1L			
	Cement / Zement CEM II [kg/m³]	400				370			
	Processed hydraulic additives / AHWZ [kg/m³]	50				0			
	Water content effectiv / Wirksamer Wassergehalt [l/m³]	178				160			
	Slump / Ausbreitmaß (10 min) [mm]	340				280			
	UCS / Einaxiale Druckfestigkeit 28d [N/mm²]	67				67			
	Max. temperature in segment / Max. Bauteiltemperatur [°C]	59				55			

G. Lab: PSD >0.125 , wet and dry sieve

No	Moisture content [%]
T1	7.82
T2	5.32
T3	3.43
T4	4.2

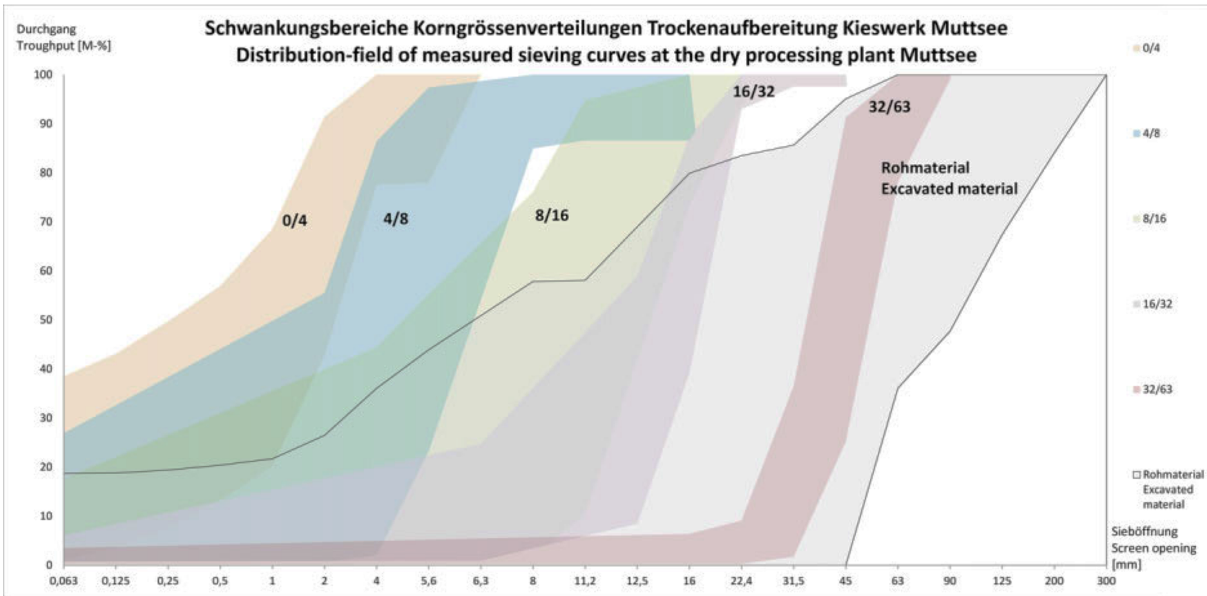
	T1 dry	T2 dry	T3 dry	T4 dry	T1 wet	T2 wet	T3 wet	T4 wet
63	100.0 %	100.0 %	100.0 %	100.0 %	100.00 %	100.00 %	100.00 %	100.00 %
32	83.1 %	67.0 %	59.0 %	64.6 %	82.00 %	69.07 %	79.15 %	75.48 %
22.4	71.8 %	48.0 %	50.7 %	53.4 %	69.00 %	59.47 %	69.55 %	65.80 %
16	68.3 %	41.0 %	43.2 %	45.6 %	68.67 %	53.07 %	63.15 %	59.40 %
11.2	62.6 %	32.0 %	36.7 %	33.3 %	62.70 %	43.95 %	52.81 %	51.52 %
8	53.9 %	29.7 %	32.7 %	27.7 %	56.02 %	39.18 %	42.85 %	47.60 %
4	38.8 %	23.1 %	26.8 %	21.6 %	39.99 %	29.39 %	32.78 %	39.81 %
2	26.2 %	20.0 %	21.8 %	18.2 %	27.19 %	26.02 %	25.84 %	34.79 %
1	20.6 %	17.0 %	17.7 %	15.9 %	21.86 %	22.06 %	20.49 %	30.54 %
0.5	16.7 %	14.0 %	14.1 %	13.4 %	18.50 %	18.57 %	16.34 %	25.74 %
0.25	12.9 %	11.4 %	11.2 %	10.7 %	15.52 %	15.45 %	13.17 %	20.34 %
0.125	9.2 %	8.8 %	8.0 %	7.7 %	12.49 %	10.70 %	10.31 %	14.76 %
0.063	2.6 %	4.3 %	2.1 %	0.7 %	9.27 %	7.73 %	7.75 %	10.41 %
0.01	0.0 %	0.0 %	0.0 %	0.0 %	0.00 %	0.00 %	0.00 %	0.00 %

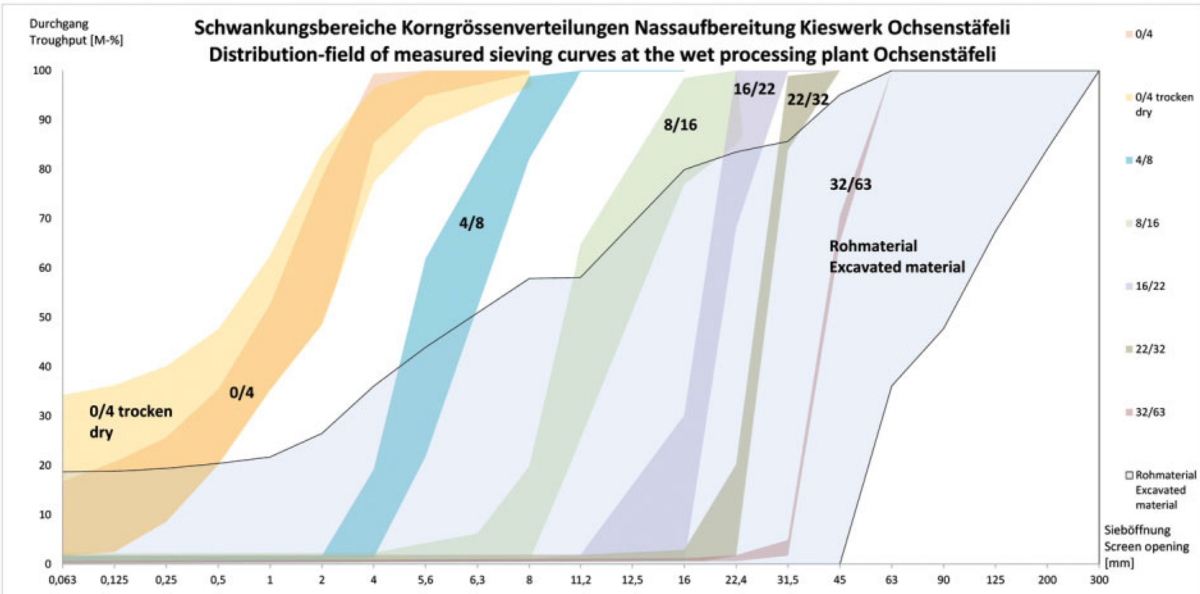




H. PSDs from Linthal TBM and D&B 2015, dry and wet.

The Excavated material are the maximum and minimum values of TBM spoil(fine PSD) and blasted rock(coarse PSD). [20]





I. PSDs from Swizz TBM projects <1998

PSD's from five different TBM projects in Switzerland before 1998. Shaded area the Swiss boundary conditions for concrete aggregate. An average filler content of 9% (Dmax=32 mm)

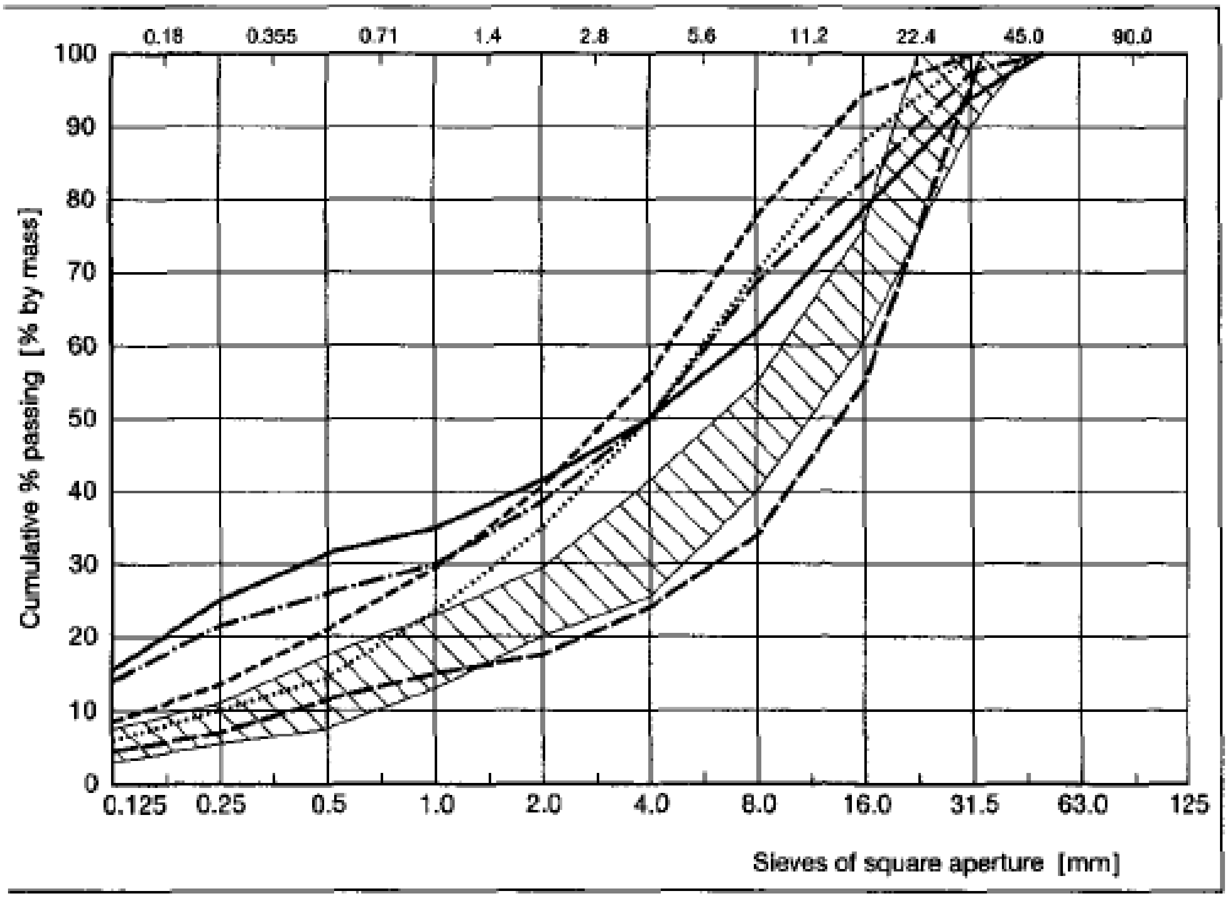
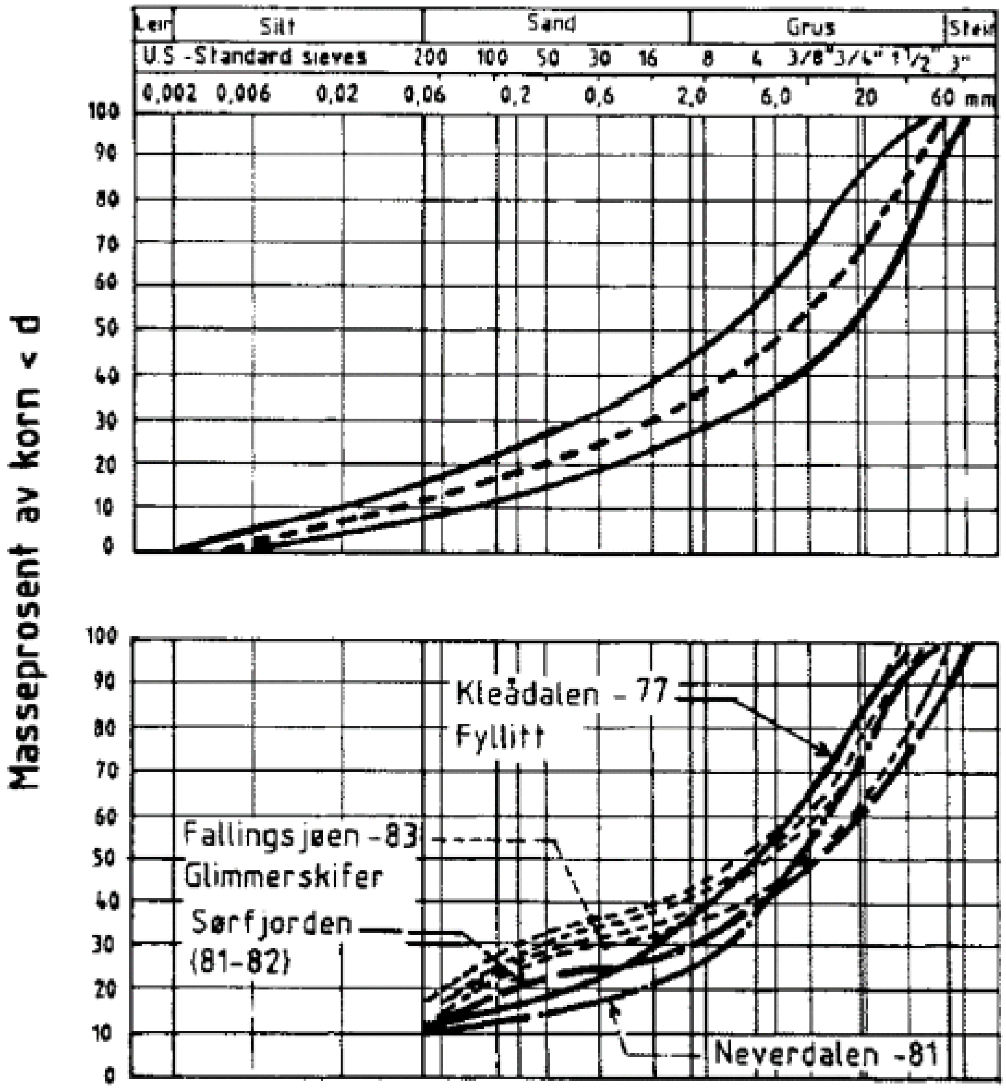


Fig. 1 – Particle size distribution of the 5 TBM materials (shaded area within SIA standard 162, art. 5, 14, 24; Fuller).

J. PSDs from Norwegian TBM projects 1977-1983.

Lower figure: Shows 4 Norwegian TBM projects between 1977-1983. Approximately filler content 12 %(Dmax=63mm)[51]. The PSDs are from Kleådalen 1977(phyllite), Fallngsjøen 1983, Sørfjorden 1981-82, Neverdalen 1981.

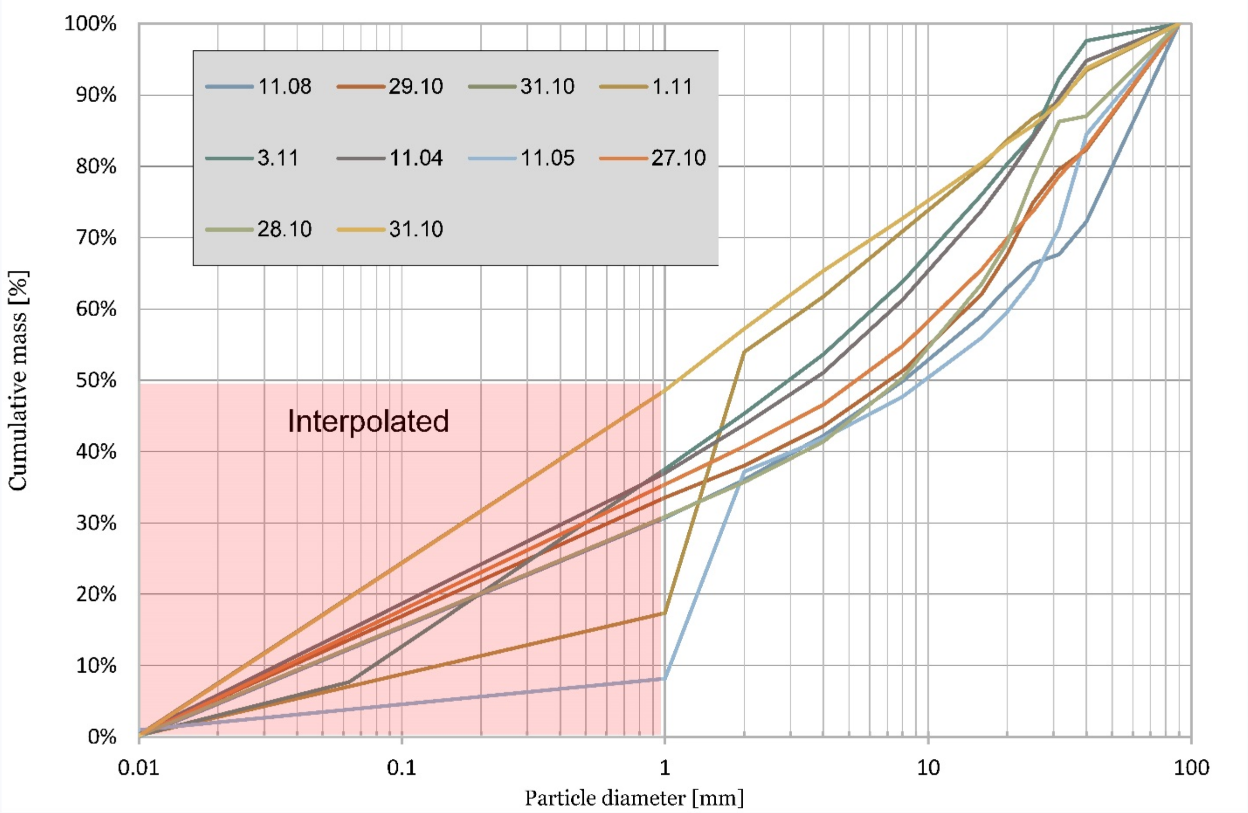


Figur 9 Kornfordelingskurver fra norske TBM-tunneler (Statkraft/NGI)

K. PSDs from Follo line 2016

Each dry test varies between 3-5 kg done at Åsland at site laboratory. All the sieve curves miss the <0.125 mm sieve though Interpolating between 1mm and 0.063 mm indicated average 14%.

	11.08	29.10	31.10	1.11	3.11	11.04	11.05	27.10	28.10	31.10
0	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %
0.063										
0.125										
1	30.7 %	33.5 %	48.6 %	17.4 %	37.5 %	37.0 %	8.2 %	35.4 %	30.8 %	48.6 %
2	36.0 %	38.0 %	57.2 %	54.0 %	45.3 %	43.8 %	37.2 %	40.7 %	35.7 %	57.2 %
4	42.2 %	43.5 %	65.3 %	61.7 %	53.6 %	51.0 %	41.8 %	46.6 %	41.4 %	65.3 %
8	49.8 %	51.3 %	72.7 %	70.9 %	63.8 %	61.3 %	47.7 %	54.8 %	50.3 %	72.7 %
16	59.1 %	62.1 %	80.4 %	80.0 %	76.0 %	73.8 %	56.0 %	65.5 %	63.5 %	80.4 %
20	62.9 %	67.7 %	83.3 %	83.7 %	80.3 %	78.6 %	59.6 %	69.9 %	69.3 %	83.3 %
25	66.4 %	74.9 %	85.7 %	86.7 %	84.2 %	83.9 %	64.1 %	73.7 %	78.3 %	85.7 %
31.5	67.6 %	79.6 %	88.8 %	89.1 %	92.3 %	89.6 %	71.3 %	78.6 %	86.3 %	88.8 %
40	72.3 %	82.3 %	93.7 %	93.4 %	97.6 %	94.8 %	84.5 %	82.7 %	87.0 %	93.7 %
63	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %



L. PSDs from Ulriken 2016

Green and red curves are boundry curves in accordance with Norwegian road authorities (SVV) for validating the granular material as stabilizing mass in road construction. Blue curve are the actuall test result. None of the PSDs are accepted in terms of grading as they all excess the amounts above 0.125 mm or miss large enough particles .

Laboratorium: Arna - I henhold til H014 labprosess: 14.423, 14.424, 14.432, 14.433, 14.434, 14.439

Prøveophav: (B) Byggherre (E) Entreprenør (P) Produsent

NCC

Diverse steinforekomster

Korngradering

Oppdragnr.	131170002	Oppdragsnavn	TBM masse nye Ulriken 2017
Prosjektnummer	112012	Prosjektnavn	TBM v/Gry Stenersen
Ansvarsområde	3	Ansvarlig	Arna

Prøvedata

Prøvenr	1(P)				
Uttatt dato	19.01.2017				
Uttatt kl.					
Uttakssted	På veg Tunnell				
Analysetype	Vatsikt				
Massetak					
Består av					
Grenseverdinr.	0-63				
Vegnr/HP	KV1 Nye Ulriken				
Meter/*profil	466430-466432				
Avstand høyre kant					
Dybde	-				
Vanninnhold (%)	0.1				
Vannabsorpsjon (%)					
Humus (Glødetap)					
Fraksjon (mm)	0.0 - 63.0				
Overstørrelse	5.1				
Understørrelse					
% <63µm av <delsikt	14.2 (22.4 mm)				
% <20µm av <delsikt					
Finstoffinnhold f	8.7				
Godkjent siktekurve	Nei				

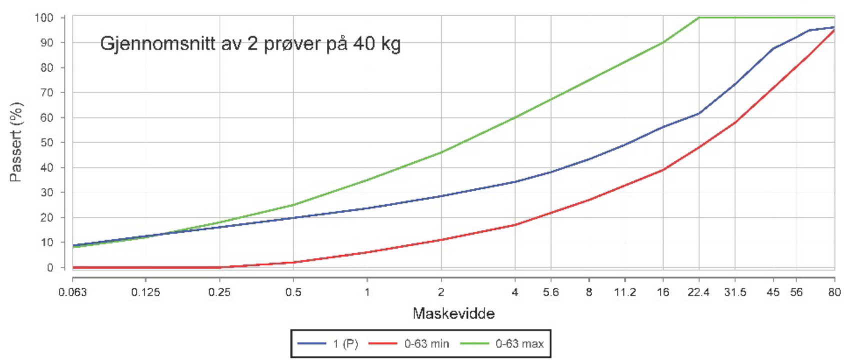
Siktedata - Passert (%)

	µm				mm												
Pr.nr.	63	125	250	500	1	2	4	5.6	8	11.2	16	22.4	31.5	45	56	63	80
1(P)	8.7	12.5	16.1	19.8	23.7	28.5	34.3	38.2	43.3	49.1	56.2	61.6	73.4	87.6	92.2	94.9	96.2

Merknader, Korngradering

03.02.2017 Da bekrefter jeg at vi leverte 80 kg stein til dere for sikting i dag, som er datert 19.01.2017 og tatt fra tunnelens kilometer 466 430 ? 466 432.
Med vennlig hilsen Leon Eide Byggeleder TBM

Sand			Grus		
Fin	Middels	Grov	Fin	Middels	Grov



Pr.nr	Vegnr	Meter/*profil	HP	Avst.hk.	Dybde(m)	Jordart	Cu (* = Cu75)	TG
1(P)	KV1				-		256.3	

Sted: Arna

Dato: 07.02.17

Signatur: Liv Vaagsnes

Laboratorium: Arna - I henhold til H014 labprosess: 14.423, 14.424, 14.432, 14.433, 14.434, 14.439

Prøveopphav (B) Byggherre (E) Entreprenør (P) Produsent

Diverse steinforekomster

Korngradering tilslag

Oppdragnr.	**131160011**	Oppdragsnavn	**Test av TBM masse nye Ulriken TNL**
Prosjektnummer	**112012**	Prosjektnavn	**TBM v/Gry Stenersen**
Ansvarsområde		Ansvarlig	

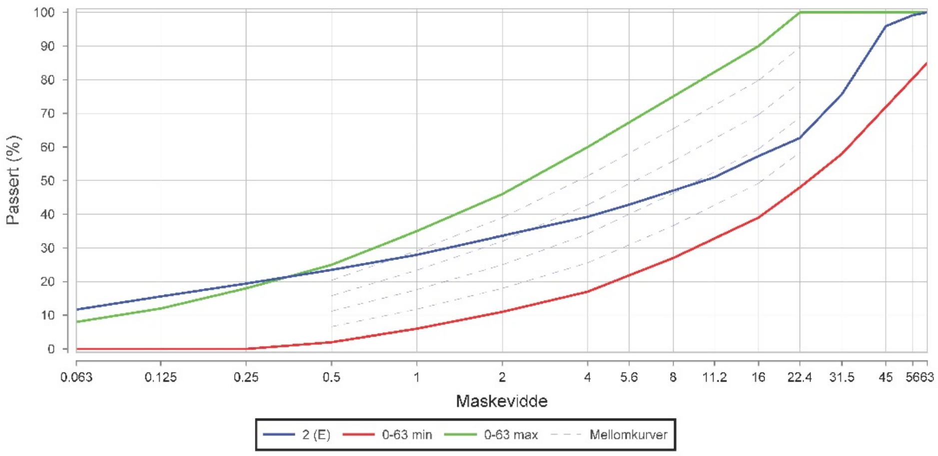
Prøvedata

Prøvenr	2(E)				
Uttatt dato	23.08.2016				
Uttatt kl.					
Uttakssted	Produksjonsted				
Analysetype	Våtsikt				
Massetaknavn					
Består av	Knust fjell				
Grenseverdinr.	0-63				
Vanninnhold (%)	4.1				
Vannabsorpsjon (%)					
Humus (Glødetap)					
Fraksjon (mm)	0.0 - 63.0				
Overstørrelse	0.0				
Understørrelse					
% <63µm av <delsikt	18.6 (22,4 mm)				
% <20µm av <delsikt					
Finstoffinnhold f	11.7				
Godkjent siktekurve	Nei				

Siktedata - Passert (%)

	µm				mm											
Pr.nr.	**63**	**125**	**250**	**500**	**1**	**2**	**4**	**5.6**	**8**	**11.2**	**16**	**22.4**	**31.5**	**45**	**56**	**63**
2(E)	11.7	15.6	19.4	23.5	28.0	33.6	39.2	42.9	47.0	51.0	57.3	62.7	75.7	95.9	99.2	100.0

Det blei 3.stk bøtter tilsammen 50.1 kg, alt siktet gjennom 22,4mm, det under har vi splittet med til 3,3kg for så å vaske på 0,063 sikte duk.



Sted: Arna Dato: 01.09.16 Signatur: Liv Vangsnes

Laboratorium: Arna - I henhold til H014 labprosess: 14.423, 14.424, 14.432, 14.433, 14.434, 14.439

Prøveopphav: (B) Byggherre (E) Entreprenør (P) Produsent

Diverse steinforekomster

Korngradering

Oppdragnr.	**131160010**	Oppdragsnavn	**Jenbaneverket Utbygging Arna - Bergen**
Prosjektnummer	**960242**	Prosjektnavn	**Utbygging Arna-Bergen**
Ansvarsområde		Ansvarlig	

Prøvedata

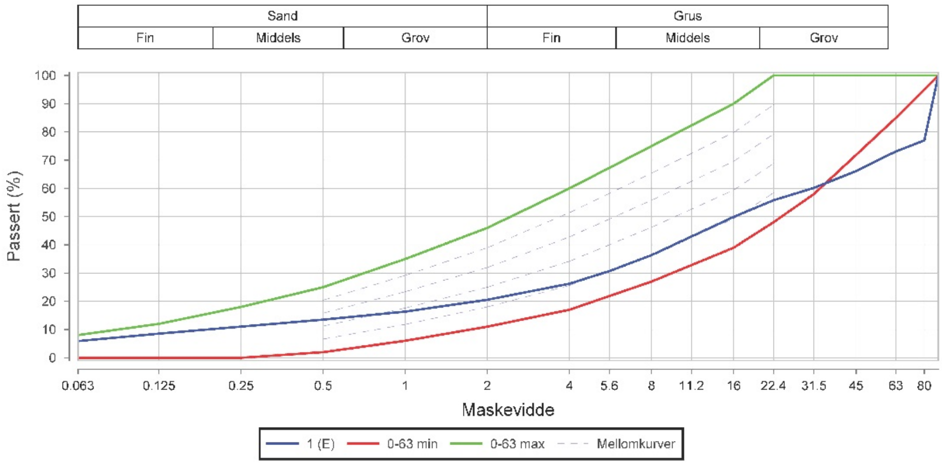
Prøvenr	1(E)				
Uttatt dato	26.04.2016				
Uttatt kl.					
Uttakssted	Produksjonsted				
Analysetype	Våtsikt				
Massetak					
Består av	Knust fjell				
Grenseverdinr.	0-63				
Vegnr/HP	PV1				
Meter/*profil	*532,7				
Avstand høyre kant					
Dybde	-				
Vanninnhold (%)	5.2				
Vannabsorpsjon (%)					
Humus (Glødetap)					
Fraksjon (mm)	0.0 - 63.0				
Overstørrelse	26.9				
Understørrelse					
% <63µm av <delsikt	10.5 (22,4 mm)				
% <20µm av <delsikt					
Finstoffinnhold f	5.9				
Godkjent siktekurve	Nei				

Siktedata - Passert (%)

	µm				mm												
Pr.nr.	63	125	250	500	1	2	4	5.6	8	11.2	16	22.4	31.5	45	63	80	90
1(E)	5.9	8.5	11.0	13.5	16.3	20.5	26.2	30.7	36.4	42.9	49.9	55.8	60.2	66.1	73.1	77.0	100.0

Prøvenr. 1

03.05.2016	1 sekk 12 Kg 0-32 , NTNU nr. 1 - TM 532,7



Pr.nr	Vegnr	Meter/*profil	HP	Avst.hk.	Dybde(m)	Jordart	Cu (* = Cu75)	TG
1(E)	PV1	*532,7			-		164.7	

Sted: Arna Dato: 03.05.16 Signatur: Liv Vangsnes

Diverse steinforekomster

Korngradering

Oppdragnr.	131160011	Oppdragsnavn	Test av TBM masse nye Ulriken TNL
Prosjektnummer	112012	Prosjektnavn	TBM v/Gry Stenersen
Ansvarsområde		Ansvarlig	

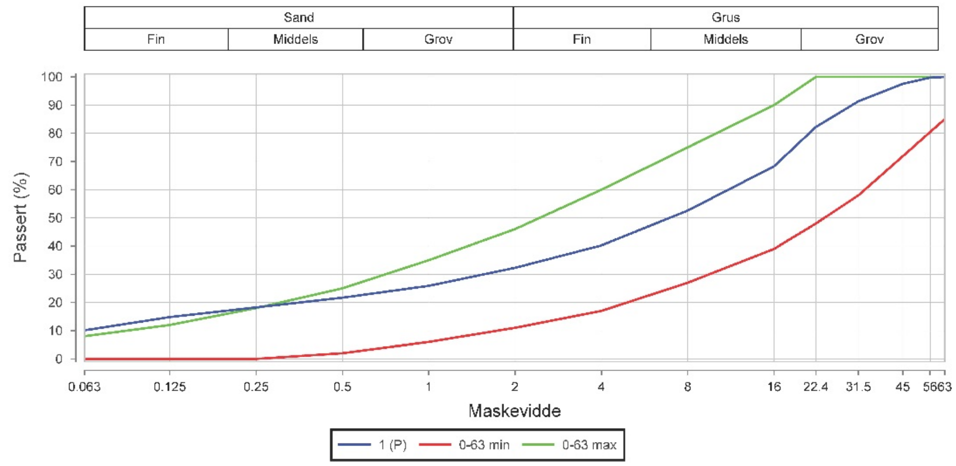
Prøvedata

Prøvenr	1(P)				
Uttatt dato	26.04.2016				
Uttatt kl.					
Uttakssted	Produksjonsted				
Analysetype	Våtsikt				
Massetak					
Består av					
Grenseverdinr.	0-63				
Vegnr/HP	KV1 TBM				
Meter/*profil	*718,4				
Avstand høyre kant					
Dybde	-				
Vanninnhold (%)	0.6				
Vannabsorpsjon (%)					
Humus (Glødetap)					
Fraksjon (mm)	0.0 - 63.0				
Overstørrelse	0.0				
Understørrelse					
% <63µm av <delsikt	12.3 (22,4 mm)				
% <20µm av <delsikt					
Finstoffinnhold f	10.1				
Godkjent siktekurve	Nei				

Siktedata - Passert (%)

	µm				mm									
Pr.nr.	63	125	250	500	1	2	4	8	16	22.4	31.5	45	56	63
1(P)	10.1	14.8	18.2	21.7	25.9	32.3	40.2	52.6	68.3	82.2	91.3	97.5	99.7	100.0

12.05.2016 4 stk. Bøtter à 15 kg ,Uttatt på Band i tunnel TM 718,4



Pr.nr	Vegnr	Meter/*profil	HP	Avst.hk.	Dybde(m)	Jordart	Cu (* = Cu75)	TG
1(P)	KV1	*718,4			-		*21.8	

Sted: Arna

Dato: 12.05.16

Signatur: Liv Vangsnes

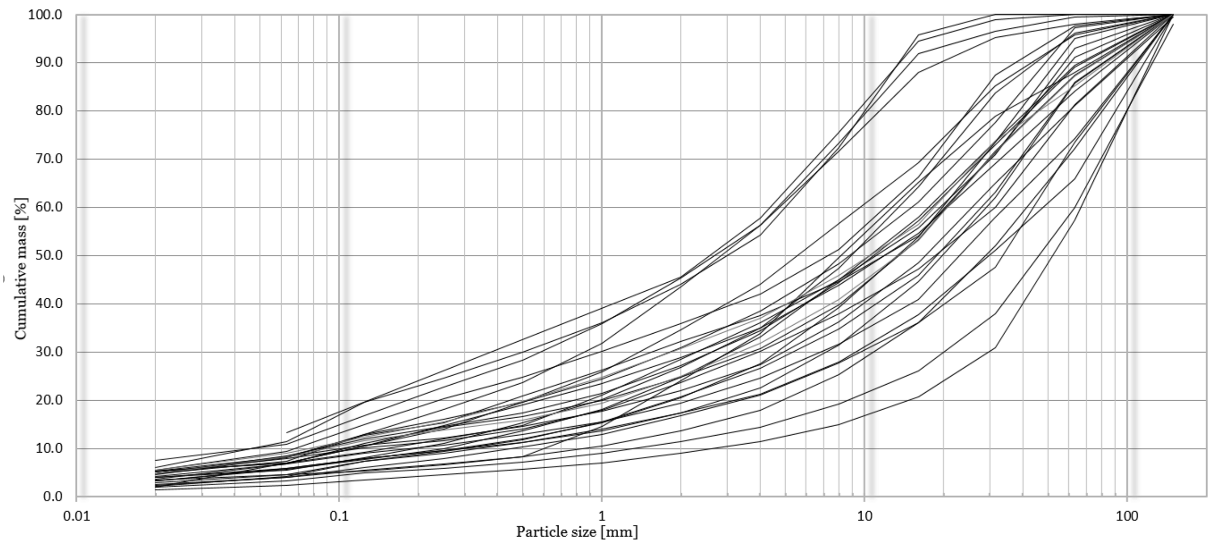
Laboratorium: Arna - I henhold til H014 labprosess: 14.423, 14.424, 14.432, 14.433, 14.434, 14.439

Prøveopphav: (B) Byggherre (E) Entreprenør (P) Produsent

M. PSDs from Gotthard Base Tunnel 2000-2006

Source: AlpTransit Gotthard AG (Amsteg)
Dry sieved samples with average 3-10 kg for each test. Average density 2.7 kg/m^3

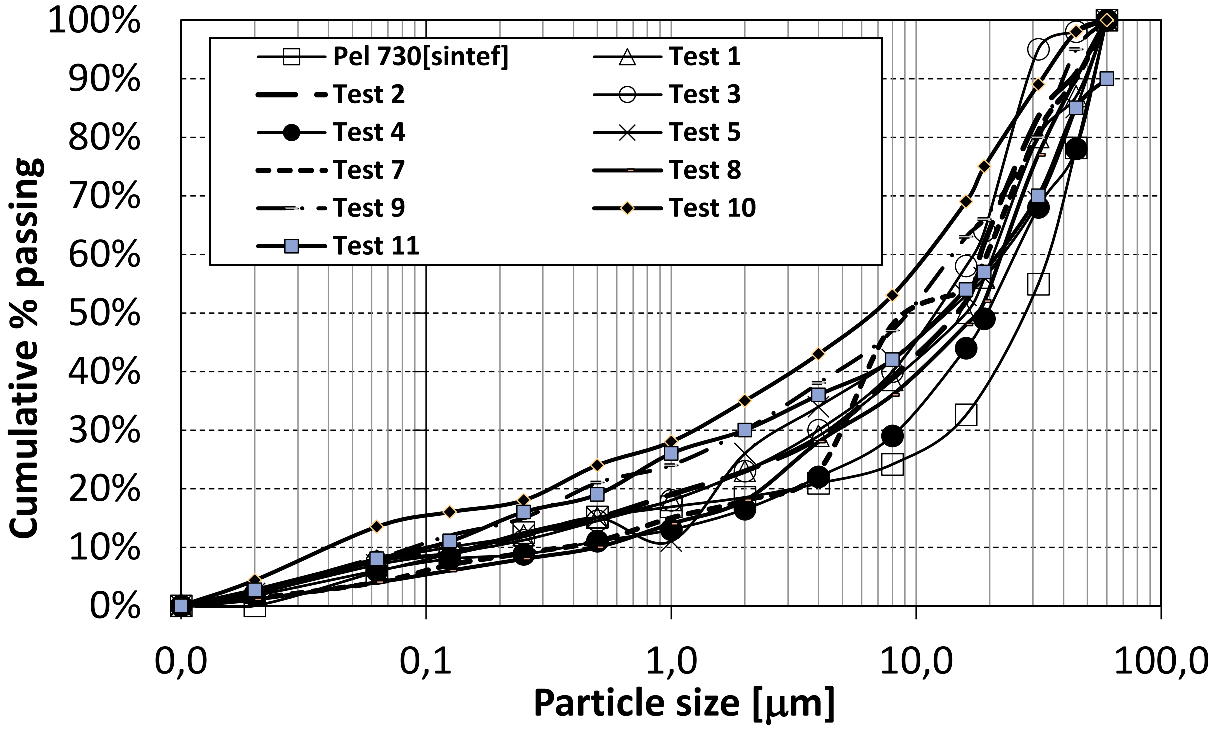
Spoil [mm]	Origin	Date	Particle size distribution[mm]													Maximum particle[mm]
			0.02	0.063	0.125	0.25	0.5	1	2	4	8	16	31.5	63	150	
0/150	TBM	22.5.2000	2.0	7.1	10.6	14.8	19.1	23.6	29.0	35.1	44.0	54.6	69.1	84.2	100.0	98
0/150	TBM	26.5.2003	4.9	7.5	13.0	18.2	23.7	31.9	43.6	56.4	73.3	92.0	96.6	99.6	100.0	66
0/150	TBM	28.8.2003		13.4					45.5	57.8	75.7	94.6	99.0	100.0	100.0	40
0/150	TBM	7.10.2003	6.1	11.5	19.7	24.6	30.0	36.1	44.1	54.3	72.5	95.8	100.0	100.0	100.0	26
0/150	TBM	20.11.2003	2.2	4.2	7.5	9.0	11.3	14.1	17.4	21.4	27.9	37.8	51.1	66.0	100.0	138
0/150	TBM	20.1.2004	5.5	9.4	15.1	20.3	24.8	30.2	35.9	42.1	51.4	66.3	87.5	97.6	100.0	70
0/150	TBM	6.2.2004	7.5	10.9	16.9	22.8	28.4	36.0	45.4	56.3	71.7	88.1	95.2	98.0	100.0	98
0/150	TBM	10.3.2004	5.3	7.0	10.5	14.1	19.6	26.0	34.6	44.1	56.8	69.4	85.2	95.9	100.0	77
0/150	TBM	2.4.2004	4.0	5.6	8.2	11.1	15.4	20.2	26.8	35.1	47.5	64.3	83.8	96.2	100.0	73
0/150	TBM	4.5.2004	3.6	4.7	5.3	6.7	8.4	14.6	24.0	34.0	49.6	65.2	78.9	88.1	100.0	142
0/150	TBM	8.6.2004	5.4	7.1	9.3	12.1	14.8	21.1	28.5	36.1	45.0	55.8	71.0	93.1	100.0	104
0/150	TBM	8.7.2004	2.6	4.0	5.5	6.8	8.4	10.5	13.7	18.0	25.3	36.2	52.0	72.2	100.0	121
0/150	TBM	2.9.2004	3.0	4.7	7.4	9.5	11.8	15.6	20.7	26.7	34.9	45.9	63.2	86.0	100.0	112
0/150	TBM	6.10.2004	5.1	8.0	10.2	11.6	14.1	17.9	23.8	30.2	37.9	47.3	60.1	81.3	100.0	115
0/150	TBM	11.11.2004	5.4	8.4	10.7	12.3	14.6	17.7	22.0	27.5	36.3	48.5	65.0	81.2	99.5	155
0/150	TBM	8.12.2004	2.0	3.4	5.0	5.9	7.3	9.0	11.4	14.4	19.3	26.2	38.0	60.0	98.0	164
0/150	TBM	15.2.2005	4.9	8.5	12.0	14.7	17.5	21.5	27.3	34.4	44.4	57.3	73.0	89.2	100.0	118
0/150	TBM	2.3.2005	4.7	8.2	12.9	16.1	19.6	24.5	31.0	38.5	48.3	61.1	77.7	97.3	100.0	72
0/150	TBM	13.4.2005	4.9	8.4	12.7	15.3	21.0	26.3	32.2	37.7	44.6	54.1	71.4	91.2	100.0	80
0/150	TBM	3.5.2005	2.4	4.1	6.1	7.9	10.4	13.0	16.8	21.2	27.8	36.1	47.7	73.5	100.0	118
0/150	TBM	8.6.2005	3.4	5.9	7.9	9.7	11.3	13.8	17.5	22.6	31.5	44.6	62.1	85.8	100.0	101
0/150	TBM	6.7.2005	3.4	5.7	7.8	10.0	13.7	18.2	24.9	33.2	45.0	58.0	73.8	89.6	100.0	143
0/150	TBM	11.1.2006	4.3	6.8	11.1	14.5	16.7	20.0	24.8	30.7	39.9	53.3	71.8	87.5	100.0	107
0/150	TBM	8.3.2006	5.6	9.0	12.5	15.6	19.9	24.8	30.8	37.1	45.9	56.5	73.7	85.2	100.0	127
0/150	TBM	5.4.2006	4.1	6.0	8.0	9.7	12.0	15.3	20.5	27.7	39.2	53.9	73.6	95.0	100.0	79
0/150	TBM	4.5.2006	4.9	8.3	11.7	13.9	16.0	19.5	25.0	31.8	41.0	53.2	71.5	87.2	100.0	110
0/150	TBM	1.6.2006	3.7	6.8	9.1	10.7	12.9	15.6	19.5	24.6	31.7	41.0	58.0	74.4	100.0	148
0/150	TBM	5.7.2006	1.4	2.5	3.6	4.6	5.8	7.1	9.0	11.4	15.0	20.8	30.9	57.4	100.0	113



N. PSDs from Fløyfjell TBM 1988 summarized

Shows 11 different PSDs from Fløyfjell Tunnel TBM project in Bergen, 1988. Test 6 was not acquired. Hydrometric analysis done of particles below 19 mm sieve to measure the content of <20 µm

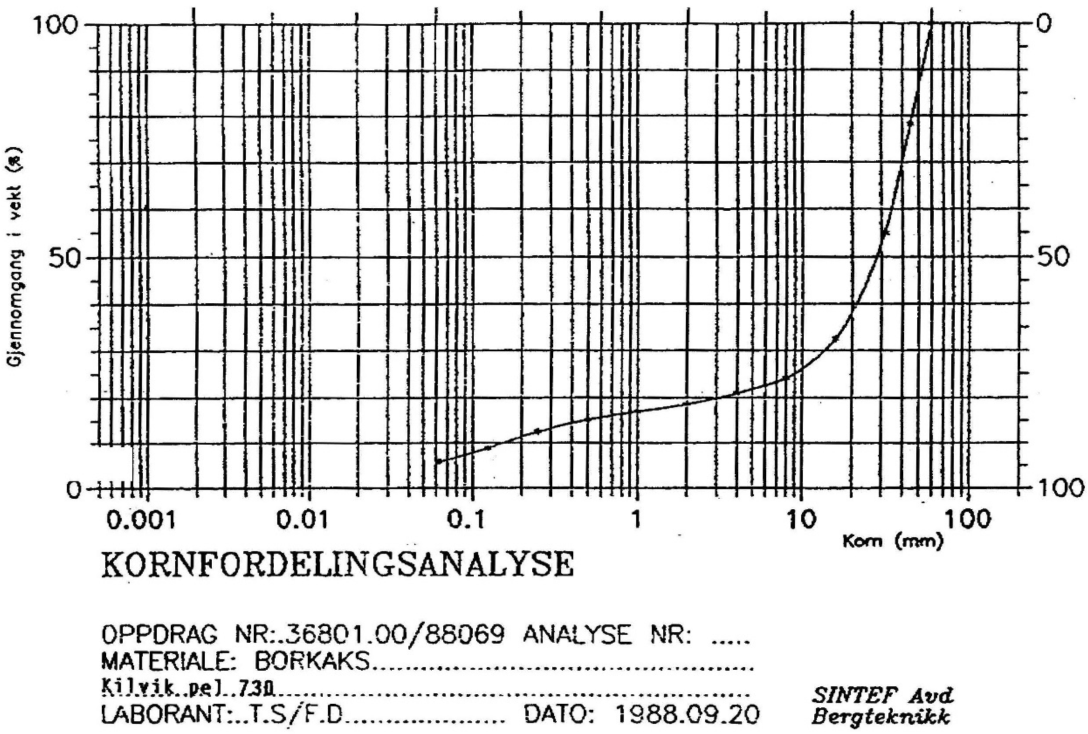
	20.09.88 m= 14370 g Sintef	18.09.84 Hornblendsifer/grønsskifer(tip)	20.09.88 Granistisk gneis(tip) pel 96	21.09.84 Granitisk gneis(tip) Pel 107	1984 Hornblende skifer(tip)	1984 Granitic gneiss(tip) pel 169	21.09.84 Granitisk gneis (bånd) Pel 822	84 Granitic gneiss (belt)	Granitic gneiss (belt pel 169	Granitisk gneis (belt) pel 866	Medium foliated granitic gneiss(12,5 % glimmer) pel 1310
Diameter (mm)	Pel 730[sintef]	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9	Test 10	Test 11
60	100,0 %	100,0 %	100,0 %	100,0 %	100,0 %	100,0 %	100,0 %	100,0 %	100,0 %	100,0 %	90,0 %
45	78,17 %	87,0 %	91,0 %	98,0 %	78,0 %	85,0 %	90,0 %		95,0 %	98,0 %	85,0 %
31,5	54,9 %	80,0 %	83,5 %	95,0 %	68,0 %	69,0 %	81,0 %	77,0 %	80,0 %	89,0 %	70,0 %
19	NA	56,0 %	62,0 %	64,0 %	49,0 %	56,0 %	59,0 %	52,0 %	66,0 %	75,0 %	57,0 %
16	32,6 %	50,0 %	52,0 %	58,0 %	44,0 %	53,0 %	54,0 %	48,0 %	63,0 %	69,0 %	54,0 %
8	24,2 %	38,5 %	39,0 %	40,0 %	29,0 %	42,0 %	48,0 %	36,0 %	47,0 %	53,0 %	42,0 %
4	20,9 %	29,0 %	28,7 %	30,0 %	22,0 %	34,0 %	23,0 %	28,0 %	38,0 %	43,0 %	36,0 %
2	18,5 %	23,0 %	23,0 %	23,0 %	16,5 %	26,0 %	18,0 %	18,0 %	30,0 %	35,0 %	30,0 %
1	16,9 %	18,0 %	19,0 %	18,0 %	13,0 %	11,0 %	15,0 %	14,0 %	24,0 %	28,0 %	26,0 %
0,5	15,2 %	15,0 %	15,0 %	14,5 %	11,0 %	15,0 %	11,0 %	10,0 %	21,0 %	24,0 %	19,0 %
0,25	12,5 %	12,0 %	12,0 %	11,2 %	8,8 %	12,0 %	9,0 %	8,0 %	15,0 %	18,0 %	16,0 %
0,125	8,9 %	10,0 %	9,0 %	9,0 %	8,0 %	9,0 %	7,0 %	6,0 %	12,0 %	16,0 %	11,0 %
0,063	5,8 %	7,7 %	8,0 %	7,5 %	6,0 %	7,0 %	4,0 %	4,0 %	8,0 %	13,5 %	8,0 %
0,02	0,00 %	2,19 %	2,15 %	2,03 %	1,74 %	2,12 %	1,27 %	1,08 %	2,03 %	4,37 %	2,72 %
0,01	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %



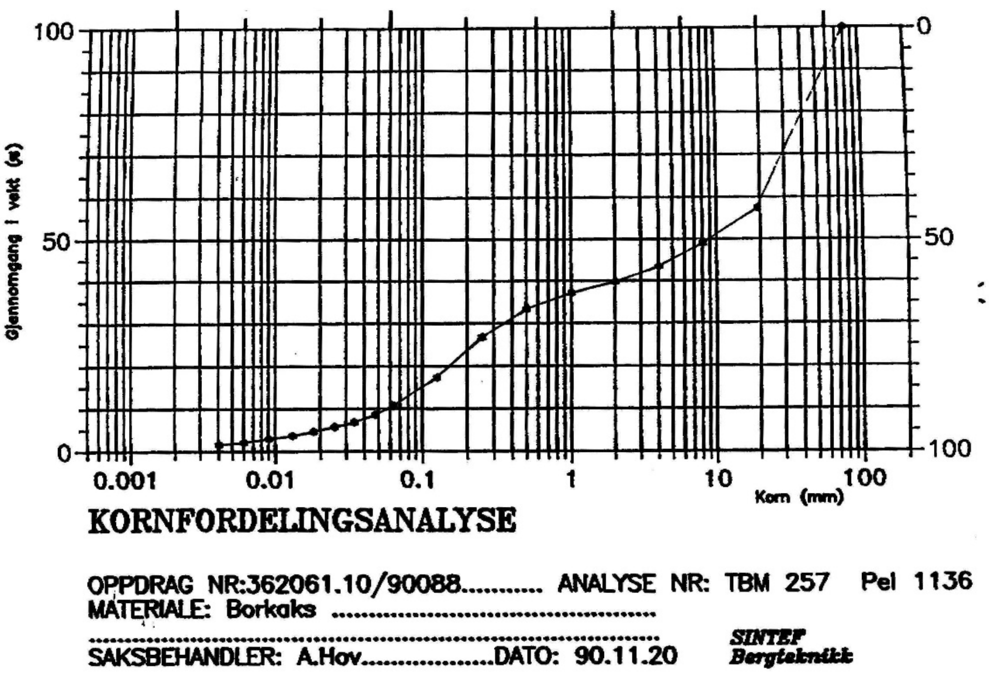
O. PSDs from Fløyfjellet TBM 1988 (source data)

Pel 730[sintef]

Fløyfjell 1988 (Ø 8,5 m, 17 inch cutters), Kilvik, Svartisen

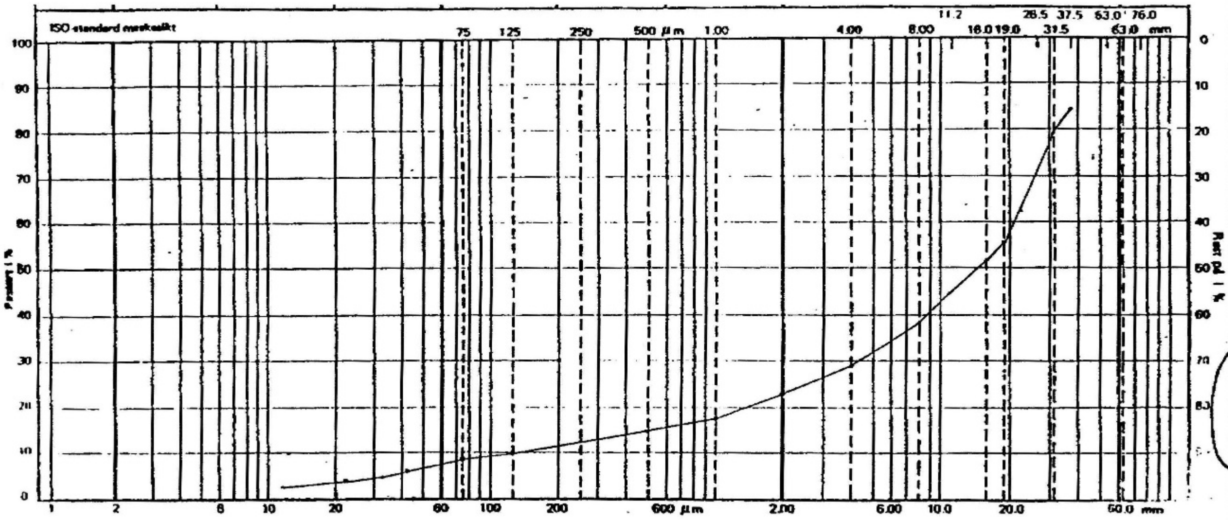


Staupåga, Svartisen 1990, (Ø 3,5 m, 19 inch cutters)



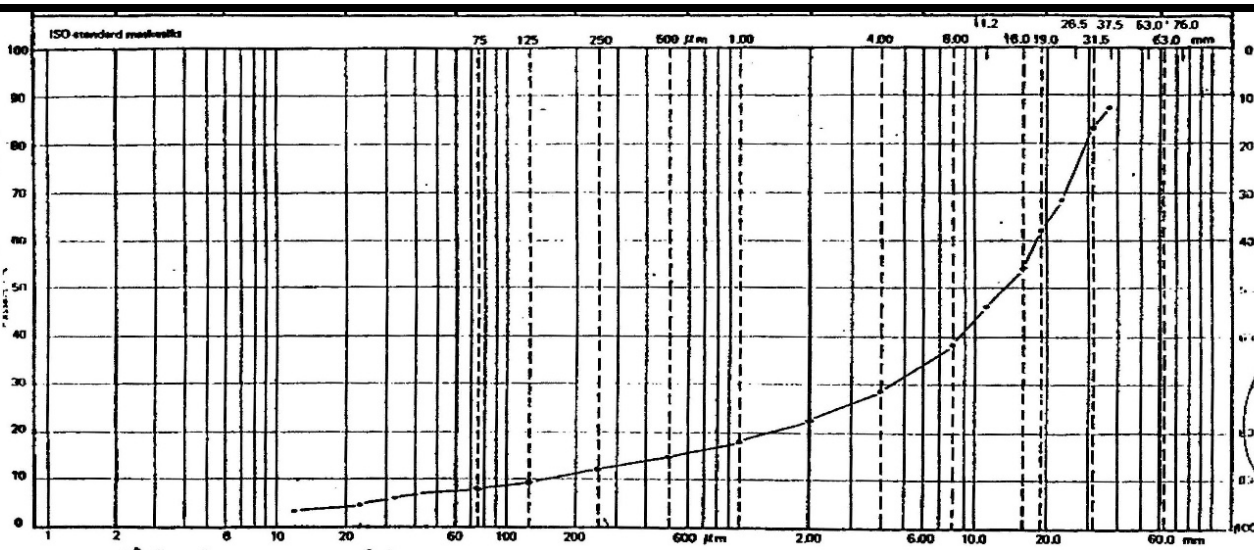
Test 1-12(11)

Fløyfjellet, 1984 (Ø 7.8 m, 17 inch cutters)



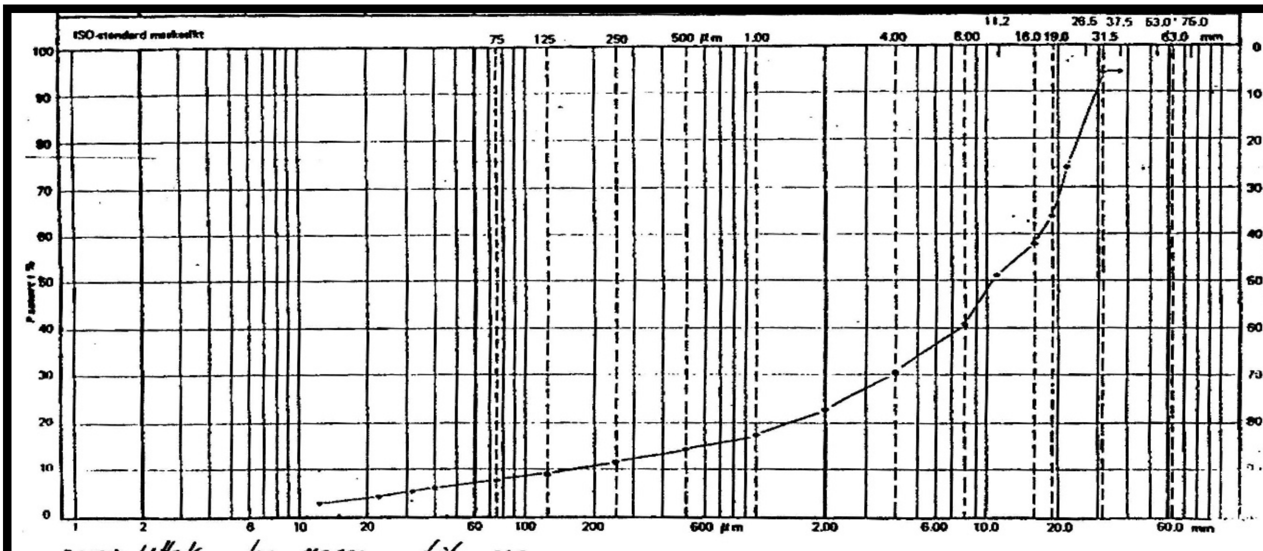
Prøvested:

Prøve nr.	Profil/hull nr.	Dybde	Kurve	Jordartsbetegnelse	C_u	% < 20 µm	Telegruppe	Humus
9196			———	Hornblendeskifer/grønnskifer		6,9 %	T2	
			— — —					
			—·—·—					
			--·--·--					
			—x—x—					
			—xx—xx—					



Prøvested: Uttak for masse til veg

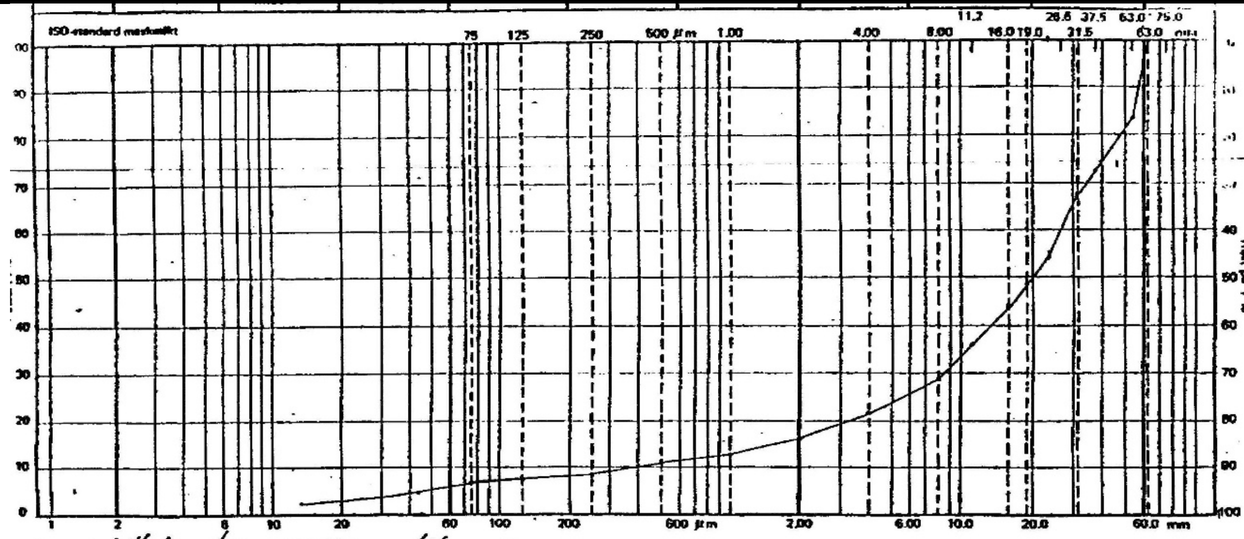
Prøve nr.	Profil/hull nr.	Dybde	Kurve	Jordartsbetegnelse	C_u	% < 20 µm	Telegruppe	Humus
2208			———	Granittisk gneis		6,8	T2	
			— — —					
			—·—·—					
			--·--·--					
			—x—x—					
			—xx—xx—					



Prøvested: Uttak for masse til veg

Prøve nr.	Profil/hull nr.	Dybde	Kurve	Jordartsbetegnelse	C_u	% < 20 µm	Telegruppe	Humus
2209			——	Granittisk gneis (båndet)		6,4	T2	

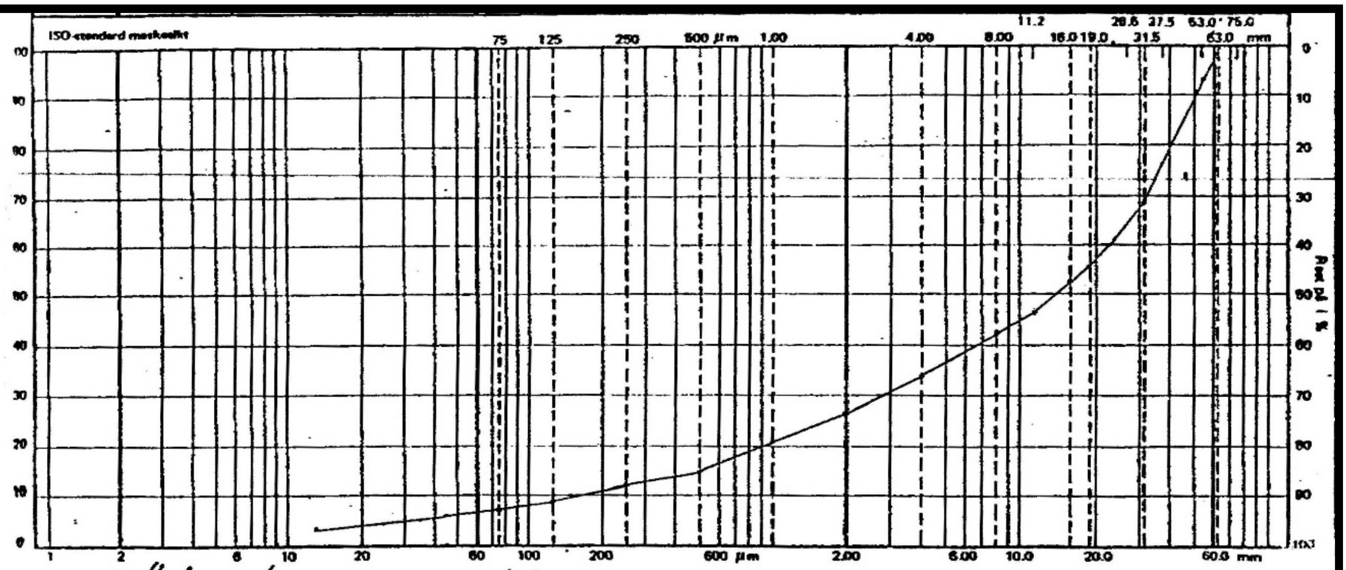
ØYFJELLTUNNEL Dato 2/4-84 Oppdrag/Ark. nr. Prøve 3 Bilag nr. Rd. 107



Prøvested: Uttak for masse til veg

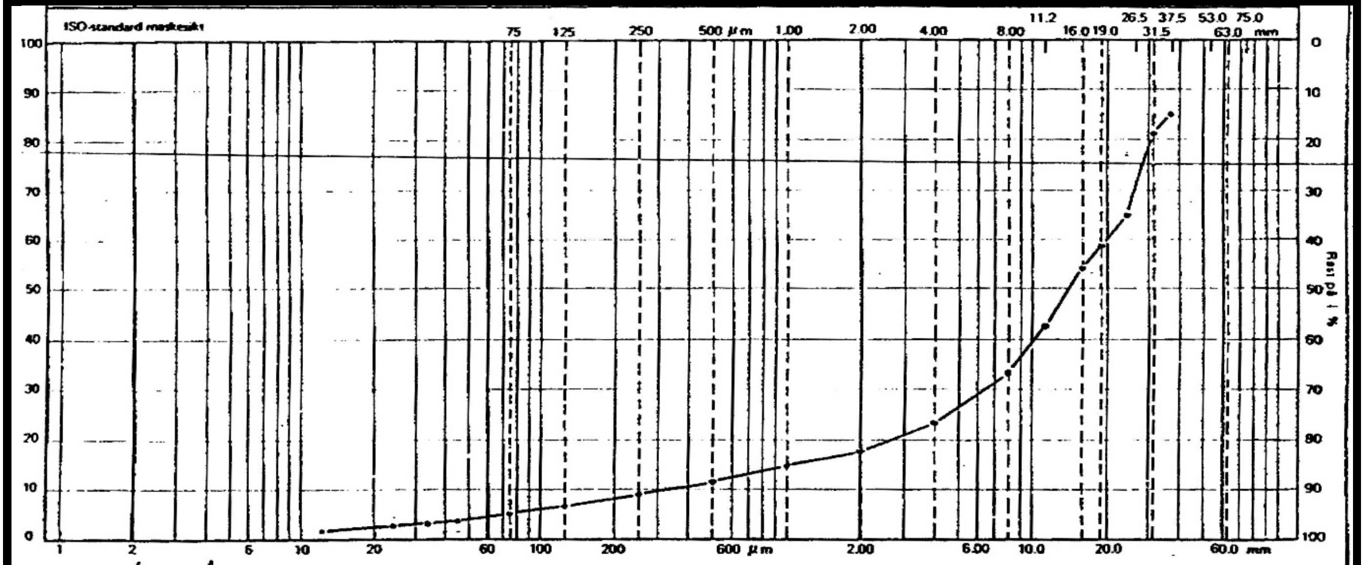
Prøve nr.	Profil/hull nr.	Dybde	Kurve	Jordartsbetegnelse	C_u	% < 20 µm	Telegruppe	Humus
2227 (Nr 4)	148		——	Hornblendeskifer		5.5	T2	

ØYFJELLTUNNEL Dato Nr 4 Oppdrag/Ark. nr. Bilag nr.



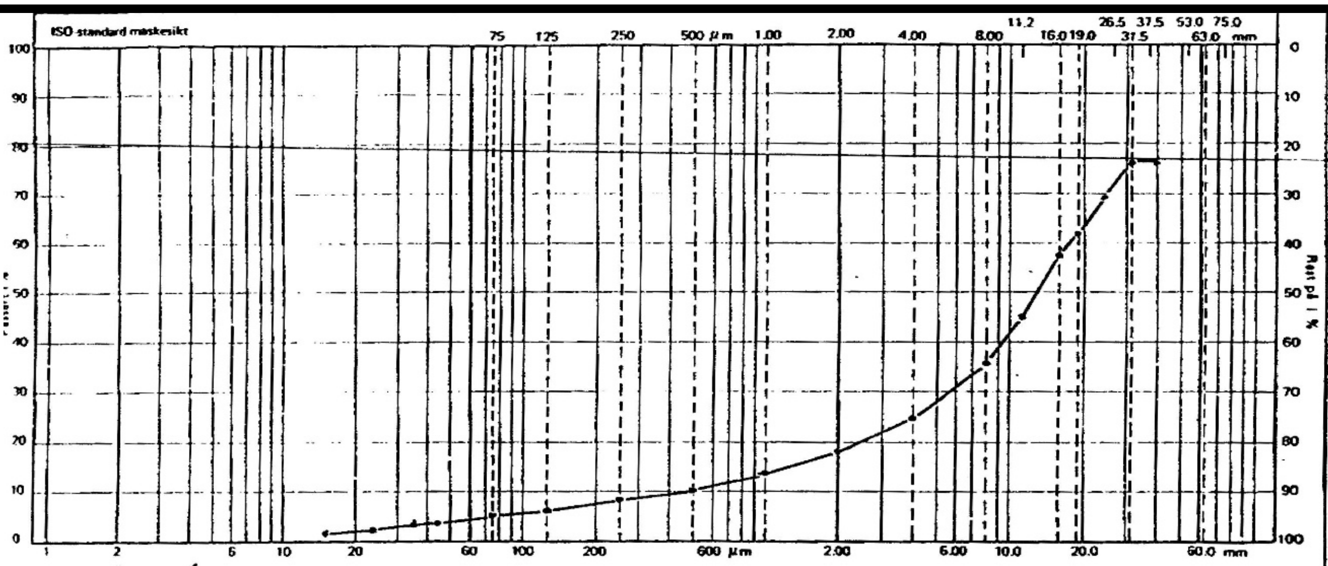
Prøvested: Uttak for masse til veg

Prøve nr.	Profil/hull nr.	Dybde	Kurve	Jordartsbetegnelse	C_u	% < 20 µm (Matr. pass. 19 mm)	Telegruppe	Humus
2228 (Nr 5)	169		———	Granittisk gneis		6,7	T2	
			— — —					
			—·—·—					
			—··—··—					
			—x—x—					
			—xx—xx—					



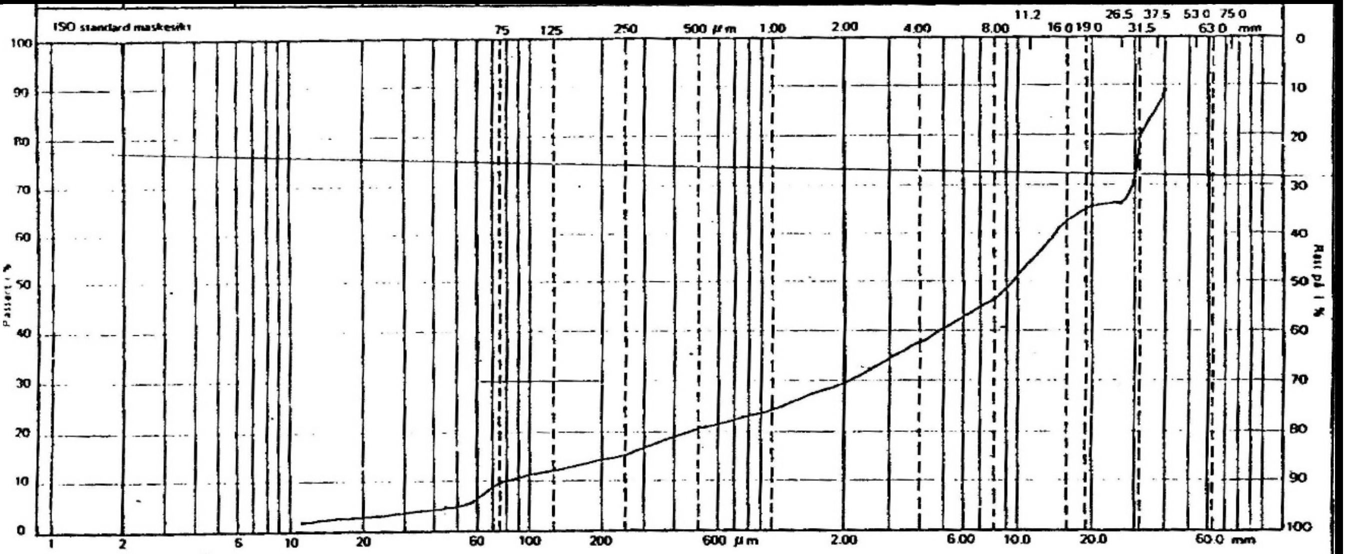
Prøvested: Lagerhaug

Prøve nr.	Profil/hull nr.	Dybde	Kurve	Jordartsbetegnelse	C_u	% < 20 µm (Matr. pass. 19 mm)	Telegruppe	Humus
2366	822		———	Båndet granittisk gneis		4	T2	
			— — —					
			—·—·—					
			—··—··—					
			—x—x—					
			—xx—xx—					



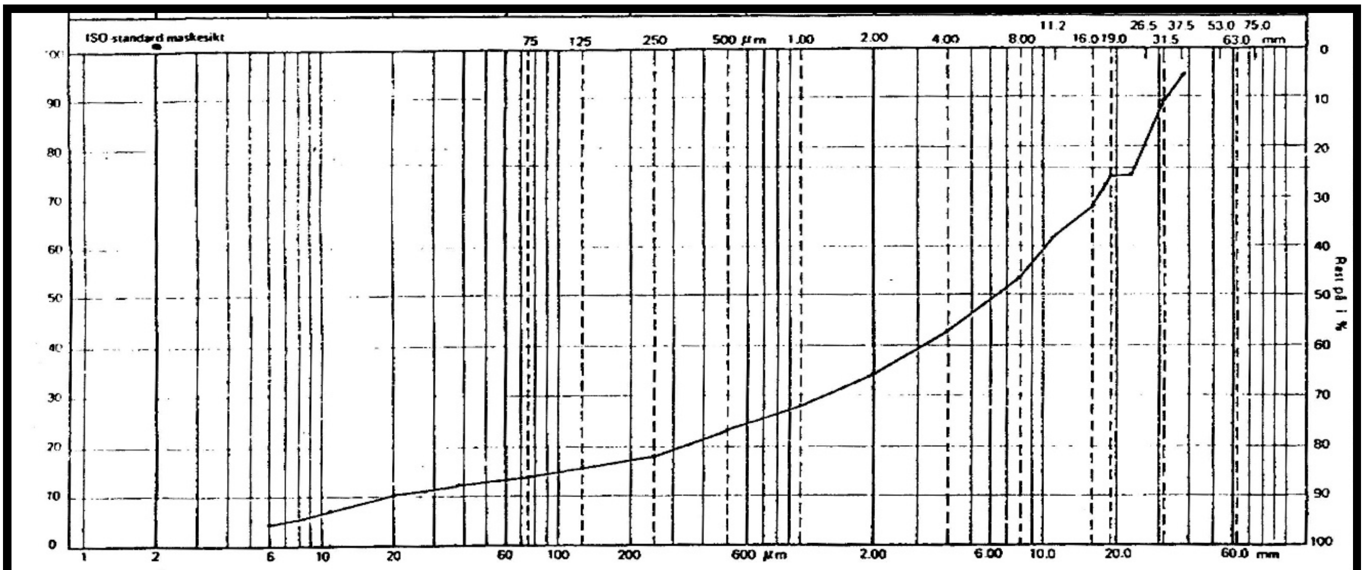
Prøvested: Lagerhaug

Prøve nr.	Profil/hull nr.	Dybde	Kurve	Jordartsbetegnelse	C_u	% < 20 µm (matr. pass. 19 mm)	Telegruppe	Humus
2367	822	NR8		Båndet granittisk gneis		3,4	T2	



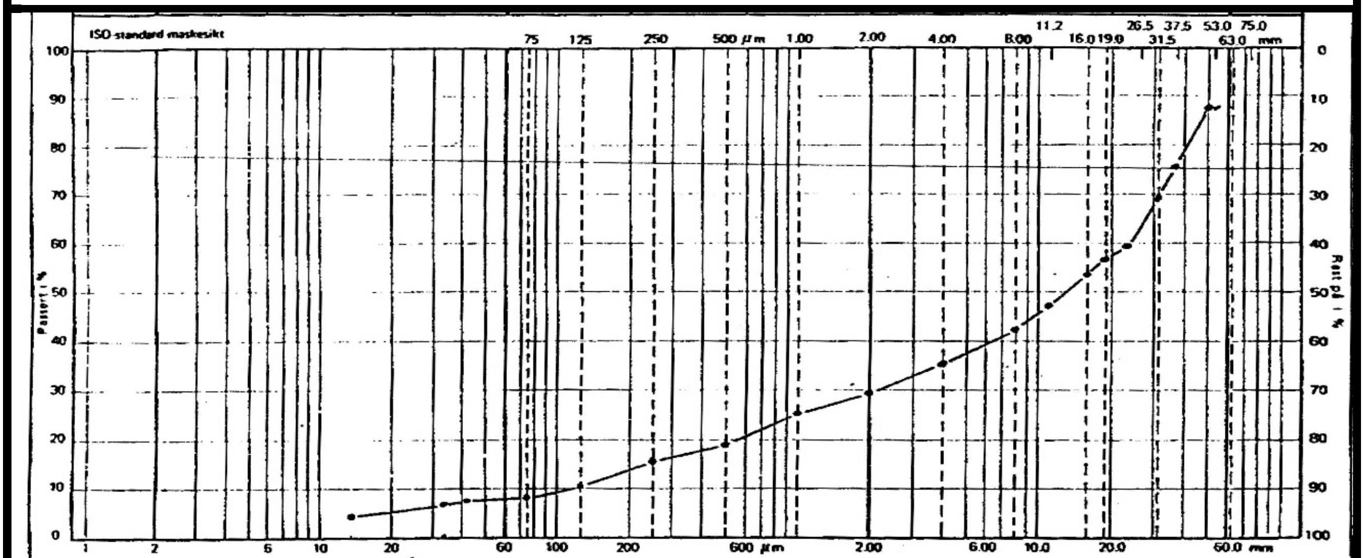
Prøvested: Lagerhaug

Prøve nr.	Profil/hull nr.	Dybde	Kurve	Jordartsbetegnelse	C_u	% < 20 µm (matr. pass. 19 mm)	Telegruppe	Humus
2375	866	LAGERH.		Båndet granittisk gneis		6,4		



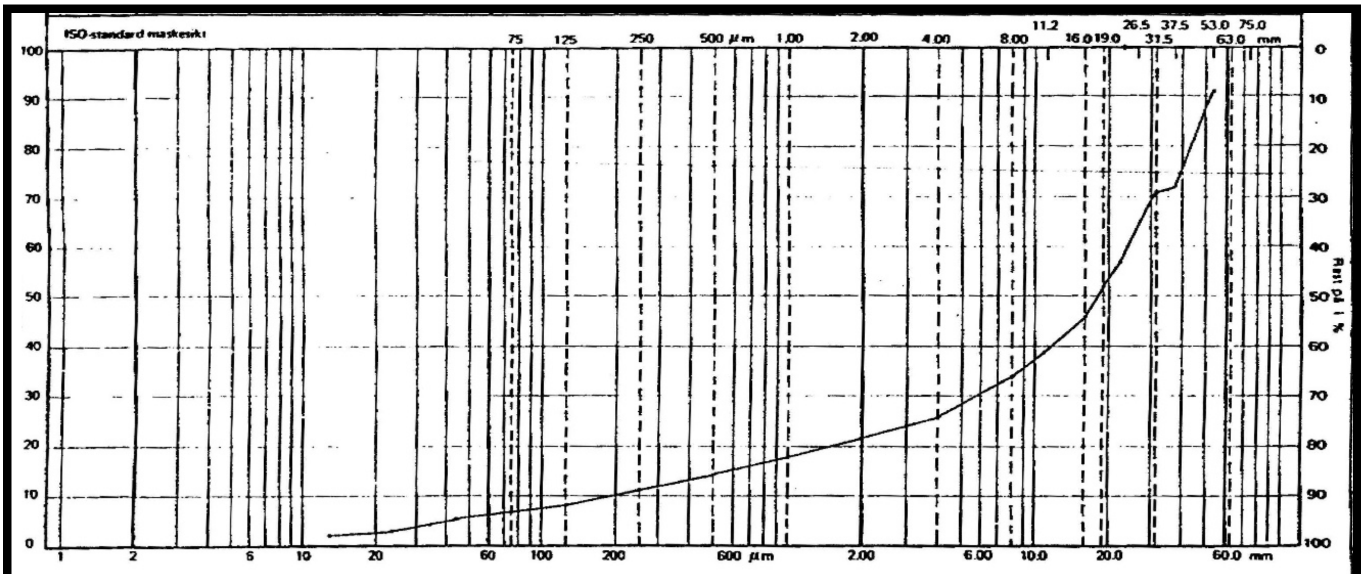
Prøvested: Lagerhaug

Prøve nr.	Profil/hull nr.	Dybde	Kurve	Jordartsbetegnelse	C_u	% < 20 µm (matr. pass. 19 mm)	Telegruppe	Humus
2376	866	LAGERH.		Båndet granittisk gneis		13,8		
			—x—x—					
			—xx—xx—					



Prøvested: Fløyfjelltunnelen (Lagerhaug)

Prøve nr.	Profil/hull nr.	Dybde	Kurve	Jordartsbetegnelse	C_u	% < 20 µm (matr. pass. 19 mm)	Telegruppe	Humus
11	1310			Middels foliert granittisk gneis		8,6 %	T2	
				Den inneholder 10-15 %				
				glimmer.				
			—x—x—					
			—xx—xx—					



Prøvested:

Prøve nr.	Profil/hull nr.	Dybde	Kurve	Jordartsbetegnelse	C_u	% < 20 µm (matr. pass. 19 mm)	Telegruppe	Humus
2536			———					
			— — —					
			–·–·–					
			———					
			—x—x—					
			—xx—xx—					