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Reusing and recycling of railway ballast

Master's thesis in Civil and Environmental Engineering
Supervisor: Professor Elias Kassa
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Abstract

The aim of this study is to research the possibilities of reusing and recycling of used railway ballast, by modifying its properties and stiffening the ballast. Literature review, laboratory testing and short interviews has been used to discuss this subject.

Properties of the used ballast is investigated through laboratory tests, using the standards for newly produced aggregates. This gave an overview of the current quality of the ballast layer and indicated the amount of material that would be removed during a ballast cleaning operation.

To modify the materials, several binding agents has been used. The effect of them was investigated by using repeated load triaxial test, measuring deflection to calculate stiffness and permanent deformation. The results showed that dependent on the binder, the ballast can increase or reduce the stiffness several times the value of untreated material. This opens possibilities for the railway agencies to greatly modify their lines and could make it easier to solve issues in transition zones of different stiffness.

The permanent deformation of the ballast also showed effect of stabilization with binding agents. The effects were not as severe as for material stiffness, but significant enough to be evaluated as possible treatment procedure for either new or old railway lines.

The research includes binding agents as polyurethane (Elastotrack), organosilanes (Zycobond), lignosulphonate (Dustex) and bitumen (70/100 and 160/220).

Keywords: Railway ballast, Crushed rock, Stabilization, Repeated triaxial load test

Sammendrag

Målet med denne forskningen er å undersøke muligheter ved gjenbruk og gjenvinning av brukt jernbaneballast, ved å endre egenskapene og stivheten til ballasten. Litteratur, laboratorie tester og korte intervjuer er benyttet for å diskutere dette temaet.

Egenskaper av brukt ballast er undersøkt ved laboratorie tester, ved å benytte standard for nyprodusert ballast. Dette ga en oversikt over kvaliteten på ballastlaget og indikerte mengden av materiale som vil bli fjernet under en ballast rense operasjon.

For å modifisere materialene har flere bindemidler vært benyttet. Effekten av dem har blitt undersøkt med gjentakende treaksiale last tester. De måler bøyning og blir brukt til å regne ut stivhet og permanent deformasjon. Resultatene viste at avhengig av bindemiddel kan ballasten øke eller redusere stivhetene flere ganger verdien av ubehandlet ballast. Dette åpner opp muligheter for jernbaneforetakene til å endre linjer og gjøre det enklere å løse problemer ved overgangssoner med ulik stivhet.

Den permanente deformasjonen av ballasten viste også effekt av stabilisering med bindemidler. Effekten var ikke like stor som for stivhet, men markant nok til å bli ansett som en mulig løsning for både nye og gamle jernbanelinjer.

Forskningen inkluderer bindemidler som polyurethane (Elastotrack), organosilan (Zycobond), lignosulfonat (Dustex) og bitumen (70/100 og 160/220).

Nøkkelord: Jernbaneballast, knust puk, stabilisering, treaksiale tester

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Many individuals from different companies has been involved in this research. Their eagerly and constant contribution is deeply appreciated. Professor Inge Hoff (NTNU), Professor Mai Britt Engenes Mørk (NTNU), Bent Lervik (NTNU), Jan Erik Molde (NTNU), Daniel Hatcher (Baneservice), Pål Buskum (Bane NOR), Alf Helge Løhren (Bane NOR), Jan Ove Flå (Bane NOR) and Geir Svanø (Bane NOR) are all greatly acknowledged for their assistance. Further, I want to thank my friends and family for their support.

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Abbreviations

LVDT	Linear variable displacement transducers
NTNU	The Norwegian University of Science and Technology
PAH	Polycyclic aromatic hydrocarbons
NGU	Geological survey of Norway
LSL	Load sequence level
LA	Los Angeles
RLTT	Repeated Load Triaxial Test
MS LSL	Multi-stage low stress level

1 Introduction

This master thesis is aiming to researching the current and possible future reuse and recycling of railway ballast in Norway. The focus is on used material and the biggest fractions that are removed from the railway line through ballast cleaning.

1.1 Background

Ballasted tracks are by far the most common in Norway, even though there are some projects looking into other solutions, such as Follobanen whose planning slab-tracks for parts of the tunnels (Bane NOR, 2018) . In a ballasted track, the ballast degrades with use, so to ensure a safe and comfortable travel, it is needed to maintain the good quality of the ballast. One of the ways to do so, is by using a ballast cleaner. In short, such a machine removes the ballast beneath the sleepers and sieves it. If the particle size is different from the limits, the particles will be removed, and fresh ballast will be added. With around 50km of track getting ballast clean each year, this process generates a lot of material that is no longer wanted in the track. It is mainly this material that will be discussed and researched in this thesis.

1.2 Objectives

The objectives of this thesis are to investigate the properties of used railway ballast, and to determine if it is possible to modify some properties to improve the materials stiffness and resistance to permanent deformation.

1.3 Methodology

The different information gatherings during the thesis are presented below

1.3.1 Literature review

The literature review was in the start used to narrow the research field and find ideas for testing procedures. Later, it was used to back up statements and assist in analyzing of the laboratory data.

1.3.2 Lab testing

Most of the information used in the research is gathered from the laboratory parts of the thesis. Two periods of laboratory testing were performed, one in cooperation with Norsk Stein AS and another with NTNU. The first lab period investigated ballast from the railway in Stavanger and compared it to requirements for newly produced ballast. The second lab period studied possibilities of modifying the ballast properties with additives.

Additional to the two mentioned laboratory periods, there was an outsourced laboratory test, thin section analysis. The work was done by the Professor Mai Britt E. Mørk at Department of Geoscience and Petroleum.

1.3.3 Interview

Short qualitative interviews from the main companies involved in ballast cleaning is among the inputs for information gathering. The representatives got a choice between a 20-30 minutes phone-interview or a mail with a questioner specially made for each interviewee.

1.3.4 Analysing

The tests from the first laboratory period is analyzed and compared with the current requirements. For the second testing period, the results is compared to untreated material, using that as a reference to determine the effect of the different binders. The outsourced testing is used to determine the type of material that is being tested and slightly give an overview of the mineralogy of the materials.

1.4 Limitations

This thesis is discussing the Norwegian railway, and uses material provided by the Norwegian Railway Administration (Bane NOR). The focus of the thesis will be within the bigger fractions of the ballast waste.

Testing material for geometrical and mechanical properties of the ballast is only obtained from one location. It is therefore unsure if it is representative for the rest of the Norwegian lines.

To reduce the time for laboratory testing with binding agents, there will only be two samples for each binder and content. Increasing the amount by one for each binder costs half a month of laboratory work and is therefore avoided.

Chemical properties of the ballast have not been tested.

2 Literature review

In this chapter some of the topics that has been researched during the pre-study is included. There is a lot of interesting research that has some correlation with the subject, but to keep this thesis short and precise it is chosen to only include what is of highest relevancy for the project.

2.1 Regulations on railway ballast

The specific object of the project is to reuse the ballast or to recycle it with the use of additives to strengthen its properties. To reach the goal, the ballast needs to be tested and compared with the current demands set by the Norwegian Railway Administration in the technical regulations (Bane NOR, 2015). The demands are based on mechanical, geometrical and chemical properties. The geometrical requirements are listed in Table 1, the mechanical requirements are listed in Table 2, while the chemical requirements are shown in Table 3:

1) Geometrical

Table 1: Geometrical requirements

Property	Category	Reference	Trial method
Railway ballast size	D=63mm, d=31.5mm	NS-EN 13450, p. 6.2	
Grading	Cat. E	NS-EN 13450, p. 6.3	NS-EN 933-1
Fine particles	Cat. A	NS-EN 13450, p. 6.4	NS-EN 933-1
Fines	Cat. D	NS-EN 13450, p. 6.5	NS-EN 933-1
Flakiness index	Cat. FI_{IK}	NS-EN 13450, p. 6.6.1	NS-EN 933-3
Shape index	Cat. SI_{20}	NS-EN 13450, p. 6.6.2	NS-EN 933-4
Particle length	Cat. E	NS-EN 13450, p. 6.7	

2) Mechanical

Table 2: Mechanical requirements

Property	Category	Reference	Trial method
Resistance to fragmentation	Cat. $LA_{RB}20$ *	NS-EN 13450, p. 7.2	NS-EN 1097-2
Resistance to wear	Cat. $MDE_{RB}15$	NS-EN 13450, p. 7.3	NS-EN 1097-1
* For tracks with speed less than 160km/h and yearly traffic less than 5 MGT, $LA_{RB}24$ is accepted			

3) Chemical

The contents of heavy metals and Arsenic should not be higher than the limits in the Norwegian law of pollution, "Forurensningsloven" (Klima- og miljødepartementet, 1983).

In addition, it is demanded that used ballast is also tested for polycyclic aromatic hydrocarbons (PAH), which usually has its source from creosote and fossil fuels. The requirements correlate with the Norwegian law of pollution and are listed in Table 3 for both heavy metals and PAH-compounds.

Table 3: Chemical requirements

Heavy Metals		PAH- compounds	
Product	Requirement (mg/kg)	Product	Requirement (mg/kg)
Arsenic	8	Σ PAH	2
Lead	60	Naphthalene	0.8
Cadmium	1.5	Fluorene	0.8
Mercury	1	Fluoranthene	1
Copper	100	Pyrene	1
Zinc	200	Benzo(a)pyrene	0.1
Chromium (III)	50		
Chromium (IV)	2		
Nickel	60		
Cyanide	1		

2.1.1.1 Deviations geometrical and mechanical properties

Bane NOR is accepting some deviations from the requirements to the railway ballast. For example, on tracks for maintenance purposes where traffic is slow moving, the top 15 cm of the ballast layer can be changed to the fraction of 15-22mm, while the below ballast is the common 31.5-63mm (Bane NOR, 2015).

Also, on lines with low traffic, side tracks and stations there can be deviations to the demands, but it should be evaluated individually for each site based on the operating situation (Bane NOR, 2015).

2.1.1.2 Changes in the requirements

It's been many changes in the technical regulations over the years. In short, the biggest and most relevant changes ballast happened in the mid 90's, when ballast fractions changed from 25-50 to 25-63. And in 2009 when the fractions changed again, this time to 31.5-63, which is the current standard.

2.2 Ballast cleaning

The railway ballast is being degraded with use and will over time reduce the quality of the track. That could be due to crushing of the ballast, infiltration of fines from material beneath, pollution, waste from trains and further.

After a certain time, it is needed to perform operations to improve the quality of the track. Ballast cleaning is a common maintenance solution in such situations, and is widely used, not only in Norway, but also in the rest of the world.

2.2.1 General information

In average 50-75 km is getting ballast cleaned yearly (Buskum, 2019). Currently this work is conducted by Baneservice, who is a big national entrepreneur in the railway community of Scandinavia. But this can change, as Bane NOR is only offering 3 years contracts on services like ballast cleaning (Hatcher, 2019).

Baneservice is using a cleaning train with a normal progress of 120m/h. But due to boundaries within track access and the time to both assembly and disassembly, it is not possible work at that speed for a long time, leading to the progress of around 50-75km a year. This is also affected by the quality of the track and the amount of fines in the line (Hatcher, 2019) (Buskum, 2019).

2.2.2 How it is done

A ballast cleaning machine is removing the ballast beneath the sleepers and sieving it. The materials bigger than the geometrical limits of diameter 63 mm and smaller than diameter 31.5 mm will be taken away (Hatcher, 2019). While clean ballast is added to the track. To perform this operation effectively, several wagons are connected to the cleaning machine to move and store the fouled ballast

Later, the line gets supplied with fresh ballast, this is usually done by driving a train with wagons of fresh ballast and distributing it out where it seems needed. A third train will drive the line to spread and brush the ballast. Following will be a train to stabilize the line with heavy vibrations. Baneservice is using a stabilizing train with a vibrating effect equal to 50 000 driven tonnage, in just one passing (Hatcher, 2019).

2.2.3 Materials retained after cleaning

During the cleaning process a lot of particles below 31.5 mm is removed from the track. They can be divided into 5 groups dependent on their values of pollution, given by the Norwegian Environment Agency (Temoen, 2009).

- | | | |
|----|-----------|------------|
| 1) | Very good | (uncommon) |
| 2) | Good | (common) |
| 3) | Passable | (common) |
| 4) | Poor | (common) |
| 5) | Very poor | (uncommon) |

The level of pollution used to determine the future of the ballast waste, by directly delivering category 4 and 5 to deposits. The coarse material from category 1 and 2 was reused in road constructions or cable traces, while the coarse material of category 3 could be reused after a risk evaluation. All fines were sent to deposits.

From 2016, all material of category 2 to 5 was sent to treatment and cleaned. The company doing this cleaning is Erling Rolstad AS. The material below 4mm, fines, are still sent to deposits, as those fractions usually are heavier polluted than the coarser material. After the cleaning process is completed, the material is sold as recycled material for landfills or for sanding purposes, to increase friction on pavements.

In 2007, NGU conducted some tests to the material gathered by the ballast cleaner machine. They found that 11% of the masses removed from the track was of a fraction size less than 4 mm (Ottesene & Hauhland, 2007) .

2.3 Ballast stiffness and binding

2.3.1 Ballast stiffness

Stiffness is the materials ability to resist deflection. There are different ways to measure the stiffness of ballast. In a laboratory, it is commonly measured with triaxial testing and by calculating resilient modulus. Which is a measure on applied pressure over deflection.

2.3.2 Effect of additives for binding

There are previous studies indicating that binding the ballast particles with adhesives or binders will change the stiffness, durability and permanent deformations in the track. The following sub-chapters will give a quick intro to some of stabilizing additives.

2.3.2.1 Bitumen stabilized

Stabilizing the ballast with the use of bitumen has been researched by several Universities (Giunta, et al., 2018) (D'Angelo, et al., 2018), for instance researchers at the University of Nottingham performed tests with bitumen stabilized ballast. They found a significant decrease in permanent ballast deformation and the deformation rate. The idea behind bitumen stabilized ballast is to increase the durability of the ballast and thereby increase its lifetime. Their procedure is simple, as the bitumen is poured over the ballast after the tracks are laid, or as a maintenance solution instead of ballast cleaning. The study tested both clean and fouled ballast and received fairly similar results in percentage improvements for both cases (D'Angelo, et al., 2016).

There are also different application methods, such as using foamed bitumen or mixing the ballast with bitumen while placing the ballast. The latter would of course require a bigger intervention.

2.3.2.2 Polyurethane stabilized

Another research presented at the Joint Rail conference in 2010 looked into ballast bonding with the use of polyurethane coating. The tests were performed on new clean ballast and compared with similar but unmodified ballast. The results showed a significant increase in the shear resistance of the polyurethane bound ballast. The project recommended using polyurethane in high impact areas, such as switches and turnouts (Dersch, et al., 2010) .

Since 2009, China has reinforced 12.5 km of ballasted track with the use of polyurethane. Generally seeing an increase in stability and a reduction of maintenance costs. Additionally, 3 new high-speed lines are under construction, with the use of polyurethane stabilized ballast (Guoqing, et al., 2019).

There are several other published research examples with the use of polyurethane binding, for instance researchers at the Korean Railroad Research Institute who performed both uniaxial and triaxial testing with polyurethane-mixed coarse aggregates, finding a predictable and linear relationship between the amount of polyurethane in the mixture, the stiffness and strength of the material (Su Hyung, et al., 2017).

2.3.2.3 Hot-mix asphalt trackbeds

At the University of Kentucky, a research into the use of hot-mix asphalt track beds was done in 2013. They researched maintenance solutions with the use of asphalt layers. Different solutions were investigated and most of them used a combination with commonly used granular with the asphalt mix. The benefit was given in improved load distribution capabilities and decreasing load-induced subgrade pressure (Rose, 2013).

2.3.2.4 Lignosulphonate

The material is based from lignin which is a renewable material, extracted as a byproduct from the timber and pulp industry. Lignin is an environmentally friendly chemical (Alazigha, et al., 2016). There are several studies into the use of lignin-based additives, mostly within clay and silty materials, but also some at bigger fractions. Such as the research at NTNU with fractions 0/30, where they found stabilization with lignosulphonate to increase the mechanical properties of the material (Barbieri, et al., 2019).

2.3.2.5 Organosilanes

Organosilanes is a nano-polymer product that has been used in several researches, mainly for finer particles (Padmavathi, et al., 2019). In 2018 there was research into stabilizing fractions at 0/30 at NTNU with organosilanes, and it was found to improve the mechanical properties of the samples (Barbieri, et al., 2019).

3 Materials and testing

This chapter describes the materials used for testing and the test procedures. Each of the different tests are given a slight introduction to cover the most important steps of the procedure. For further information regarding the test procedures, please follow the referred standard. The testing is divided in two, one for each of the test locations, Tau (Stavanger) and NTNU (Trondheim).

An overview of the results is shown in the last subchapter, 3.3 Results of testing.

3.1 Material Origin

Two different materials are used for the testing in this project. The first material was tested at Tau in Stavanger in accordance with NS-EN 13450, "Aggregates for railway ballast" (Standard Norge, 2009). This was done to determine the geometrical and mechanical properties of the ballast.

The second material was used for testing at NTNU in Trondheim according to NS-EN 13286, "Unbound and hydraulically bound materials" (European committee for standardization, 2004). This testing was conducted to determine the effect of stabilizing with different binders.

3.1.1 Sample material for testing at Tau

The sample material for the first testing campaign was obtained by Bane NOR and taken from Sørlandsbanen, a track that was constructed in 1943 (Nomeland, 2014).

The ballast was removed from the track due to renewal of hatches along the line around km 516 (Kartverket, Geovekst og kommuner - Geodata AS | Jernbaneverket, 2019), it was then stored in piles. To gather the sample, the material was taken out with shovel and placed in bags by Bane NOR. The way of collecting the material, and the fact that samples are only available in one location, makes it less representative for the entire national line. 100 kg of sample material was gathered.

The section of the line where the material was gathered was BaneData ballastcleaned in 1975 and in 1992 (BaneData, 2019). In both years the requirements for the ballast fraction was 25-50, with an over- and undersize of maximum 10%.

3.1.2 Sample material for testing at NTNU

This material was taken from the track at Marienborg in Trondheim, approximately at km 550 (Kartverket, Geovekst og kommuner - Geodata AS | Jernbaneverket (2), 2019). The initial plan was to get the materials from a different location, but that did not happen due to issues outside of the projects control. Bane NOR were not able to provide information on the ballast from the new place. It was clearly used in the track for some time, as the shapes were worn and not sharp as when new. A total of 500 kg of material was gathered, additional geological examinations were performed for further characterization.

3.1.3 Thin Section Analysis on material from Marienborg

To retrieve information on the geological properties of the material from Marienborg, they were sent for an external thin section analysis. Professor Mai Britt E. Mørk (NTNU, Department of Geoscience and Petroleum) carried out the analyses.

The sample material was clearly divided in two rock types. A sample of each of them was analyzed. The analysis showed that the material from Marienborg was mainly granite and gneiss. The granite had a high content of feldspar, as shown in Figure 1. Figure 2 shows the gneiss with high amounts of amphibole.

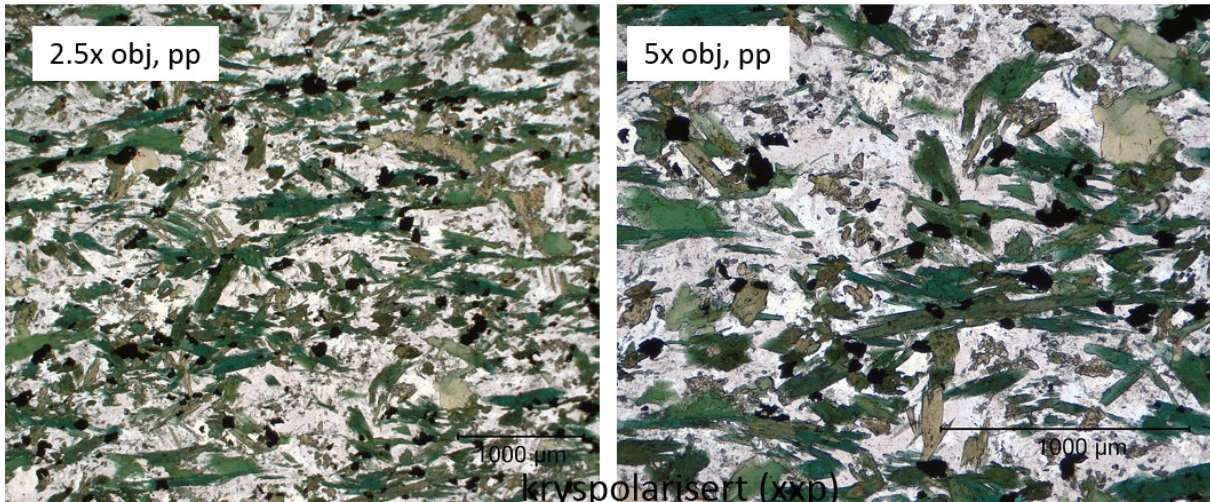


Figure 1: Microscopic picture with plane polarized light from analyzing the material.

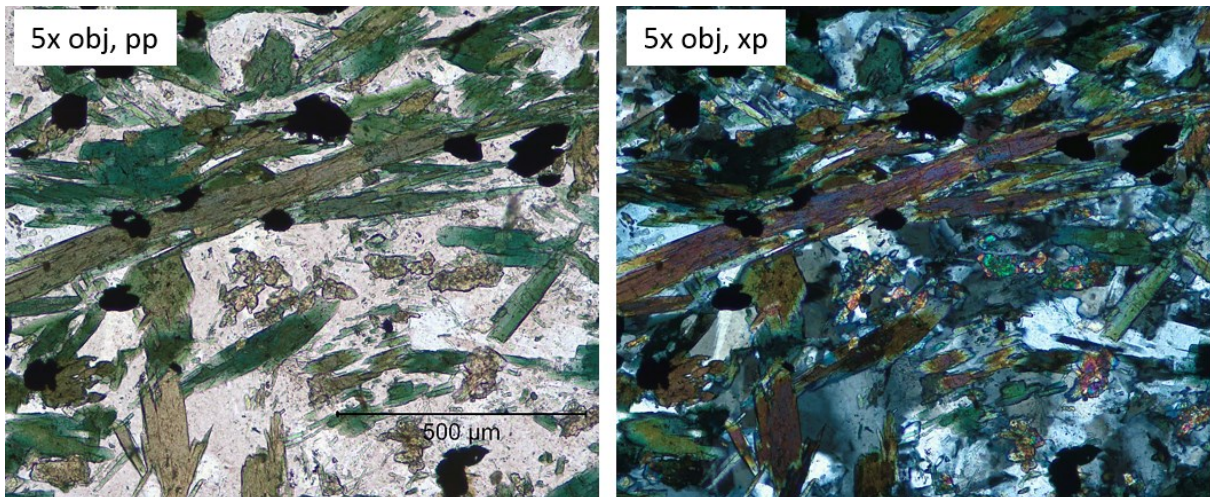


Figure 2: Microscopic picture in plane polarized light (left) and cross polarized light (right) from analyzing the material.

3.2 Standards and test procedures for testing at Tau

The collaboration with Norsk Stein gave the opportunity of conducting tests at their lab in Tau, Stavanger. The goal of the testing was to get an overview of the condition of used ballast, and a slight overview of the grading curves.

The following sub-chapters describe briefly the tests procedures.

3.2.1 Geometrical tests

The geometrical tests are carried out according to NS-EN 13450 (Standard Norge, 2009) and NS-EN 933, "Tests for geometrical properties of aggregates" (Standard Norge, 2012).

3.2.1.1 Grading

Grading is determined by sieving the samples. The requirements for the different classes are shown in Table 4 (Standard Norge, 2009, 6.3). The requirements are to be within class E.

Table 4: Requirements for grading, NS-EN 13450 (Standard Norge, 2009)

Sieve size mm	Railway ballast size 31,5 mm to 50 mm			Railway ballast size 31,5 mm to 63 mm		
	Percentage passing by mass					
	Grading category					
	A	B	C	D	E	F
80	100	100	100	100	100	100
63	100	97 to 100	95 to 100	97 to 99	95 to 99	93 to 99
50	70 to 99	70 to 99	70 to 99	65 to 99	55 to 99	45 to 70
40	30 to 65	30 to 70	25 to 75	30 to 65	25 to 75	15 to 40
31,5	1 to 25	1 to 25	1 to 25	1 to 25	1 to 25	0 to 7
22,4	0 to 3	0 to 3	0 to 3	0 to 3	0 to 3	0 to 7
31,5 to 50	≥ 50	≥ 50	≥ 50	-	-	-
31,5 to 63	-	-	-	≥ 50	≥ 50	≥ 85

NOTE 1 The requirement for passing the 22,4 mm sieve applies to railway ballast sampled at the place of production.

NOTE 2 In certain circumstances a 25 mm sieve may be used as an alternative to the 22,4 mm sieve when a tolerance of 0 to 5 would apply (0 to 7 for category F).

3.2.1.2 Fine Particles

To test this, the quantity of the fine particles is assessed according with the standard NS-EN 933-1, using a sieve size of 0.5 mm. The standard thoroughly explains the procedure, while the main points are listed below:

- Dry the sample in a heater (110 degrees C), cool it and weight it (M_1)
- Wash the sample by placing it in a container, add water and wait 24h to let fines separate
- Use a wet sieve of 0.5 mm, pour the contents of the container on to the sieve and wash with water until the water passing the sieve is clear.
- Dry the material above the sieve as described in the first point above, then weight it (M_2)
- Sieve the material once again to ensure all fines are removed from the sample test, then weight the material above the sieve (P)
- Calculate the percentage of fines passing the 0.5 mm sieve with the following calculation:

$$f = \frac{(M_1 - M_2) + P}{M_1} \cdot 100$$

- The sample is categorized by using the value of f and placing it in Table 5

The Norwegian Railroad administration is using category A as the requirement.

Table 5: Requirements for fine particles, NS-EN 13450 (Standard Norge, 2009)

Sieve size mm	Maximum percentage passing by mass			
	Fine particle category			
	A	B	Declared	C
0,5	0,6	1,0	> 1,0	No requirement
NOTE The requirement applies to railway ballast sampled at the place of production.				

3.2.1.3 Flakiness Index

The procedure for determining the flakiness index is described in NS-EN 933-3. The procedure is briefly described below:

- Dry the sample by heating in oven at 110 degrees C, cool it and record the mass as M_0
- Sieve the material with the sieves shown in Table 6, according to the procedure explained for fine particles.

Table 6: Types of sieves to be used

Sieve sizes in millimeters													
100	80	63	50	40	31.5	25	20	16	10	8	6.3	5	4

- Weigh and discard the particles above sieve 100mm and below sieve 4mm.
- Sieve all the particles above each sieve separately in a corresponding bar-sieve
- Weight the material for each particle size that passes through the bar-sieve.
- Calculate the sum of material that passed sieve 100mm to 5mm, record it as M_1
- Calculate the sum of material that passed the bar sieves and record it as M_2
- Calculate the overall flakiness index FI , using the following formula

$$FI = \frac{M_2}{M_1} \cdot 100$$

- Determine the classification of the sample according to the value of FI and Table 7.

The Norwegian Railroad administration uses classification FI_{IK} , which has no requirements.

Table 7: Requirements for flakiness, NS-EN 13450 (Standard Norge, 2009)

Flakiness Index	Category FI
≤ 15	FI_{15}
≤ 20	FI_{20}
≤ 35	FI_{35}
> 35	$FI_{declared}$
No requirement	FI_{NR}

3.2.1.4 Shape Index

The shape index of a sample is determined by using NS-EN 933-4, the test procedure mainly comprises the following operations:

- Dry the sample by heating at 110 degrees Celsius
- Sieve the samples and discard the material passing the 4mm sieve.
- Weight the material and ensure that the minimum requirements is met, see Table 8:

Table 8: Minimum requirements for shape index testing, NS-EN 933 (Standard Norge, 2012)

Upper aggregate size D	Test portion mass (minimum)
mm	kg
63	45
32	6
16	1
8	0,1

NOTE 1 For the other upper aggregate sizes D , appropriate test portion masses may be interpolated from those given in Table 1.

NOTE 2 For aggregates of particle density less than 2,00 Mg/m³ or more than 3,00 Mg/m³ in accordance with EN 1097-6 an appropriate correction should be applied to the test portion masses given in Table 1 based on the density ratio, in order to produce a test portion of approximately the same volume as those for aggregates of normal density.

- The test is performed for each particle size range at $D_i \leq (2 \cdot d_i)$
- Discard the material passing d_1 and above D_1
- Record mass of the particle as M_1
- Measure the length L and the thickness E and set aside the particles with L/E ratio above 3. Those particles are classified as non-cubical particles.
- Record the mass of the non-cubical particles as M_2
- Calculate the shape index with the following formula:

$$SI = \frac{M_2}{M_1} \cdot 100$$

- Determine the classification by comparing the SI-value and Table 9:

The Norwegian Railroad administration uses requirements of SI_{20} .

Table 9: Requirements for shape, NS-EN 13450 (Standard Norge, 2009)

Shape Index	Category SI
≤ 10	SI_{10}
≤ 20	SI_{20}
≤ 30	SI_{30}
5 to 30	$SI_{5/30}$
> 30	$SI_{Declared}$
No requirement	SI_{NR}

3.2.1.5 Particle length

The length of the particles is measured with a gauge or caliper, it is a simple procedure. The main operations are:

- Ensure a sample size of more than 40kg
- Weight the material with a length above 100 mm
- Use Table 10 to determine the category of the material based on the percentage of mass with length above 100mm

Table 10: Requirements for particle length, NS-EN 13450 (Standard Norge, 2009)

Percentage by mass with length \geq 100 mm in a greater than 40 kg sample					
Particle length category					
A	B	C	D	Declared	E
4	6	8	12	> 12	No requirement

The Norwegian Railroad administration uses classification E, which has no requirements to the particle lengths.

3.2.2 Physical and mechanical tests

Below, the physical and mechanical tests are shortly described below. They're following NS-EN 13450 and NS-EN 13450, "Tests for mechanical and physical properties of aggregates" (Standard Norge, 2011).

3.2.2.1 Resistance to fragmentation

The Los Angeles (LA) test procedure is described in NS-EN 1097-2, this is a test commonly used for road construction. Annex A of the standard is made for railway ballast and is adopted for testing. A LA- machine and enough steel balls at proper mass is needed to conduct the testing. The procedure comprises the following operations:

- Start with at least 15kg of particle size 31.5 to 50mm.
- Sieve the material to with a 50mm, 40mm and 1.5mm. Discard particles above 50mm and below 31.5mm sieve.
- Mix 5kg of material between 31.5- and 40mm with 5kg of material at 40- to 50mm
- Place the material in the machine together with 12 steel balls with a total weight of 5210 (+/- 90) grams
- Rotate the drum 1000 times at a speed of 31 to 33 revolutions a minute.
- Sieve the material at 1.6mm and weight the material retained by the sieve (m)
- Calculate the LA_{RB} -value with the following formula

$$LA_{RB} = \frac{10\,000 - m}{100}$$

- Classify the material by comparing the results with Table 11:

Table 11: Requirements for resistance to fragmentation, NS-EN 13450 (Standard Norge, 2009)

Los Angeles coefficient	Category LA_{RB}
≤ 12	$LA_{RB} 12$
≤ 14	$LA_{RB} 14$
≤ 16	$LA_{RB} 16$
≤ 20	$LA_{RB} 20$
≤ 24	$LA_{RB} 24$
> 24	LA_{RB} Declared
No requirement	LA_{RB} NR

The Norwegian railroad administration adopts the requirements of $LA_{RB} 20$. For tracks with a speed below 160 km/h the requirements are reduced to $LA_{RB} 24$.

Due to the lack of material in the correct fraction, it was decided to deviate from the code and use the fractions for road aggregates. This means that the aggregates were changed to 3250 g of 10/12 and 1750 g of 12/14, with 4750 g of steel balls at 500 revolutions. The rest of the procedure was the same as described above.

3.2.2.2 Resistance to wear

Micro-Deval test is used to determine the materials resistance to wear. The procedure is explained in NS-EN 1097-1, for railway ballast the Annex A of the standard is used. To conduct this test a special equipment for rotating the material is needed. A short description of the procedure is:

- Start with 25 kg of material in size 31.5- to 50mm.
- Dry the materials in an oven at 110 degrees C.
- Sieve the material to separate the fractions of 31.5- to 40mm and 40- to 50mm.
- Mix a test specimen by adding 5kg of each the two particle sizes.
- Place the test specimen into the machine and add 2 (+/- 0.05) liters of water.
- Start the machine. Stop it after 14 000 (+/- 10) revolutions.
- Sieve the material in a 1.6mm sieve under a stream of water.
- Weight the material above the sieve (m).
- Calculate the coefficient of the Micro-Deval test by using the following formula:

$$M_{DE, RB} = \frac{10\,000 - m}{100}$$

- Determine the classification by using the values of $M_{DE, RB}$ and Table 12.

Table 12: Requirements for resistance to wear, NS-EN 13450 (Standard Norge, 2009)

micro-Deval coefficient	Category $M_{DE} RB$
≤ 5	$M_{DE} RB 5$
≤ 7	$M_{DE} RB 7$
≤ 11	$M_{DE} RB 11$
≤ 15	$M_{DE} RB 15$
> 15	$M_{DE} RB$ Declared
No requirement	$M_{DE} RB$ NR

The Norwegian railroad association adopts the requirements of $M_{DE, RB}^{15}$.

3.2.2.3 Density and water absorption

This test was done as preparation for the Nordic Mill Abrasion test, which needs the density of the tested material. The procedures are following NS-EN 1097-6. In short, they are explained below:

- Dry 2 kg material with $D_{max}=16$.
- Place the material in a pycnometer and fill it up with water at $22 \pm 3^\circ\text{C}$.
- Let it stand for 24 hours.
- Overfill the pycnometer and avoid getting air bubbles, then place a cover on the top of the pycnometer.
- Dry the outside of the pycnometer and record weight as M_2
- Remove the aggregate from the water and let it drain for a few minutes.
- Refill the pycnometer as before, cover it, dry it and record weight as M_3
- Use a towel to surface-dry the aggregate, then record its weight as M_1
- Dry the aggregate at $110 \pm 5^\circ\text{C}$ and record the weight as M_4
- The density of the material is calculated by following the formula below:

$$\text{Density} = \rho_w \cdot \frac{W_4}{M_4 - (M_2 - M_3)}$$

- Water absorption is calculated by using the formula below:

$$WA_{24} = \frac{M_1 - M_4}{M_4}$$

3.2.2.4 Nordic Mill Abrasion test

NS-EN 1097-9 describes the Nordic Mill Abrasion test, which is common for road aggregates. It measures the gravels ability to resist degradation from studded tires.

The procedure is as follows:

- Create two samples of 8/16, with $65 \pm 1\%$ of 8/14 and $35 \pm 1\%$ of 14/16.
- The total weight of the sample should be 1034 ± 5 g, by following the formula:

$$M_1 = \frac{1000 \cdot \rho_p}{2.65} \pm 5$$

- Weight and place the material in the Nordic Mill test-rig. Set it to 5400 revolutions at 90 rotation per minute, with 2 liters of water and 7000 g of steel balls.
- After running, place the material at a sieve of 2 mm and wash it.
- Dry the material at 110°C
- Sieve it at a 2 mm sieve
- Measure the weight of the material as M_2
- Calculate the percentage lost from M_1 to M_2
- The result is the average value of the two samples.

3.2.3 Chemical tests

The Norwegian Railway Administration gave NGU a task of creating a guideline for testing the chemical properties of the ballast. This manual mainly describes how to gather the

sample, while it states that the specific testing are to be conducted by accredited laboratories (Eggen & Ottesen, 2007). Due to the lack of knowledge on testing and less relevancy for the thesis, it has been decided to ignore all chemical tests.

3.2.4 Repeated Load Triaxial Test (RLTT)

The Repeated Load Triaxial Test (RLTT) is following NS-EN 13286-7. The multi-stage low stress level (MS LSL) loading sequence is used for this project.

Testing with a triaxial rig is more complicated than carrying out the tests previously described, and it is also less common. Therefore, the following subchapters describes the test procedures thoroughly. The first subchapter gives an overview of the whole process, while the following subchapters give a more detailed description from sample creation to running the test.

3.2.4.1 How the testing works

The apparatus applies two kinds of pressure: one is confining pressure, the other is a cyclic deviatoric pressure at a given frequency, both stress paths are described by the standard. The specimen is placed inside a chamber filled with water, and the confining pressure is achieved and adjusted by means of pressurized air. The deviatoric pressure is applied by a hydraulic jack. During testing, deflection is measured using linear variable displacement transducers (LVDTs). Both axial and radial deflection are measured. The registered deflection is used for the analyzing of the test. Figure 3 shows a quick overview of the triaxial rig.

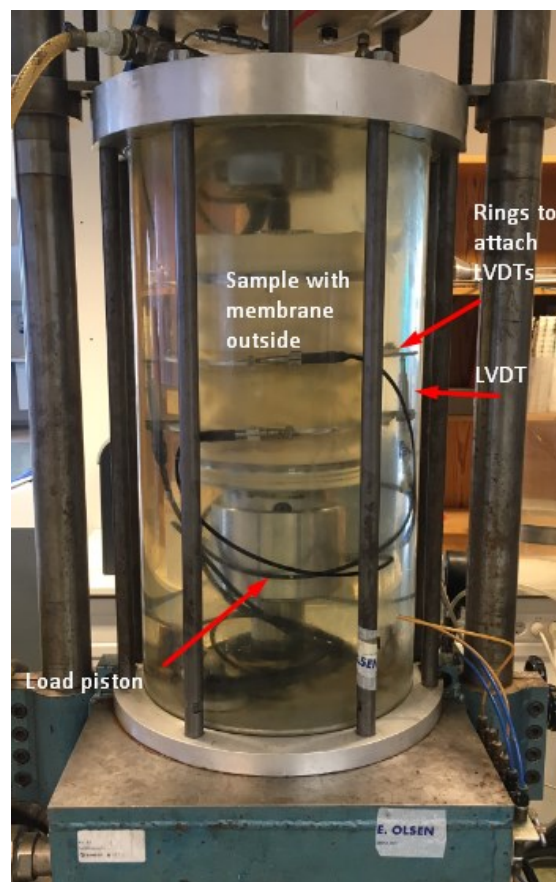


Figure 3: Simple overview of triaxial rig

3.2.4.2 Creating sample

The creation of a test sample needs to take into considerations the correct fraction, grading curve, width, height and moisture content. Furthermore, the material should have cured for a sufficient amount of time. This operation is usually time demanding. The procedure to create the samples may be summarized as follows:

Dry and sieve the material to get the correct fractions. Weight up bags of 1.7 kg with the combination of 70% 22.4/25 and 30% 25/31.5. A deviation of $\pm 2g$ is accepted. Put 3 bags of 1.7kg into a bigger bag and write down sample number and total weight, which should be $5\ 100 \pm 3g$. Figure 4 shows the procedure.



Figure 4: A) Hand sieving + machine sieving, B) Bags of 1.7kg with 70% 22.4/25 and 30% 25/31.5, C) Bags with complete sample rock material.

Table 13 displays the main characteristics of the tested samples, including each type of additive used and curing time. The research investigates several types of additives as binding agents, they are described in more detail below.

Table 13: Planned samples.

Binder type	Binder content (%)	Count (number)	Curing time (days)	Note
Unbound	0 %	2	0	-
Bitumen 70/100	3 %	2	2	Hot! 160 °C ("heat" gloves)
Bitumen 160/220	2.5 %	2	2	Hot! 160 °C ("heat" gloves)
Lignosulphonate	0.75 %	2	7	-
Organosilanes	1.5 %	2	7	-
Polyurethane	1.5 %	2	2	Avoid inhalation (Gas mask)
Polyurethane	2 %	2	2	Avoid inhalation (Gas mask)

The department had no previous experience with polyurethane. Therefore, a secure job analysis was done to ensure that safety rules were respected during testing. This analysis is available in annex B.

For the creation of the bitumen samples, the material and the binder were stored in a heater at 160 degrees for 3 hours prior to application. Then they were mixed together in a heated bowl properly, as shown Figure 5A. The material was then poured into a mold and compacted in 3 layers (each of 1.7kg), by means of a Kango 950X vibratory hammer (total weight of 35 kg, frequency at 25 ± 60 Hz and at amplitude of 5 mm). The mold and compacting hammer are shown in Figure 5.

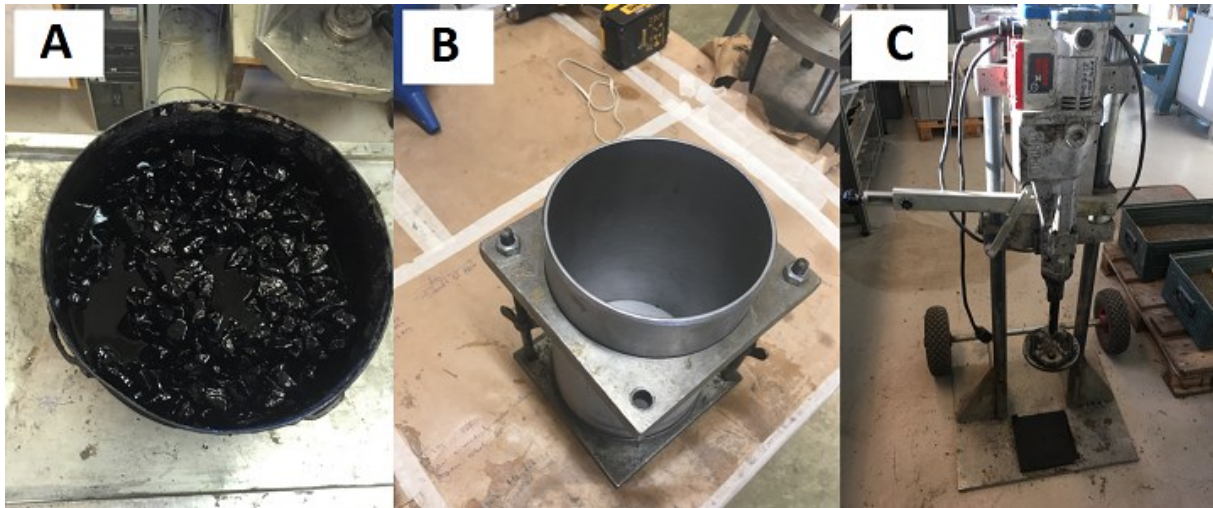


Figure 5: A) Sample material mixed with bitumen at 160 degrees, B) Mold for the sample, C) Compacting machine.

For lignosulphonate, organosilanes and polyurethane, the procedure was slightly different as the material was mixed in bags containing the binder, shaken until it was well mixed, and then compacted as with the vibratory hammer. The unbound material skipped the mixing step and went straight to compacting.

After compacting, the material was taken out of the mold. This was done by placing the mold in a device developed ad hoc, and pressing the sample out of it, as shown in Figure 6. A latex membrane was placed onto the sample during this phase. The samples containing bitumen had to cool down a bit before this operation, it was possible to proceed when the specimen temperature was approximately 70 degrees.

The curing period of a specimen begins after the completion of this extraction procedure.



Figure 6: A) Taking the sample out of the mold, B) Sample is out of mold and placed for curing.

After the curing phase, the sample is prepared for RLTT testing, a top and bottom steel plate are placed on it. They are lubricated with grease to avoid water from entering between the plate and the membrane. Plastic O-rings and hose clamps are placed around the specimen to avoid water penetration.

3.2.4.3 Preparing test equipment

The sample is placed into the rig. The LVDTs are attached on the sample, aluminum rings support the LVDTs. The operator needs to pay attention to ensure that they are placed properly, so that the displacement measures are reliable.

Afterwards the operator needs to ensure that the rig is vacuum tight, this is done by lubricating the top and bottom parts with high quality grease. These parts are in contact with the plastic shield that is placed after positioning the specimen inside the testing device, see Figure 7A. Successively, the chamber is filled up with water, as shown in Figure 7B.

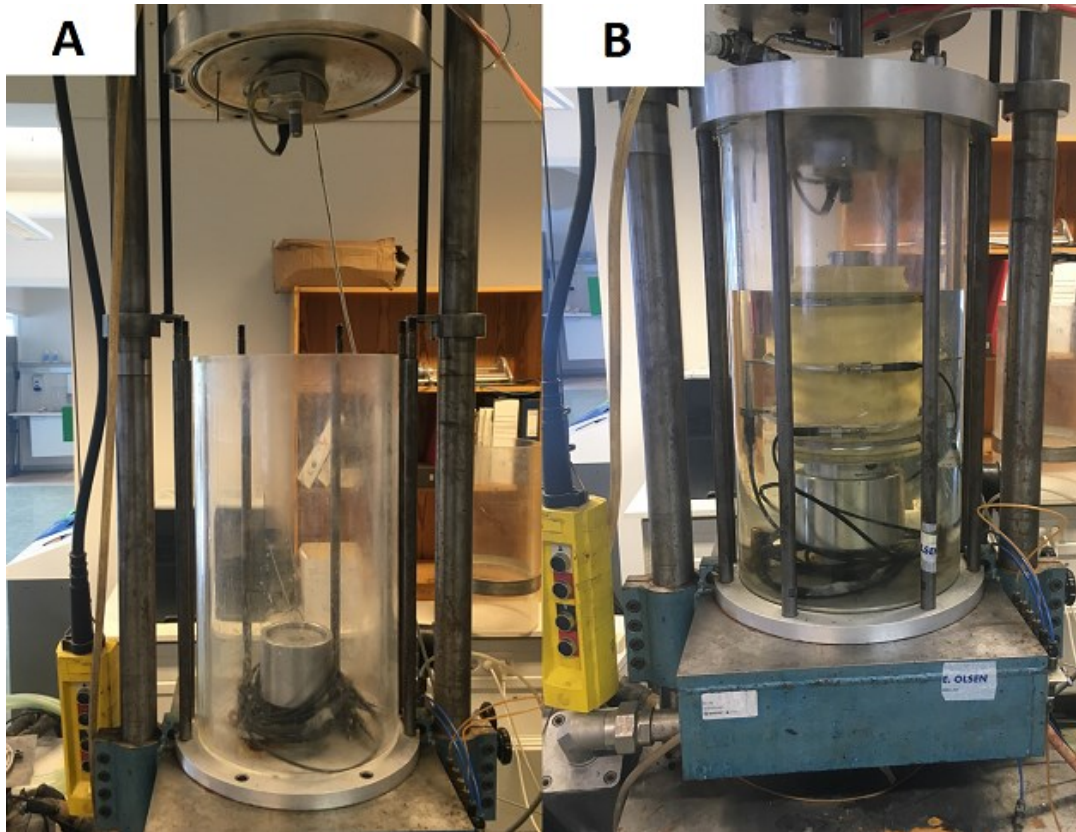


Figure 7: A) Test rig and shield, B) Test rig being filled with water.

3.2.4.4 Running test

The confining pressure is adjusted according with the MS LSL loading procedure, this is done by adjusting the amount of pressurized air.

The five loading sequences and the respective loading steps according to bulk stress and deviatoric stress are displayed in Table 14. Each load step consists of 10 000 load pulses at 10 Hz frequency. A loading sequence is interrupted if the axial permanent deformation reaches 0.5%.

Table 14: Stress levels for the multi-stage low stress level test (European committee for standardization, 2004).

Sequence 1			Sequence 2			Sequence 3			Sequence 4			Sequence 5		
Confining stress, σ_3 kPa	Deviator stress, σ_d kPa		Confining stress, σ_3 kPa	Deviator stress, σ_d kPa		Confining stress, σ_3 kPa	Deviator stress, σ_d kPa		Confining stress, σ_3 kPa	Deviator stress, σ_d kPa		Confining stress, σ_3 kPa	Deviator stress, σ_d kPa	
constant	min	max	constant	min	max	constant	min	max	constant	min	max	constant	min	max
20	0	20	45	0	60	70		80	100	0	100	150	0	100
20	0	40	45	0	90	70	0	120	100	0	150	150	0	200
20	0	60	45	0	120	70	0	160	100	0	200	150	0	300
20	0	80	45	0	150	70	0	200	100	0	250	150	0	400
20	0	100	45	0	180	70	0	240	100	0	300	150	0	500
20	0	120	45	0	210	70	0	280	100	0	350	150	0	600

During testing, the LVDTs register the deflections for each pulse, which are the data used during the analyzing of the samples. Figure 8 shows a picture of the tested samples.



Figure 8: Tested samples. On the left side, aggregates tested without any additives. On the right side, stabilized samples.

3.3 Results of testing

The tests were conducted as described in the chapter 3 Materials and testing. Results are shown in Table 15 and Table 16 for the testing conducted at the laboratory to Norsk Stein, in Stavanger.

Table 15: Results of tests at Tau, Stavanger.

Conducted tests	Date	Result
Grading	13/2/19	-
Fines	13/2/19	0.63 %
Shape Index	12/2/19	16.1 %
Flakiness Index	12/2/19	7.6 %
Los Angeles	15/2/19	22.3
Water absorption	13/2/19	0.2 %
Density	13/2/19	2.742
micro-Deval	13/2/19	7.8
Nordic Mill Abrasion	14/2/19	12.0

Table 16: Results from grading test.

Sieve size	Weight (g)		Percent (%)	
	In sieve	Acc.	In sieve	Acc.
63	0	0	0.0 %	0 %
50	2 095.5	2 095.5	4.8 %	5 %
40	3 457.6	5 553.1	7.9 %	13 %
31.5	11 526.5	17 079.6	26.3 %	39 %
22.4	16 888.2	33 967.8	38.6 %	78 %
Bottom	9 814.6	43 782.4	22.4 %	100 %
Sum	43 782.4		100 %	

18 samples were originally created for RLTTs; because of errors during the creation process, the total of valid tested samples has been reduced to 14, they are shown in Table 17.

The raw data consists of approximately 5 million lines with 28 readings from different loggers, Figure 9 as a representative part. The raw data for all samples are available in Annex C.

Figure 9: Part of results from sequence 1 for sample 09.

Table 17: Overview of the samples and general information on them.

Sample number	Test date	Sample type	Binder content (%)	Curing time (days)	Weight before testing (g)	Weight after testing (g)	Weight difference (g)
1	08.04.2019	Untreated	0.00	0	5098	5094	-4
3	12.04.2019	Bitumen 160/220	2.39	2	5226	5216	-10
5	15.04.2019	Bitumen 70/100	3.97	2	5310	5298	-12
6	16.04.2019	Bitumen 70/100	2.99	2	5254	5254	0
7	17.04.2019	Bitumen 160/220	3.32	2	5272	5258	-14
8	25.04.2019	Lignosulphonate	0.68	9	5135	5135	0
9	26.04.2019	Lignosulphonate	0.64	10	5133	5133	0
10	18.04.2019	Untreated	0.00	0	5101	5101	0
11	30.04.2019	Organosilanes	1.90	6	5198	5186	-12
13	11.05.2019	Organosilanes	1.43	9	5174	5176	2
14	06.05.2019	Polyurethane	1.43	2	5173	5175	2
15	07.05.2019	Polyurethane	1.47	2	5174	5177	3
17	09.05.2019	Polyurethane	2.02	2	5204	5198	-6
18	10.05.2019	Polyurethane	1.87	2	5197	5192	-5

As an example, Figure 10 displays the resilient modulus of a bitumen sample, showing the stiffness of the material in different confining pressures. The vertical axis shows the

resilient modulus, while the horizontal axis shows the number of load cycles. The different colors refer to different values of confining pressure.

Figure 11 shows the permanent deformation of sample stabilized with polyurethane. The vertical axis shows the permanent deformation, while the horizontal axis indicates the number of load cycles. The different colors refer to different values of the confining pressure.

These graphs are available for all the samples and can be seen in Annex A. The data are further analyzed and discussed in the next chapter.

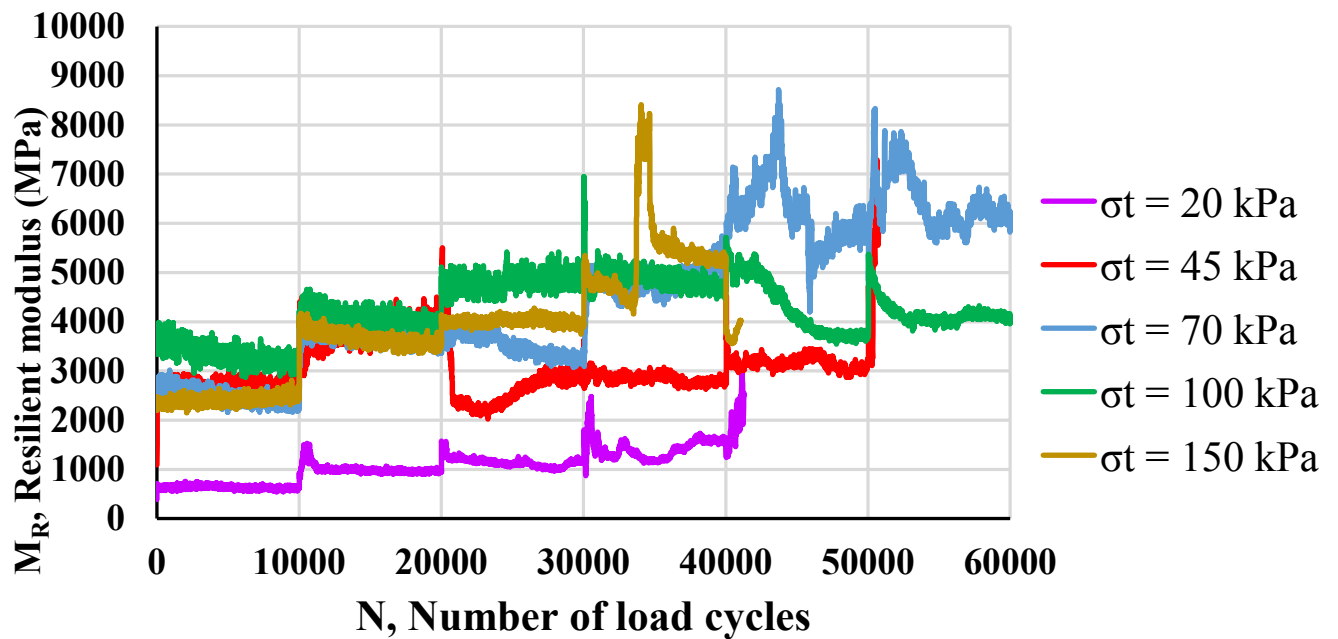


Figure 10: Resilient modulus of sample 07.

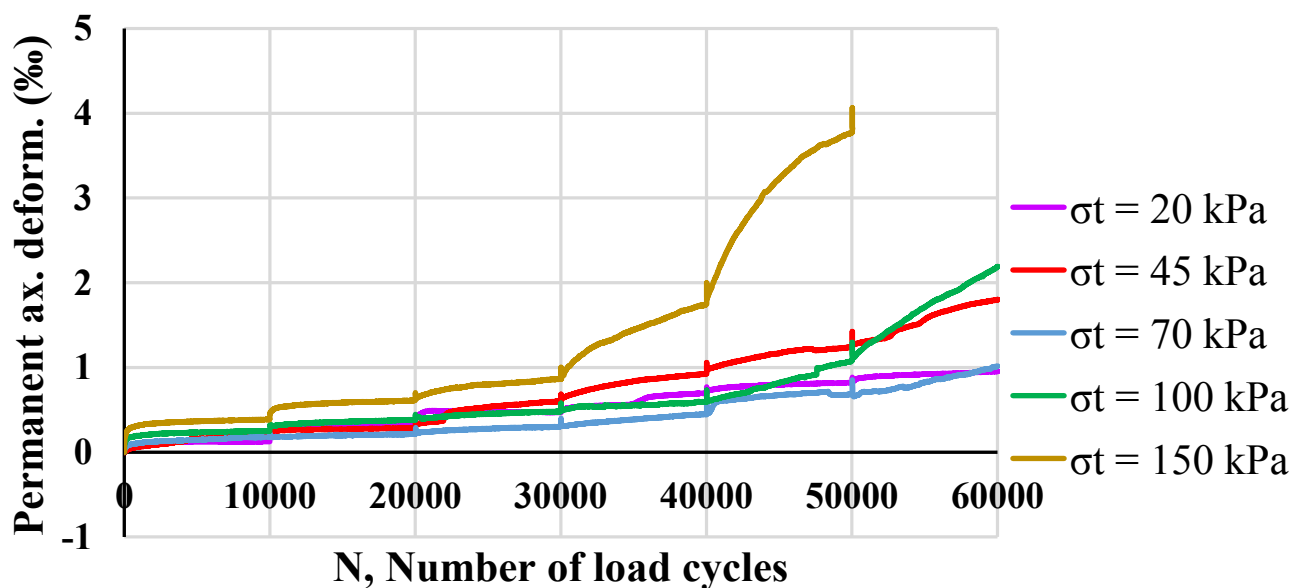


Figure 11: Permanent deformation of sample 14.

4 Discussion

The following subchapters discuss the test results and compare them with current standards, for the testing conducted at Tau. The testing at NTNU is compared with untreated material to evaluate benefits and downsides of the different binders.

4.1 Testing at Tau

In previous chapters, the requirements for the ballast material has been described and the results from the project has been presented. Following is a comparison of the tested material and the current requirements, see Table 18 for a quick summary.

Table 18: List of tests passing the requirements for railway ballast

Completed tests	Date	Result	Within limits?
Grading	13/2		NO
Fines content	13/2	0.63 %	NO
Shape Index	12/2	16.1 %	YES
Flakiness Index	12/2	7.6 %	-
Los Angeles	15/2	22.3	NO
Water absorption	13/2	0.2 %	-
Density	13/2	2.742	-
micro-Deval	13/2	7.8	YES
Nordic Mill abrasion	14/2	12.0	-

4.1.1 Geometrical properties

As expected, the grading of the used material is not matching the desired grading curves. In fact, the curves are way off the requirements, as shown in Figure 12. It contains too much fines, and generally lack the amounts of material with higher diameter. A reason for this, could be that the requirements were 25/50 at the time of ballast cleaning, but even while comparing to those requirements, the results deviate significantly, see Figure 13. Therefore, the most likely reason for this grading is degradation of the ballast.

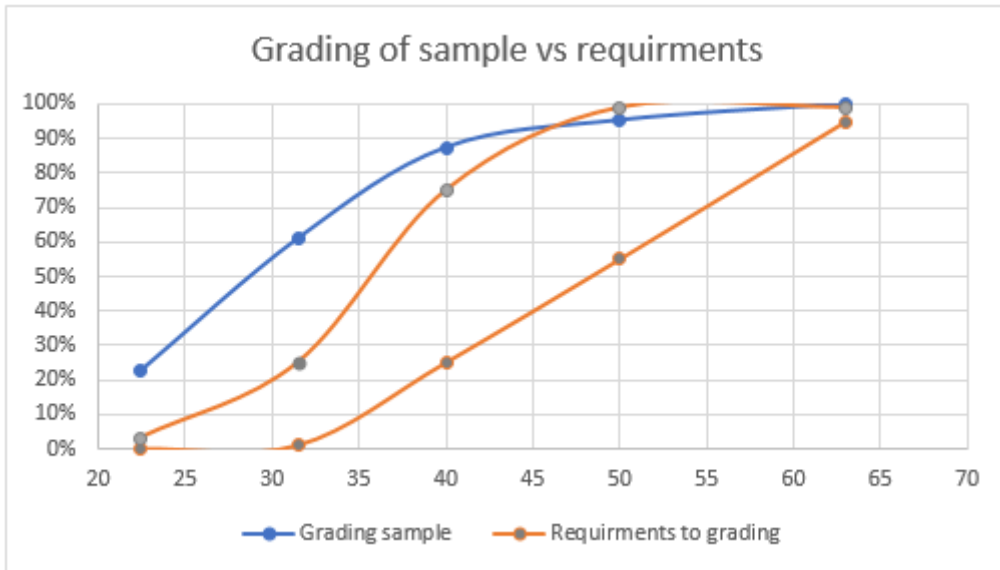


Figure 12: Comparison of samples grading and the requirements. The sample is clearly outside of the designated area.

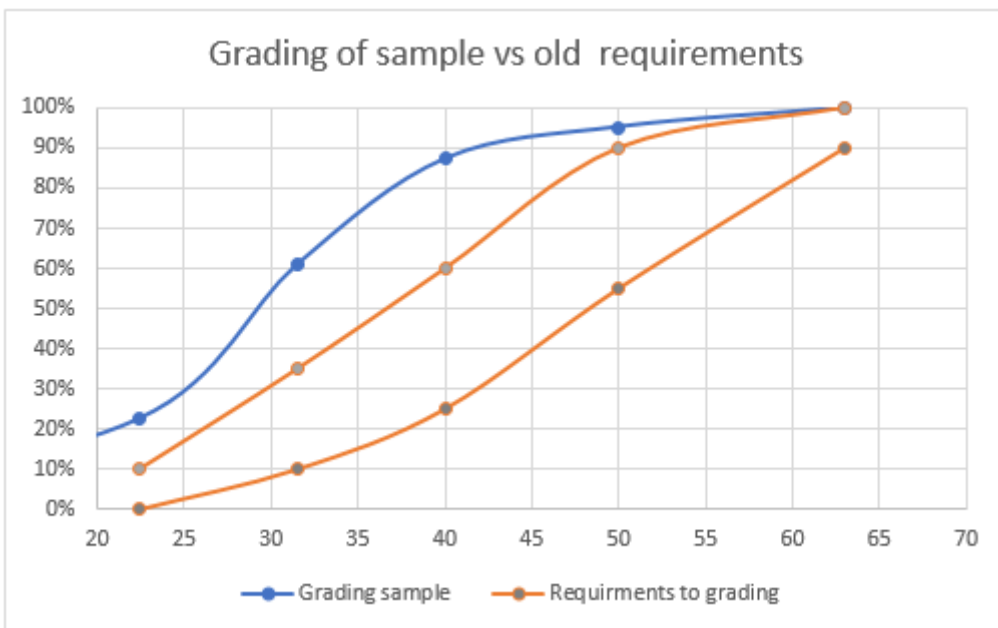


Figure 13: Comparison of samples grading and the old requirements.

For the fines content, the tested material is not within the requirements, as expected after many years of service. It should be noted that the value of 0.6% probably could be higher, as the material was stored in piles for some time before the samples were taken.

Both values for shape and flakiness are good, and within normal requirements. For the Norwegian railroad administration, the flakiness index is not used but its value is high enough to be within the best category, and therefore applicable to most purposes, as road construction or for those countries who use flakiness index in their railway requirements.

By following the outer lines of the grading requirement of Figure 12, an amount of 41 % can be directly reused. After such a reuse, a significant amount of material in fraction 0/31.5 remain. See Table 19 for an overview of the possible reuse, the grading and the remaining material fractions.

Table 19: Possible directly reusable material

Sieve size	Weight (g)		Possible reuse		Reused material	Material left
	In sieve	Percent	G. curve	Amount		
63	0	0 %				
50	2095.5	5 %	5 %	862.5	41 %	1233
40	3457.6	8 %	20 %	3450	100 %	0
31.5	11526.5	26 %	50 %	8625	75 %	2901
22.4	16888.2	39 %	25 %	4312.5	26 %	12575
Bottom	9814.6	22 %	3 %	517.5	5 %	9297
Sum	43782.4			17768	41 %	26014

4.1.2 Mechanical properties

The micro Deval value was well inside the requirements for both railway ballast and road aggregate and is not a limitation to the use of the material.

The Los Angeles value was on the other hand not as good. Also, it was tested with the fractions for road aggregates, making the results a bit unclear to whether the LA for railway ballast would be the same. By studying several tests of an aggregate with both testing methods, it is possible to see some correlation. Unfortunately, no literature seems to confirm or deny this, and there hasn't been enough time to do additional testing to prove this correlation.

As an aggregate to road construction, the material would fit very well, passing the requirements for all classes, except for the asphalt layer with traffic more than 15 000 vehicles a day (Statens vegvesen, 2014).

The Nordic Mill Abrasion test is not relevant for the railway but was done to investigate the possibilities of reusing the material for road construction. The value of is good, but not enough to be used in the higher traffic classes. The requirements are reached for up to a daily traffic of 3000 vehicles for the asphalt layer. All below layers are ok (Statens vegvesen, 2014).

4.1.3 Summary of material properties

The properties of the material after testing at Tau, show that none of the material is within requirements for new railway ballast, due to the high and unsure Los Angeles value and the grading curve.

If looking away from the LA value, a 41% of the material could be directly reused. Though, after what the literature review has shown, during ballast cleaning, only the fraction sizes are relevant. Letting all particles between 31.5 and 63 mm stay in the track. From the geometrical testing, that accumulates to 39 % of the material, making 61 % ballast waste.

Among the ballast waste, 63% of the material is of fraction 22.4/31.5, which is the reason why that fraction was used in triaxial testing. It is possible to discuss the choice of fraction, as it is natural to assume that a more well graded material would deliver better results in both stiffness and resistance to permanent deformation (Nålsund, 2010).

4.2 Testing at NTNU

The triaxial testing at NTNU delivered interesting results, which is compared in the following subchapters. There are two comparisons, one for stiffness and the other for permanent deformation. Those are discussed in separate subchapters, but first a brief discussion on factors contributing to variations in the results and how they have been dealt with.

4.2.1 Possible factors contributing to variation and countermeasures

The procedures were quite complex and unfortunately there were some significant variations, leading to drastic measures in order to reduce the errors of the results. They will be explained below.

4.2.1.1 Variation in deflection on LVDTs

The tests showed a variation in deflection on the triaxial LVDTs. The deflection was in some situations so severe that they showed a deflection 3 to 4 times the opposite side. An example showing the two side LVDTs is shown in Figure 14. The last axial LVDT is inside the jack and showed deflection that was somewhat in the average of the two side LVDTs.

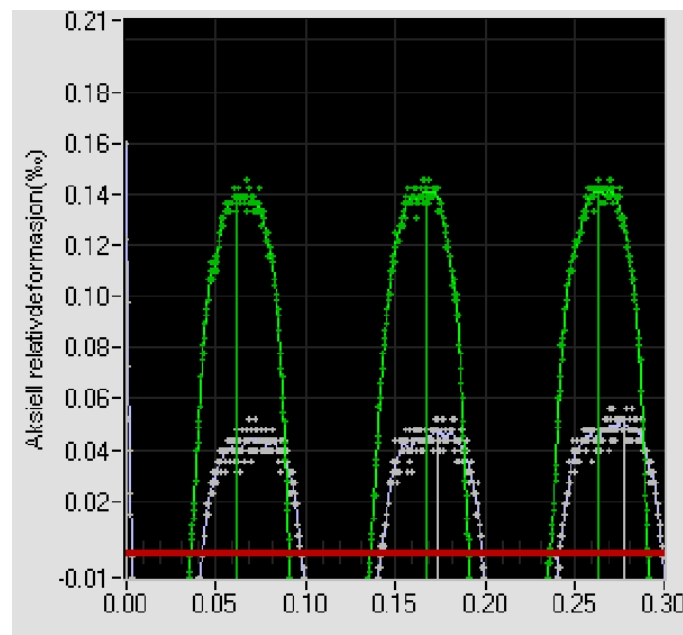


Figure 14: Relative axial deformation (‰) for right and left side of the sample.

Due to the high variation on the side LVDTs, it has been decided to analyze the results based on only one LVDT, the one in the jack.

4.2.1.2 Increased confinement from latex membranes

During testing it was obvious that some samples had bigger axial deformation than others, leading to a radial increase of the sample. This will increase the confinement from the latex membrane.

As is seen from the results and from the graphs that presented later, there is a correlation in increased confinement and resilient modulus, giving the samples with higher radial strain an increase in stiffness.

This phenomenon has been researched at NTNU and said to be of little relevancy for the possible amount of radial strain occurring during tests (Uthus, 2007).

4.2.1.3 Variation in compacting

When creating the samples, there are a lot of variables that can affect the end results. It has been a focus to do everything the same way with all binders, for all samples, as far as possible. Even if it was done perfectly, it would still be room for variations here, as some samples, bound or not, might benefit of a different way of compacting or handling. It is believed that especially untreated and organosilanes stabilized would benefit from a better compaction. This is mainly due to their weak shear strength after sample creation, and therefore a high chance that they lose their original shape while curing or during transport. That would lead to a decreased sample height and increased radial size. For the organosilanes, this could have been solved by letting the sample dry for some days while in the mold. For the unbound material it could have been solved by keeping it in vacuum or increasing the confining pressure on them. None of which were done in this testing.

4.2.1.4 Optimal binder content

Five minor samples with different binder content for each type of binder were created before the testing started. This was done to get a slight overview over which binder contents that were optimum. This is not any accurate research, but it was needed as there is a lack of research into this field for some of the tested binders in combination with coarse material. It might be that some of the binders could perform significantly better with a different binder content.

4.2.1.5 Minor sources affecting test results

There are several other minor sources affecting the results.

- Testing temperature of the water varied from 23.8 to 24.2°C between the different samples. This was unintentional and likely due to inside temperature changes. The effect of this is assumed to be little and will be neglected in this thesis.
- Variation in confinement pressure. At highest it was recorded to be a difference in 5% from the standard. This will have an effect.
- Moisture content was not measured before running the tests and could have differed. The variation is assumed to be small, since the material was treated the same way for all samples and since the samples is not containing fines. The effect is likely of little relevancy for the results.

4.2.2 Comparison of stiffness

The first of the two parameters that are compared is the stiffness, it is calculated by using the following formula to express resilient modulus:

$$M_R = \frac{\Delta\sigma_{d,dyn}}{\epsilon_{r,v}}$$

The $\Delta\sigma_{d,dyn}$ is the dynamic deviatoric stress, while $\epsilon_{r,v}$ represent the axial resilient vertical strain. An illustration of resilient strain is shown in Figure 15. The downside of this formula is that it only takes one confinement pressure into account.

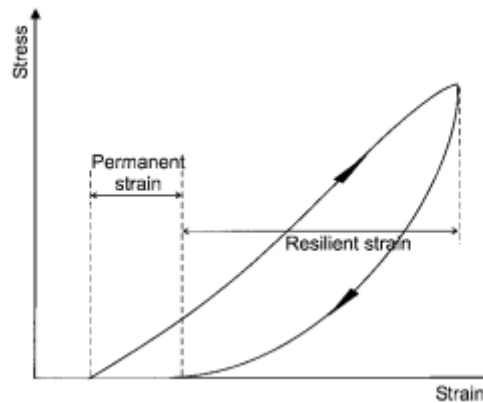


Figure 15: Strain during one load cycle (Lekarp, et al., 2000).

In 1971, Hicks and Monismith found an effective solution to connect the resilient modulus and the bulk stress, effectively solving the issue with different confining pressures. This is done by applying the following formula (Hicks & Monismith, 1971):

$$M_R = k_1 \cdot \sigma_a \cdot \left(\frac{\theta}{\sigma_a}\right)^{k_2}$$

Where σ_a is a reference pressure, while both k_1 and k_2 are regression parameters. The bulk stress is represented by θ . To determine the value of these parameters, the least square method was used (Golub & Pereyra, 1973).

Calculations were done in MATLAB, based on the mentioned methods and at reference bulk stress of 100 kPa. The code used in this thesis is the same as Diego Barbieri used for his research with triaxial testing at NTNU (Barbieri, et al., 2019). The used regression parameters are shown in Table 20.

Table 20: Overview of k-values for calculating stiffness.

Binder	k1	k2
Untreated	2729.2	0.72079
Organosilanes	5349.6	0.49665
Lignosulphonate	15194	0.62138
Bitumen 70/100	14037	0.20466
Bitumen 160/220	13590	0.51107
Polyurethane 1.5%	1854.5	0.022384
Polyurethane 2%	2628.5	0.24466

Comparison of the stiffness for the different binders are shown in Figure 16. Both binder content of polyurethane gives a clear reduction in stiffness, while bitumen gives a big increase. The lignosulphonate gives the highest increase of stiffness, while organosilanes gives a slight increase.

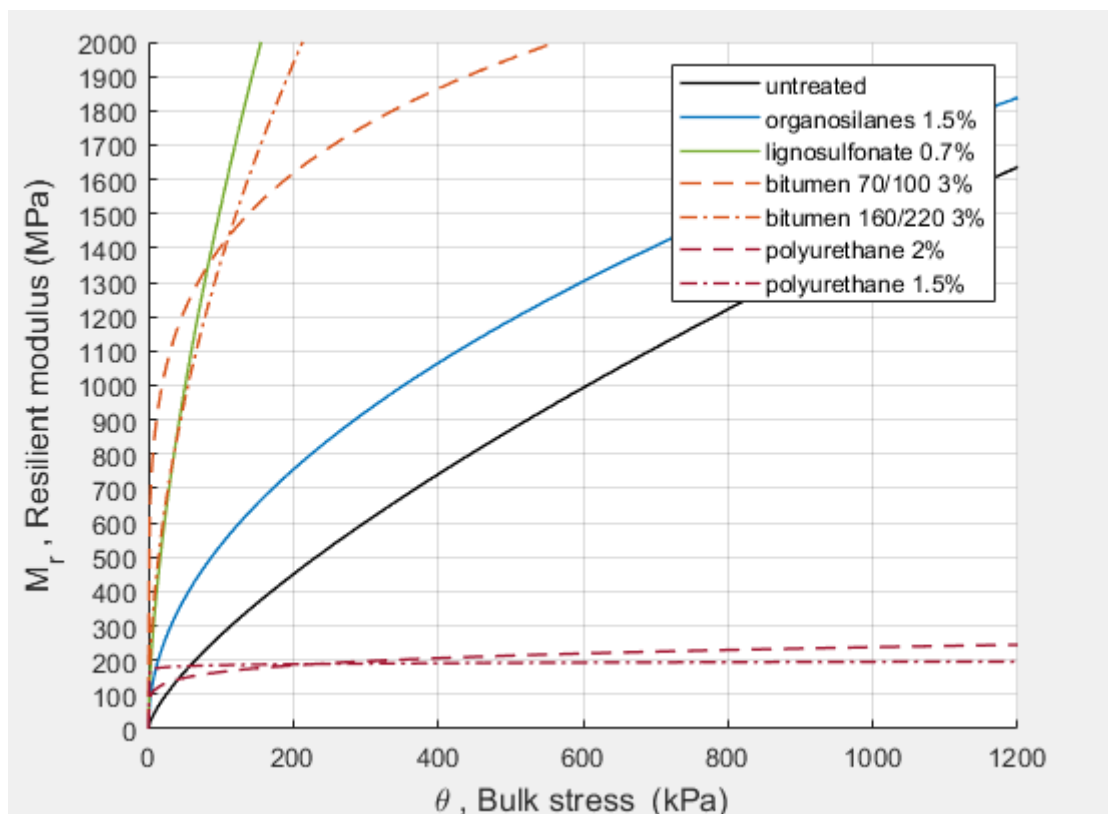


Figure 16: Comparison of resilient modulus for the average of each of the tested binders.

4.2.3 Comparison of permanent deformation

The permanent deformation was planned to be analyzed using Coulombs method (Hoff, et al., 2003). It showed to be inappropriate to use for the samples, as they sometimes had retractions after a deflection.

Due to limitations in the way of measuring the permanent deformations, with a maximum strain of 5 ‰, it got a bit difficult to use other known methods. Therefore, a simpler

approach has been used, by just evaluating the numbers as they are after the ending of each sequence. See Table 21 for an overview of the average permanent deformation after each sequence for the different binders. A graphical overview of the samples is shown in Figure 17.

Table 21: Overview of average permanent deformation for each sequence

	LSL1	LSL2	LSL3	LSL4	LSL5
Unbound	5	4.6	2.495	0.685	2.185
Bitumen 160/220	5	5	3	2.605	3.4
Bitumen 70/100	5	5	3.005	2.64	2.845
Lignosulphonate	5	4.625	3.38	2.66	3.47
Organosilanes	5	3.46	2.435	2.355	3.005
Polyurethane 1.5%	0.615	1.15	0.88	1.64	4.3
Polyurethane 2%	2.625	4.225	3.115	2.32	4.25

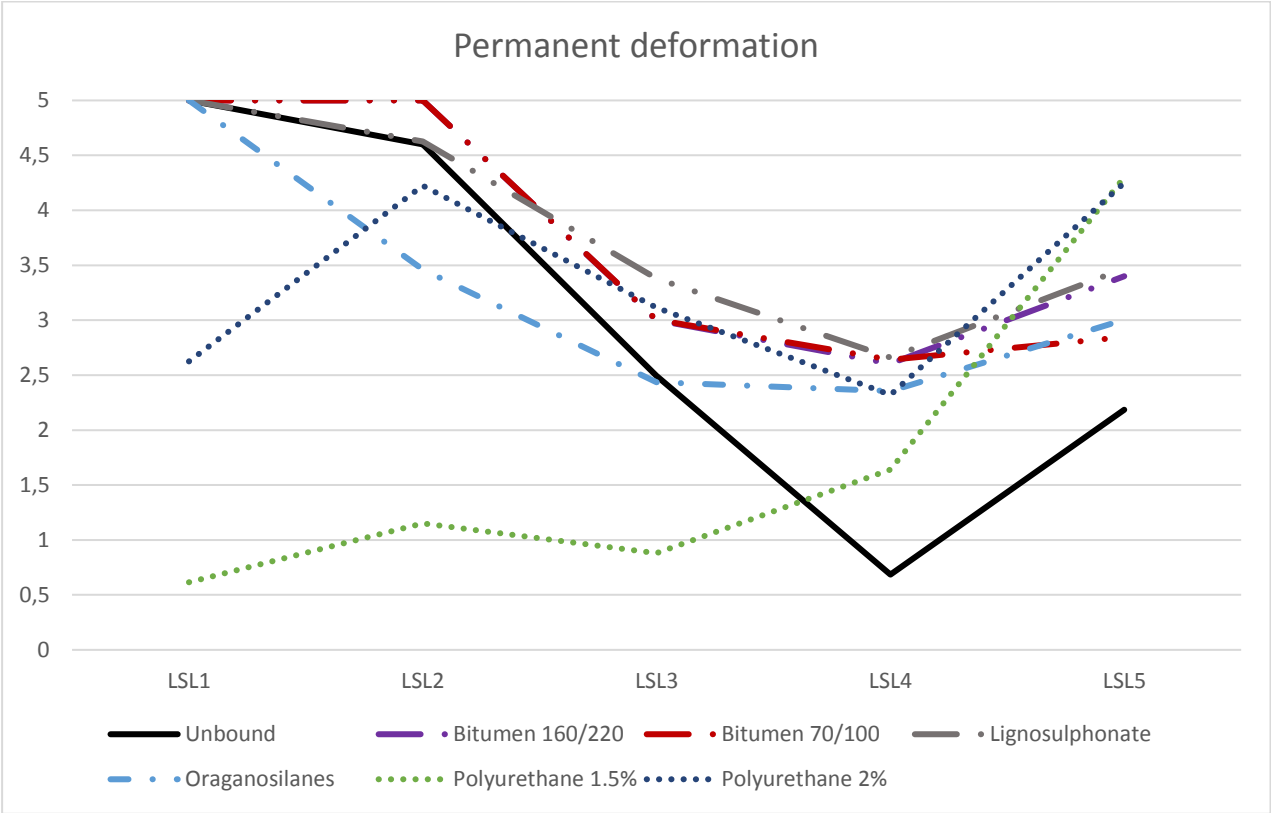


Figure 17: Plot of average permanent deformation for each sequence.

All binders, except polyurethane seems has a high permanent deformation in the first sequences, making them hard to compare to each other. The improvement with using polyurethane versus untreated or other binders is significant, especially at 1.5% binder content, which shows the lowest permanent deformation for all the samples.

A reduction in permanent deformation is seen with increasing confinement pressure for all the samples, even though they are experiencing increased deviatoric pressure. This correlation is seen until the start of the last sequence, where the deviatoric stress is increasing at a bigger rate, leading to increasing permanent deformation for all the samples.

4.2.4 Comparison of sample after testing

After the testing was finished in the triaxial rig, the samples were examined by eye to look after damage. They were also measured to see if there was any intrusion of water into the samples, as that would have affected the test results. A weight comparison would also show if there was a loss of particles during handling or while attaching measuring equipment.

No big change in weight was noticed. At most it was 10-14 grams lost, which in all cases was due to binder stuck at the end plates of the sample. This was especially for bitumen and organosilanes samples. One sample had a weight increase by 3 grams, but that is assumed to be due to faults during weighting. Either before or after the sample was tested, as there were no other signs of contamination. This means there was no intrusion of water in any of the samples.

The durability of the different binders is a bit different, especially for the lignosulphonate stabilized sample, as it had lost most of its binding effect. Most of the particles in the bottom and top of the sample was no longer bound to each other, the core of the sample was still bound. This effect was seen in a lower scale for the organosilanes stabilized sample. For bitumen stabilized samples the binding were still solid, and it looked similar to before testing. The same was the case for polyurethane stabilized samples.

Drainage is an important property of the railway ballast. This has not been researched in this thesis, but by evaluating the sample by eye, it's possible to give an educated guess on how it would work. As for polyurethane, Lignosulphonate and organosilanes, its assumed to be draining the water very well. Possibly a bit worse than untreated material, but not likely to be an issue. The bitumen stabilized samples have a significant higher binder content and can block what normally would have been a gap between particles, leading to a decrease in water penetration.

5 Conclusion

The research aimed to find ways of improving used ballast through modifications with binding agents. This has been investigated through several laboratory tests, firstly to find the properties of used ballast and which fractions it would be natural to continue work with. Later, to measure the effects of the different binding agents with repeated load triaxial tests.

The geometrical testing on ballast from Sørlandsbanen showed that 61% of the ballast are outside of the requirements and would be removed during future ballast cleaning.

The mechanical tests show the material is degrading with use. The LA value is slightly outside the requirements, while the micro-Deval still shows good results.

The triaxial testing showed that it is possible to modify the stiffness of the material. The effect of the different binders was huge in both directions. For stabilization with polyurethane it gave a reduction in stiffness of about one third of the value for untreated material. In the other end of the scale, a stabilization with lignosulphonate gave an increase in stiffness of about five times the value of untreated material. Bitumen stabilized also gave an increase with about twice the amount for bitumen 70/100 and three times the amount for bitumen 160/220. Organosilanes showed the smallest change, with an increase in stiffness of about 30%.

The materials resistance to permanent deformation is also possible to modify with the use of binders. The biggest change in permanent deformation was reached while stabilizing with polyurethane, especially at a binder content of 1.5%, giving a reduction of roughly 50%. The other binders didn't show big differences but were all slightly worse than the untreated material.

A general correlation is seen in the decrease of permanent deformation with increasing confinement pressure. This was not among the study goals of this thesis, but it shows the importance of proper confinement for the aggregates in the track bed.

6 Recommendations for future work

Additional research into this subject is needed. Some research that would be valuable and interesting to investigate are listed below:

- 1) Cost and environmental benefits of modifying ballast, both regarding modifying new ballast, and improving used ballast as a part of maintaining the railroad.
- 2) Testing with different binder contents, to find an optimal content.
- 3) Bigger scale testing with sample sizes of $1 m^3$ or on an active railway line.
- 4) Testing ballast with different geological properties to understand the effect of different ballast mixed with binding agents.
- 5) Examine the long-time degradation of mechanical properties for ballast. This can be done by conducting laboratory tests and comparing the results with properties at time of delivery.

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Appendices

- Annex A Graphs with partially analyzed data for triaxial testing
- Annex B Safe job analysis for work with polyurethane
- Annex C ZIP file with raw data from RLTT

