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Laboratory Investigation of Quarry Fines for Use in the Construction Industry

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Abstract

Quarry fines are by-products of the aggregate extraction and production processes. Because such fine material cannot be marketed, it becomes a burden for the aggregate industry, resulting in stockpiles of financially unexploited material. Even though previous research has been focused on minimizing the generation of quarry fines, far too little attention has been paid to maximizing their utilization instead. The aim of this thesis is to investigate whether 0/2 mm and 0/4 mm quarry fines can be utilized as alternative materials in the construction industry, specifically in the unbound layer of a road or as filling against a bridge. The methodology consisted of four laboratory tests that investigated the water content, particle size distribution and percentage of filler content, optimum moisture content (OMC) and maximum dry density (MDD) relationship as well as bearing capacity of the materials. The results show that the amount of filler content (<0.063 mm) can significantly impact the material's water-holding capacity as well as its compaction capabilities. After comparing the bearing capacity measurements to the technical requirements of the Swedish Transport Administration, it was found that the 0/2 mm fits the necessary requirements for use in the unbound layer of either a flexible or rigid pavement but not as filling against a bridge. Further research is needed to determine the material's relationship to water absorption and resistance to freezing and thawing cycles, as it is difficult to assess its suitability for road construction solely on these results; however, despite its limitations, the study provides some valuable insights into the potential applications of quarry fines.

Keywords

quarry fines, water content, optimum moisture content, maximum dry density, bearing capacity

Sammanfattning

Stenmjöl är en biprodukt från ballastutvinnings- och produktionsprocesserna. Eftersom sådant fint material inte kan marknadsföras blir det en börda för ballastindustrin, vilket resulterar i lager av ekonomiskt outnyttjat material. Även om tidigare forskning har varit inriktad på att minimera genereringen av stenmjöl, har alldeles för lite uppmärksamhet ägnats åt att maximera dess utnyttjande istället. Syftet med detta examensarbete är att undersöka om 0/2 mm och 0/4 mm stenmjöl kan användas som alternativa material i byggbranschen, specifikt i det obundna lagret av en väg eller som fyllning mot en bro. Metodiken bestod av fyra laboratorietester som undersökte vattenhalt, partikelstorleksfördelning och andel fyllmedelshalt, optimal fukthalt och maximal torrdensitetsförhållande samt materialens bärighet. Resultaten visar att mängden fyllmedelsinnehåll (<0,063 mm) avsevärt kan påverka materialets vattenhållande förmåga såväl som dess packningsförmåga. Efter att ha jämfört bärighetsmätningarna med Trafikverkets tekniska krav visade det sig att 0/2 mm är lämplig att använda i det obundna lagret av antingen en flexibel eller styv beläggning men inte som fyllning mot en bro. Ytterligare forskning behövs för att fastställa materialets förhållande till vattenabsorption och motståndskraft mot frys- och upptiningscykler, eftersom det är svårt att bedöma dess lämplighet för vägbyggen enbart utifrån dessa resultat; men trots sina begränsningar ger studien några värdefulla insikter om de potentiella tillämpningarna av stenmjöl.

Nyckelord

stenmjöl, vatteninnehåll, optimal fukthalt, maximal torrdensitet, bärighet

Preface

This thesis concludes my two years of studies at KTH Royal Institute of Technology, a journey that was initiated amongst a pandemic. The thesis was performed at the Department of Civil and Architectural Engineering, Division of Soil and Rock Mechanics in collaboration with NCC's road laboratory in Upplands Väsby, from January till June 2022.

First and foremost, I would like to thank my supervisor at KTH, Professor Stefan Larsson, for all the guidance and support he provided me with from the beginning.

I would also like to thank my supervisor at NCC Per Murén, for motivating me to research the current topic as well as Hassan Hakim, Hampus Johansson and Tomas Åström at the laboratory, who warmheartedly welcomed me into their workspace and provided me with assistance whenever I needed it.

Last but not least, I would like to thank my mother for her unconditional support over the years and my partner for always believing in me.

Stockholm, June 2022
Antonia Filippidi

Nomenclature

Abbreviations

AMA	Allmän Material- och Arbetsbeskrivning (General Material and Job Description)
MDD	Maximum dry density
OMC	Optimum moisture content
SGU	Sveriges geologiska undersökning (Geological Survey of Sweden)
VTI	Statens Väg- & Transportforskningsinstitut (The Swedish National Road and Transport Research Institute)

Definitions

Bearing capacity	maximum load, single or accumulated, which can be accepted with regard to the occurrence of cracks or deformations
Compaction	the densification of soil in fills and embankments achieved by the mechanical compression of the particles
Deformation module (*Ev*)	quantity used to characterize the deformability of the soil
Dimensioning	choosing materials and determining the required thicknesses for the various layers in the superstructure
Hydraulically bound	the particles are bonded to each other through chemical compounds
Oscillating roller	type of roller suitable for vibration-sensitive areas

Standard deviation	a measure of the amount of variation in a set of values calculated by the formula: $s = \sqrt{\frac{1}{n-1}\sum_{i-1}^{n}(x_i - \bar{x})^2}$
Segregation	when the fine particles separate from the coarser ones, since the latter ones tend to settle more

Greek Symbols		**Units**
ρ	Bulk density	[g/cm^3]
ρ_d	Dry density	[g/cm^3]

Latin Symbols		**Units**
Cc	Curvature coefficient	[-]
Cu	Uniformity coefficient	[-]
d	Lower sieve size	[mm]
D	Upper sieve size	[mm]
D_{10}	Diameter for 10% finer by weight	[mm]
D_{30}	Diameter for 30% finer by weight	[mm]
D_{60}	Diameter for 60% finer by weight	[mm]
Ev_1	Deformation module obtained in the first loading (in static plate load)	[MPa]
Ev_2	Deformation module obtained in the second loading (in static plate load)	[MPa]
f	Percentage of filler content (in sieve analysis)	[%]
m_1	Mass of the mould (in modified Proctor compaction)	[g]
m_2	Mass of the mould with the moist mixture (in modified Proctor compaction)	[g]

m_3	Mass of the dry mixture (in modified Proctor compaction)	[g]
M_{dry}	Mass of the dry sample (in water content)	[g]
M_{tray}	Mass of the tray (in water content test)	[g]
M_{wet}	Mass of the wet sample (in water content)	[g]
M_1	Mass of the dry sample (in sieve analysis)	[g]
M_2	Mass of the wet sample (in sieve analysis)	[g]
n	Number of test points	[-]
P	Mass of retained material in the pan (in sieve analysis)	[g]
s	Standard deviation	[-]
V	Volume of the mould (in modified Proctor compaction)	[cm^3]
w	Water content	[%]
$\bar{x}Ev_2$	Arithmetic mean of measured Ev_2	[MPa]

Contents

1. Introduction

Construction aggregates are the foundation of our modern society and the primary source of material in the building industry (Poulin et al., 1994). Aggregates can be either naturally occurring materials such as sand and gravel, found in eskers or mined and crushed from rock quarries. An estimated 100 million tonnes of construction aggregates are produced in Sweden annually (SGU, 2021), with large quantities of quarry by-products, including fines and dust, inevitably produced during the extraction and production processes (Mitchell, 2009). The handling and disposal of quarry fines can generate an excessive amount of dust under dry conditions, which can pose an imminent threat to the environment, however, they are composed of the same mineral substances with the parent rock that they are excavated from so they are usually inert or non-hazardous (Petavratzi and Wilson, 2008). In addition, such fine material is often difficult for quarries to sell as specifications for fine aggregates rarely meet the requirements in the construction industry, leading to a substantial excess of fines stockpiling, making it one of the biggest problems the aggregate industry is facing (Hudson et al., 1997). Although various studies have been conducted in order to minimize the generation of quarry fines and their subsequent environmental impacts (Langer et al., 2003; Birch et al., 2008; Mitchell et al., 2008), far too little attention has been paid to finding sustainable ways to maximize their usage instead.

Sweden has historically used natural gravel resources as the primary source of building materials; however, gravel is regarded as an invaluable resource as it is an important groundwater reservoir material, supplying drinking water to local communities (EEA, 2008). Exploitation of natural gravel is therefore often in conflict with the preservation of future drinking water resources, especially in areas where the occurrence of natural gravel is rather limited. Luckily, the introduction of European Standards and technical requirements for aggregates used in the construction industry have led to a dramatic shift from gravel towards crushed rock, encouraging a high level of material substitution. What further necessitates the substitution of construction aggregates is the fact that Sweden's population is expected to reach 12.6 million by 2070 (Statistics Sweden, 2021). This societal transformation is expected to have a significant impact on the environment, since the increased demand for building materials will necessitate higher aggregate production (SGU, 2021). Since the construction industry is closely intertwined with the aggregate production (Poulin et al., 1994), consumption, and thus aggregate demand, is estimated to rapidly increase over the next two decades. Therefore, it is crucial to investigate potential alternative materials that could supplement or even entirely replace the current ones used in various areas of the construction industry, even if they do not fulfill standard technical specifications.

1.1. European Standards

The introduction of European Standards for aggregates addressed the need for specifications for a wide range of applications and allowed the use of a larger range of aggregate resources (Petavratzi and Wilson, 2008). The European Standard SS-EN 13242+A1:2007 "*Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction*" refers to different types of resources that can be used as aggregates and can be either natural, recycled, or manufactured materials. Regardless of the choice of the material used, the size of the aggregates must be described using the designations d/D, with d representing the lower limit and D representing the upper limit of the sieve size. In the aforementioned standard, aggregates with $D \leq 6,3$ mm and $d = 0$ are characterized as fine aggregates. Many quarries, including the quarry in Arlanda that provided the material for this investigation, also refer to material finer than 4 mm as fine aggregates. However, there is no consistent definition throughout the construction industry, which can appear misleading in the published literature. The term “fine aggregates” is also known as “fine materials”, “quarry fines”, “quarry waste”, “quarry by-products”, “crushed rock aggregates” or “crushed stone aggregates” or as “stenmjöl”, “finmaterial”, “krossmaterial” or “bergkross” in Swedish. It is important to note that, in the context of this thesis, all of the above phrases are considered equal and can be used interchangeably, however for clarity, the term “quarry fines” will be used from now on.

1.2. Aim and objectives

The aim of this thesis is to enhance the Swedish industry understanding of quarry fine utilisation by examining fines the size of 0/2 mm and 0/4 mm. The materials are collected from the quarry Långåsen in Arlanda, Sweden and are investigated in the laboratory for their initial water content, particle size distribution and percentage of filler content, optimum moisture content (OMC) and maximum dry density (MDD) relationship as well as bearing capacity. The bearing capacity measurements are then compared to the Swedish technical requirements provided by the Swedish Transport Administration (Trafikverket) in order to determine whether such fine material can be utilized in the unbound layer of a road or as filling against a bridge. The main research question addressed by this thesis is therefore whether quarry fines can be used as alternative materials in the Swedish construction industry. This thesis is primarily aimed at academics (master’s and doctoral students, professors, and researchers) as well as laboratory technicians and industry professionals.

1.3. Limitations

The main limitation of this thesis was that the material originated from a single quarry, hence only one type of lithology was investigated. It is therefore unknown as to how a different rock type would behave when subjected to the laboratory tests performed in this investigation.

1.4. Thesis outline

The thesis begins with an introductory chapter, in which the background, the aim and objectives as well as the limitations of the thesis are presented. Chapter 2 consists of a brief overview of the theoretical background regarding road construction and requirements provided by the Swedish Road Administration. Chapter 3 is dedicated to the literature review of this thesis. Chapter 4 elaborates on the materials and the laboratory tests performed in this investigation. Chapter 5 presents the obtained results provided by the laboratory tests while Chapter 6 is dedicated to the discussion of the findings and provides suggestions for future work. Finally, Chapter 7 summarizes the purpose and the most important findings of this thesis.

2. Background

One of the ways quarry fines can be utilized in the construction industry is in pavement design as filling in the unbound base or sub-base layer. The purpose here is not to describe how roads should be designed and constructed, but rather provide a brief theoretical background on what a road pavement consists of, what the purpose of each layer is and what are the requirements for aggregates to be used in the unbound base layer of a road or as filling against a bridge. The technical terms, also presented in Swedish, were modified after the Swedish Transport Administration documents (Trafikverket 2005a, 2005b, 2005c, 2011, 2016a, 2016b, 2017) therefore, it should be noted that some terms may differ across international literature, for instance, the wear layer can be found as surface or wearing course, the base layer as base course, the subsoil as subgrade and so on.

2.1. Road construction

A road construction mainly consists of two parts: the superstructure (*överbyggnad*) and the substructure (*underbyggnad*), as shown in Figure 1. The terrace area (*terrassyta*) that separates them is produced by excavating or filling in the earth so that the surface is even (Trafikverket, 2011). The subsoil (*undergrund*) is the natural undisturbed material beneath the substructure, and the bank slope (*bankslänt*) or filling slope (*fyllningsslänt*) is the filling material on the roadside.

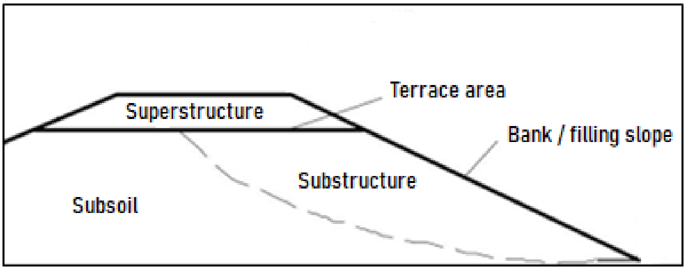


Figure 1. Typical structure of road construction (Modified after Trafikverket, 2005a)

As shown in Figure 2, the superstructure typically consists of several different layers, including a wear layer (*slitlager*), a bound (*bundet*) and unbound (*obundet*) base layer (*bärlager*), a reinforcement layer (*förstärkningslager*) and a protective layer (*skyddslager*), each with different functions and properties. The general rule is to use layers of compacted materials that gradually increase in quality and strength from the subsoil to the road surface, as the latter is meant to endure heavy traffic loads and is also exposed to environmental elements such as temperature and frost, among others.

The wear layer is the upper top layer of a road construction. The purpose of the bound and unbound layers is to distribute the traffic load from the road surface so that no harmful stresses and deformations occur in the underlying layers (Trafikverket, 2011). The most common material in the bound base layer is asphalt gravel while the unbound base layer usually consists of crushed gravel or crushed rock. The reinforcement layer, along with the other layers, distributes the traffic load to the subsoil while also absorbing stresses transmitted from the base layers. The largest particle size should not be larger than half the layer thickness and range between 60-130 mm (Trafikverket, 2011). The protective layer is not always necessary. In frost-susceptible soils, the protective layer is laid directly on the subsoil to avoid or lessen frost-heave. Furthermore, if the subsoil consists of fine-grained materials like silt and clay, the protective layer can function as a barrier between the subsoil and the reinforcement layer (Trafikverket, 2011).

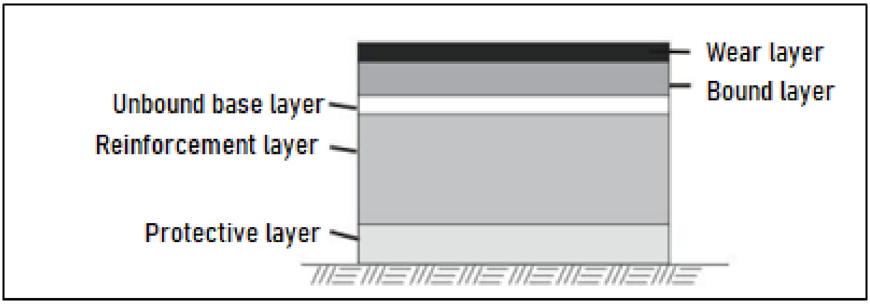


Figure 2. Typical structure of superstructure (Modified after Trafikverket, 2005a)

Two main types of superstructures are found in the Swedish road network: flexible and rigid, both of which consist of different layers. A flexible or asphalt pavement is a superstructure composed of only unbound layers or unbound and bitumen-bound layers combined (Trafikverket, 2005b). Bitumen-bound layers consist of bituminous binders and granular materials. A rigid or concrete pavement is a superstructure with at least one hydraulically bound layer (Trafikverket, 2005b). This type of superstructure consists of wear and support layers that are stabilized with cement, concrete or bitumen and is used for heavier traffic loads.

2.2. Technical requirements and advice

This section is mainly about the technical requirements and advice provided by the Swedish Transport Administration (Trafikverket) as well as the reference work AMA (Allmän Material- och Arbetsbeskrivning / General Material and Job Description), which includes requirements for materials, methods, and techniques for use in the Swedish construction industry. The general and geotechnical requirements for unbound layers in a road, the requirements for bearing capacity for both flexible and rigid pavements as well as the requirements for filling against a bridge are discussed.

2.2.1. General requirements

According to the Swedish Transport Administration's requirements for unbound layers in road construction (Trafikverket, 2017) the materials must have such properties that the superstructure design essentially retains its strength properties throughout the assumed service life, which is typically 20 years for new construction (Trafikverket, 2005a). Such material may only be used if they are approved from an environmental and health point of view and also do not cause any problems with reuse, destruction, or disposal. For roads with either bound or unbound wear layers, both the base and the reinforcement layer must be resistant to weathering and frost-lifting, while the protective layer must be non-frost-lifting and draining. Any excess water, for example during and after thawing, should be able to drain quickly. The base and reinforcement layers also need to be rigid enough to withstand permanent deformations from traffic (Trafikverket, 2017).

2.2.2. Geotechnical requirements

Determining the right type of material to build a road on is of great importance for proper dimensioning. Rock materials for road purposes are classified into three types (rock types 1, 2 and 3) in terms of durability and strength, based on the ball mill value (Trafikverket, 2016a). The materials investigated in this thesis correspond to rock type 1, according to Fehrm (2019), and therefore the ball mill value, determined in accordance with SS-EN 1097-9 "*Determination of resistance to wear by abrasion from studded tyres - Nordic test*", must be no more than 18. The micro-Deval value determined in accordance with SS-EN 1097-1 *"Determination of resistance to wear (micro-Deval)"* must not exceed 13 and the Los Angeles value determined in accordance with SS-EN 1097-2 "*Determination of resistance to fragmentation*" must not exceed 40 (Trafikverket, 2016b).

2.2.3. Bearing capacity requirements

The requirements for the bearing capacity apply to the mean value for all test points and depending on whether five or eight test points are selected for the measurements, the requirements vary (Trafikverket, 2017). In this case, the number of approved test points must be at least 7 out of 8 or 4 out of 5. The requirements also differ depending on whether the construction is flexible or rigid, as shown in Tables 1 and 2, respectively, where n is the number of test points, $\bar{x}$ is equal to the arithmetic mean of measured Ev_2, Ev_1 and Ev_2 are the deformation modules obtained in the first and second load samples, Ev_2/Ev_1 is the bearing capacity ratio and s is the standard deviation. There are also requirements for the bearing capacity ratio. These requirements apply to each individual point and depend on the measured bearing capacity at that point (Trafikverket, 2017).

Table 1. Requirements for bearing capacity and bearing capacity ratio for unbound layer of a new flexible construction (Trafikverket, 2017)

Flexible construction			
Test points	$\bar{x}Ev_2$ **(MPa)**	**Measured at each point (MPa)**	Ev_2/Ev_1
n = 8	$\geq 140 + 0.96 * s$	If ≤ 140	≤ 2.8
n = 5	$\geq 140 + 0.83 * s$	If > 140	$\leq 1 + 0.013 * Ev_2$

Table 2. Requirements for bearing capacity and bearing capacity ratio for unbound layer of a new rigid construction (Trafikverket, 2017)

Rigid construction			
Test points	$\bar{x}Ev_2$ **(MPa)**	**Measured at each point (MPa)**	Ev_2/Ev_1
n = 8	$\geq 120 + 0.96 * s$	If ≤ 120	≤ 2.8
n = 5	$\geq 120 + 0.83 * s$	If > 120	$\leq 1 + 0.015 * Ev_2$

The requirements for bearing capacity when filling against a bridge is that the arithmetic mean $\bar{x}Ev_2$ must be over or equal to 120 MPa, the number of test points need to be at least 2 out of 3 and at each test point the bearing capacity ratio Ev_2/Ev_1 must be less or equal than 2.8 as shown in Table 3.

Table 3. Requirements for bearing capacity for when filling against a bridge (Trafikverket, 2017)

Filling against a bridge		
Test points	$\bar{x}Ev_2$ **(MPa)**	Ev_2/Ev_1
n = 3	≥ 120	≤ 2.8

2.2.4. Compaction requirements

In general, when filling with material that must be compacted, it is recommended that the procedure must be carried out with medium-graded or multi-graded material (Trafikverket, 2005c). The material must be free from ice and snow, plant residues, roots, and other unfit material. For best compaction results, all layers should be compacted close to optimal moisture content with a deviation of ± 1.5%. The compaction of the unbound layers must be carried out with a vibrating or oscillating roller, which must be driven at a low and constant speed of 2.5–4.0 km/h (Trafikverket, 2005c), while in the reference work AMA it is suggested that it should be driven at a speed of 3.0 ± 1.0 km/h (Svensk Byggtjänst, 2020).

3. Literature review

Quarry fines may be used in several bound and unbound applications in the construction industry. Examples of such areas are in unbound aggregate mixtures, in general fill applications as well as in concrete and asphalt mixtures and even in soil stabilization techniques. As the main purpose of this thesis is to determine whether quarry fines can be qualified as substitute for use in road construction or as filling against a bridge, only research related to those cases is presented. It should be noted however that no relevant literature was found regarding the latter.

In a study by Rezende and de Carvalho (2004) on the use of quarry fines in road construction in Brazil, an experimental road was constructed in order to investigate its long-term performance. The authors found that quarry fines can successfully be used as construction material for flexible pavements, especially in base layer. The results indicated that the moisture content can influence its performance, as heavy precipitation can decrease its strength characteristics. Therefore, the authors suggested an appropriate drainage system installed. However, as the experimental road was only destined for low traffic volume (60-80 km/h), it is inconclusive whether such material can withstand higher traffic loads. Soosan et al. (2005) found that quarry dust can be mixed and added in problematic clayey soils as it can considerably improve its engineering properties by increasing the MDD and therefore decreasing the OMC, concluding that such mix can be potentially used as sub-base in flexible constructions.

Manning and Vetterlein (2004) conducted a study on the exploitation of quarry fines in the UK and found that the lithology can have a major impact on the amount of fines generated from the crushing process. In particular, they found that aggregates produced by crushed limestone generated 20 to 25 percent fines during the crushing process, while sandstone aggregates produced up to 35 percent fines. As for igneous rocks, the fines produced by the crushing process ranged for 10 to 30 percent. It is evident therefore that the lithology of a quarry can significantly influence the amount of fines generated. Mitchell et al.

(2001) was part of the *REFILL* project that investigated fines from a sandstone quarry in Ireland (Leahill Quarry) in an attempt to find replacements for high-cost fillers. Their research focused on incorporating fines the size of 0/2 mm in the wearing layer of asphalt mixtures and it was found that the mixtures were not suitable due to the high filler content (23%) but when fines with 3 mm size were blended with the mixtures, the filler content was reduced to 15% and hence that blend was deemed satisfactory for use in asphalt mixtures. Based on a literature review study from Muttuvelu and Kjems (2021) on permeable pavements and specifically unbound subbase materials, the authors concluded that well-graded materials that contained a large amount of fines were more susceptible to higher moisture content. Specifically, if the moisture content were to increase more than the OMC, the material was prone to loss in bearing capacity, therefore an increase in moisture content could lead to a permanent deformation of the subbase material and the material would no longer be suitable.

Quarry fines have also been investigated in Sweden, with Wallhamn AB commissioning NCC in 1993 to build a storage area for containers the size of 60.000 m^2. The contract conditions were that a bay with a water depth between 0.5 – 1.0 meters would be filled. The bottom consisted of clay with a depth to bedrock between 1 and 18 meters. The storage area was built up of 0/2 mm material, which was laid out in two layers with the first layer 0.5 meters above sea level and the second layer 2 meters above sea level. The surface was finally topped with 20 cm 0/32 mm material and sealed with 5 cm 0/18. The area was inspected one year after completion and no settlements could be detected. According to Johnning (n.d.), working with quarry fines was easy to handle and the bearing capacity during construction settled down very easily and therefore minimal efforts needed to be made for final compaction. The area is presumably still in very good condition today.

In another case, Öberg-Högsta (2000) investigated on behalf of NCC Ballast and in collaboration with the Department of Geotechnics of Chalmers University of Technology, whether crushed 0/2 mm material could be used in cover layers at landfills or for construction in general. It was found that such material mixed with bentonite could potentially be used as a waterproofing layer as well as in other areas of construction such as in noise barriers, landscape modelling and as filling material.

4. Materials and methods

The quarry fines, the sizes of 0/2 mm and 0/4 mm (Figure 3), were gathered from the Långåsen quarry in Arlanda, Märsta (Figure 4) and sent to NCC's road laboratory in Upplands Väsby. Each material was packed into a 25 kg bucket and transferred for investigation at the laboratory. The collected quarry fines originated from granodiorite bedrock, an intrusive igneous rock composed of quartz, feldspar, and mica according to Fehrm (2019).

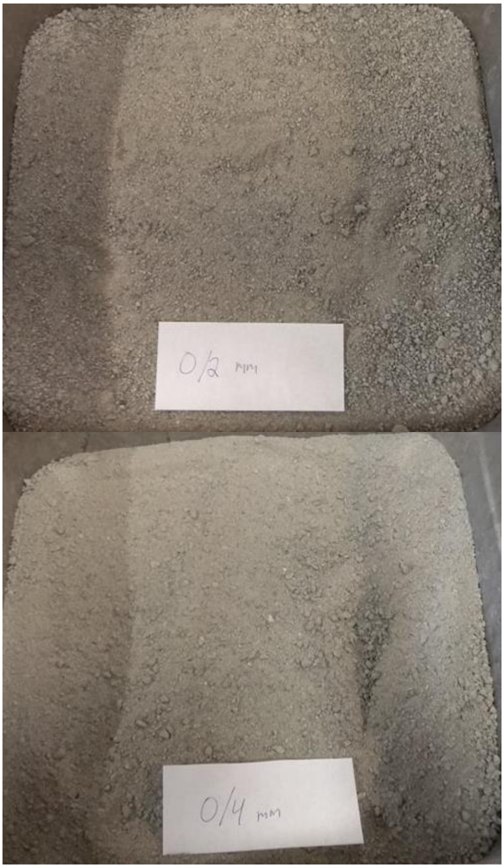


Figure 3. Samples of the 0/2 mm (top) and 0/4 mm (bottom) materials in 5 kg trays before the initiation of the laboratory tests

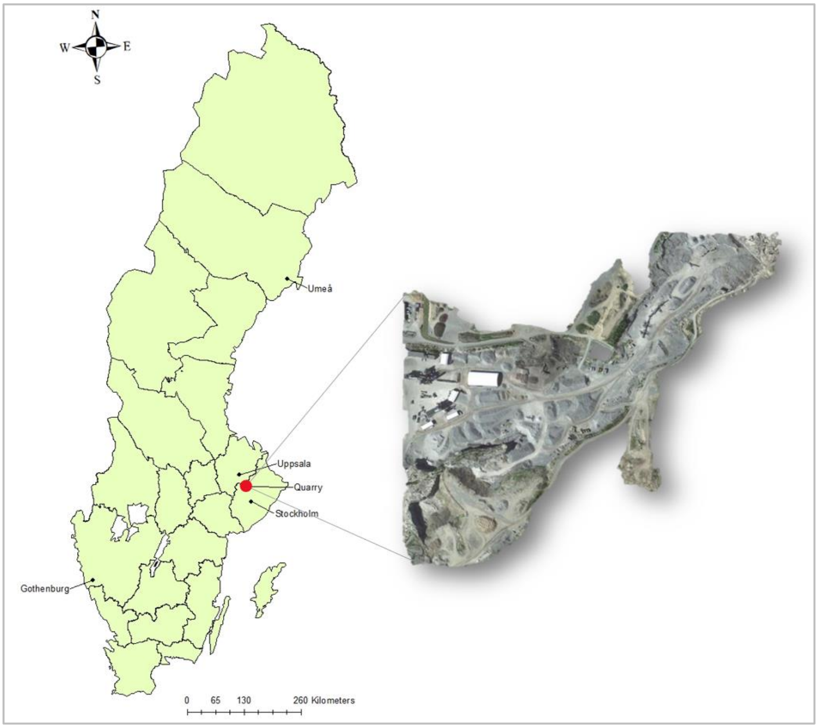


Figure 4. To the left, the map of Sweden constructed in ArcMap using data from Lantmäteriet with the location of several major cities and the location of the quarry illustrated with a red dot. To the right, the Långåsen quarry in Arlanda, Märsta as shown in Google Maps.

Four laboratory tests were conducted for each material, as shown in Table 4: water content, sieve analysis, modified Proctor compaction and static plate load.

Table 4. Timeframe of laboratory tests and each property determined

Laboratory test	Property determined	Week
Water content	Natural moisture	8
Sieve analysis	Filler content percentage	8
Modified Proctor compaction	MDD-OMC relationship	8-9
Static plate load	Bearing capacity	18

The first was done in order to determine the initial water content of the samples after they were collected from the quarry and the second in order to confirm that the range in grain size distribution of the samples was correct and also to determine the filler content, which corresponds to material smaller than 0.063 mm. The third test was performed in order to determine the relationship between the samples' OMC and MDD whereas the fourth test was performed in order to determine the bearing capacity of the materials. The first three tests were performed during weeks 8 and 9, while the static plate load was carried out during week 18 since it had to be performed outdoors and no rain or snow was allowed to come into contact with the laid-out material.

In order to obtain the necessary amount of materials required for investigation, the materials were reduced to test portions with the aid of a riffle box, according to the European standard SS-EN 932-2:1999. This was done in order to prevent any selection bias taking place and therefore avoid interfering with the test portions as well as minimize segregation.

4.1. Water content

The reduced samples were dried in a ventilated oven in order to determine their water content according to the European standard SS-EN 1097-5:2008. The minimum mass of the test portion required for the test was based on the value of the upper (D) sieve size in millimeters, and if $D \geq 1$ mm the minimum weight should be $0.2 * D$, otherwise if $D < 1$ mm the minimum mass should be 200 g. As the specimens consisted of 0/2 mm and 0/4 mm material, the minimum masses were calculated and found to be 400 g and 800 g, respectively. However, as that is the minimum amount required, in reality the samples weighed more as it was not required to yield the exact value with the predetermined one.

Once the masses of the test portions were decided, they were placed in clean and dry trays, with the mass of each tray weighed and recorded as M_{tray} in g. The test portions were then spread out on their trays and weighed, with the wet test portion determined as M_{wet}, by subtracting the mass of each tray. Following that, the trays were placed in the oven

(Figure 5) to dry at approximately 110 °C, with occasional stirring to aid with the evaporation of the water. After the trays had cooled, the mass of each dry sample was determined as M_{dry} by subtracting the mass of the tray.

Figure 5. The ventilated oven that was used for the water content determination test

As a result, the natural water content (w) was defined as the difference in mass between the wet (M_{wet}) and dry sample (M_{dry}) and expressed as a percentage of the mass of the dry sample (M_{dry}), according to equation (1):

$$\boxed{w = \frac{M_{\text{wet}} - M_{\text{dry}}}{M_{\text{dry}}} * 100} \quad (1)$$

The results are presented in Table 5.

4.2. Sieve analysis

In order to determine the particle size distribution of the samples, the wet sieving method according to the European standard SS-EN 933-1:2012 was adopted. The method is based on dividing and separating the material into sieves with gradually decreasing aperture sizes, allowing only smaller and smaller material to pass through each time. The minimum masses of the test portions for both 0/2 mm and 0/4 mm material were 200 g. However, similarly with the water content determination test, the actual sizes of the test portions were larger as it was not required to yield the exact values.

Each test portion's weight was recorded as total dry mass M_1. Following that, each specimen was washed, until the water passing the 0.063 mm sieve was clear, before being put in the oven to dry at approximately 110 ^{o}C for 1 hour. The reason for washing the material was to reduce the amount of filler content in the fines. After drying, each specimen's weight after washing was recorded as M_2 and put into the sieving column which consisted of sieves whose aperture sizes decreased from top to bottom. The remaining material was collected in a pan. Each column was then mechanically shaken for about 10 minutes and the sieves were removed one by one, starting with the largest aperture size opening. The material was put into a bowl and the retained material was weighted and recorded as P. The scale was reset to zero after each sieve in order to obtain more precise weight measurements. As a result, the percentage of filler (*f)* passing the 0.063 mm sieve was calculated according to equation (2):

$$\boxed{f = \frac{(M_1 - M_2) + P}{M_1} * 100} \quad (2)$$

The results are presented in Figures 9 and 10, while more analytical data can be found in Appendix A.

4.3. Modified Proctor compaction

The Modified Proctor compaction test was performed according to the European standard SS-EN 13286-2:2010 in order to determine the OMC and MDD of the materials. The mixtures were prepared by subdividing the material into at least five samples, each weighing approximately 2.5 kg and mixing each sample thoroughly with different amounts of water to give a suitable range of water contents. A quantity of moist mixture was then placed in the 100 mm cylindrical mould (Figure 6) so that when compacted it would occupy around one fifth of the height of the mould. The mould's mass (m_1) and volume (V) were recorded in g and cm^3, respectively. Each sample was compacted into the mould in 5 layers with a compactor consisting of a 4.5 kg rammer that fell freely from a height of 457 mm onto the surface of the mould. Each layer was compacted by 25 blows and the procedure was repeated four times so that the amount of mixture would sufficiently fill the mould. After compaction, the mould together with the moist mixture were then weighed and its mass was recorded as m_2 in g. Afterwards, the mixture was removed from the mould and was put in the ventilated oven to dry for a day. After it had dried, the mass of the dry mixture was recorded as m_3 in g. As a result, the bulk (ρ) and dry (ρ_d) density were calculated according to equations (3) and (4) respectively:

$$\boxed{\rho = \frac{m_2 - m_1}{V}} \quad (3)$$

$$\boxed{\rho_\mathrm{d} = \frac{m_3}{V}} \quad (4)$$

The reason this test is called modified is because the mass of the rammer and the height of the drop are different compared to the standard procedure, resulting in a higher compactive effort. In other words, this method is capable of achieving higher MDD at lower OMC. In addition, the reason for the 100 mm diameter mould was due to the fact that the dimensions of the mould needed to be at least 4 times the upper limit size of the sample, which in this case were 2 and 4 mm respectively, therefore the smallest diameter form available was chosen. The results of each gradation are presented as compaction curves in Figures 11 and 12, respectively, while more analytical data can be found in Appendix B.

Figure 6. The cylindrical mould used for the modified Proctor compaction test

4.4. Static plate load

The static plate load test (*statisk plattbelastning*) was performed according to TDOK 2014:0141 (Trafikverket, 2014) which is based on the German standard DIN 18134 "*Soil - Testing procedures and testing equipment - Plate load test*". The purpose of this test was to investigate whether the 0/2 mm and 0/4 mm materials could meet the technical requirements for use in the unbound layer of a road or for filling against a bridge. For that reason, an experimental setup was built in which both 0/2 mm and 0/4 mm materials were spread out and compacted at the NCC laboratory's asphalt-paved backyard, as shown in Figures 7 and 8. The materials were compacted next to each other in a rectangular that was approximately 9 m long and 6 m wide, with the aid of a 445 kg vibratory plate. The 0/2 mm material was first laid out and compacted in a layer with a thickness of approximately 130 to 140 mm, and then the second layer was created with the remaining material spread out on top and immediately compacted. The purpose was for the final compacted layer to have a thickness of approximately 200 mm. The same procedure was followed for the 0/4 mm. As shown in Figure 7, once the first layer of the 0/4 mm material was laid out, its surface became dry very rapidly due to being directly under the sun, so when the remaining material was laid out, there was a noticeable difference in colour. Because of that, some water was sprinkled on top to aid in the compaction process. It should be noted that the amount of water added was not measured and therefore did not correspond to the OMC that was obtained at the laboratory. Measurements were conducted in a total of 6 test points, 3 for the 0/2 mm and 3 for the 0/4 mm, approximately in the middle of the layers, as shown in Appendix C.

Figure 7. The first layer of 0/4 mm showing in light grey and the second layer in darker grey. It is evident that the material dried up rather quickly due to it being directly under the sun.

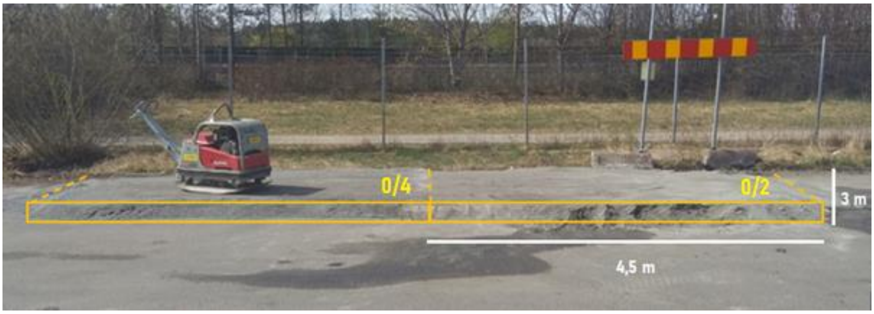


Figure 8. The 0/4 mm (left) and 0/2 mm (right) compacted materials. The length of each layer was approximately 4.5 meters and the width approximately 3 meters. The water is due to the wetting of the material for proper compaction.

As for the static plate load test, it is an in-situ method used for determining the bearing capacity (*bärighet*) and compaction of soil layers, during which a circular steel plate of 300 mm is loaded and unloaded using a hydraulic pump. The plate is loaded stepwise up to a pressure of 0.5 MPa, then released to zero pressure and then reloaded up to 0.45 MPa, which is 90% of the original pressure. The reason for this is that the first cycle involves an initialization of contact between the plate and the layer, and because this deformation does not entirely reverse during the unloading phase, the material is thus more packed at the second loading, resulting in a smaller settlement. The settlement that occurs at each step is measured and should not exceed 5 mm per loading, while the deformation modules Ev_1 and Ev_2 are calculated based on the pressure and deformation fitting curves, which are shown in Appendix D. The bearing capacity ratio Ev_2/Ev_1 (*bärighetskvot*) is also calculated, which is an indirect measure of the degree of compaction. More details on the procedure and the necessary equipment are described in the Swedish Road Administration’s method descriptions (Trafikverket, 2014) as well as in the foreign standard DIN 18134 “*Soil - Testing procedures and testing equipment - Plate load test*”. The results are presented in Table 7.

5. Results

The results obtained from the laboratory tests regarding natural moisture, particle size distribution and percentage of filler content, OMC-MDD relationship as well as bearing capacity measurements are presented below.

5.1. Water content

According to equation (1), it was found that the 0/2 mm material had higher water content percentage compared to the 0/4 mm, as shown in Table 5. More specifically, the water content of the 0/2 mm was 13.8%, while the 0/4 mm was 10.4%, indicating a 3.4% difference between the two gradations.

Table 5. Tray and sample weights for each material as well as their calculated water content presented in percentage

Property (unit)	**Symbol**	**0/2**	**0/4**
Mass of tray (g)	M_{tray}	317.1	321.6
Wet sample & tray (g)	M_{wet} & M_{tray}	1691.9	1587.2
Wet sample (g)	M_{wet}	1374.8	1265.6
Dry sample & tray (g)	M_{dry} & M_{tray}	1525.1	1467.5
Dry sample (g)	M_{dry}	1208	1145.9
Water content (%)	w	**13.8**	**10.4**

5.2. Sieve analysis

According to equation (2), it was found that for the 0/2 mm material the percentage of particles finer than 0.063 mm is 15.8% while for the 0/4 mm material is 12.8%, as shown in Table 6.

Table 6. Dry masses before and after washing for each material as well as the calculated filler percentage for each material

Property (unit)	**Symbol**	**0/2**	**0/4**
Dry mass (g)	M_1	633.1	677.9
Dry mass after washing (g)	M_2	564.4	606.6
Dry mass of filler removed by washing (g)	$M_1 - M_2$	68.7	71.3
Percentage of filler (%)	f	**15.8**	**12.8**

From the wet sieving method, it was also possible to construct the particle size distribution curves for each material, as shown in Figures 9 and 10, respectively. The main reason for performing the sieve analysis was to confirm that the materials provided were indeed within the range of 0/2 mm and 0/4 mm. In addition, an effort was made to evaluate the grade of the materials based on the coefficient of uniformity (*Cu*) and the coefficient of gradation (*Cc*), which were determined by equations (5) and (6):

$$\boxed{C_U = \frac{D_{60}}{D_{10}}} \quad (5)$$

$$\boxed{C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}}} \quad (6)$$

where D_{10}, D_{30} and D_{60} are the particle diameters at which 10%, 30% and 60% of the soil by weight is finer. The coefficient of uniformity (*Cu*) was equal to 17.5 and 25 for the 0/2 mm and 0/4 mm respectively while the coefficient of curvature (*Cc*) was approximately 0.6 and 1.5 respectively. Therefore, according to EN ISO 14688-2:2018, the materials can be classified as multi-graded or well-graded.

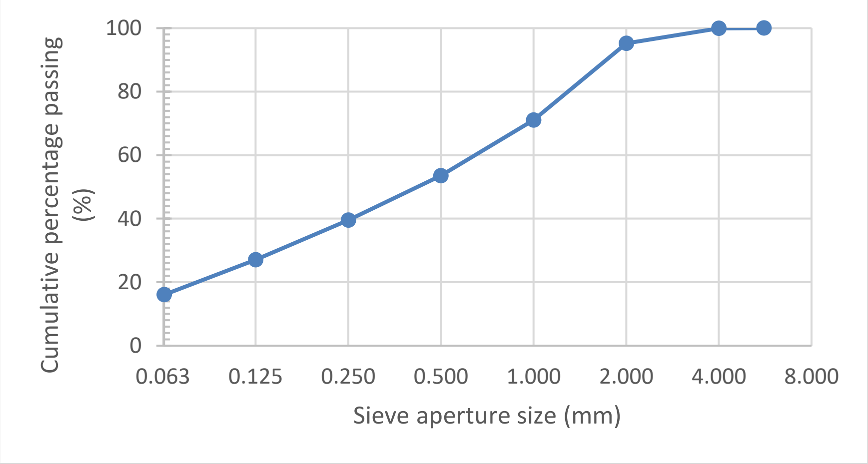


Figure 9. Particle size distribution curve for the 0/2 mm material

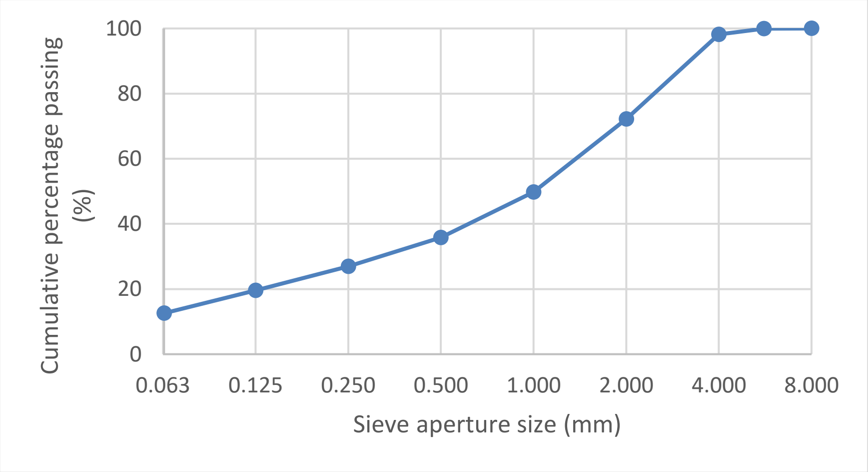


Figure 10. Particle size distribution curve for the 0/4 mm material

5.3. Modified Proctor compaction

The modified Proctor compaction results allow for a conclusion to be drawn with regard to the OMC at which the mixture can be properly compacted in order to achieve a given dry density. In total, 15 samples were prepared, 8 for the 0/2 mm material and 7 for the 0/4 mm, as shown in Appendix B. From the tested samples it was found that the OMC for the 0/2 mm material is 6.9% with a MDD of 2.05 g/cm³, while for the 0/4 mm material the OMC is 4.9% with a MDD of 2.09 g/cm³, as shown in Figures 11 and 12, respectively.

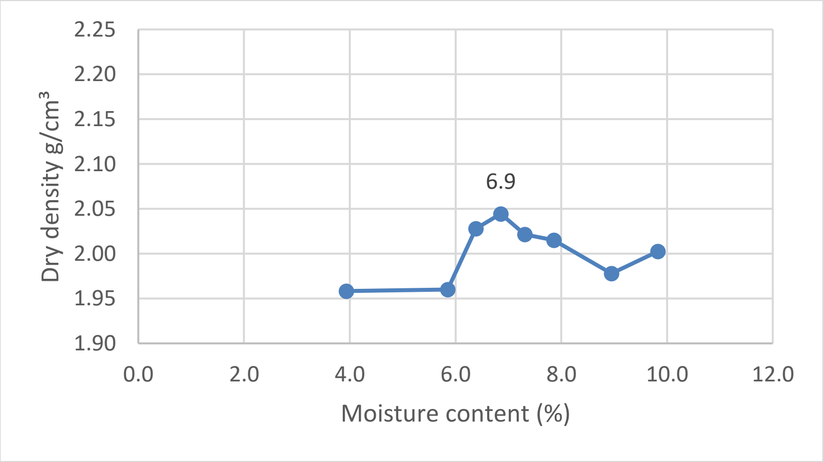


Figure 11. Compaction curve of 0/2 mm material with OMC of 6.9% and MDD of 2.05 g/cm^3

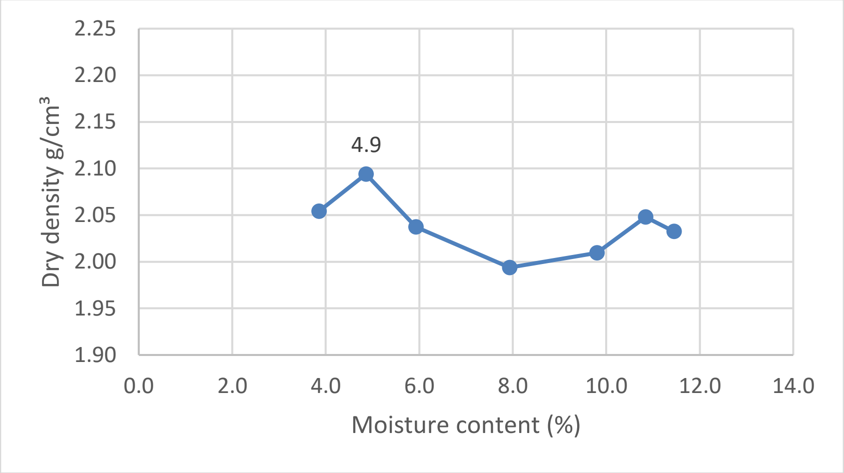


Figure 12. Compaction curve of 0/4 mm material with OMC of 4.9% and MDD of 2.1 g/cm^3

Generally, if a mixture is non self-draining, there is an OMC at which the dry density reaches its maximum value. However, if the dry density of the mixture is such that between 0.3% and 0.5% of the water is lost during compaction, then the OMC-MDD relationship cannot be specified. In that case, the water content of the mixture is referred to as "bleeding water content". As shown in Figure 13, such phenomenon was observed on sample No. 7 of the 0/4 mm material, where the material became fully saturated at 12% added water content and thus a pool of water was formed on its surface.

Figure 13. Self-draining mixture (sample No. 7) during compaction of material 0/4 for moisture content 12%

According to SS-EN 13286-2:2010, the bleeding water content can be calculated by adding the initial water contents of the sample in question (sample No. 7) and the sample before it (sample No. 6) and then dividing the result by two. In other words, the bleeding water content for sample No. 7 is actually 11.5%.

5.4. Static plate load

The measurements for the static plate load were conducted in a total of 6 test points, 3 for the 0/2 mm (TP1, TP2, TP3) and 3 for the 0/4 mm (TP4, TP5, TP6). The layout of the test points can be found in Appendix C. The deformation modules Ev_1 and Ev_2 measured in MPa as well as the ratio between the deformation modulus (Ev_2/Ev_1) are reported for each measuring point in Table 7. It is important to note that a significant difference between the deformation modules Ev_1 and Ev_2 means that the material could be packed better, whereas a small difference means that it is already properly packed. Therefore, the lower the bearing capacity ratio, the greater the degree of compaction.

Table 7. Deformation modules Ev_1 and Ev_2 for each measuring point and the corresponding bearing capacity ratio

Material	Test points	Ev_1 (MPa)	Ev_2 (MPa)	Ev_2/Ev_1
0/2	TP1	47.1	106.5	2.26
	TP2	51.1	117.6	2.30
	TP3	65.4	155.8	2.38
0/4	TP4	55	109.8	2.00
	TP5	43.1	123.7	2.87
	TP6	59.3	134.5	2.27

5.4.1. Comparison with technical requirements

Based on the obtained values of Ev_2 and the bearing capacity ratio Ev_2/Ev_1, an evaluation of the results can be done by comparing the values with the technical requirements provided by the Swedish Transport Administration (Trafikverket). As shown in Table 8, the requirements vary depending on the type of construction, whether it is as an unbound base layer of a flexible or rigid road or as filling against a bridge.

Table 8. Requirements for bearing capacity and bearing capacity ratio depending on the type of construction (Trafikverket, 2017)

Type of construction	Ev_2 (MPa)	Ev_2/Ev_1
Flexible pavement	If ≤ 140	≤ 2.8
	If > 140	$\leq 1+0.013*Ev_2$
Rigid pavement	If ≤ 120	≤ 2.8
	If > 120	$\leq 1+0.015*Ev_2$
Filling against bridge	≥ 120	≤ 2.8

After performing the necessary bearing capacity ratio calculations, as shown in Appendix E, it was found that almost all test points have values within limits, except for TP5 that has a bearing capacity ratio of over 2,8 that is over the permissible limit. As shown in Table 9, the values that are exceeding the permissible limits even after the calculations are highlighted in red, while the rest are values within the limits.

Table 9. Evaluation of the results based on the technical requirements for road construction and filling purposes (Trafikverket, 2017). Values exceeding the limit are highlighted in red.

		Flexible		**Rigid**		**Filling**	
Material	**Test point**	**Ev_2 (MPa)**	**Ev_2/Ev_1**	**Ev_2 (MPa)**	**Ev_2/Ev_1**	**Ev_2 (MPa)**	**Ev_2/Ev_1**
0/2	TP1	106.5	2.26	106.5	2.26	106.5	2.26
	TP2	117.6	2.30	117.6	2.30	117.6	2.30
	TP3	155.8	2.38	155.8	2.38	155.8	2.38
0/4	TP4	109.8	2.00	109.8	2.00	109.8	2.00
	TP5	123.7	2.87	123.7	2.87	123.7	2.87
	TP6	134.5	2.27	134.5	2.27	134.5	2.27

6. Discussion

The aim of this master thesis was to investigate certain properties of 0/2 mm and 0/4 mm quarry fines, such as natural water content, percentage of filler content, OMC-MDD relationship as well as bearing capacity, in order to determine whether they are suitable for use in the construction industry.

The water content determination test revealed that the 0/2 mm material had a higher water content (13.8%) than the 0/4 mm (10.4%). According to the sieve analysis using the wet sieving method, both materials are well-graded, with the 0/2 mm material having a higher percentage of filler content (15.8%) than the 0/4 mm (12.8%). These results reflect those of Courard et al. (2020) who also investigated 0/4 mm materials and found that the water content ranged from 11,9 to 14,7%. These findings suggest that there is a correlation between a high percentage of filler and a high percentage of natural moisture content, which is consistent with the findings of Muttuvely and Kjems (2021) that well-graded materials with a high percentage of fillers are more susceptible to higher moisture content. A possible explanation is that the 0/2 mm contains a lot more smaller particles than the 0/4 mm, resulting in smaller pore space and therefore water can be held tighter in its pores.

According to the findings of the modified Proctor tests, the 0/2 mm material had a higher OMC (6.9%) than the 0/4 mm (4.9%), although the MDD was very similar for both 0/2 mm (2.05 g/cm^3) and 0/4 mm (2.09 g/cm^3). This result is likely to be related to the higher percentage of filler contained in the 0/2 mm than the 0/4 mm material. Zhang et al. (2019) and Hou et al. (2019) recently studied the moisture-density relationship of 0/4 mm quarry fines by using the standard Proctor test. As a result, the former found that the MDD that could be achieved from the Proctor test was 2,04 g/cm^3 and with an OMC of 9,3%, while the latter found that the MDD ranged from 2,08 to 2,27 g/cm^3 while an OMC of 7,9 to 10,4% respectively. The MDD achieved in this study for the 0/4 mm was 2.09 g/cm^3, albeit at a significantly lower OMC of 4,9%. This confirms that the modified Proctor method is capable of achieving higher MDD at lower

OMC than the standard Proctor test. However, no studies could be found where quarry fines the size of 0/2 mm were investigated, therefore no comparison is possible. This further proves the novelty of this subject and how few to no studies have been conducted with regard to 0/2 mm quarry fines.

Furthermore, one of the samples from the 0/4 mm material was found to exhibit the effect of “bleeding water content”, which can occur when a sample becomes oversaturated and cannot absorb any more water. What is remarkable, however, is that the bleeding water was in the form of a pool on top of the sample rather than flowing from the bottom of the mould, as would be expected. Nonetheless, this bleeding water was essentially lost and was not accounted for when the compaction curve was plotted. After oven drying the sample, it became evident that it contained less water than what was originally added, and this reduction in moisture yielded a higher dry density.

Another unanticipated finding was that after achieving the OMC, the MDD of both 0/2 mm and 0/4 mm increased again instead of decreasing. It is unclear as to why that occurred and it is therefore suggested that additional laboratory tests be undertaken in the future, especially for water contents higher than the optimum water content achieved in this investigation. It is also worth noting that the 0/4 mm was more difficult to compact in the laboratory than the 0/2 mm. It was observed that as one portion of the sample would get compacted, the opposing side would heave, forming a “U” shape within the mould. These observations imply that some amount of fines may be required in the material to facilitate proper compaction, as the fines’ role would be to fill the intergranular space during compaction. This finding is also confirmed by Dawson (1989) who claimed that the reason for it could be that the compaction equipment used in the laboratory is too small to compact such fine material without introducing any significant edge effects.

The static plate load findings show that the 0/2 mm material is best suited for use in the unbound layer of a flexible or rigid pavement. However, it should be noted that the impact of vertical and horizontal stresses caused by vehicle motion, as well as long-term pavement deterioration were not considered in this investigation, therefore it is uncertain whether the material is suitable for low traffic roads or highways. As for the 0/4 mm it would have the same potential if it were not for one of the three test points exhibiting higher value than what the requirements allow. Both 0/2 mm and 0/4 mm materials are deemed unsuitable for use as filling against a bridge, based on the fact that 2 out of 3 test points exhibit values below the requirements. However, despite the promising results of the 0/2 mm material, questions still remain as the amount of water added to aid with the compaction was not measured and thus the effect of OMC on material compaction was not investigated. These results should therefore be interpreted with caution.

One of the limitations of the static plate load method is that it provides measurements only for certain points and does not consider the entire road surface where traffic loads are generally applied. Another limitation is that it is conducted over a short period of time, meaning that any settlement measured relates to short-term settlements and is not indicative of long-term deformation (Patel, 2019). These limitations are also supported by Shaban et al. (2021), who in addition argue that the test results can only be evaluated for the specific conditions under which the test is performed. According to Lehmann et al. (2020), the dynamic plate load test could be a viable alternative method for determining the deformation module of the secondary loading Ev_2, as the static plate load is significantly more expensive, time-consuming and requires experienced professionals to process the results. Despite these limitations, Decký et al. (2022) recommend using the static plate load method to assess a soil's bearing capacity and degree of compaction as long as the moisture content is within an acceptable range.

Several questions, however, remain unanswered for the time being, as these results are only valid for the investigated quarry fines and may not be representative of fines produced at other quarries. It is therefore suggested that additional laboratory and field testing be conducted to better our understanding of quarry fine utilization in the construction industry. If the same materials are to be investigated again, laboratory tests to determine particle density and water absorption (SS-EN 1097-

6:2013) as well as resistance to freezing and thawing (SS-EN 1367-1:2007) are recommended. The former is important for investigating how the material behaves when water penetrates into its water accessible voids, whereas the latter is important for northern regions with cold climates as it provides information on how the material behaves when subjected to the cyclic action of freezing and thawing.

7. Conclusion

The aim of this thesis was to investigate the potential use of 0/2 mm and 0/4 mm quarry fines in the construction industry and more specifically in the unbound layer of a road or as filling against a bridge. The 0/2 mm material was found to exhibit higher water content, filler content and OMC than the 0/4 mm material, indicating that the gradation of the material can have a significant impact on its ability to retain water, as the smaller the range of the particles is, the smaller the available pore space, and thus the water can be held on more tightly between the particles. When the bearing capacity measurements were compared to the technical requirements provided by the Swedish Transport Administration, it was found that the 0/2 mm material is slightly more suitable for use in road construction than the 0/4 mm. However, despite these promising results, there are various uncertainties to be considered, and therefore further investigation is needed, particularly with regard to the material's water absorption and compaction capabilities as well as its resistance to freezing and thawing cycles.

References

Birch, W., Datson, H. & Lowndes, I., 2008. Reducing the environmental effect of aggregate quarrying: Dust, Noise and Vibration. *Sustainable aggregates, University of Leeds and University of Nottingham.* [online] Available at: https://miningandblasting.pdf [Accessed 24 March 2022].

Courard, L., Rondeux, M., Zhao, Z., & Michel, F., 2020. Use of Recycled Fine Aggregates from C&DW for Unbound Road Sub-Base. *Materials, 13*(13), 2994, pp. 26. [online] Available at: https://doi.org/10.3390/ma13132994 [Accessed 18 February 2022].

Dawson, A.R., 1989. General report: the specification of granular materials for unbound pavement layers. *Unbound Aggregates in Roads*, pp. 17-26. [online] Available at: https://doi.org/10.1016/B978-0-408-04355-7.50012-1 [Accessed 8 March 2022].

Decký, M., Drusa, M., Papán, D., Šrámek, J., 2022. The relationship between dynamic and static deformation modulus of unbound pavement materials used for their quality control methodology. *Materials, 15*(8), 2922, p. 20. Available at: https://doi.org/10.3390/ma15082922 [Accessed 6 July 2022].

European Environment Agency (EEA), 2008. *Effectiveness of environmental taxes and charges for managing sand, gravel and rock extraction in selected EU countries.* [online] Available at: https://www.eea.europa.eu/publications/eea_report_2008_2/file [Accessed 7 March 2022].

Fehrm, M., 2019. *Petrografisk beskrivning, förenklad metod* [Petrographic description, simplified method]. Internal NCC report. Unpublished. (In Swedish)

Hou, W., Qamhia, I., Mwumvaneza, V., Tutumluer, E. and Ozer, H., 2019. Engineering characteristics and stabilization performance of aggregate quarry by-products from different sources and crushing stages. *Frontiers in Built Environment,* *5*(130), pp. 13. [online] Available at: https://doi.org/10.3389/fbuil.2019.00130 [Accessed 11 July 2022].

Hudson, W.R., Little, D.N., Razmi, A.M., Anderson, V. & Weissmann, A.J., 1997. An investigation of the status of by-product fines in the United States. *ICAR Technical Reports*. [online] Available at: http://hdl.handle.net/2152/35314 [Accessed 27 March 2022].

Johnning, P., n.d. *Wallhamn*. Internal NCC report. Unpublished. (In Swedish)

Langer, W.H., Giusti, C, Emilia, R. & Barelli, G., 2003. Sustainable development of natural aggregate, with examples from Modena Provence, Italy. *Transactions-Society for Mining Metallurgy and Exploration Incorporated, 314,* pp.138-144. [online] Available at: https://www.researchgate.net/Sustainable_development_of_natural_aggregate_with_examples_from_Modena_Province_Italy [Accessed 24 March 2022].

Lehmann, S., Leppla, S. & Norkus, A., 2020. Experimental study of the modulus of deformation determined by static and dynamic plate load tests. *The Baltic Journal of Road and Bridge Engineering, 15*(4), pp. 109-124. Available at: https://bjrbe-journals.rtu.lv/article/view/bjrbe.2020-15.497 [Accessed 5 July 2022].

Manning, D. & J. Vetterlein, 2004. Exploitation and use of quarry fines. *Mist Project-Solutions*, *44,* pp.1-60. [online] Available at: http://www.mineralsolutions.co.uk/mist/mist2.pdf [Accessed 25 March 2022].

Mitchell, C.J., Evans, E. & Harrison, D., 2001. REFILL: Low-cost fillers from quarry waste. *NERC Open Research Archive*. British Geological Survey. [online] Available at: https://nora.nerc.ac.uk/id/eprint/519300/ [Accessed 25 March 2022].

Mitchell, C.J., Mitchell, P. & Pascoe, R.D., 2008. Quarry fines minimization: can we really have 10mm aggregate with no fines? In: Walton, Geoffrey, (ed.) *Proceedings of the 14th Extractive industry geology conference*. EIG Conferences, 37-44, 109 pp. [online] Available at: http://nora.nerc.ac.uk/id/eprint/4932 [Accessed 24 March 2022].

Mitchell, C.J., 2009. Quarry fines and waste. In: *Quarries & Mines 2009*. Ten Alps, 63-67, 5 pp. [online] Available at: http://nora.nerc.ac.uk/id/eprint/6290/ [Accessed 24 March 2022].

Muttuvelu, D.V. & Kjems, E., 2021. A systematic review of permeable pavements and their unbound material properties in comparison to traditional subbase materials. *Infrastructures*, *6*(12), 16 pp. [online] Available at: https://doi.org/10.3390/infrastructures6120179 [Accessed 23 March 2022].

Patel, A., 2019. Geotechnical investigation. In A. Patel (Ed.), *Geotechnical Investigations and Improvement of Ground Conditions*, pp. 87-155. Available at: https://doi.org/10.1016/B978-0-12-817048-9.00009-3 [Accessed 5 July 2022].

Petavratzi, E. & Wilson, S., 2008. Sustainable utilisation of quarry by-products. *Minerals Industry Research Organisation, English Heritage or The Department for Environment, Food and Rural Affairs*. [online] Available at: https://www.yumpu.com/sustainable-utilisation-of-quarry-by-products-sustainable-aggregates [Accessed 24 March 2022].

Poulin, R., Pakalnis, R. & Sinding, K., 1994. Aggregate resources: Production and environmental constraints. *Environmental Geology*, [online] *23*(3), pp. 221-227. [online] Available at: https://link.springer.com/10.1007/BF00771792 [Accessed 18 February 2022].

Rezende, L.R. & de Carvalho, J.C., 2004. The performance of an experimental road constructed from quarry waste. *Pavements Unbound*, p.312. [online] Available at: https://www.researchgate.net/Pavements-Unbound [Accessed 24 March 2022].

SGU, 2021. *Grus, sand och krossberg 2020*. [Gravel, sand and crushed rock 2020]. [online] Available at: https://resource.sgu.se/pp2021-3-rapport.pdf [Accessed 29 January 2022]. (In Swedish)

Shaban, A.M., Almuhanna, R.R. & Jawad, A.A., 2021. Performance characterization of unsaturated granular soils using static and dynamic plate load test. *Geotechnical Testing Journal, 44*(6)*, pp. 1821–1838*. Available at: https://www.astm.org/gtj20200191.html [Accessed 5 July 2022].

Soosan, T.G., Sridharan, A., Jose, B.T. & Abraham, B.M., 2005. Utilization of quarry dust to improve the geotechnical properties of soils in highway construction. *Geotechnical Testing Journal, 28*(4), pp. 391-400. [online] Available at: https://www.astm.org/gtj11768.html [Accessed 27 March 2022].

Statistics Sweden, 2021. The future population of Sweden 2021–2070. Demographic reports 2021:1. [online] Available at: https://www.scb.se/future_population_of_sweden.pdf [Accessed 29 January 2022]. (In Swedish)

Svensk Byggtjänst, 2020. *AMA Anläggning 20. Allmän Material–och Arbetsbeskrivning för Anläggningsarbeten*. Svensk Byggtjänst,Västerås, Sweden. ISBN: 9789179170172. (in Swedish)

Zhang, Y., Korkiala-Tanttu, L.K., Gustavsson, H. and Miksic, A., 2019. Assessment for sustainable use of quarry fines as pavement construction materials: Part I—description of basic quarry fine properties. *Materials*, *12*(8), 1209. pp. 17. [online] Available at: https://doi.org/10.3390/ma12081209 [Accessed 11 July 2022].

Öberg-Högsta, A.L., 2000. *Undersökning av krossmaterial för användning som täckskikt på deponier* [Examination of crushed material for use as a cover layer at landfills]. Internal NCC report. Unpublished. (In Swedish)

European Standards

EN 933-1, Tests for geometrical properties of aggregates – *Part 1: Determination of particle size distribution – Sieving method*

EN 932-2, Tests for general properties of aggregates — *Part 2: Methods for reducing laboratory samples*

EN 1097-5, Tests for mechanical and physical properties of aggregates – *Part 5: Determination of the water content by drying in a ventilated oven*

EN 13242+A1:2007, Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction

EN 13286-2, Unbound and hydraulically bound mixtures – *Part 2: Test methods for laboratory reference density and water content – Proctor compaction*

EN ISO 14688-2:2018, Geotechnical investigation and testing – Identification and classification of soil – Part 2: Principles for a classification (ISO 14688-2:2017)

Foreign Standard

DIN 18134, Soil - Testing procedures and testing equipment - Plate load test, English translation of DIN 18134:2012-04

Technical requirements and advices

Trafikverket, 2005a. *ATB VÄG 2005 - Kapitel A Gemensamma förutsättningar* [Chapter A Common prerequisites] TDOK 2005:112. [online] Available at: https://www.trafikverket.se/contentassets/c19c23215b0f477a8e179c8aa4082c98/kapitel_a_gemensamma_forutsattningar.pdf [Accessed 29 January 2022]. (In Swedish)

Trafikverket, 2005b. *ATB VÄG 2005 - Kapitel C Dimensionering* [Chapter C Dimensioning] TDOK 2005:112. [online] Available at: https://www.trafikverket.se/contentassets/c19c23215b0f477a8e179c8aa4082c98/kapitel_c_dimensionering.pdf [Accessed 29 January 2022]. (In Swedish)

Trafikverket, 2005c. *ATB VÄG 2005 - Kapitel E Obundna material* [Chapter E Unbound materials] TDOK 2005:112. [online] Available at: https://bransch.trafikverket.se/contentassets/c19c23215b0f477a8e179c8aa4082c98/kapitel_e_obundna_material.pdf [Accessed 29 January 2022]. (In Swedish)

Trafikverket, 2011. *TRVK Väg - Trafikverkets tekniska krav Vägkonstruktion* [TRVK Road - The Swedish Transport Administration's technical requirements Road construction] TDOK 2011:264. [online] Available at: https://trafikverket.ineko.se/Files/sv-SE/10750/RelatedFiles/2011_072_TRVK_vag_2.pdf [Accessed 18 March 2022]. (In Swedish)

Trafikverket, 2014. *Bestämning av bärighetsegenskaper med statisk plattbelastning* [Determination of load-bearing properties with static plate load] TDOK 2014:0141, Version 1.0. [online] Available at: https://trvdokument.trafikverket.se/fileHandler.ashx?typ=showdokument&id=32bfae39-4122-461f-90b0-350d7523838a [Accessed 27 January 2022]. (In Swedish)

Trafikverket, 2016a. *Trafikverkets tekniska krav för geokonstruktioner-TK Geo 13* [The Swedish Transport Administration's technical requirements for geoconstructions-TK Geo 13] TDOK 2013:0667, Version 2.0. [online] Available at: https://trvdokument.trafikverket.se/fileHandler.ashx?typ=showdokument&id=46592c07-199a-4d8b-b417-d82362c9f806 [Accessed 2 February 2022]. (In Swedish)

Trafikverket, 2016b. *Trafikverkets tekniska råd för geokonstruktioner-TR Geo 13* [The Swedish Transport Administration's technical advice for geoconstructions-TR Geo 13] TDOK 2013:0668, Version 2.0. [online] Available at: https://trvdokument.trafikverket.se/fileHandler.ashx?typ=showdokument&id=a0d1b708-6b17-437e-b3b2-42bf6c571281 [Accessed 2 February]. (In Swedish)

Trafikverket, 2017. *Obundna lager för vägkonstruktioner* [Unbound layers for road construction] TDOK 2013:0530. [online] Available at: https://trvdokument.trafikverket.se/fileHandler.ashx?typ=showdokument&id=82fbe538-3ccd-456f-9674-1fd0e170db34 [Accessed 27 January 2022]. (In Swedish)

Appendix A – Sieve analysis data

0/2			
Sieve aperture size (mm)	**Weight retained (g)**	**Percentage retained (%)**	**Cumulative percentage passing (%)**
5.6	-	-	100
4.0	0.1	0.0	99.98
2.0	30.4	4.8	95.2
1.0	152.6	24.1	71.1
0.5	111.2	17.6	53.5
0.25	88.2	13.9	39.6
0.125	79.5	12.6	27.0
0.063	69.6	11.0	16.0
Material in the pan	31.4		
Total	563		

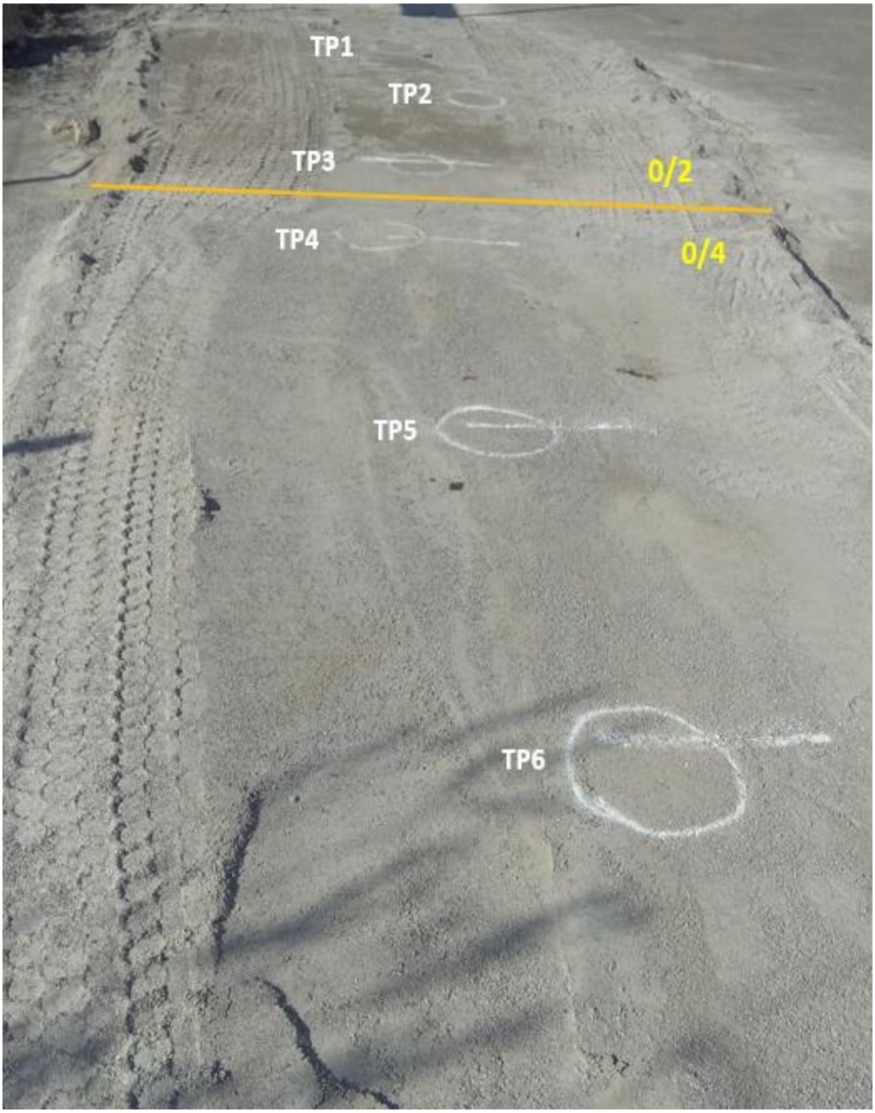
0/4			
Sieve aperture size (mm)	**Weight retained (g)**	**Percentage retained (%)**	**Cumulative percentage passing (%)**
8.0	-	-	100
5.6	0.6	0.1	99.91
4	12.1	1.8	98.13
2	175.5	25.9	72.24
1	152.1	22.4	49.80
0.5	94.9	14.0	35.80
0.25	59.8	8.8	26.98
0.125	50.2	7.4	19.58
0.063	47.5	7.0	12.57
Material in the pan	15.2		
Total	607.9		

Appendix B – Modified Proctor compaction data

0/2								
Property (unit)	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Sample 6**	**Sample 7**	**Sample 8**
Dry weight (g)	2454	2782.3	2572	2540.8	2504.8	2982.8	2519.1	2477.1
Added water (%)	4.0	6.0	6.5	7.0	7.5	8.0	9.0	10.0
Added water (g)	98.2	166.9	167.2	177.9	187.9	238.6	226.7	247.7
Moist sample + cylinder weight (g)	7674.3	7711.1	7789	7814.5	7800.2	7803.8	7786.6	7828.2
Cylinder weight (g)	5761.8	5761.8	5761.8	5761.8	5761.8	5761.8	5761.8	5761.8
Moist sample weight (g)	1912.5	1949.3	2027.2	2052.7	2038.4	2042	2024.8	2066.4
Dried sample (g)	1840.1	1841.5	1905.5	1921	1899.5	1893.2	1858.5	1881.5
Water weight (g)	72.4	107.8	121.7	131.7	138.9	148.8	166.3	184.9
Cylinder volume (cm^3)	939.6	939.6	939.6	939.6	939.6	939.6	939.6	939.6
Actual water ratio (%)	3.9	5.9	6.4	6.9	7.3	7.9	8.9	9.8
Bulk density (g/cm^3)	2.035	2.075	2.158	2.185	2.169	2.173	2.155	2.199
Dry density (g/cm^3)	1.958	1.960	2.028	2.044	2.022	2.015	1.978	2.002
Water density (g/cm^3)	0.9971	0.9971	0.9971	0.9971	0.9971	0.9971	0.9971	0.9971

0/4							
Property (unit)	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Sample 6**	**Sample 7**
Dry weight (g)	2647.5	2651.8	2669.7	2395.7	2251.2	2644	2495.9
Added water (%)	4.0	5.0	6.0	8.0	10.0	11.0	12.0
Added water (g)	105.9	132.6	160.2	191.7	225.1	290.8	299.5
Moist sample + cylinder weight (g)	7766.1	7824.9	7789.6	7783.8	7834.8	7894.8	7890.1
Cylinder weight (g)	5761.8	5761.8	5761.8	5761.8	5761.8	5761.8	5761.8
Moist sample weight (g)	2004.3	2063.1	2027.8	2022	2073	2133	2128.3
Dried sample (g)	1929.9	1967.5	1914.3	1873.4	1888	1924.4	1909.7
Water weight (g)	74.4	95.6	113.5	148.6	185	208.6	218.6
Cylinder volume (cm^3)	939.6	939.6	939.6	939.6	939.6	939.6	939.6
Actual water ratio (%)	3.9	4.9	5.9	7.9	9.8	10.8	11.4
Bulk density (g/cm^3)	2.133	2.196	2.158	2.152	2.206	2.270	2.265
Dry density (g/cm^3)	2.054	2.094	2.037	1.994	2.009	2.048	2.032
Water density (g/cm^3)	0.9971	0.9971	0.9971	0.9971	0.9971	0.9971	0.9971

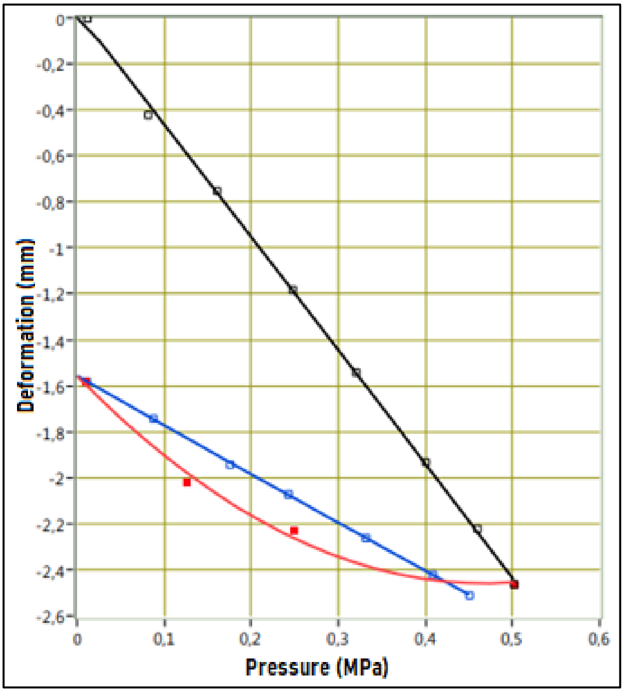
Appendix C – Test points (Static plate load)



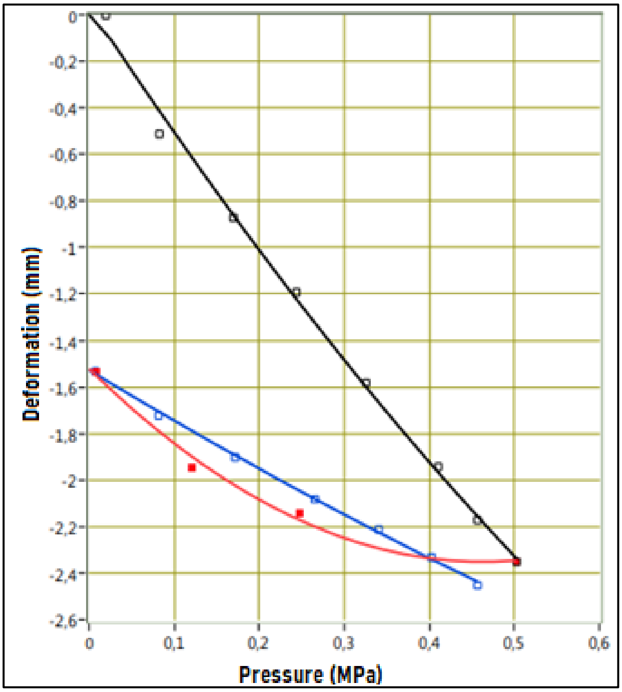
Appendix D – Pressure & Deformation values and graphs for each test point (Static plate load)

Note: The black line represents the first loading (Ev1) up to 0.5 MPa, the blue the unloading and the red the second loading (Ev2) up to 0.45 MPa.

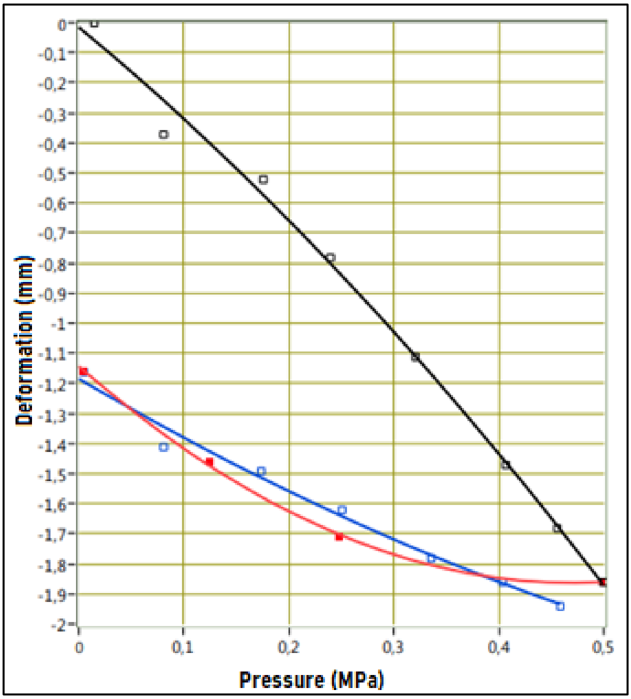
TP1	
Pressure (MPa)	Deformation (mm)
0.011	0
0.081	0.42
0.16	0.75
0.247	1.18
0.32	1.54
0.4	1.93
0.459	2.22
0.501	2.46
0.248	2.23
0.125	2.02
0.01	1.58
0.087	1.74
0.175	1.94
0.242	2.07
0.331	2.26
0.408	2.42
0.45	2.51



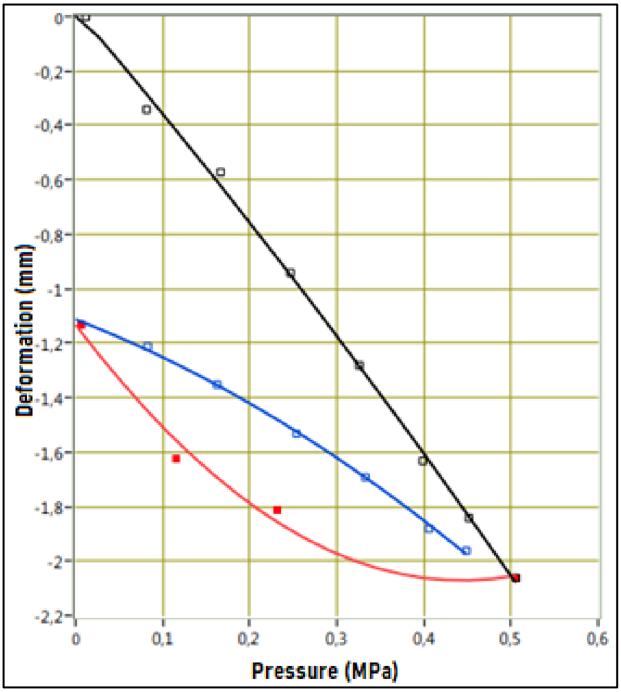
TP2	
Pressure (MPa)	Deformation (mm)
0.019	0
0.082	0.51
0.169	0.87
0.243	1.19
0.325	1.58
0.41	1.94
0.456	2.17
0.502	2.35
0.246	2.14
0.12	1.94
0.007	1.53
0.081	1.72
0.171	1.9
0.265	2.08
0.34	2.21
0.402	2.33
0.456	2.45



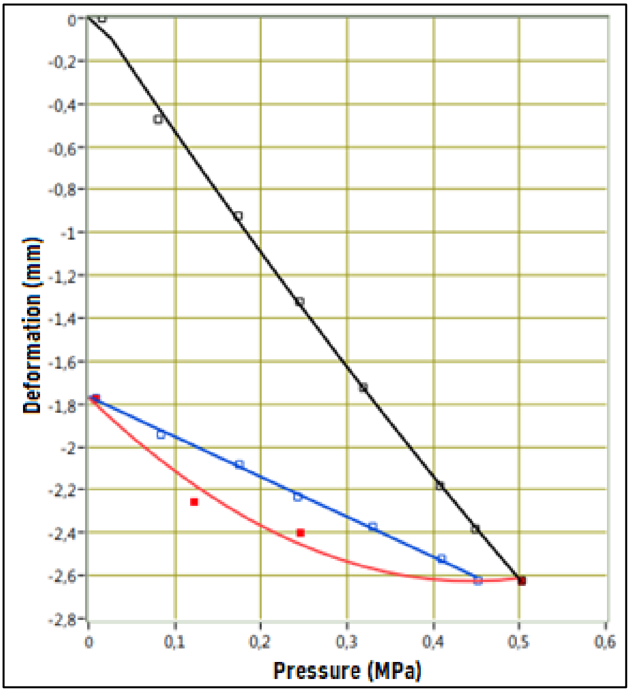
TP3	
Pressure (MPa)	Deformation (mm)
0.014	0
0.08	0.37
0.175	0.52
0.239	0.78
0.32	1.11
0.406	1.47
0.455	1.68
0.499	1.86
0.247	1.71
0.123	1.46
0.004	1.16
0.08	1.41
0.173	1.49
0.25	1.62
0.335	1.78
0.403	1.86
0.458	1.94



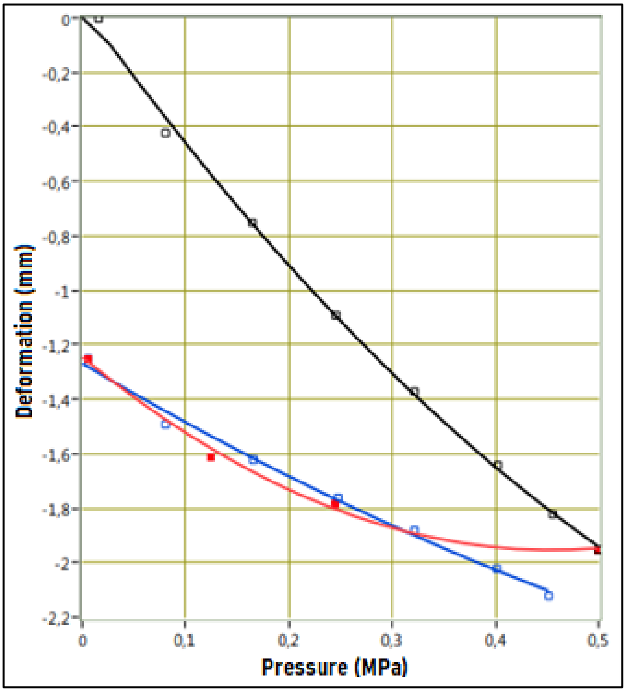
TP4	
Pressure (MPa)	Deformation (mm)
0.011	0
0.081	0.34
0.166	0.57
0.246	0.94
0.325	1.28
0.398	1.63
0.451	1.84
0.505	2.06
0.231	1.81
0.114	1.62
0.006	1.13
0.082	1.21
0.162	1.35
0.253	1.53
0.332	1.69
0.405	1.88
0.448	1.96



TP5	
Pressure (MPa)	Deformation (mm)
0.015	0
0.08	0.47
0.173	0.92
0.244	1.32
0.318	1.72
0.407	2.18
0.448	2.38
0.502	2.62
0.245	2.4
0.121	2.25
0.008	1.77
0.083	1.94
0.174	2.08
0.242	2.23
0.329	2.37
0.409	2.52
0.451	2.62



TP6	
Pressure (MPa)	Deformation (mm)
0.015	0
0.08	0.42
0.164	0.75
0.245	1.09
0.321	1.37
0.402	1.64
0.455	1.82
0.499	1.95
0.244	1.78
0.124	1.61
0.005	1.25
0.08	1.49
0.165	1.62
0.247	1.76
0.321	1.88
0.401	2.02
0.451	2.12



Appendix E – Calculations for Ev_2/Ev_1

Flexible TP3: $Ev_2/Ev_1 = 1 + 0.013 * 155.8 = 1 + 2.0254 = 3.0254 \approx 3.0$

Rigid TP3: $Ev_2/Ev_1 = 1 + 0.015 * 155.8 = 1 + 2.337 = 3.337 \approx 3.3$

Rigid TP5: $Ev_2/Ev_1 = 1 + 0.015 * 123.7 = 1 + 1.8555 = 2.8555 \approx 2.9$

Rigid TP6: $Ev_2/Ev_1 = 1 + 0.015 * 134.5 = 1 + 2.0175 = 3.0175 \approx 3.0$