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The use of recycled materials as binders to stabilize soft clay in laboratory

Master Thesis

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Abstract of master's thesis

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ABSTRACT

Construction on the site with soft clay is difficult in many ways. The challenges are the low undrained shear strength and high compressibility of soft clay. Mass stabilization, as one of the ground improvement method, is able to improve properties of soft clay.

During mass stabilization process, the adding of suitable binders improves strength and load bearing capacity of soft clay. Mass stabilization is an economical and environmentally friendly ground improvement method when binders based on recycled materials are used. Binder is the main matter, which defines the environmental and economical effects of mass stabilization.

The objective of this thesis was to find out the most suitable type of binder or binder mixture and the right proportion of ingredients for soft clay in Depot of Vuosaari, Helsinki. This study dealt with tests of several kinds of binder in laboratory condition for further in-situ mass stabilization. Gypsum from VTT Oy, ashes mixture from Ecolan Oy and fly ash from HELEN Oy were the main researched materials in this study. Cement and lime-cement mixture were also used as the reference materials. Unconfined compression tests were the main tests carried out to evaluate and measure the undrained shear strength of stabilized clay. Samples were tested at the age of 28 days and 3 months. In addition, in the aim of getting more comprehension of binders, bending test and compression test were performed on pure binders. In this study, all the binders took a certain degree of increase to the strength of soft clay. Ashes mixture from Ecolan mixed with cement performed as the best combination with a highest undrained shear strength (over 600 kPa).

Keywords soft clay, mass stabilization, binder, recycled materials, laboratory tests

PREFACE

This thesis is about the use of recycled materials as binders to stabilize soft clay in laboratory. The work has been carried out in Geotechnical Laboratory of Aalto University and financially supported by both Aalto University and Ramboll Finland Oy. My supervisor was Professor Leena Korkiala-Tanttu. I would like to express my gratitude for her enthusiastic attitude and advice throughout my studies. I am also grateful to my advisor, Master of Science (Tech.) Juha Forsman, for offering comprehensive background of this study and supporting me in carrying it out.

A number of people have also supported me in various ways for this thesis, and I would like to express my special thanks to them.

• VTT Technical Research Centre of Finland Ltd, Ecolan Oy and HELEN Oy, for offering recycled materials as binders, which are the main research materials in this study.

• City of Helsinki for sampling and delivering soil samples from Vuosaari site.

• Matti Ristimäki, for assisting in preparing samples and performing tests on numerous samples of stabilized clay in the laboratory.

• Veli-Antti Hakala and Jukka Piironen for offering test materials (cement), providing test machine for bending test and compression test of pure binders, carrying out parts of the tests in pure binders.

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Finally, but not least, I would like to thank all the members of my family and my friends for their endless support and encouragement, also in my studies.

Espoo, February 2019

Tianlingzi Xiong

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

W_{soil}	mass of clay in the mixture
ρ_{wet}	wet density of clay
V_{total}	total volume of the mixture
W_{binder}	mass of binder in the mixture
ρ_{binder}	required density of binder
c_u	undrained shear strength
c_{urfc}	undrained shear strength of remolded soil
c	constant, dependent on the tip angle of the cone
g	acceleration due to gravity at free fall
m	mass of cone
i	average cone penetration
q_u	unconfined compression strength
σ_1	vertical stress
ε	vertical strain
ΔH	vertical compression of specimen
H_i	initial height of specimen
P	vertical load acting on the specimen
A_1	initial cross-sectional area of specimen
R_f	flexural strength
F_f	load applied to the middle of the prism at fracture
R_c	compressive strength
F_c	maximum load at fracture
UCT	unconfined compression test

FCT	fall cone test
LCM	lime-cement mixture
BT	bending test
CT	compression test

1. INTRODUCTION

Construction on the site with soft clay subgrade is not an ideal solution. The challenges are the low undrained shear strength and high compressibility of soft clay. Ground improvement should be implemented to optimize engineering properties of soft clay. In situ deep mixing methods are applicable to stabilize soft clay.

Mass stabilization is one of the deep mixing methods. It was developed in Finland in the early 1990's. During mass stabilization process, the adding of suitable binders improves strength and load bearing capacity of soft clay. It is an economical and environmentally friendly ground improvement method when binders based on recycled materials are used. This ground improvement method is especially suitable for soft soil such as clay, peat and mud. The main objectives of mass stabilization include decreasing settlement, improving stability and stiffness of soft soil, treatment of contaminated soils and improving the construction conditions.

From geotechnical aspect, the result of the mass stabilization method and the rate of improvement are variable depending on many factors. One of the main factors is the type and amount of binder or binder mixture. Binder is the stabilizing agent, which chemically reacts with the soil. Cement and lime or a mixture of them are commonly used as binders, and besides them, industrial recycled materials are also used for cost saving reasons.

Optimization on type and quantity of binder should be made in laboratory before in-situ processes. It is important to the result of mass stabilization. The objective of this thesis was to find out the most suitable type of binder or binder mixture and the right proportion of ingredients for soft clay from Depot of Vuosaari, Helsinki. This study dealt with tests of several kinds of binder in laboratory condition for further in-situ mass stabilization. Gypsum from VTT, Ashes mixture from Ecolan Oy and fly ash from Helen Oy were three different research materials in this study. Cement and lime-cement mixture were also used as the reference materials.

Binders were tested in laboratory condition mainly based on unconfined compression test. Fall cone test was also carried out as an auxiliary method. Those binders were mixed with cement separately in three kinds of different mixture rate and amount. Cement and lime-cement mixture were also used in this study as reference materials.

However, this study was focused on laboratory tests to define the hardening process and behavior of different binders. On-site tests are necessary for further study. In addition, more consideration of environmental issues should be studied since this study was only for mechanical properties consideration.

2. LITERATURE SURVEY

Using binders to stabilize soft clay is the core concept of deep mixing method, to which mass stabilization also belongs. Mass stabilization, as the main discussed method in this study, will be introduced in the first section of chapter 2. It includes both the classification and techniques aspects.

In order to control the stabilization process smoothly and successfully, it is necessary to comprehend the effects of soil on stabilization. In addition, before selecting the recycled materials as a binder, introducing the basic knowledge of binder is required. Since in this study, soft clay is the stabilized aggregate, the binders for soft clay were the main research objects.

2.1 Mass stabilization

This ground improvement method is especially suitable for soft soil such as clay, peat and mud. The main objectives of mass stabilization include decreasing settlement, improving stability and stiffness of soft soils, protecting from contaminated soils and improving the construction conditions. (Forsman et al., 2015). Soft clay was the aggregate for testing in this study. In mass stabilization process, the strength properties and load bearing capacity of soft clay are improved by adding suitable binders. (Lahtinen & Niutanen, 2009).

2.1.1 Classification of ground improvement methods

There are many different kinds of classification ways to group numerous ground improvement techniques. Lietaert and Maucotel (2012) summarizes three different classification methods, from which, the one proposed by Technical Committee 211 of the ISSMGE covers all the available ground improvement treatments. This classification method assorts all the treatments into five categories:

- A: Ground improvement without admixtures in non-cohesive soils or fill materials,

- B: Ground improvement without admixtures in cohesive soils,

- C: Ground improvement with admixtures or inclusions,

- D: Ground improvement with grouting type admixtures,

- E: Earth reinforcement.

Using admixtures or not, soil types and admixtures types are the main elements to differentiate ground improvement methods from these five categories. Mass stabilization, according to this classification method, belongs to type C as a mixing method. The Deep Mixing System is shown in Figure 2.1.

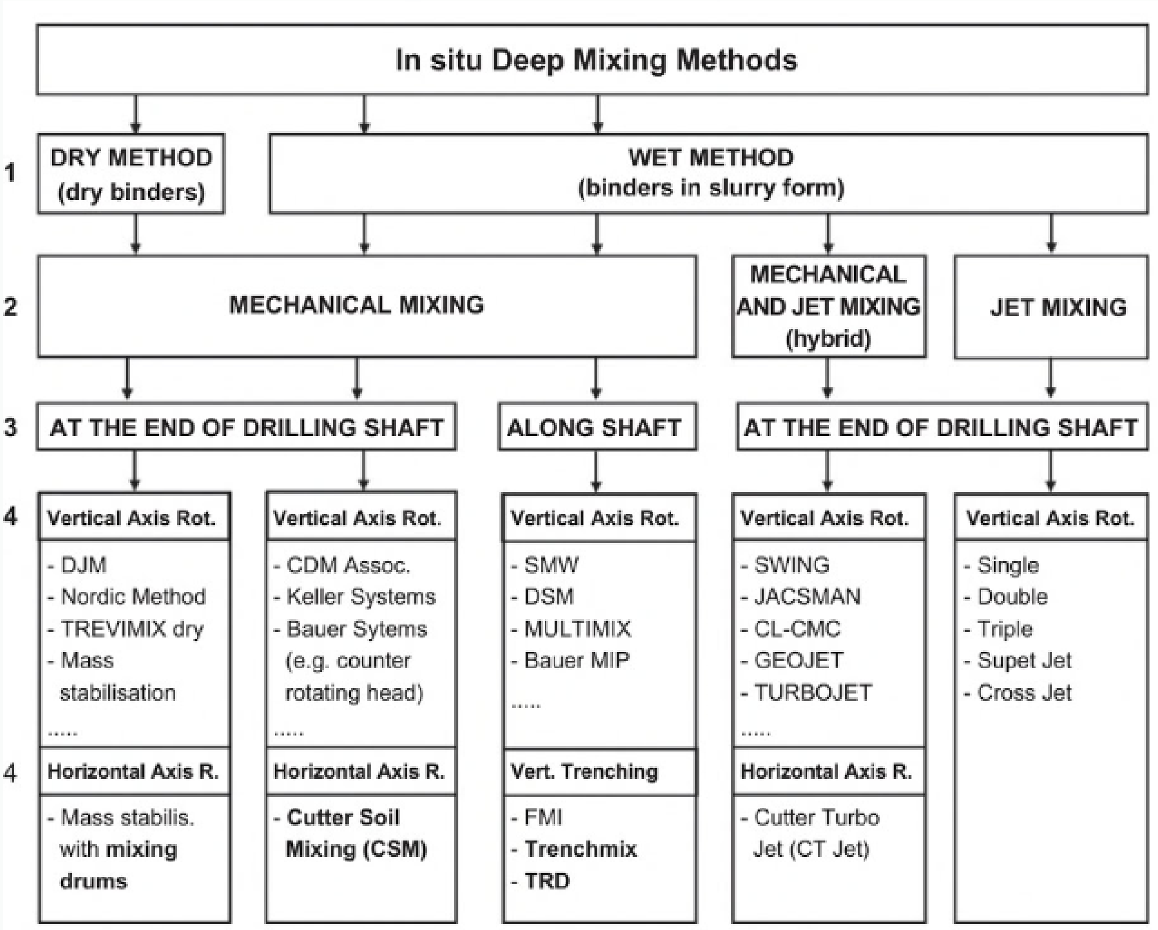


Figure 2.1 *Updated classification scheme of deep soil mixing (DSM) system (Topolnicki 2012)*

2.1.2 Techniques of mass stabilization

Mass stabilization equipment is used in the stabilization work at site. The composition of mass stabilization equipment is shown in Figure 2.2. Excavator with a mixing tool, as the basic machinery unit, is connected with a pressure feeder and a detached mixing tool. Control unit and data acquisition system are also part of the whole mass stabilization system.

The processes of stabilization work at site include clearing, filling and levelling up the ground surface and partitioning stabilization blocks. During the process of soil stabilization, the soil is premixed first. Pre-mixing of soil makes an even pre-stabilization soil mass hence a predictable result in the future. (Forsman et al., 2018). Soil is homogenized by feeding binding agent in from the head of mixing unit, which is moved both vertically and laterally in the stabilized layer. By this way, the binder is fed and mixed as evenly as possible. (Forsman et al., 2015).

Whether bespoke machinery or common construction machinery is used depends on the task and scope of project (Forsman et al., 2015). When the circumstance is favorable enough, stabilization can be carried out to depth of 7-8 meters. Normally, the optimal stabilization depth is about 3-5 meters (Forsman et al., 2018).

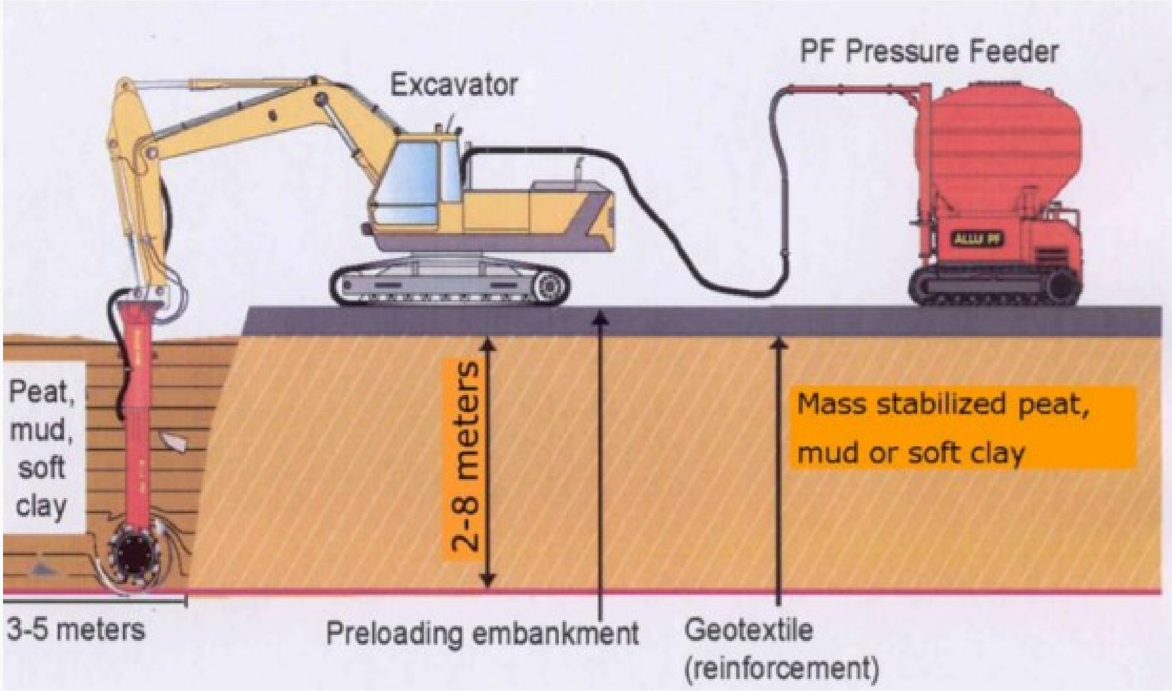


Figure 2.2 *Principle of the mass stabilization method and equipment (Forsman et al., 2015)*

Two mixing methods are mentioned in Forsman et al., (2018). One is dry mixing, in which stabilizer is added to the soil in dry state. Dry mixing method is usually used in mass stabilization. The other is wet mixing when stabilizer is added to the soil in slurry state, mixed with water. Dry technique is usually used in “Nordic stabilization method”, while wet mixing requires additional type and design of feeder and also higher binder addition rate. (Forsman et al., 2018).

2.1.3 Advantages of mass stabilization

From the technical point of view, mass stabilization can improve the bearing capacity and stability of soil mass by increasing the strength of soft soil. Mass stabilization will also reduce the settlement and mitigate vibration of construction or structure. In addition, from environmental aspect, mass stabilization can be used to solidificate contaminated soil. By bounding the harmful substances together, the solubility is decreased. The use of recycled materials is also an environmental friendly custom, thereby saving the natural resources. (Forsman et al., 2015). In addition, the reduction of using expensive materials and the simplified construction process can make the whole mass stabilization project cost saving. Reducing the need of transportation of weak or contaminated soil also decreases expenses and environmental impacts. (Forsman et al., 2015).

2.2 Impacts of mass stabilization on soil

To determine whether mass stabilization method is appropriate for a project or not, some basic investigation of soil is need, which include the depth of the soil layers, the water content, density, classification of the soil, its strength, compressibility and the pH value.

From geotechnical aspect, the characteristics of soil change significantly as the result of mass stabilization. The final result of the mass stabilization method and the rate of change depend on many factors. One is related to the material itself, such as the type of soil, the type and amount of binder or binder mixture. The others are external factors, such as compaction load, curing time and temperature. (Forsman et al., 2015).

On the other hand, mass stabilization process will also alter the characteristics of soil. These characteristics include index properties (i.e., water content, density, plasticity, etc.), strength, compressibility and water permeability. The failure mechanism of stabilized soil also changes, which leads to a more brittle material than the original soil. (Forsman et al., 2015). The impact of stabilization on the unconfined compressive strength and the deformation of clay is shown in Figure 2.3 (Forsman et al., 2015).

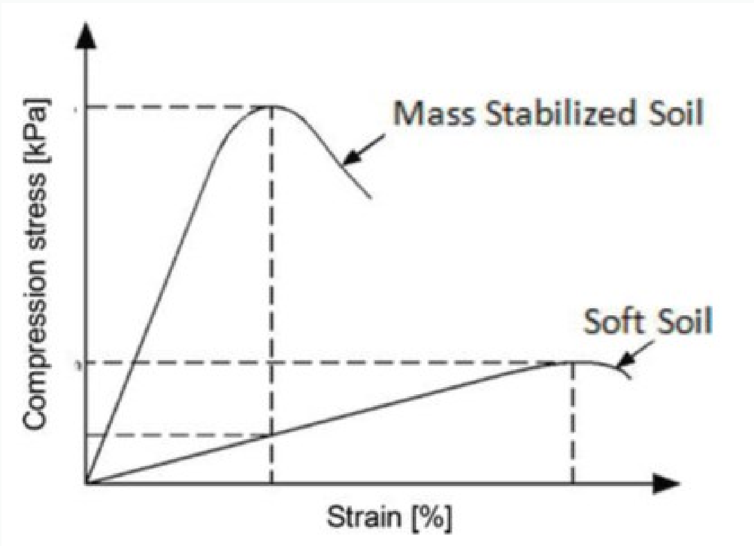


Figure 2.3 *The impact of stabilization on the unconfined compressive strength and the deformation of clay* (Forsman et al., 2018).

2.3 Binders for mass stabilization

Binder is the stabilizing agent, which creates chemical bonds between grains to change its deformation and strength properties (Forsman et al., 2018). Optimization of type and quantity of binder should be tested in laboratory before in-situ processes, which is crucial to the result of mass stabilization. Types of binder and influence of binder on soil properties should be studied before choice of binder. (Forsman et al., 2015).

The selection of suitable binders depends on target strength, material price and its availability. In the whole unit price of mass stabilization, around 70 % is the cost on the binder. The choice of efficient and economical binder is important to the cost saving for the whole project. (Forsman et al., 2017). In some case, leaching and permeability features should also be considered (Forsman et al., 2015).

2.3.1 Types of binder

Cement and lime are the most commonly used binders in mass stabilization, from which, lime is usually used by mixing with cement. As mentioned in section 2.1, the use of industrial recycled materials as binders is economical and environmental friendly. These various recycled materials include for example slags, fly ash (from coal or bio combustion), silica fume and gypsum components. The choice of binder or mixture depends on soil properties. (Forsman et al., 2015).

Cement

Cement is produced by introducing raw materials into a kiln. The maximum temperature of kiln is approximately 1500 ºC to change the chemical composition of these materials. The main ingredient in cement is limestone. It is crushed with a silica source (e.g. sand or clay), an alumina source, and an iron source (e.g. mill scale). Then it is introduced into a kiln to be heated. This process transforms the raw materials into clinker, which is mainly comprised of calcium silicates and calcium aluminates. The clinker is then further processed by grinding with the addition of a small quantity of gypsum to create cement. (Kosmatka et al., 2002).

As the most commonly used binder in mass stabilization, cement has a significant advantage. Cement develops the strength of stabilized mass in relatively short time during the initial curing. The long-term development is nevertheless more unremarkable than that of other binders. Moreover, soil stabilized by cement is usually hard but brittle. Fortunately, this feature does not influence the final function that much since the structure originated from mass stabilization is a thick slab-like and coherent mass layer. (Forsman et al., 2015).

It is worth noting that the mixing quality is especially important when cement is used as a binder in mass stabilization since the movement of calcium ions in aggregate is low. Therefore, if the mixing of cement with aggregate is not enough, the potential heterogeneity will not improve with time. (Forsman et al., 2015).

Suitable cement products used in mass stabilization based on the EN 197- standard are: composite Portland cement with normal initial strength (CEM II / BM (S-LL*) 42.5 N), Portland cement with limestone with high early strength (CEM II / A-LL 42.5 R), Portland cement with high initial strength (CEM I 52.5 R), and SR-cement (CEM I 42.5 n-SR3). (Forsman et al., 2015).

Lime

Quicklime (CaO) is the most used lime in stabilization, but also hydrated lime ($Ca(OH)_2$) is used sometimes. Practically, lime products are always used in the form of mixture with other binder, from which cement is the most common case. (Forsman et al., 2015).

Quicklime is produced in the similar processes of cement, by heating limestone in a kiln (Figure 2.4). The maximum temperature in the kiln is around 1000 ºC, which is lower than the heat needed in cement production. The calcium carbonate ($CaCO_3$) content present in a high calcium limestone is converted into calcium oxide (CaO) during calcination to release carbon dioxide (CO_2) (Boynton, 1980). The by-product of cement clinker production is cement kiln dust (CKD) while the by-product of quicklime clinker production called lime kiln dust (LKD), which are all fine grained. However, the LKD generally has a higher lime content. (Mackie, 2010).

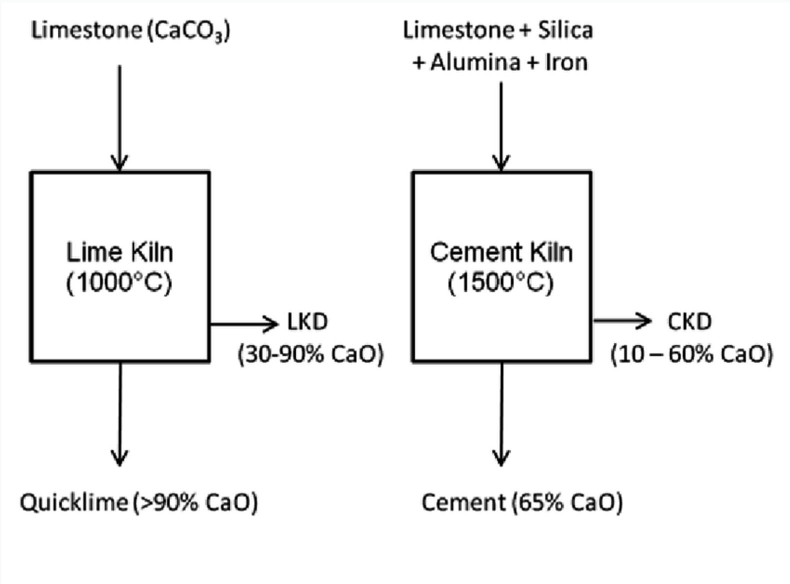


Figure 2.4 *Comparison of the production of quicklime and cement clinker (Mackie, 2010).*

The hydration will occur in quicklime because of the large amounts of calcium oxide. The lime contacts with the pore water in the soil and the calcium hydroxide is formed. It could be concluded that lime has two significant differences with cement. Slaking process and flocculation of clay particles will take place due to the formed calcium hydroxide absorbed onto the soil particles. Those will change the soil into a much coarser and drier condition. (Boardman etal., 2001). In addition, other part of the calcium hydroxide will react with the silica and alumina of minerals contained in the soil, those reactions are called as pozzolanic reactions. From pozzolanic reactions, calcium aluminate silicate hydroxide (CASH), calcium silicate hydroxide (CSH) and/or calcium aluminate hydroxide (CAH) are formed. However, when using cement, CSH is primarily formed since pozzolanic reaction happens in a much lesser degree. (Åhnberg, 2006). Two other differences between lime and cement also exists. One is that lime has a slow initial curing effect with long term reactions, which is totally converse from cement. Additionally, the movement of lime to surrounding soil is much higher than of cement, which make the mixtures much homogeneous to refine the final structures. (Forsman et al., 2015). This curing difference from cement and lime is explained in Figure 2.5.

The combination of advantages from each other makes mixture of lime and cement the dominating binder nowadays. The use of different binders with the years in Sweden is shown in Figures 2.6, which proves the huge demand of lime-cement mixtures in deep mixing (included the use in column and mass stabilization).

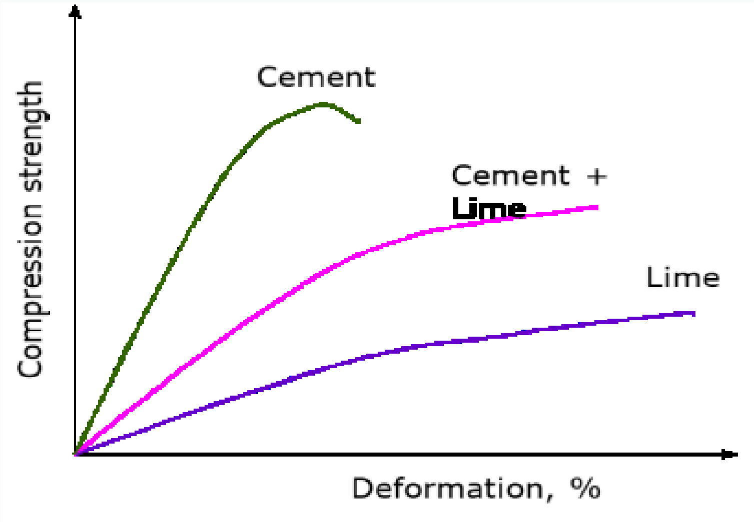


Figure 2.5 *Difference of deformation and compression strength of cement and lime binders (Åhnberg 2006).*

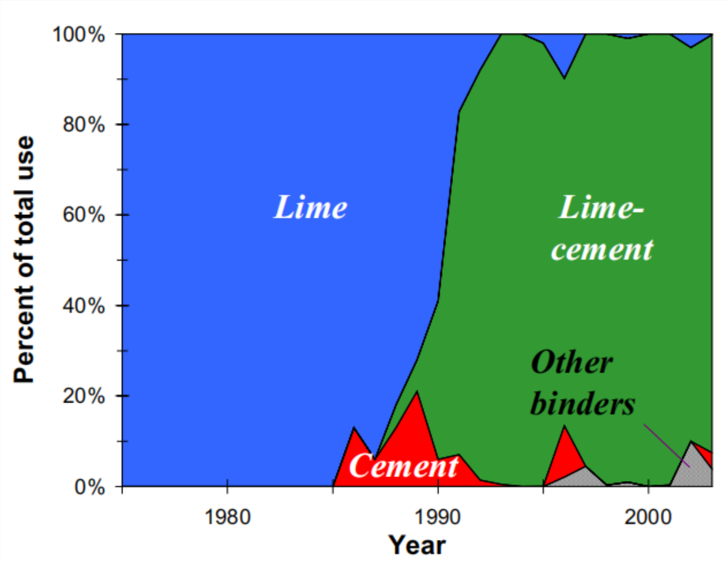


Figure 2.6 *Binders used for deep mixing in Sweden. Mainly used in column stabilization. (Åhnberg 2006).*

By-products

The high price and high CO_2 emissions of cement encourages for the search of alternatives. (Forsman et al., 2018). Industrial recycled materials seem to be suitable alternative. These recycled materials from industry include various slags, ashes and gypsum products. Slag and fly ash may need an activator (such as cement) to activate the start of hydration process, so they are normally used together with commercial binder component. The aim of using by-products is to improve the technical properties and also to decrease the binder costs. (Forsman et al. 2015). The hardening effect of various types of binders are illustrated in Table 2.1 to have a clear contrast.

Table 2.1 *Hardening effect of binders in different combinations on Nordic soils (EuroSoilStab 2002).*

binder	Silt (0 to 2%)	Clay (0 to 2%)	Organic soils, clay (2 to 30%)	Peat (50 to 100%)
Cement	xx	x	x	xx
Cement + gypsum	x	x	xx	xx
Cement + furnace slag	xx	xx	xx	xxx
Lime + cement	xx	xx	x	-
Lime + gypsum	xx	xx	xx	-
Lime + slag	x	x	x	-
Lime + gypsum + slag	xx	xx	xx	-
Lime + gypsum + cement	xx	xx	xx	-
lime	-	xx	-	-

XXX very good binder in many cases

XX good in many cases

X good in some cases

\- not suitable

2.3.2 Reactions of binder with clay

During the stabilization processes, the binder will first neutralize the soil, after which the additional binder is effective to the stabilization (Forsman et al. 2018). As what is suggested in Janz & Johansson (2002) and Babasaki et al., (1995), the stabilization reactions start when the binder amount is over the minimum limited value.

When mixing binder with soft clay using dry method, the binder will chemically react with pore water during the curing process. This reaction reduces the water content of clay. In addition, the pH value of stabilized soil will rise quickly. (EuroSoilStab 2002). Although the generation processes differ from different binder and soil type, the general characteristics are similar. Figure 2.7 presents a rough outline of the chemical processes taking place and the main reaction products formed when mixing common binders into a soil. The reaction of quicklime and cement have been described in section 2.3.1. As for slag, alkaline activation is needed. Calcium oxide (CaO), Silica (SiO_2) and ferric oxide (Fe_2O_3) mainly react in hydration process and the mainly products are CSH with a little amount of CAH and CASH. As for fly ash, the pozzolanic reactions also exist. (Åhnberg, 2006).

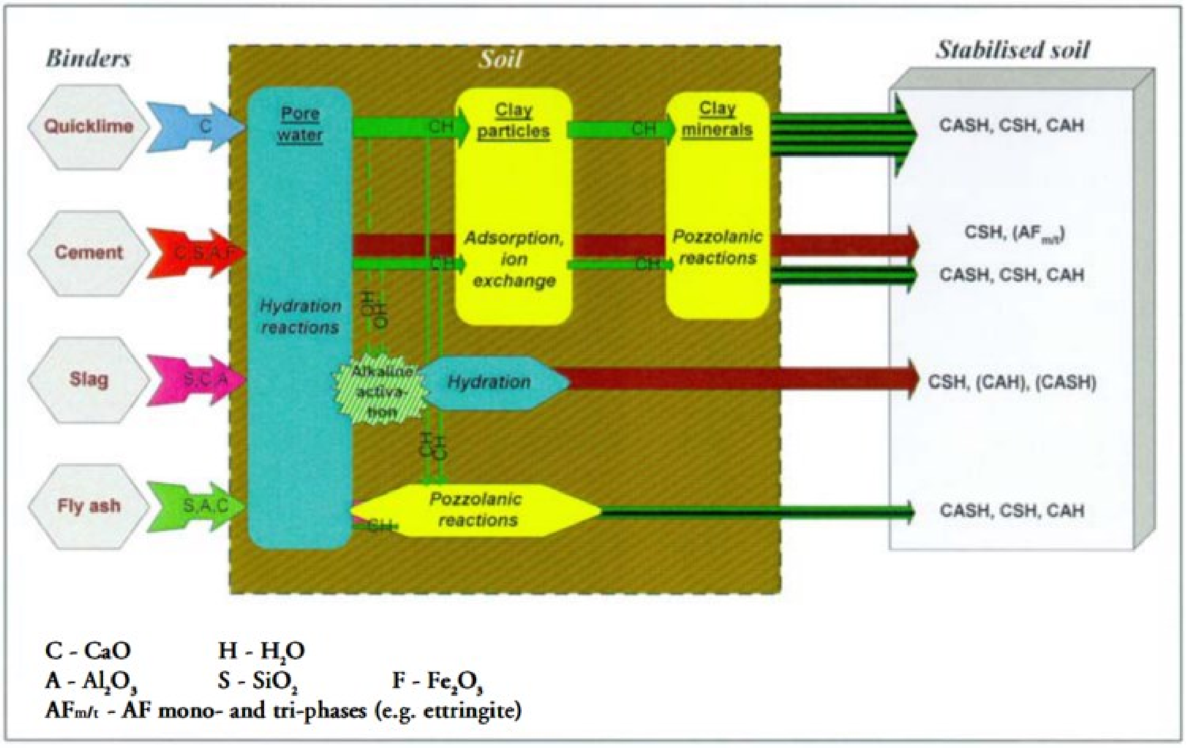
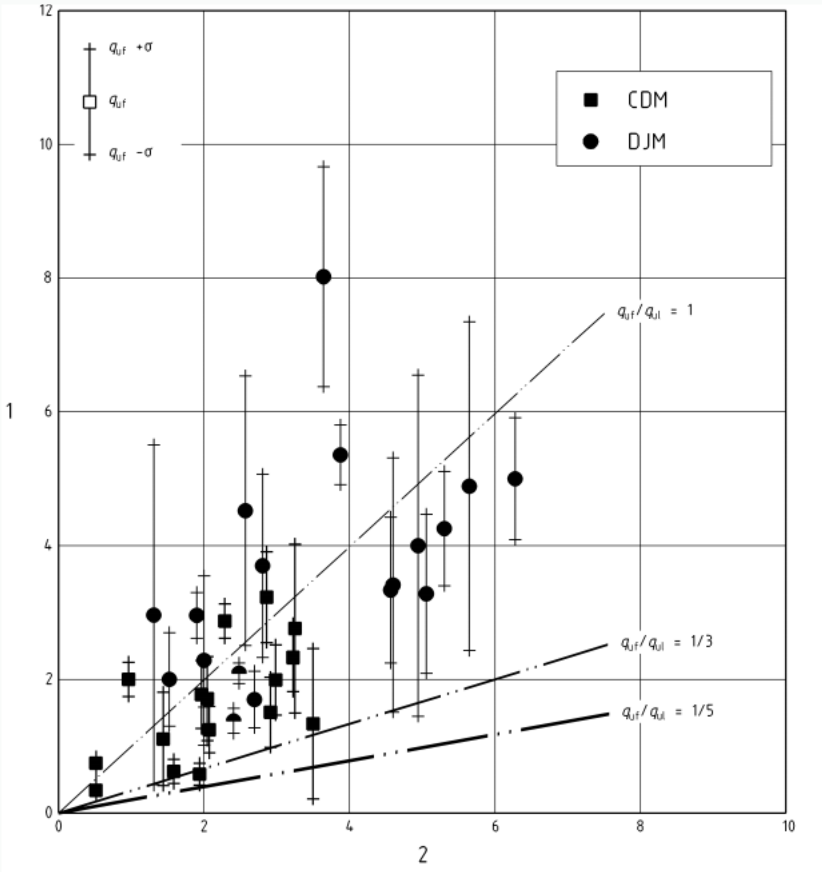


Figure 2.7 *Rough outline of the principal chemical reactions and reaction products formed by different types of binders in a soil. (Åhnberg 2006).*

2.4 Difference between laboratory and field test

Soils in filed and laboratory have different mixing and different curing conditions, which cause the difference between mixed soils from field and laboratory. Some conclusions of difference in soft plastic clay from field-mixed and laboratory-mixed sample were displayed in European Standard EN 14679-2005. The results were gotten under the premise that the same mixing method (Swedish dry mixing) was used and samples were used under a standardized quality control system. According to the accumulated experience, the ratio of field strength and laboratory mixed sample strength is in the range 0.2 to 0.5. In granular soils, the ratio of field and laboratory-mixed sample strength is likely to be significantly higher. In granular soils, the fines content largely determines the ratio.

Difference between field and laboratory samples from another two methods are also mentioned in European Standard EN 14679-2005. One is Cement Deep Mixing Method (CDM), which is the most common wet mixing method in Japan. The other is Dry Jet Mixing Method (DJM), the typical dry mixing method in Japan. Japanese experience from accumulated data by CDM and DJM on land are summarized in Figure 2.8. As for CDM, the ratio of field strength and laboratory mixed sample strength is in the range 1/3 to 1, and a small part of samples are even in a ratio bigger than 1. As for DJM, the ratio of field strength and laboratory mixed sample strength is in the range 1/3 to 1.



1. Field strength q_{uf}, MPa

2. Laboratory strength q_{ul}, MPa

Figure 2.8 *Relation between strength results of field and laboratory tests for on-land constructions. (Standard EN 14679-2005).*

3. LABORATORY TEST

In this study, soft clay with different kinds of binders or binder mixture were the main research objects. Unconfined compression test (UCT) and fall cone test (FCT) were the primary laboratory tests in this study for stabilized clay. The objective of laboratory tests was to choose the most favorable binder recipe, to optimize the addition rate of binder, so as to ensure the quality of the final result. In this chapter, test methods, the details of test materials (clay and binders) and the processes of laboratory tests are stated in turn.

3.1 Test Methods

The laboratory tests were based on the hypothesis that the strength and deformation properties of stabilized soils are similar to the cemented and over-consolidated natural soils. By this way, the same set of parameters about strength and deformation describing can be used for stabilized soils.

Laboratory tests in this study included index tests, fall cone test (FCT) and unconfined compression test (UCT). The soil used in this study was soft clay from Depot of Vuosaari, Helsinki. The binders used in this study were gotten directly from industries. Cement and Lime were used in this study as the reference materials and all the recycled materials were used mixed with cement as activator.

Several material properties were tested in the laboratory for evaluating the quality and quality variation of the aggregate. These tests include:

·water content, (%)

·wet density, (kg/m^3)

·particle density, (kg/m^3)

·organic materials, (%)

·grain size distribution

·pH

Furthermore, study of mass stabilization is mainly based on the assumption of undrained conditions. Undrained strength parameters are most implemented during data collection and design. (Åhnberg, 2006). Therefore, after the index tests of soil aggregate, unconfined compression test was the main test implemented for the mass strength properties. Undrained shear strength and deformation moduli E_{50} were determined.

3.2 Test Materials

3.2.1 Clay

Only one type of soil was used in this laboratory study. It was soft clay (Figure 3.1) sampled from the location in Depot of Vuosaari, Helsinki. The location of the test soil sampling area and the geological map are shown in Figure 3.2. However, it seems that the geology is very varying, and the geological map is not exact on the sampling area. All the laboratory tested soft clay was received from Ramboll Finland Oy in seven sealed plastic buckets separately. Samples were collected by disturbing sampling from sampling point 1 (PL 1, as shown in Annex 2 in a depth of 3.0 - 5.0 m). Structure of ground layers are shown in Table 3.1. The ground level is + 2.1 m, and the ground water is at level - 0.2 (about 1 meter from the bottom of the test pit).

The index properties of soft clay in this study included water content, density, unit weight, particle density, organic materials, grain size distribution and pH value. These properties were determined from laboratory tests based on European standard EN ISO-17892-1, EN ISO-17892-2, EN ISO-17892-3 and EN ISO-17892-4. As for the particle density tests, organic materials tests and grain size distribution tests, four of seven buckets of clay were chosen to be tested and then to get the average values for clay. The results are presented in chapter 4.

Figure 3.1 Depot *of Vuosaari. Soft clay samples in buckets, depth 3.0-3.3 m (photo Tianlingzi Xiong 26.02.2018).*

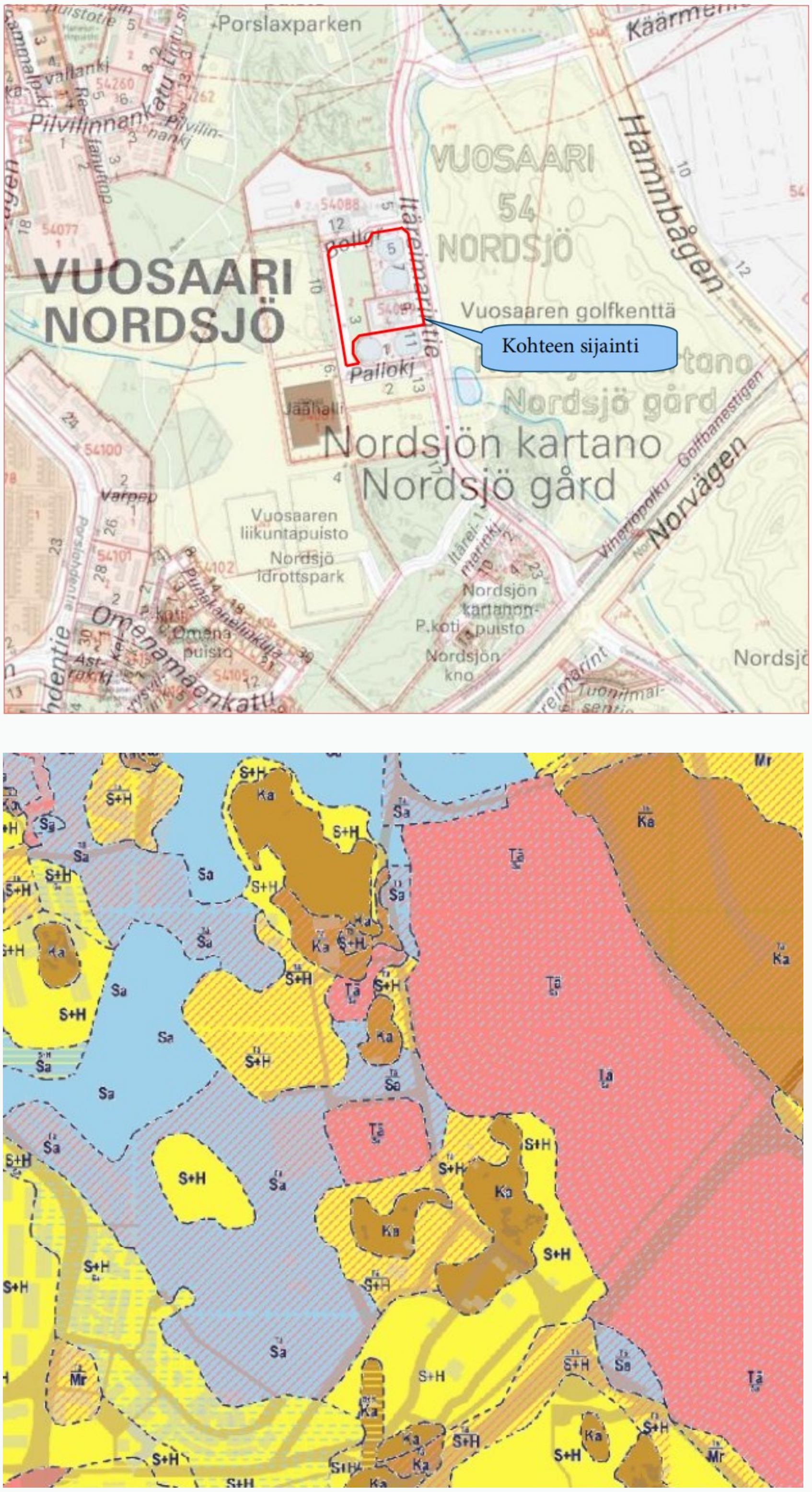


Figure 3.2 Depot *of Vuosaari. Location of the test soil sampling area ("Kohteen sijainti") and the geological map (Source: Helsinki City Map Service).*

Table 3.1 *Depot of Vuosaari. Ground layers of sampling site.*

Depth (m)	Soil Type
0.0 - 1.3	Waste disposal, boulders grains 100-300 mm
1.3 - 2.2	Sludge *
2.2 - 3.0	Sand
3.0 - 5.0	Clay

** sludge is from old waste water treatment plant.*

3.2.2 Binders

Five kinds of binders were used in this study, among which cement and lime were used as the reference materials. The other three were as the main research objects. They were from VTT, Ecolan Oy and HELEN Oy respectively. All these three recycled materials were used with mixing of cement as an activator. The amount of the binders used for stabilization varied from 50 to 225 kg/m^3.

The index properties of binders tested in this study included density, unit weight, particle density, and pH value. Before the use of binders, they were put into the oven for totally drying, so the water content was not necessary here.

Cement

Cement is a hydraulic binder, which encloses the soil as a glue. The hydration and strength development are fast. Cement is not dependent of the reaction with minerals but may still stabilize soil materials more or less. Cement is composed of calcium, silicon, aluminum, iron and sulphate. There are many different types of cement. Plus-cement Plus CEM II / B-M (S-LL) 42.5 N (Figure 3.3) was used in this study. The chemical composition of plus-cement is given in Table 3.2.

Table 3.2 *Plus-cement (Finnsementti Oy 2018)*

Chemical composition [%]	
CaO	63 - 65
SiO_2	20 - 22
Al_2O_3	4.0 - 5.4
Fe_2O_3	2.8 - 3.3
MgO	2.5 - 3.2

Alloying elements [%]	
Limestone	63 - 65
Blast furnace slag	20 - 22

Figure 3.3 *Plus-cement CEM II/B-M (S-LL) 42.5 N (photo Tianlingzi Xiong 13.03.2018).*

Lime-cement mixture (LCM)

Lime is mainly used in the form of quick lime (CaO) and sometimes also in the form of hydrated lime (Ca $(OH)_2$) for stabilization purposes. In practice, lime products are nowadays used as a mixture with other binder components, among which cement is the most commonly used. In this study, quick lime was mixed with cement.

The name of the material used in this study is Nordkalk TerraTM KC50 from Nordkalk Oy (Figure 3.4). It was manufactured by mixing raw materials in weight ratios of 50 % lime and 50 % cement. Raw materials of this mixture are Nordkalk Oy Ab's burned and ground lime QL 90T (CaO) at Lohja Tytyri Mill and Finnsement's Parais plant's Plus CEM II / B-M (S-LL) 42.5 N. The properties of the quicklime QL 90T are given in Table 3.3.

Table 3.3 *Quicklime QL 90T (Nordkalk Oy 2018)*

Chemical composition [%]			
CaO	83.8	K_2O	0.35
SiO_2	7.5	Na_2O	0.20
MgO	2.1	MnO	0.05
Al_2O_3	1.7	P_2O_5	0.04
Fe_2O_3	0.64		
Available CaO	77	Residual CO_2	2.7

Particle size [%]	
< 0.090 mm	83.7
< 0.200 mm	99.7
< 2.000 mm	100

Figure 3.4 *Nordkalk Terra^{TM} KC50 (photo Tianlingzi Xiong 14.03.2018)*

Gypsum slurry, VTT

Gypsum is one of the materials that can be used as binder in mass stabilization. In this study, gypsum slurry from water treatment plant of a gold mine offered by VTT was used. The gypsum slurry is generated in a process of water treatment, where sulphate is removed from the water by adding lime milk at a high pH, whereby the soluble sulphate of water precipitates as plaster and magnesium in the form of magnesium hydroxide. The solids produced are separated by a thickener after the precipitation, and this substrate is the test material we received to the laboratory.

The chemical composition of gypsum slurry was 70 % $CaSO_4 \cdot 2H_2O$ and 30 % $Mg(OH)_2$. The slurry contained about 40 % solids and 60 % water. By heating in the oven in a high temperature of 150 °C, the gypsum slurry (chemical formula - $CaSO_4 \cdot 2H_2O$) was transformed to calcium sulfate hemihydrate (chemical formula - $CaSO_4 \cdot 0.5H_2O$).

The gypsum slurry, which was covered with water is shown in Figure 3.5. It was delivered to Geotechincal Laboratory of Aalto University in 9th March, 2018. The oven dried (150 °C) gypsum sludge is also shown in Figure 3.6.

Figure 3.5 *Gypsum slurry, delivered by VTT (photo Tianlingzi Xiong 09.03.2018).*

Figure 3.6 *Oven dried (left) and grinded (right) gypsum slurry (photo Tianlingzi Xiong 05.04.2018).*

Ash mixture, Ecolan

The ash mixture was from Ecolan Oy (Figure 3.7). This mixture was used for research and development. The binder was a mixture of 80 % fly ash and 20 % cement. The fly ash was from coal burning and the cement is CEM 42.5N cement. The ash mixture is shown in Figure 3.7. It was delivered to Aalto University Geoengineering Laboratory in 14th March, 2018 by Ecolan Oy.

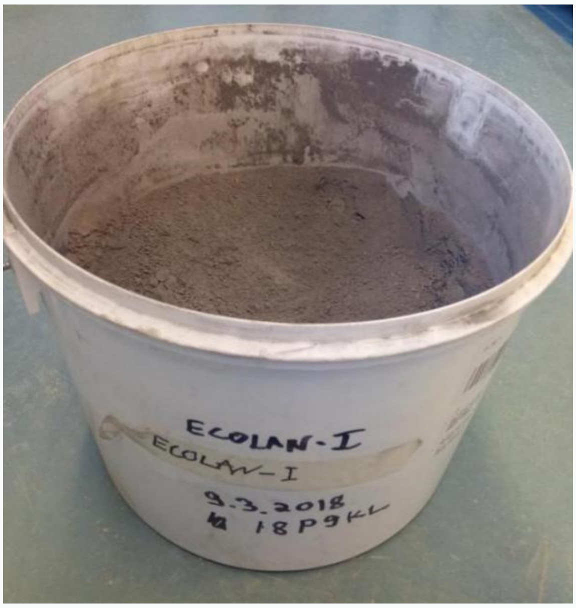


Figure 3.7 *Ash mixture, delivered by Ecolan - I (photo Tianlingzi Xiong 14.03.2018).*

Fly ash, Helen

Ash is a fine-grained residue from coal combustion process. Fly ash is collected from glue gases in some type of filter. The ash is collected from the filters for storage in soils or heaps. (Rudus Oy 2008). The work of sealing is necessary for protecting fly ash from spreading during transportation (Mäkelä & Höynälä 2000). The ash used in this study is coal burning ash.

Fly ash has fine grains, which consists of spherical and needle like granules. Its granularity corresponds to the granular grain. (Mäkelä & Höynälä 2000). The ash deposits are divided into incinerators coal, alloy and co-incineration based on raw materials. Coal burning ashes are often more uniform than incineration or co-incineration ashes. (Ramboll Finland Oy 2012). The analysis of main constituents is shown in Table 3.4. The bucket of fly ash is shown in Figure 3.8. It was delivered to Aalto University Geoengineering Laboratory in 22th March, 2018 by HELEN Oy.

Table 3.4 *Fly ash (Source: HELEN report for fly ash, 2010)*

Chemical composition [%]			
SiO_4	55.60	K_2O	2.42
Al_2O_3	20.80	Na_2O	1.64
Fe_2O_3	6.77	MnO_2	<0.10
TiO_4	0.85	P_2O_5	0.56
CaO	7.54	Cl	0.001
MgO	2.93		

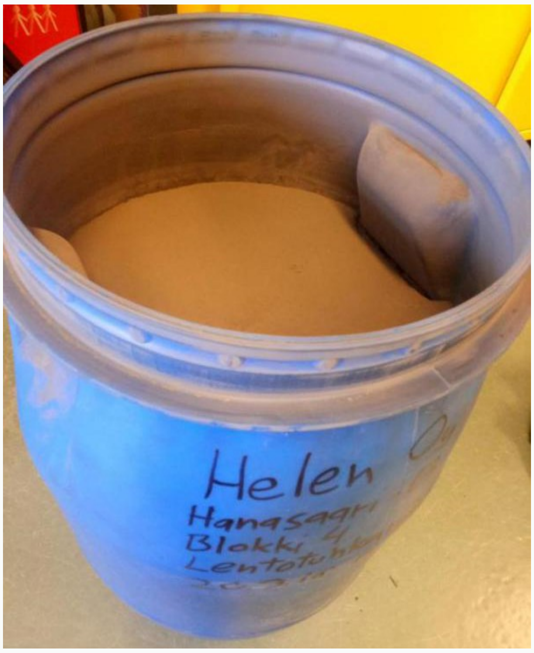


Figure 3.8 *Fly ash, delivered by HELEN Oy (photo Tianlingzi Xiong 22.03.2018).*

3.3 Preparation of samples

First, the binder delivered by VTT stored in water condition was oven-dried. The water content of other dry binders (cement, lime-cement mixture, Ecolan ash mixture and HELEN fly ash) was also tested to make sure they are dry enough for the dry mixing. The prepared clay samples were mixed with the objective binders in specific amounts. The amount of clay was determined from Formula 1. Since the designed binder amounts (kg/m^3) were decided already, and the volume of the tubes for making samples was also known, the mass of binder needed in every sample was also clear.

$$W_{\text{soil}} = \rho_{\text{wet}} \cdot V_{\text{tube}} \qquad (1)$$

where

W_{soil} = mass of pure clay in the mixture (kg)

ρ_{wet} = wet density of clay (kg/m^3)

V_{tube} = volume of the tube for filling the clay-binder mixture.

Soft clay and binder or binder mixture were mixed in the mixing machine (Figure 3.9) for a minimum three minutes to get a thoroughly mixing. The maximum amount of mixtures for every mixing process was one liter. The mixing was stopped until getting a homogeneous color of mixture (Figure 3.10).

Figure 3.9 *Mixing machine used in the mixing of the clay and binder (photo Tianlingzi Xiong 20.03.2018).*

Figure 3.10 *Clay + binder sample after mixing (photo Tianlingzi Xiong 20.03.2018).*

The mixtures were then fed into cylindrical containers (Figure 3.11) by hand. The dimension of sample was 50 mm diameter and 100 mm height. During the feeding process, compaction of sample was done by manual tapping of the tube. Every tube of sample was completed by three times of compaction. During every time, 20 times of tapping were done. This compaction method did not follow Finnish stabilization guideline (Finnish Transport Agency 2018) since the aim was to produce as good samples as possible. As for fall cone test, the samples were in slices in dimension of 50 mm diameter and 15 mm height, therefore the compaction was handled by static compaction vertically (Figure 3.12). Every tube can make six or seven slices.

After compaction, these sample cylinders were put into thermal insulation boxes for two days keeping a constant temperature around +20 °C. After this, sample cylinders were transferred to storage room in +8 °C temperature during the curing time according to Finnish stabilization guideline (Finnish Transport Agency 2018).

Figure 3.11 *Cylindrical containers (photo Tianlingzi Xiong 20.03.2018)*

Figure 3.12 *Static compaction (photo Tianlingzi Xiong 21.03.2018)*

3.4 Penetrometer tests including fall cone test

Several types of penetrometers were considered before other laboratory tests. A pocket penetrometer borrowed from Ramboll Oy (Figure 3.13.) is a simple instrument that is used in the site for soil investigation to evaluate unconfined compressive strength for stabilized clay and stabilized clayey silt soils (Yasun, 2018). Hand penetrometer borrowed also from Ramboll Oy (Figure 3.13) for top layers is an instrument for indicative measurement of the resistance to penetration of the top layers in situ conditions of very stiff soil of stabilized soil. When using hand penetrometer, sample was very vulnerable to be broken. When using pocket penetrometer, test results were varying, which was unreliable. By contrast, fall cone test (FCT) was selected in this study as one of the methods to measure undrained shear strength (c_u) as shown in Figure 3.14.

The FCT tests were carried out following the European Standard EN ISO 17892-6-2017 for the measurement of c_u. The mass and the conical angle of the cone selected in this study were 300 g and 60°, respectively. The fall cone apparatus permitted the cone to be held firmly initially. After the tip of the cone touched the specimen surface, the cone was released instantaneously to fall freely in the vertical direction into the soil specimen. After 5 s, the penetration depth was measured by a dial gage. Five penetration tests were done from every sample slice, where each point was far enough from the previous penetration tests not to be influenced by disturbance. The represented value from FCT was adopted as the average values of three measured ones, omitting the maximum and minimum values. The average value was used for c_u according to Formula 2.

$$c_{urfc} = c \cdot g \cdot \frac{m}{i^2} \qquad (2)$$

where

c_{urfc} is the undrained shear strength of remolded soil (kPa)

c is a constant, dependent on the tip angle of the cone, where

c = 0.27 for cones with 60° tip

g is the acceleration due to gravity at free fall, usually taken as a value of 9.81 (m/s^2)

m is the mass of the cone (g)

i is the average cone penetration (mm).

From FCT, the samples were tested many times during their curing period. In the first month, four tests were performed in the first week, and two were performed every week for the last three weeks. In the second month, one test was made each week. If necessary, the tests would continue in the third month in a frequency of one time each two weeks.

Figure 3.13 *Hand penetrometer and pocket penetrometer from Ramboll Oy.*

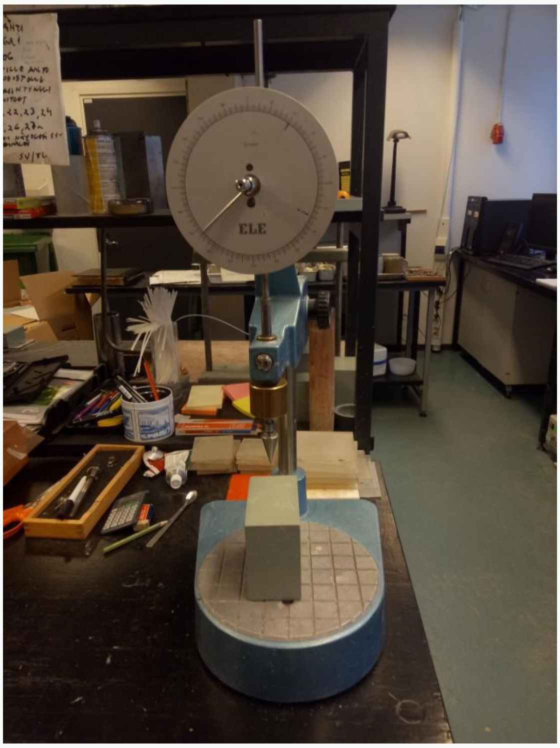


Figure 3.14 *Fall cone test machine from Geoengineering laboratory of Aalto University.*

3.5 Compression test

The Unconfined compression tests (UCT) were carried out in this study, following the European Standard EN ISO 17892-7. The peak strength was defined as the unconfined compression strength (q_u). The half of the unconfined compression strength ($q_u/2$) is a suitable value that balances the under- and over-evaluating factors well to indicate true strength. (Hiroyuki et al. 2012). It was used as the undrained shear strength (c_u). The loading machine (Figure 3.15) for performance of UCT consists of the four main parts:

a) top and bottom platen between which the soil specimen is placed

b) load frame with a drive unit to compress the soil specimen (loading press)

c) load measuring device to measure the force applied to the soil specimen

d) compression measuring device to measure the axial compression of the specimen.

Figure 3.15 *Unconfined compression test machine (photo Tianlingzi Xiong 10.07.2018).*

From UCT, the samples were tested after curing time 28 days and 3 months. For every set of tests, three specimens with the same amount of binder and curing time were tested for getting the average value. Before testing, diameter and mass of the specimen were measured for calculating stress after the whole test process. After this, specimen was placed centered on the bottom plate. Then the machine was switched on, the plate moved smoothly without fluctuations or vibrations to get the force applied on the specimen at a constant strain rate of 1.0 mm/min. The compression was stopped when the vertical strain reaches 15 %, or started to decrease, whichever was earlier. For each set of readings, the vertical strain ε and the vertical stress σ_1 shall be calculated from the Formulas 3 and 4.

$$\varepsilon = \frac{\Delta H}{H_i} \qquad (3)$$

$$\sigma_1 = \frac{P(1-\varepsilon)}{A_1} \qquad (4)$$

where

ΔH is vertical compression of the specimen, (mm)

H_i is initial height of specimen, (mm)

P is vertical load acting on the specimen, (N)

A_1 is initial cross-sectional area of specimen, (mm^2).

The undrained shear strength c_u shall be determined from Formula 5.

$$c_u = 0.5 \times q_u \qquad (5)$$

3.6 Tests of pure binders

The bending test (BT) and compression test (CT) for pure recycled binder materials without clay were carried out in Concrete Laboratory of Aalto University for a better comparison among binders from VTT (Figure 3.16), Ecolan (Figure 3.17) and HELEN (Figure 3.18). The tests followed the European Standard EN ISO 196-1-2005. The flexural strength (R_f) and compressive strength (R_c) were defined based on prismatic test specimens in size 40 mm x 40 mm x 160 mm. These specimens were casted by one part of binder and half part of water (water/binder ratio 0.50) in a mould using a jolting apparatus. The mould was made of steel and consisted of three horizontal compartments so that three prismatic specimens 40 mm x 40 mm in cross section and 160 mm in length were prepared simultaneously. After casting, the specimens were stored in the mould in a moist air room for 24 h. Then they were demolded, and then stored in a constant temperature of 20 ℃ and moisture conditions (air humidity of 60 %) until strength testing. The 7 d, 28 d and 3 month strengths were tested in this study.

Figure 3.16 *Gypsum slurry casting and casted specimens (photo Tianlingzi Xiong 24.04.2018).*

Figure 3.17 *Ecolan Ash mixture slurry casting and casted specimens after bending test (photo Tianlingzi Xiong 25.04.2018).*

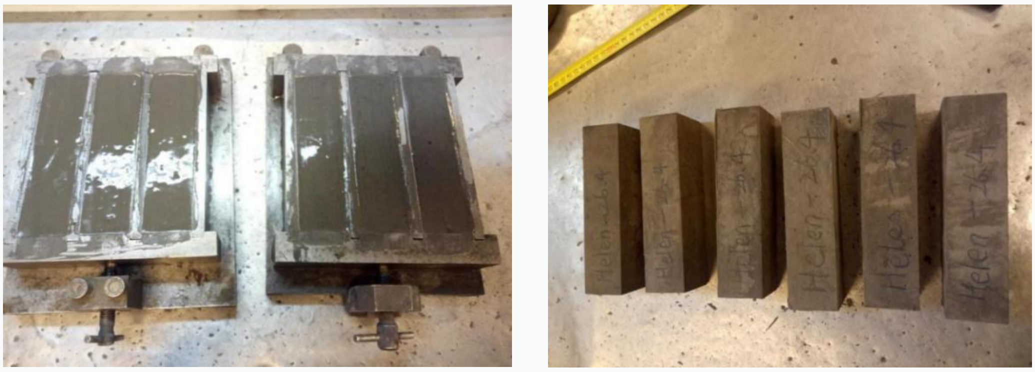


Figure 3.18 *HELEN fly ash slurry casting and casted specimens (photo Tianlingzi Xiong 26.04.2018).*

The flexural strength was measured by using a flexural strength testing machine. The apparatus was provided with a flexure device. The device incorporates three steel supporting rollers of 10.0 ± 0.5 mm diameter. One of the loading rollers was placed centrally between the other two (Figure 3.19). The apparatus for the determination of flexural strength was capable of applying loads up to 10 kN. The accuracy is ±1.0 % of the recorded load at a rate of loading of 50 ± 10 N/s. Firstly, the prism was placed in the apparatus with one side facing on the supporting rollers and with its longitudinal axis normal to the rollers. Then, the vertical load was applied by means of the loading roller to the opposite side face of the prism and it was increased smoothly at the rate of 50 ± 10 N/s until fracture happened. The flexural strength (R_f, MPa) was calculated according to Formula 6.

$$R_f = \frac{1.5 \times F_f \times I}{b^3} \qquad (6)$$

where

R_f is the flexural strength, (MPa)

b is the side of the square section of the prism, (mm)

F_f is the load applied to the middle of the prism at fracture, (N)

l is the distance between the supports, (mm).

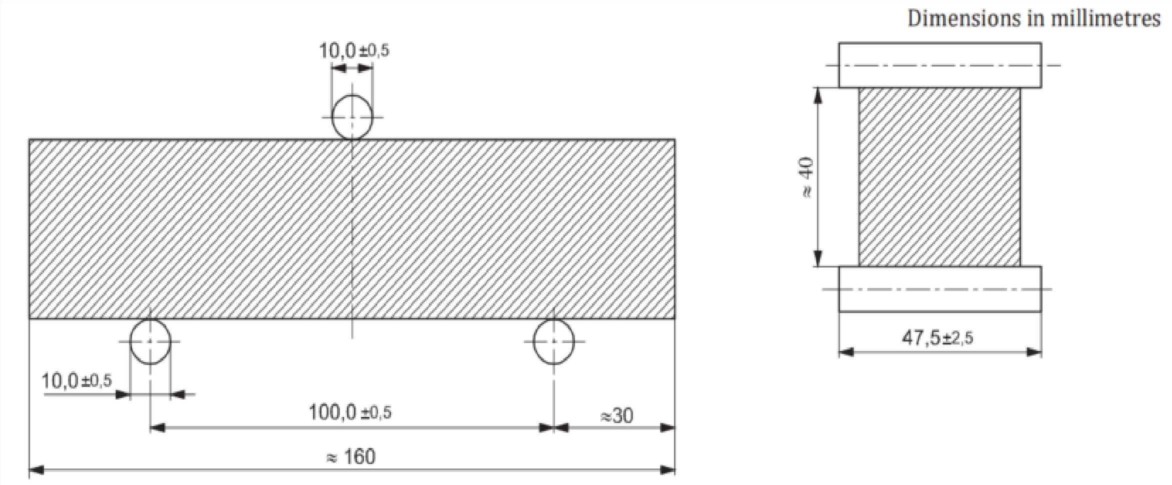


Figure 3.19 *Arrangement of loading for determination of flexural strength (SFS - EN 196-1:2016).*

The testing machine for the determination of compressive strength had an accuracy of ± 1.0 % of the recorded load in the upper four-fifths of the range being used. It provided a rate of load increase of 2 400 ± 200 N/s. The vertical axis of the ram coincided with the vertical axis of the machine and during loading, the direction of movement of the ram was along the vertical axis of the machine. The resultant of the forces passed through the center of the specimen. Every specimen was broken into two halves during the bending test, which could be used for two compression tests. The prism halves were centralized laterally to the plates of the machine, and longitudinally such that the end face of the prism over-hanged the plates or auxiliary plates by about 10 mm. The load was smoothly increased at the rate of 2 400 ± 200 N/s over the entire load application until fracture. The compressive strength (R_c, MPa) was calculated according to Formula 7.

$$R_c = \frac{F_c}{1600} \qquad (7)$$

where

R_c is the compressive strength, (MPa)

F_c is the maximum load at fracture, (N)

1 600 is the area of the plates or auxiliary plates (40 mm × 40 mm), (mm^2).

4. TEST RESULTS

4.1 Properties of clay and binders

The index properties of soft clay included water content, density, unit weight, particle density, organic materials, grain size distribution and pH value. Test results are presented in Table 4.1. As for the particle density tests, organic materials tests and grain size distribution tests, four of seven buckets of clay were chosen to be tested and then to get the average values for clay.

From the test results, soil from depth 3.0 - 3.3 m and depth 3.5 - 5.0 m were both classified as soft clay according to GEO-Classification as fat clay (lisa). The pH value 7.7 was average. Compared with soft clay in a deeper layer (depth 3.5 - 5.0 m), soft clay in depth 3.0 - 3.3 m has lower water content, therefore higher density or unit weight. Even though, as the same type of soil, this two sets of clay still has the similar particle density. As for the organic materials, clay in a deeper layer seems to have fewer organic materials tending to zero.

The index properties of binders tested in this study included density, unit weight, particle density, and pH value. Testing results are shown in Table 4.2. Among these three binders, fly ash from HELEN has the highest unit weight but lowest particle density while ashes mixture from Ecolan shows the opposite result. Both binders from Ecolan and HELEN have a high value of alkalinity greater than 12, and binder from VTT is alkaline with a pH value of 10.1.

Table 4.1 *Depot of Vuosaari. Index properties of parallel soft clay samples from depth 3.0 -3.3 m (a) and 3.5-5.0 m (b).*

a. Depth 3.0-3.3 m

	Bucket 1	Bucket 2	Bucket 3	Bucket 4	Bucket 5	Average
Water content, %	68.4	78	67	46.4	58.9	63.7
Density, g/cm^3	1.684	1.691	1.768	1.854	1.741	1.748
Unit weight, kN/m^3	16.52	16.59	17.35	18.19	17.08	17.15
Particle density, g/cm^3	2.77	2.78	-	-	-	2.78
Organic materials, %	0.08	0.35	-	-	-	0.22
GEO-Classification	liSa	liSa	-	-	-	liSa
pH	7.6	7.8	7.7	7.7	7.5	7.7

b. Depth 3.5-5.0 m

	Bucket 6	Bucket 7	Average
Water content, %	53.8	78.9	66.4
Density, g/cm^3	1.627	1.582	1.605
Unit weight, kN/m^3	15.96	15.52	15.74
Particle density, g/cm^3	2.79	2.78	2.79
Organic materials, %	0	0.04	0.02
GEO-Classification	liSa	liSa	liSa
pH	7.5	7.8	7.7

*In GEO-Classification, liSa represents fat clay.

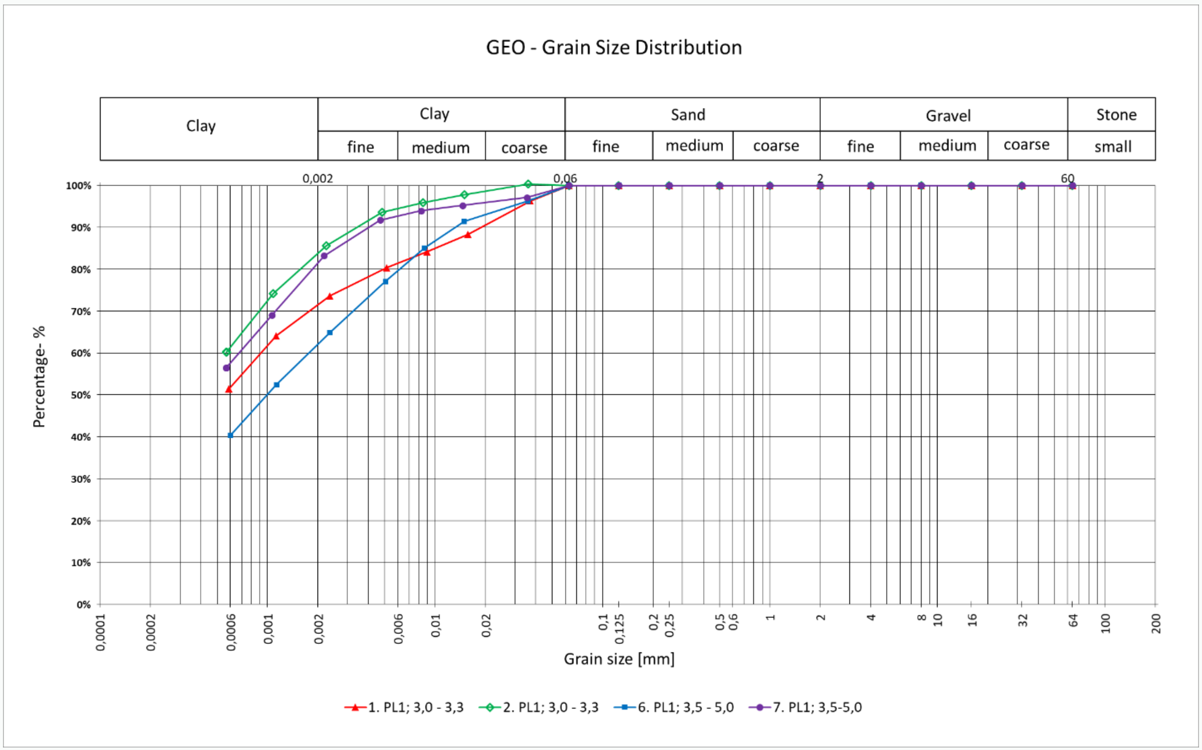


Figure 4.1 *Depot of Vuosaari. Grain size distribution of soft clay samples from depth 3.0 - 3.3 m and 3.5 - 5.0 m.*

Table 4.2 *Index properties of binders from VTT, Ecolan and HELEN.*

Binder	VTT	Ecolan	HELEN
Density, g/cm^3	0.741	0.615	0.77
Unit weight, kN/m^3	7.27	6.03	7.56
Particle density, g/cm^3	2.62	2.68	2.23
pH	10.1	12.5	12.2

4.2 Undrained shear strength in UCT

The unconfined compression tests (UCT) were carried out following the European Standard EN ISO 17892-7. The peak strength was defined as the unconfined compression strength (q_u). And the half of the unconfined compression strength ($q_u/2$) was used as the mobilized undrained shear strength (c_u). From starting the machine to reaching the peak force, three to five minutes were needed. Three typical modes of fractures from stabilized clay columns are shown in Figures 4.2 – 4.4. There was a significant vertical crack through specimen or vertical crack in the middle of specimen, along with several small cracks on the top of specimen. In addition, diagonal cracks also existed on some specimens. Those cracks were mainly caused by the shear compression failure.

Figure 4.2 *Cracks of stabilized clay column in compression test, HELEN + cement (75+75 kg/m*^{3}*), 3 months (photo Tianlingzi Xiong 11.07.2018)*

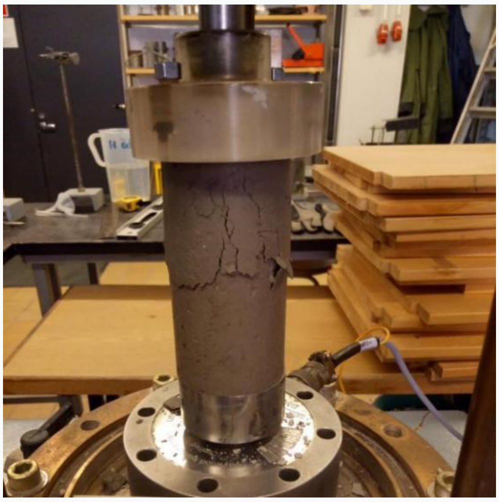


Figure 4.3 *Cracks of stabilized clay column in compression test, HELEN + cement (100+50 kg/m*^{3}*), 3 months (photo Tianlingzi Xiong 11.07.2018)*

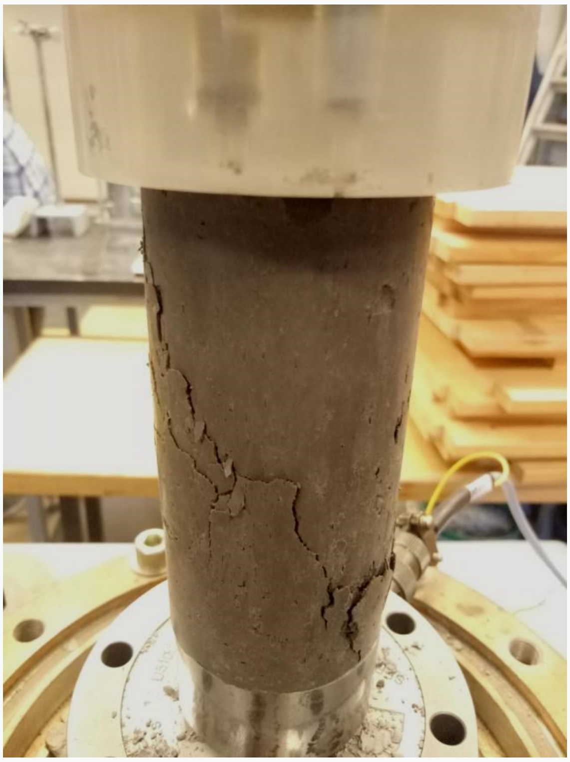


Figure 4.4 *Cracks of stabilized clay column in compression test, Ecolan+cement (75+75 kg/m^3), 3 months (photo Tianlingzi Xiong 10.07.2018)*

Three different amounts were tested for every type of binder. And for every amount of binder, three specimens were tested to get an average result. The amounts selected and summary of test results c_u in 28 d and 3 months are shown in Table 4.3. The change of strength from 28 d to 3 months are shown in Figures 4.5 - 4.9, respectively. The c_u of all the binders are illustrated in Figures 4.10 and 4.11 for a better comparison of binders. Secant moduli E_{50} were shown in Table 4.4. The conclusion of c_u for all binders and the deviations are shown in Figure 4.12. In addition, Figure 4.13 shows how the c_u changed from 28d to 3 months. Stress - strain curves from every compression test are shown in Annex 8.

When the amount of cement is 50 kg/m^3, the undrained shear strength is 139 kPa in 28 d (Figure 4.5). Strength remains the same when curing time comes to 3 months. When the amount of cement is 100 kg/m^3, strength is 2.7 times (375 kPa) in 28 d and the difference comes to 3 times (423 kPa) when curing time is 3 months. However, when cement amount increasing to 150 kg/m^3, the strength does not rise so much compared with cement in 100 kg/m^3. And strength even drops along with the curing time from 28 d to 3 months.

The strength of lime cement mixture (LCM) is 83 kPa when LCM amount is 50 kg/m^3 in 28 d (Figure 4.6). A visible increase from 82 kPa to 108 kPa happens over time 28 d to 3 months. When the amount of LCM increases to 100 kg/m^3 and 150 kg/m^3, the changes of strength over time is not so significant anymore. The strength with the amount of 100 kg/m^3 is over 2 times higher than with amount 50 kg/m^3, and the strength with the amount of 150 kg/m^3 is 1.5 times higher than with amount 100 kg/m^3.

When the amount of binder is kept the same, gypsum from VTT with more cement in a rate of 1:1 gets a better result than gypsum and cement in a rate of 2:1. It shows that when cement reaches to 75 kg/m^3 in the binder mixture, the strength is doubled than cement is 50 kg/m^3. When keeping the amount of cement at 75 kg/m^3, the double amount of gypsum gives a 1.3 times higher result.

Mixture of Ecolan ashes and cement gives a very excellent result. Even when the amount of mixture is 150 kg/m^3 and the ratio of ashes and cement is 2:1, the final strength of stabilized clay can still be 553 kPa high in 28 d and 483 kPa in 3 months. The other two amounts of mixtures also get high strengths being both over 500 kPa and strengths increase over time. The maximum strength in the reached to 622 kPa.

The strengths gotten from fly ash (HELEN) and cement mixture are similar to results gotten from gypsum (VTT) and cement mixture. It also needs a relatively high percentage of cement in the mixture and more fly ash can also give a higher strength. However, it is worth noting that the strength seems to have a decreasing trend when curing time increases and the mixture amount is 150 kg/m^3.

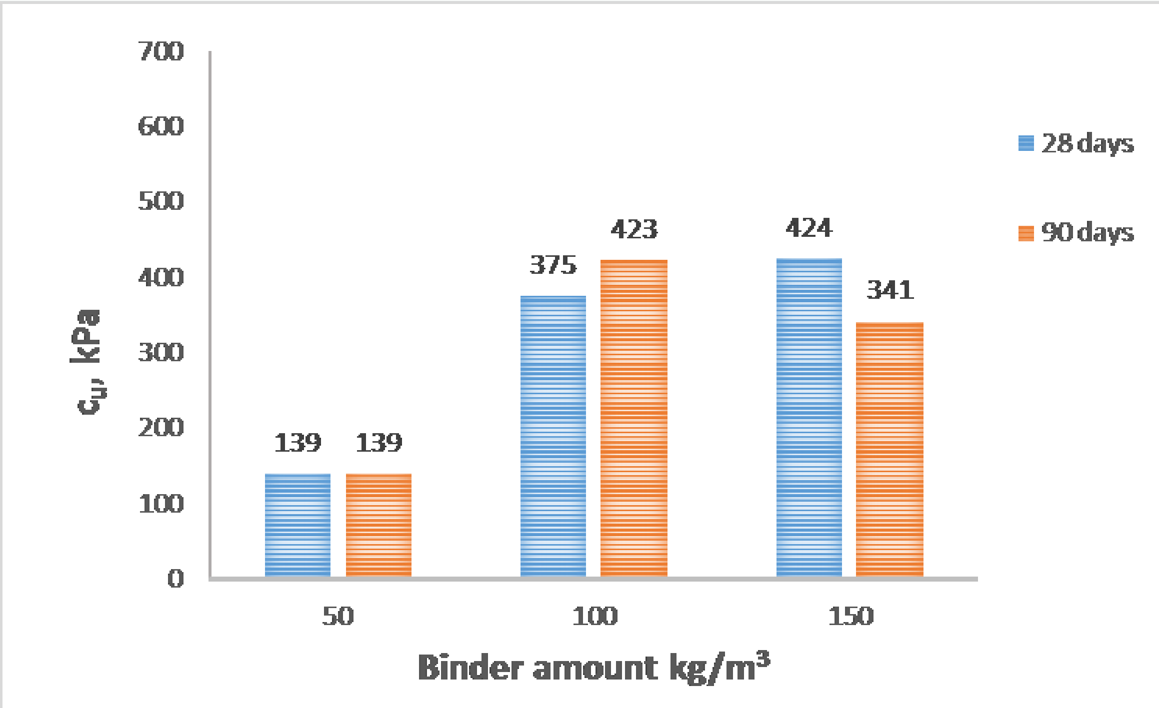


Figure 4.5 *Undrained shear strength of cement stabilized clay in 28 d and 3 months.*

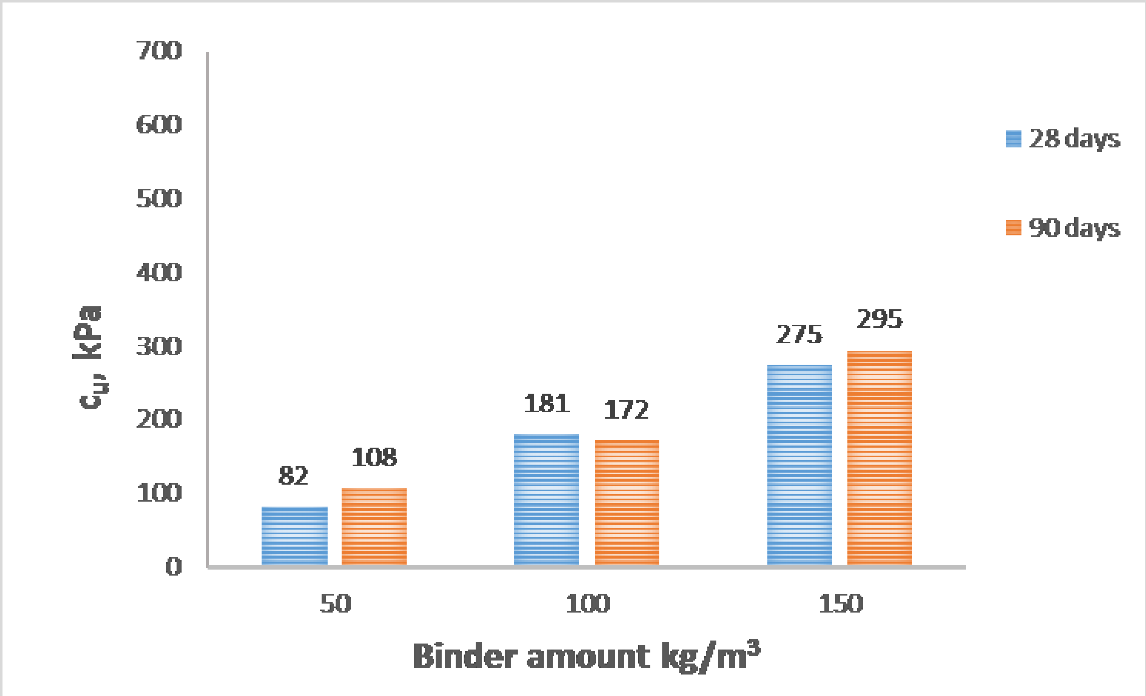


Figure 4.6 *Undrained shear strength of LCM stabilized clay in 28 d and 3 months.*

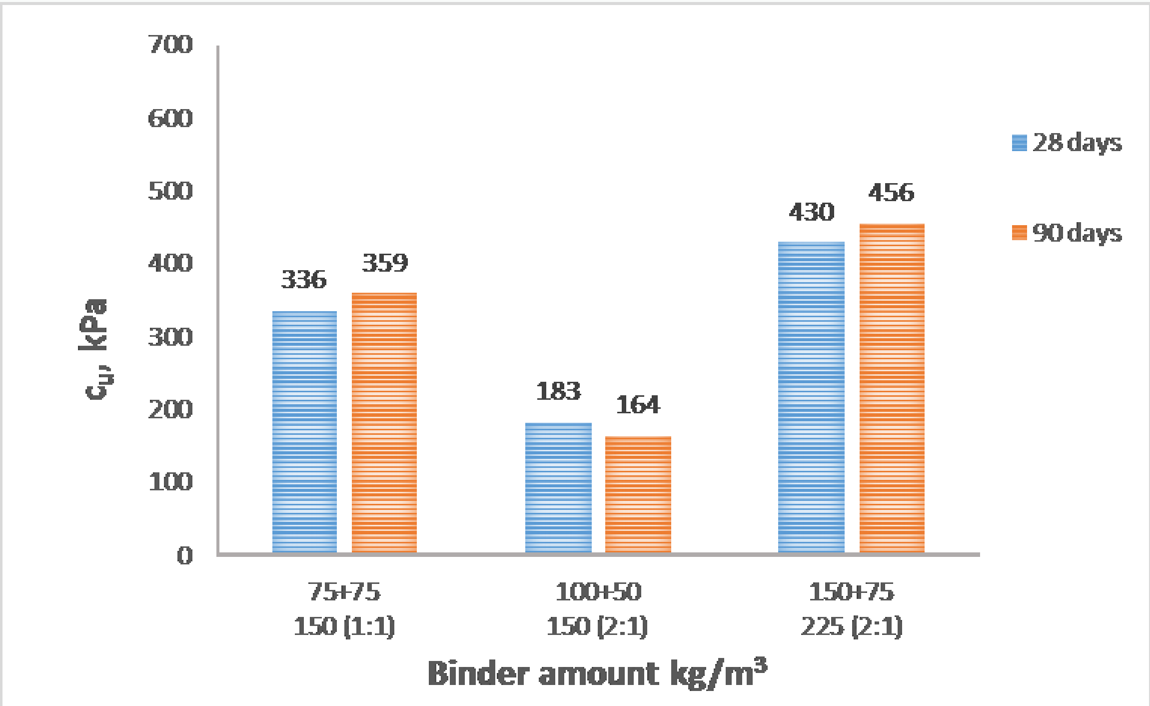


Figure 4.7 *Undrained shear strength of VTT + cement stabilized clay in 28 d and 3 months.*

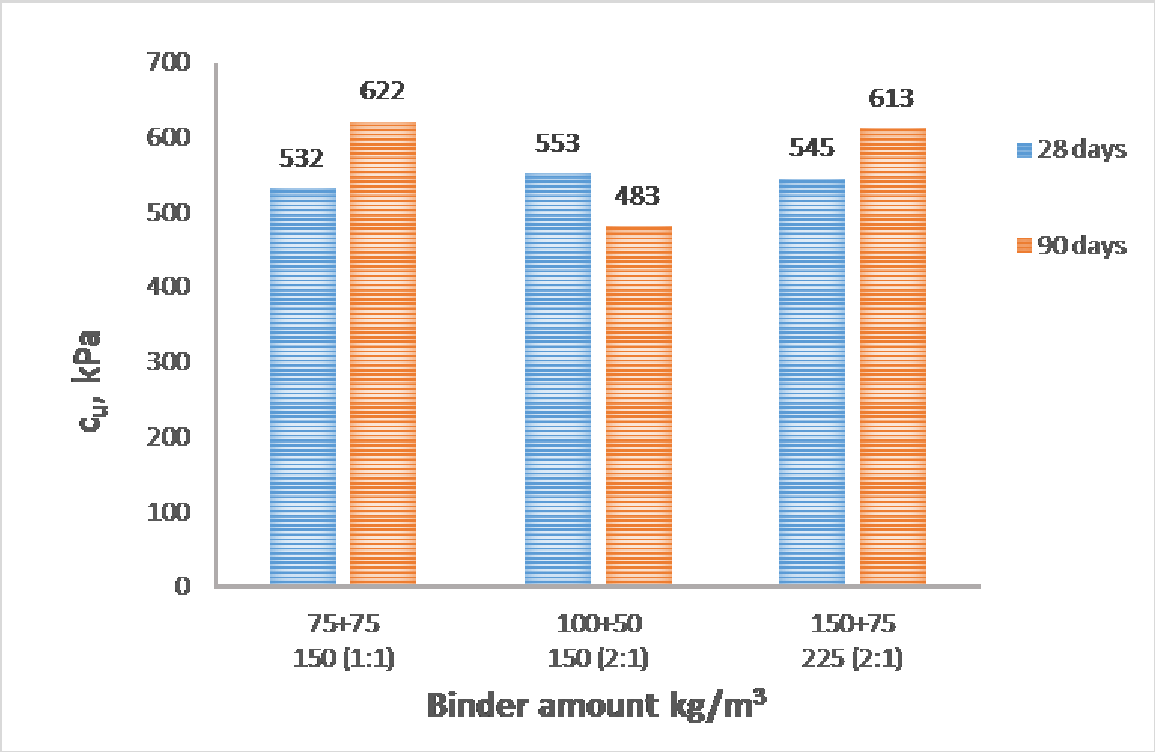


Figure 4.8 *Undrained shear strength of Ecolan + cement stabilized clay in 28 d and 3 months.*

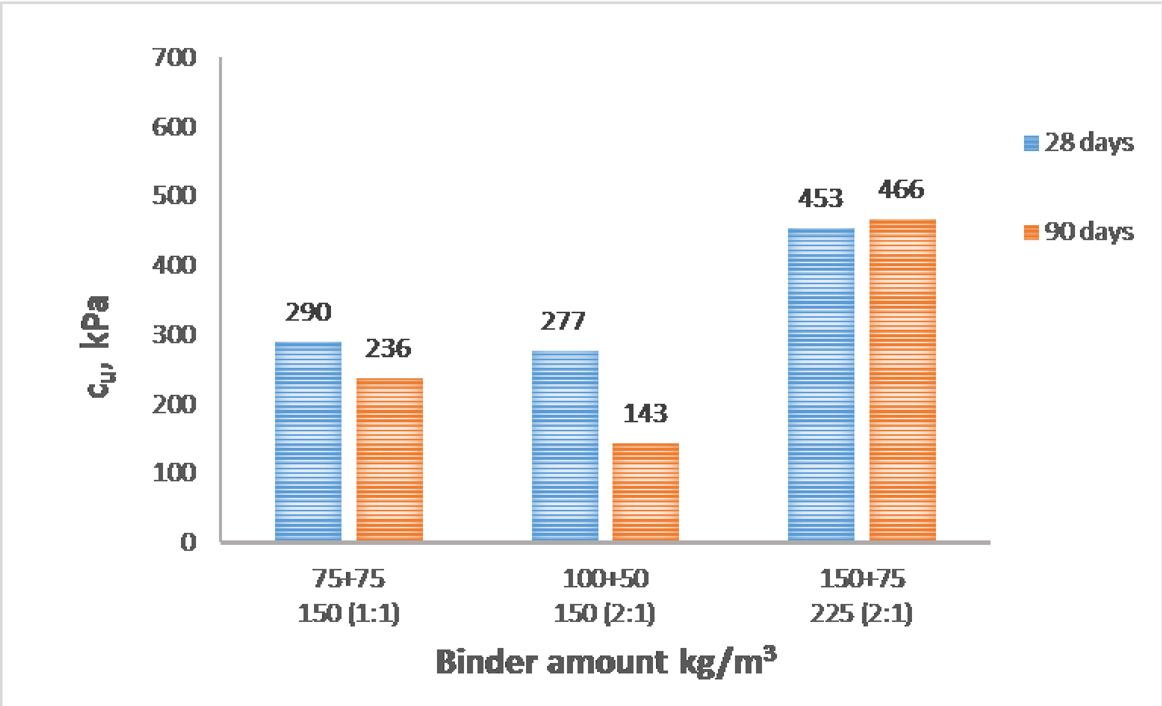


Figure 4.9 *Undrained shear strength of HELEN + cement stabilized clay in 28 d and 3 months.*

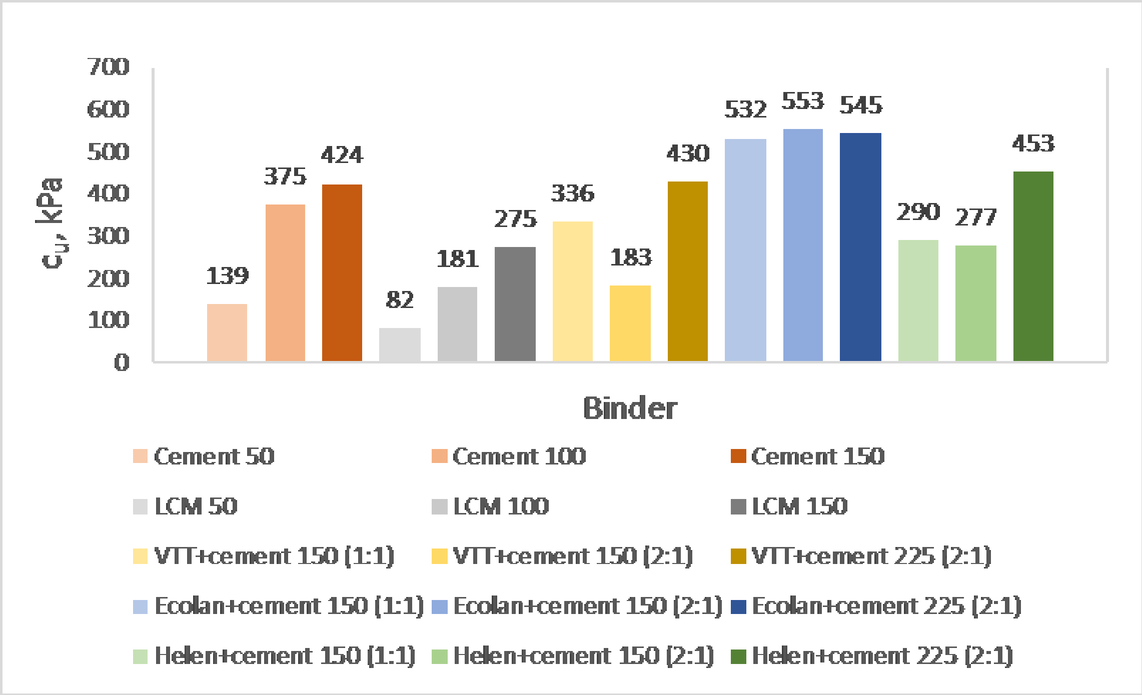


Figure 4.10 *Undrained shear strength of stabilized clay in 28 d. In the legend "Cement 50", "50" means the binder amount kg/m^3.*

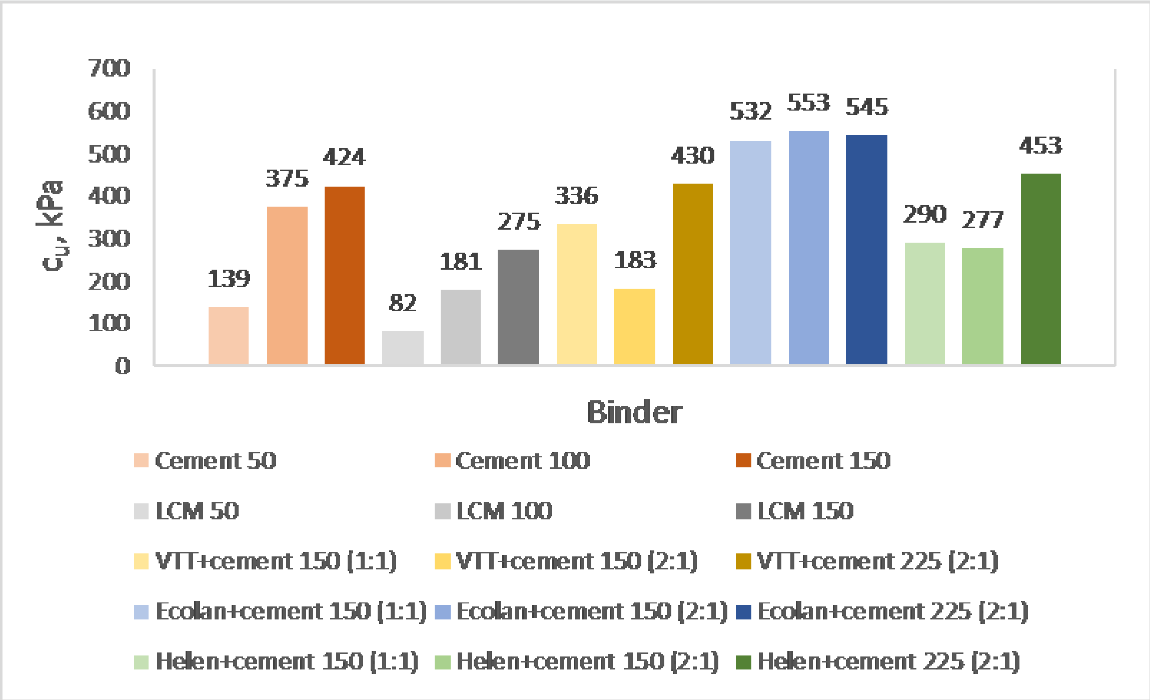
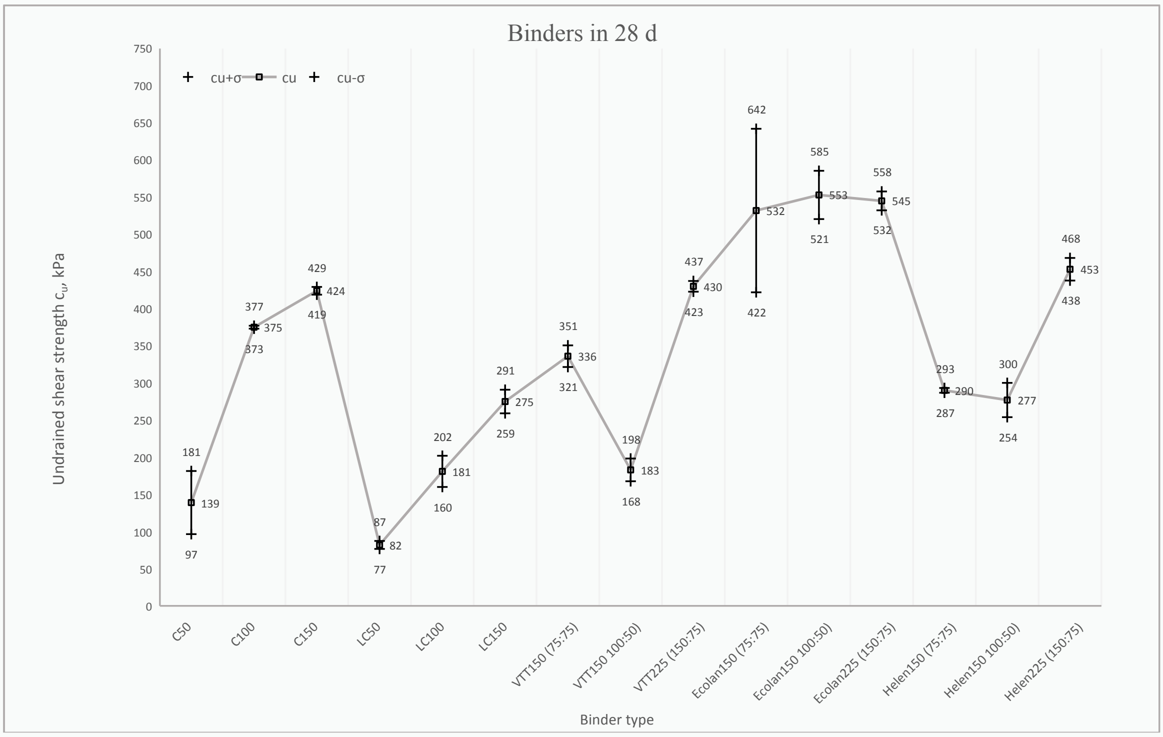


Figure 4.11 *Undrained shear strength of stabilized clay in 3 months. In the legend "Cement 50", "50" means the binder amount kg/m^3.*

Table 4.3 *Undrained shear strength of stabilized clay from UCT in 28 d and 3 months.*

Binder type	Min c_u, kPa	Max c_u kPa	Average, kPa	STDEV
		28d		
C50	90	166	139	42
C100	373	377	375	2
C150	418	427	424	5
LC50	77	87	82	5
LC100	163	204	181	21
LC150	262	293	275	16
VTT150 (75:75)	322	351	336	15
VTT150 100:50)	165	192	183	15
VTT225 (150:75)	431	436	430	7
Ecolan150 (75:75)	462	659	532	110
Ecolan150 100:50)	521	586	553	32
Ecolan225 (150:75)	532	558	545	13
Helen150 (75:75)	287	294	290	3
Helen150 100:50)	251	296	277	23
Helen225 (150:75)	443	470	453	15
		90d		
C50	61	149	139	46
C100	363	457	423	52
C150	203	507	341	154
LC50	95	115	108	10
LC100	155	182	172	15
LC150	289	301	295	6
VTT150 (75:75)	353	368	359	8
VTT150 100:50)	161	167	164	3
VTT225 (150:75)	432	478	456	23
Ecolan150 (75:75)	565	693	622	65
Ecolan150 100:50)	481	485	483	2
Ecolan225 (150:75)	478	743	613	132
Helen150 (75:75)	233	241	236	4
Helen150 100:50)	132	160	143	15
Helen225 (150:75)	444	495	466	26



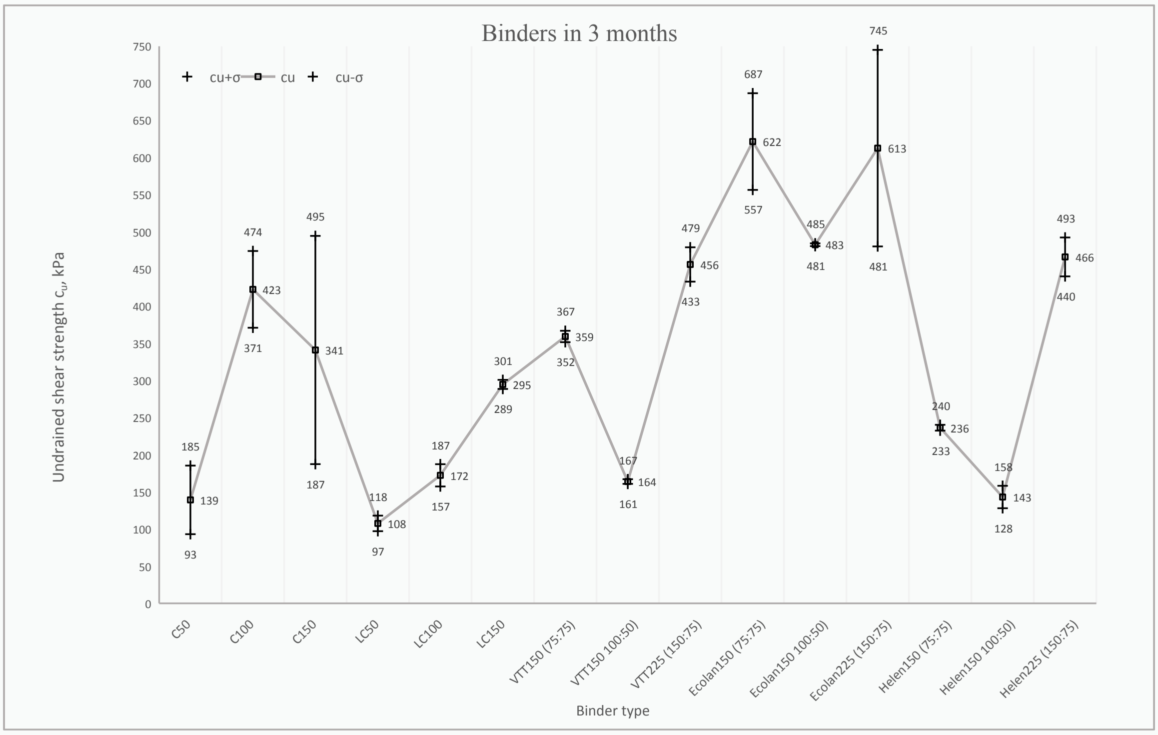


Figure 4.12 *Conclusion of undrained shear strength of stabilize clay and its standard deviations in 28 d and 3 months.*

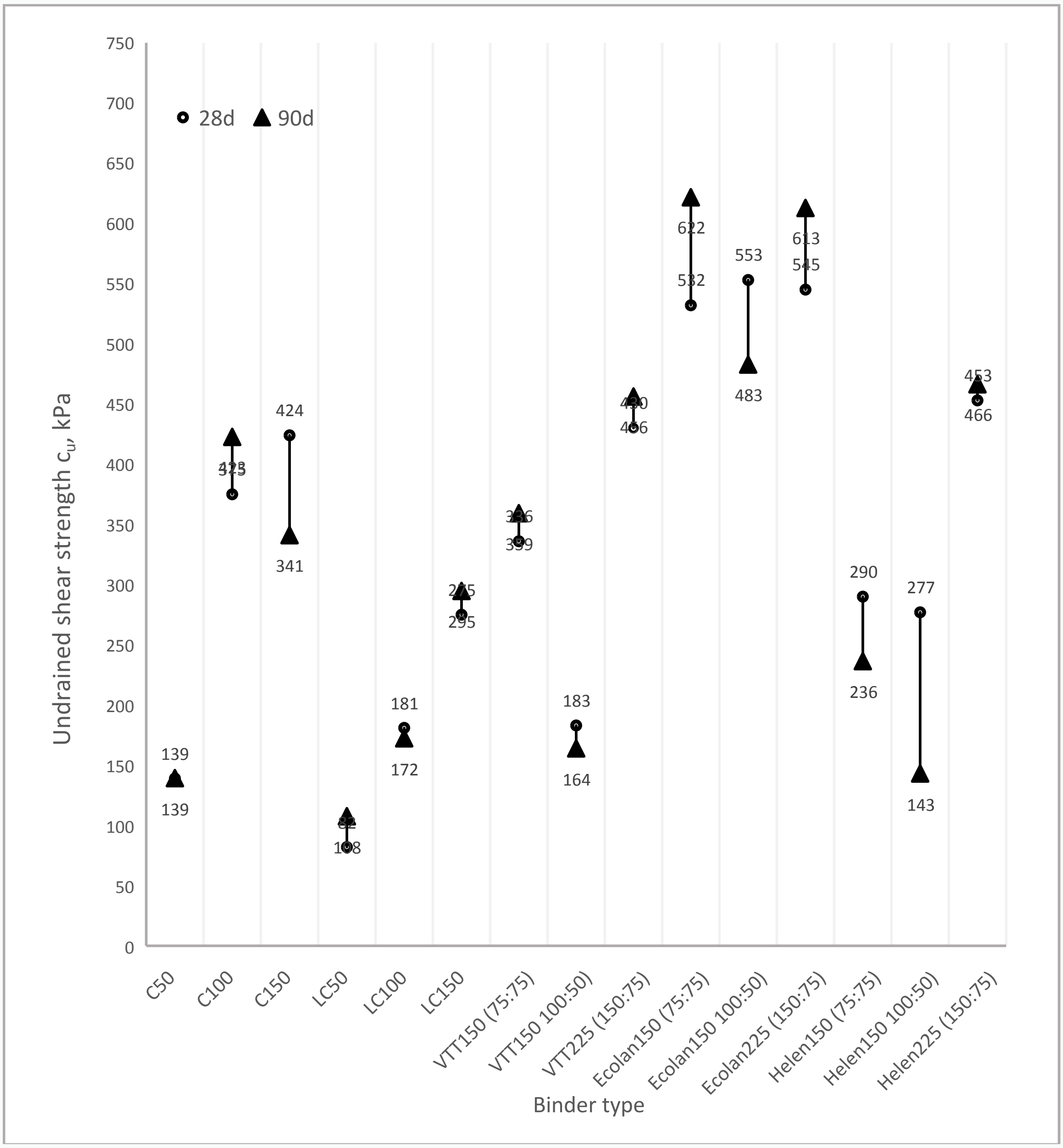


Figure 4.13 *Conclusion of undrained shear strengths of stabilized clay in 28 d to 90 d.*

Table 4.4 *Secant Moduli E_{50} of stabilized clay in UCT in 28 d and 3 months.*

Binder type	Min E50, kPa	Max E50, kPa	Average, kPa	STDEV
28d				
C50	270	414	336	73
C100	1014	1118	1056	55
C150	967	1233	1121	137
LC50	92	284	193	96
LC100	231	482	355	125
LC150	657	689	675	17
VTT150 (75:75)	712	909	830	104
VTT150 100:50)	534	854	663	169
VTT225 (150:75)	859	1487	1184	315
Ecolan150 (75:75)	1677	2189	1987	273
Ecolan150 100:50)	1141	1902	1538	382
Ecolan225 (150:75)	1427	1775	1638	185
Helen150 (75:75)	639	1040	806	209
Helen150 100:50)	793	1268	957	270
Helen225 (150:75)	1365	2280	1852	460
90d				
C50	170	466	345	155
C100	680	1656	1271	519
C150	681	1863	1077	681
LC50	187	450	342	138
LC100	585	665	612	46
LC150	801	987	873	97
VTT150 (75:75)	915	1334	1141	211
VTT150 100:50)	522	749	645	115
VTT225 (150:75)	1216	1811	1439	325
Ecolan150 (75:75)	2245	2543	2362	159
Ecolan150 100:50)	1266	2955	2073	847
Ecolan225 (150:75)	1423	2962	2339	810
Helen150 (75:75)	954	1372	1172	210
Helen150 100:50)	369	836	628	238
Helen225 (150:75)	1400	1796	1532	229

4.3 Undrained shear strength in FCT

The FCT was carried out following the European Standard EN ISO 17892-6-2017 for the measurement of undrained shear strength. The amounts of all the binders tested in this study is summarized in Table 4.5. Test results are represented separately in Figures 4.14 to 4.18.

Table 4.5 *Types and amounts of binders used in FCT.*

Binder Type	Amount (kg/m^3)		
Cement	50	150	-
LCM	50	150	-
VTT+cement	150 (75+75)	150 (100+50)	225 (150+75)
Ecolan+cement	150 (75+75)	150 (100+50)	225 (150+75)
Helen+cement	150 (75+75)	150 (100+50)	225 (150+75)

The trends of strengths growth gotten from FCT are generally reliable, since most of the coefficient of determination R^2 are bigger than 0.6, some even nearly to 0.90 as shown in Figures 4.14 to 4.18. However, the R^2 shows in LCM of 50 kg/m^3 is quite low because of the unreliable data between 10 to 20 d. These unreliable data are conjectured due to the uneven materials in the mixture process, which makes some of the samples not representative.

It is noticeable from Figures 4.14 to 4.18 that when the test samples have a relatively low strength, the variability of results is smaller, and results are also more similar as results in UCT. However, strengths were surprisingly high with samples having a high amount of binders, which is a little bit untrusted. There are two possibilities to explain the ridiculous results. One is that samples for FCT and UCT were made in different ways. Samples for FCT were made by static press, this remould process would increase the initial strength to some extent. Furthermore, as told in EN ISO 17892-6-2017, the tests method and formula are most suitable for the samples whose penetration are between 4 - 20 mm. However, since the samples in this study were stabilized clay that was in a relatively high hardness, the penetrations were usually smaller than 4 mm. As shown in Table 4.6, when the penetration is lower than 1.02 mm, the results are not available anymore, since the difference rate between FCT and UCT is larger than 1.8 times. Figure 4.19 shows the relationship between the undrained shear strength from UCT and the ratio of c_u (FCT) / c_u (UCT).

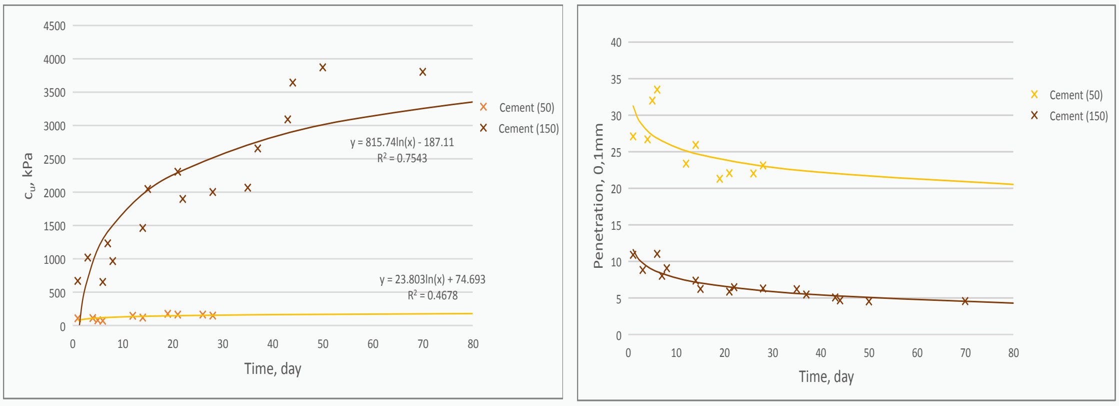


Figure 4.14 *Undrained shear strength (left) and penetration (right) of cement in FCT.*

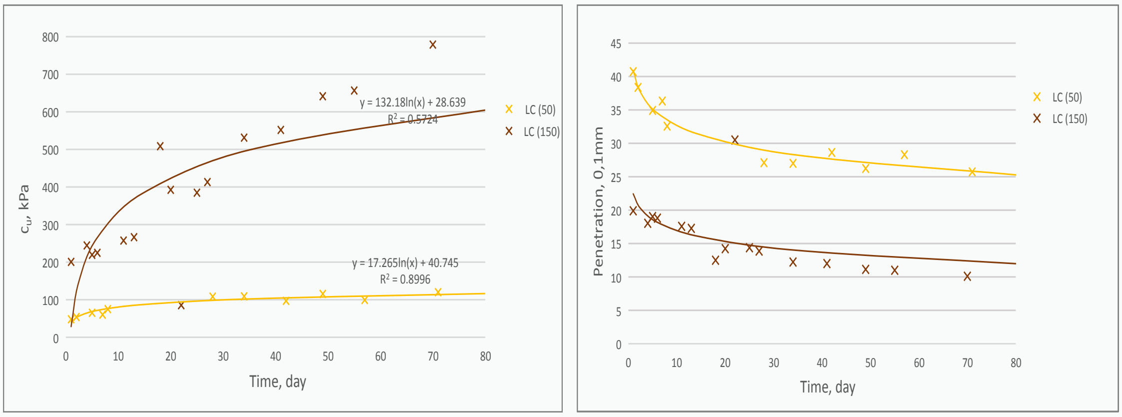


Figure 4.15 *Undrained shear strength (left) and penetration (right) of LCM in FCT.*

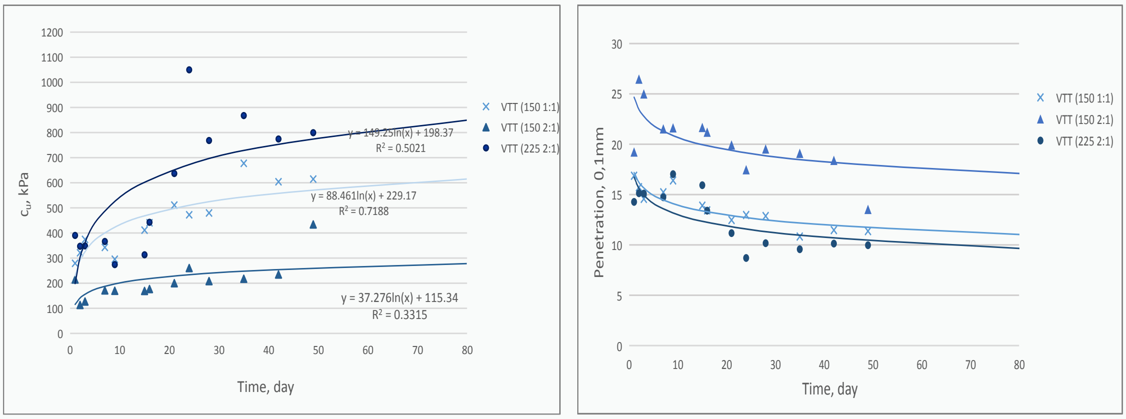


Figure 4.16 *Undrained shear strength (left) and penetration (right) of VTT +cement in FCT.*

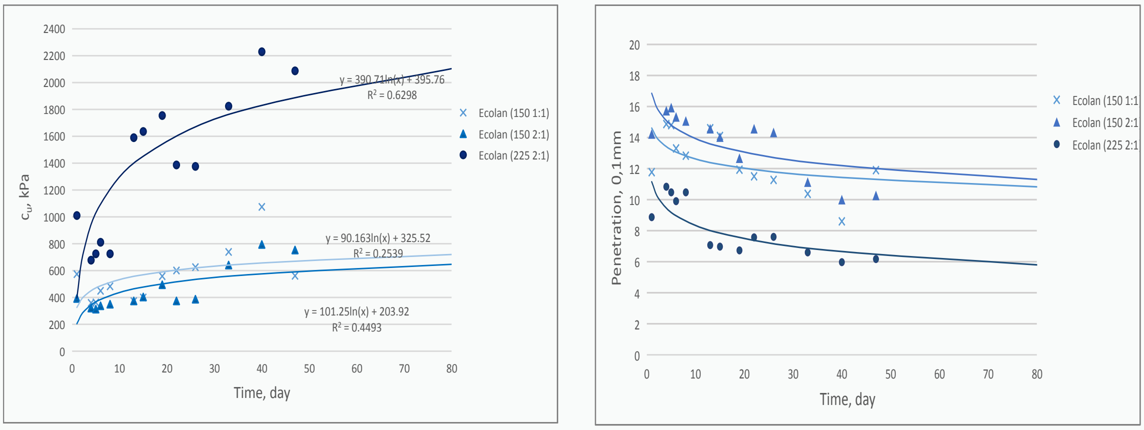


Figure 4.17 *Undrained shear strength (left) and penetration (right) of Ecolan + cement in FCT.*

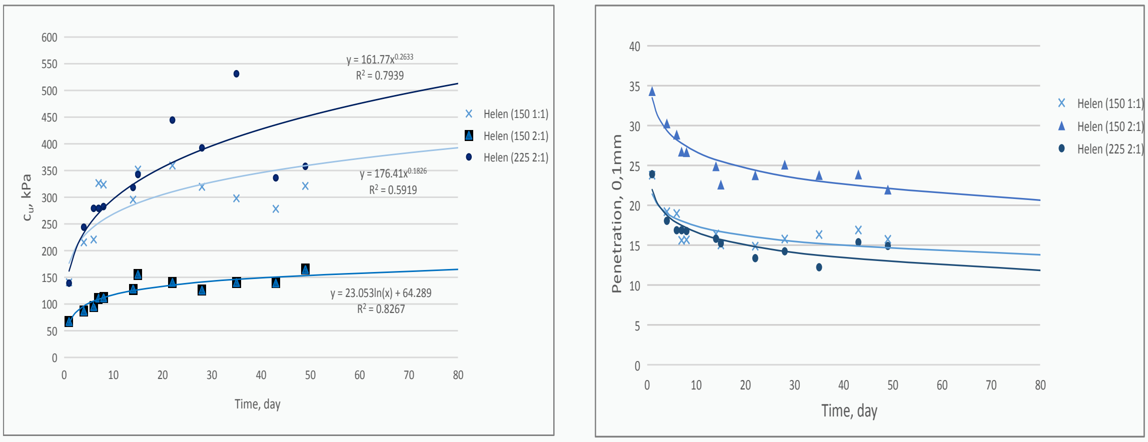


Figure 4.18 *Undrained shear strength (left) and penetration (right) of HELEN + cement in FCT.*

Table 4.6 *Comparison of undrained shear strength (c_u) in 28 d from FCT and UCT.*

Binder type and amount, kg/m^3	Penetration from FCT, mm	c_u from FCT, kPa	c_u from UCT, kPa	Ratio between strengths
Cement (50)	2.3	148	139	1.1
Cement (150)	~~0.63~~	~~2000~~	~~424~~	~~4.7~~
LCM (50)	2.71	108	82	1.3
LCM (150)	1.38	413	275	1.5
VTT+cement (75+75)	1.29	479	336	1.4
VTT+cement (100+50)	1.95	208	183	1.1
VTT+cement (150+75)	~~1.02~~	~~768~~	~~430~~	~~1.8~~
Ecolan+cement (75+75)	1.13	625	532	1.2
Ecolan+cement (100+50)	1.43	586	553	1.1
Ecolan+cement (150+75)	~~0.76~~	~~1375~~	~~545~~	~~2.5~~
HELEN+cement (75+75)	1.58	319	290	1.1
HELEN+cement (100+50)	2.51	126	277	0.5
HELEN+cement (150+75)	1.42	392	453	0.9

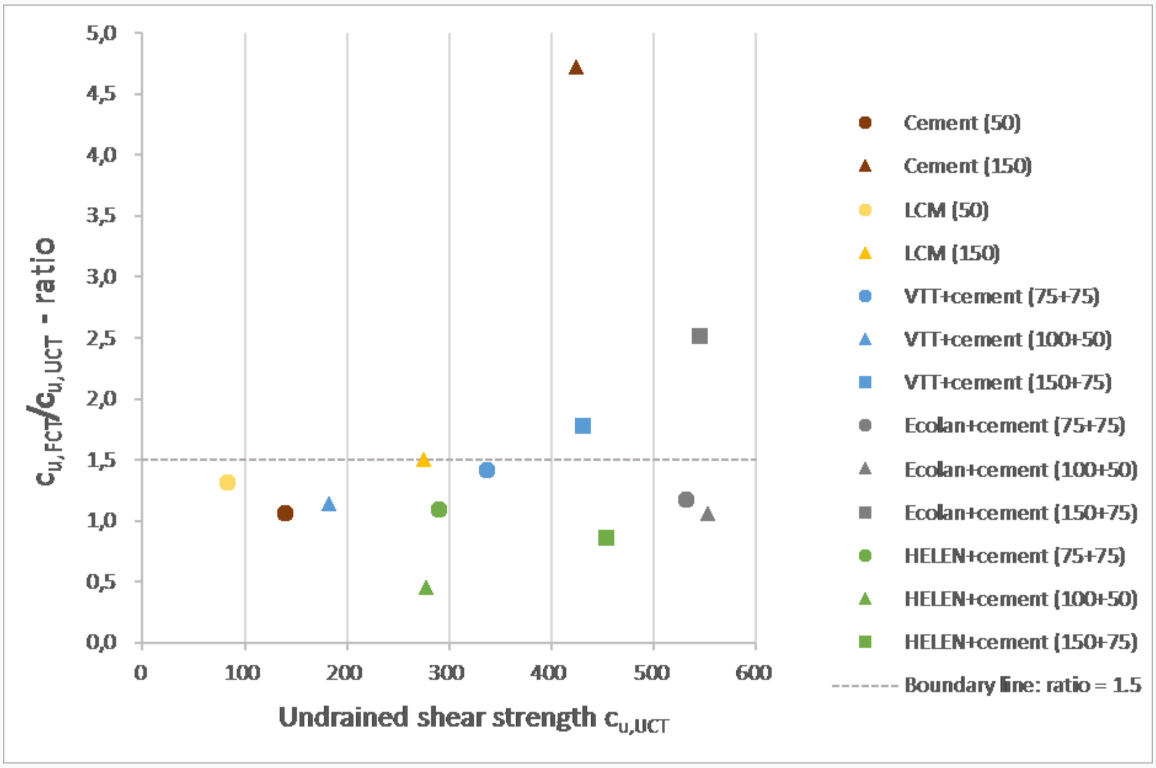


Figure 4.19 *Undrained shear strength from UCT with different ratio.*

4.4 Flexural strength and compressive strength of pure binders

Bending tests and compression tests were carried out as shown in Figures 4.20 and 4.21. Tests reports of compression tests and bending tests for pure binder from VTT, Ecolan and HELEN are shown in Annex 4. Table 4.7 and Table 4.8 summarize the minimum, maximum and also average flexural strength and compressive strength in 7 d, 28 d and 3 months respectively. Standard deviations (STDEV) were also included. The minimum, maximum and average data were concluded in Figures 4.22 and 4.23.

From Table 4.7, it is inferred that gypsum (VTT) and fly ash (HELEN) have the same flexural strength in 7 d of hardening. However, fly ash needs a long time to react and harden since gypsum keep the strength near 2000 kPa from 7d to 3 months. As for ash mixtures from Ecolan, it has the double strength from the beginning of curing compared with the other two binders. And it continues the hardening through the whole curing time, reaching to 7300 kPa.

As for the compressive strength, all the three binders have several times higher compressive strength than flexural strength. Ashes mixture from Ecolan has the largest difference between compressive strength and flexural strength. All the binders increase their compressive strengths in the whole three months. The final compressive strength in 3 months for gypsum (VTT), ashes mixture (Ecolan) and fly ash (HELEN) is 11 900 kPa, 55 300 kPa and 31 000 kPa, respectively. The change of strengths of pure binders keeps in sync with the change of stabilized clay.

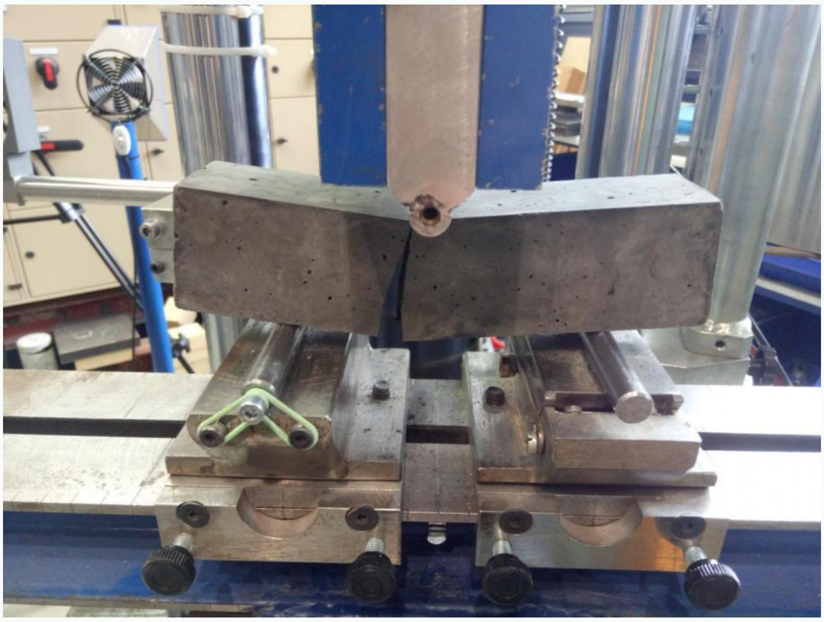


Figure 4.20 *Flexural tests for pure binder. (photo Tianlingzi Xiong 22.05.2018)*

Figure 4.21 *Compression tests for pure binder. (photo Tianlingzi Xiong 22.05.2018)*

Table 4.7 *Flexural strength.*

Binder type	Max strength, kPa	Min strength, kPa	Average, kPa	STDEV
		7d		
VTT	2020	1970	1995	35
Ecolan	4480	3770	4125	502
HELEN	2000	1900	1950	71
		28d		
VTT	2510	2010	2260	354
Ecolan	7600	5950	6775	1167
HELEN	3460	3100	3280	255
		90d		
VTT	2420	1740	2080	481
Ecolan	8050	6640	7345	997
HELEN	4410	4000	4205	290

Table 4.8 *Compression strength.*

Binder type	Max strength, kPa	Min strength, kPa	Average, kPa	STDEV
		7d		
VTT	7600	6800	7275	566
Ecolan	30870	28990	29957.5	1329
HELEN	10160	9530	9852.5	445
		28d		
VTT	9920	8930	9375	700
Ecolan	47340	35690	41700	8238
HELEN	20550	18950	19450	1131
		90d		
VTT	11980	11820	11905	113
Ecolan	57920	52890	55255	3557
HELEN	32270	29990	30987.5	1612

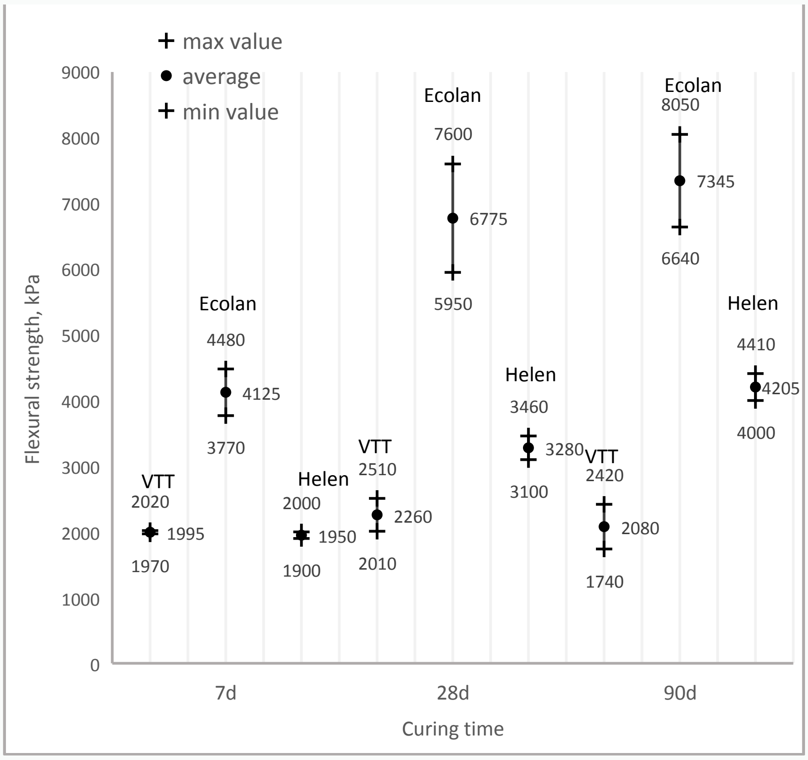


Figure 4.22 *Flexural strength results. Binders VTT, Ecolan and HELEN.*

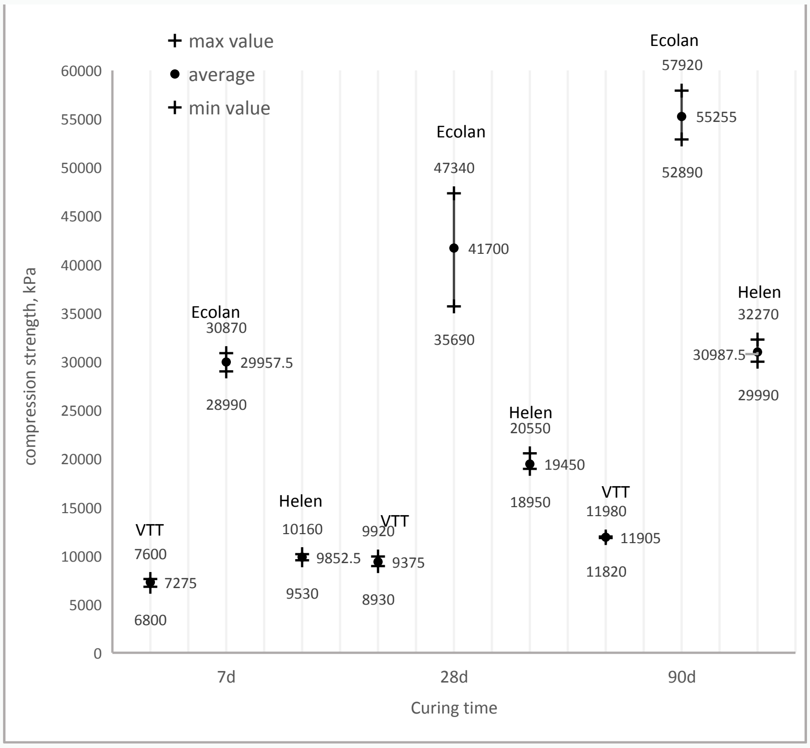


Figure 4.23 *Compression strength results. Binders VTT, Ecolan and HELEN.*

5. CONCLUSIONS

In this study, three types of binders based on recycled materials combined with cement were used to stabilize soft clay in laboratory tests. These recycled materials were gotten from VTT Oy, Ecolan Oy and HELEN Oy separately. Plus cement Plus CEM II / B-M (S-LL) 42.5 N and Lime-cement mixture Nordkalk Terra^{TM} KC50 were tested in this study as the reference materials for those three binders. Undrained shear strength c_u was tested out based on unconfined compression test and fall cone test.

In this study the compaction method of the samples did not follow Finnish stabilization guideline (Finnish Transport Agency 2018) since the aim was to produce as good samples as possible. Because of that the achieved strength are very high and not necessarily directly comparable to results from other researches where the compaction of the samples is not so effective.

The strength of stabilized clay specimens has increased after some curing days. However, the degree of increase and the suitable binder-cement ratio are different from every kind of binder.

- Gypsum from VTT mixed with cement has a good hardening effect of the clay with binder mixtures 75 and 150 kg/m^3 of gypsum mixed with 75 kg/m^3 of cement. With the mixture 100 kg/m^3 of gypsum and 50 kg/m^3 of cement, the effect was clearly lower. The reason for this is not clear. The strength was increasing slightly from 28 d to 3 months.
- Ash mixture from Ecolan Oy has an outstanding behavior among all the binders in this study. Strength is high with a relatively low amount of binder. The increase of ashes mixture does not bring the strength growth, but the cement amount from 50 kg/m^3 to 75 kg/m^3 takes an obvious growth of strength in the long-term hardening.
- Fly ash from HELEN behaved in quite similar way with gypsum from VTT. The difference is that a shorter hardening time was needed in this type of combination. The strength reached the maximum value in 28 d. Strengths tested from fall cone test (FCT) also shows that there was no significant increase from the 30th day. However, it is noticeable that a sufficient amount of cement and fly ash was needed to ensure the steady of strength in the long term. The lack of cement amount in the mixture led to a significant decrease of strength from 28 d to 3 months.

In addition, significant difference exists in the 28 d strengths from undrained compression test (UCT) and fall cone test (FCT). When the binder from VTT Oy and Ecolan Oy were in the highest amount (225 kg/m^3), strength from FCT was 1.8 times and 2.5 times separately than strength from UCT. It is inferred that when sample in a high strength, penetration tested from FCT was low. The low value of penetration made the calculation of undrained shear strength not that trusted anymore since the formula is most suitable for the samples whose penetration are between 4 - 20 mm.

From all these three types of combination, the sufficient amount of cement is crucial for the long-term strength. It is noting from UCT that when the cement is 50 kg/m^3, activator is not enough during the reaction process, which leads to the decrease of strength from 28 d to 3 months. However, strengths (when cement is 50 kg/m^3) tested from FCT were still in an increasing trend continuously. The reason of this phenomenon is not clear now, so more research is needed for this.

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APPENDICES

Annex 1. Structure of soil layers in test pit 1, 1 page.

Annex 2. Soil profile near the sampling point of stabilization test samples, 1 page.

Annex 3. Location of the sounding points, 1 page.

Annex 4. Test reports of compression tests and flexural tests, 9 pages.

Annex 5. Description of Nordkalk QL 90 T, 1 page.

Annex 6. Description of Nordkalk Terra^{TM} KC50 and KC30, 1 page.

Annex 7. Description of fly ash from HELEN, 3 pages.

Annex 8. Stress – strain curves from every compression test in UCT, 15 pages.

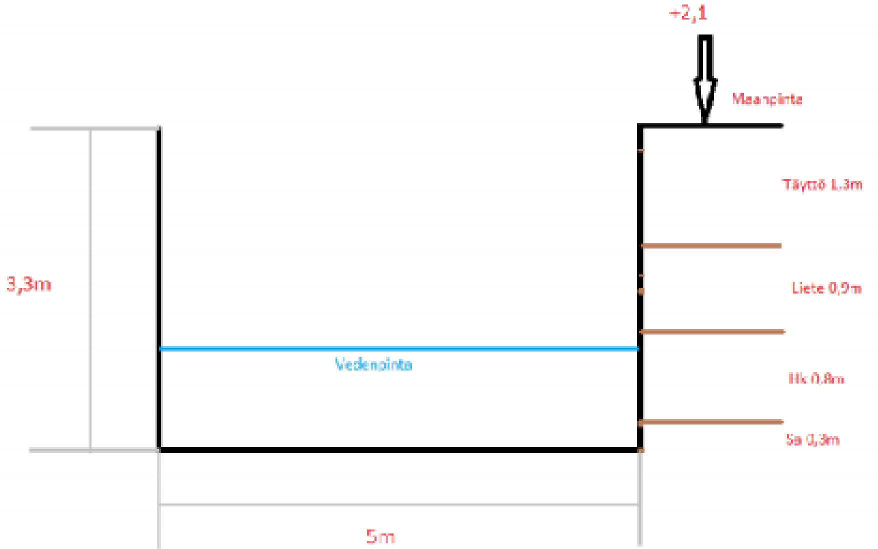
Annex 1. Structure of soil layers in test pit 1.

STARA
Pidetään Stadista huolta.
Pohjatutkimus

KOEKUOPPAPÖYTÄKIRJA

23.2.2018

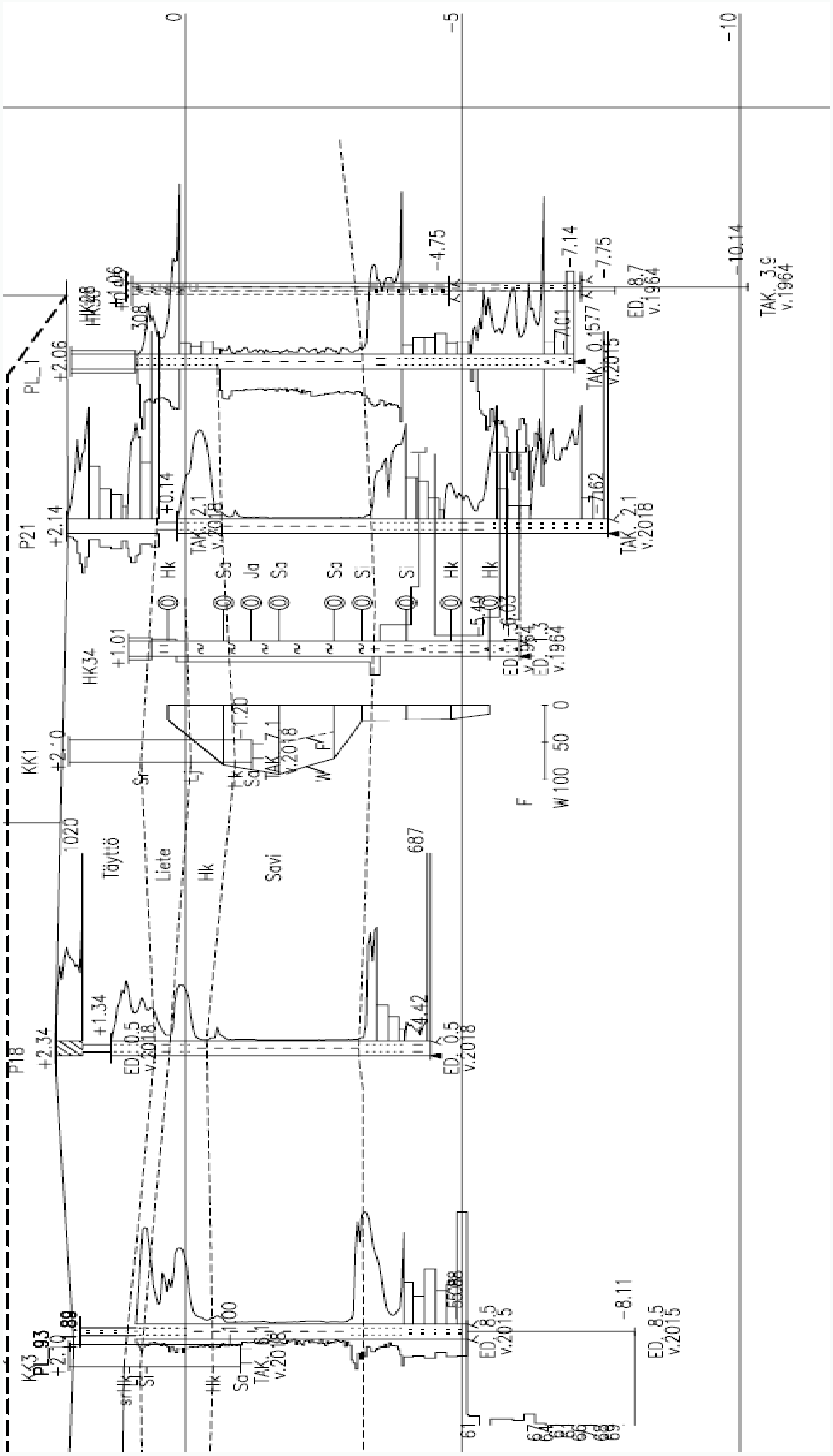
KOEKUOPPA 1. Leikkauspiirros



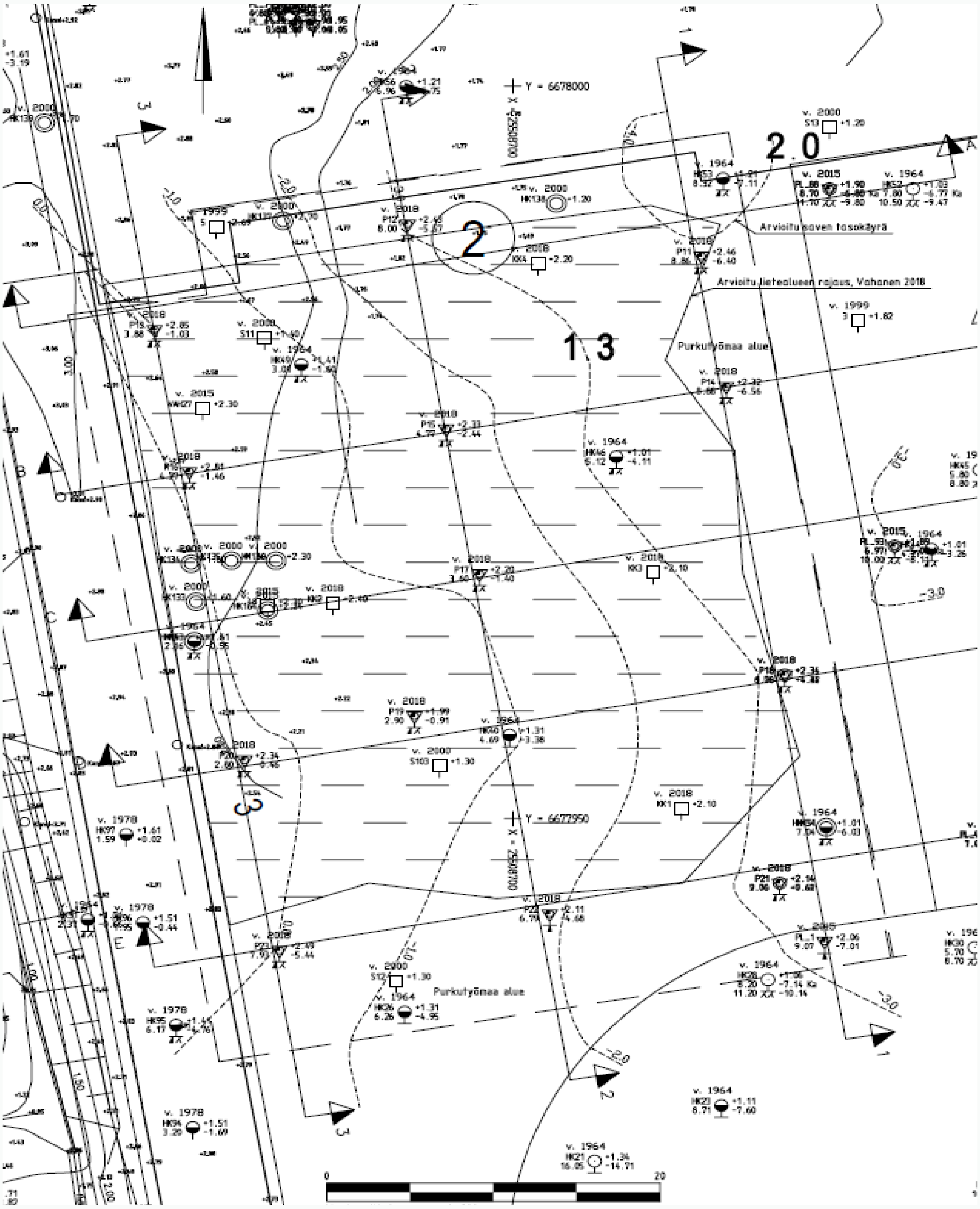
Ei mittakaavassa.

Stara Helsingin kaupungin rakentamispalvelu Osoite PL 1660, 00099 Helsingin kaupunki/Ilmalankuja 2L Puhelin +358 9 310 17000
Faksi +358 9 310 39601 Tilinumero 800012 62637 Y-tunnus 0201256-6 Alv rek FI02012566 Sähköposti stara@hel.fi, stara.kirjaamo@hel.fi
Internet www.hel.fi/stara

Annex 2. Soil profile near the sampling point of stabilization test samples.



Annex 3. Location of the sounding points.



Annex 4. Test reports of compression tests and bending tests.

Zwick / Roell

24.08.18

Flexural strength. Casted samples 7d.

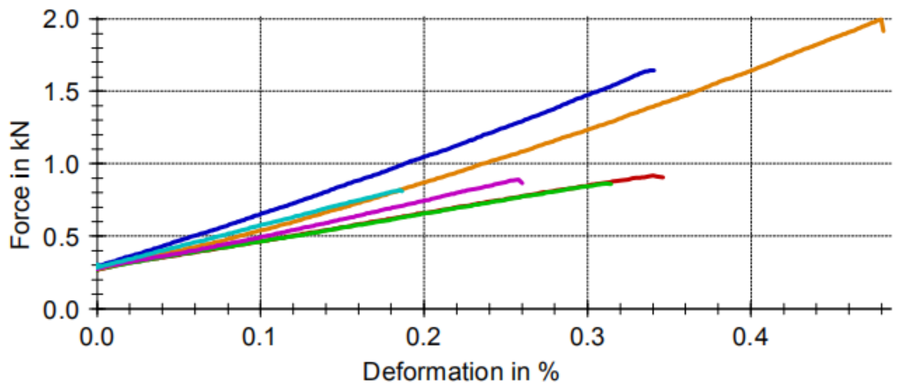
Heading	:	Flexural strength. Casted samples 7d.
Customer	:	Lasia
Test standard	:	SFS EN 196-1:2005 Taivutuskoe
Material	:	Concrete
Specimen type	:	Prisms 40 mm x 40 mm x 160 mm
Pre-treatment	:	
Tester	:	Jukka Piironen
Machine data	:	Zwick RK 250/50

Pre-load : 300 N
Test speed : 50 N/s

Test results:

Legends	Nr	Specimen no.	Specimen identifier	a_0 mm	b_0 mm	S_0 mm²	F_{max} N	σ_M N/mm²	dL at F_{max} mm	Date
	1	1	VTT-1-7d	40,5	41,4	1676,70	917	2,02	0,1	2.5.2018
	2	2	VTT-2-7d	40,4	40,2	1624,08	861	1,97	0,1	2.5.2018
	3	3	Ecolan-1-7d	40	40,8	1632,00	1640	3,77	0,1	2.5.2018
	4	4	Ecolan-2-7d	40,1	41,6	1668,16	2000	4,48	0,2	2.5.2018
	5	5	Helen-1-7d	40,3	41,1	1656,33	890	2,00	0,1	3.5.2018
	6	6	Helen-2-7d	40	40,3	1612,00	817	1,90	0,1	3.5.2018

Series graph:



Statistics:

Series n = 6	Specimen no.	F_{max} N	σ_M N/mm²	dL at F_{max} mm	a_0 mm	b_0 mm	S_0 mm²
x	4	1190	2,69	0,1	40,22	40,9	1644,88
s	2	504	1,13	0,0	0,2137	0,5727	25,94
ν	53,45	42,41	42,15	30,96	0,53	1,40	1,58

180523-BT-7d.zs2

Page 1/1

Zwick / Roell

Flexural strength. Casted samples 28 d

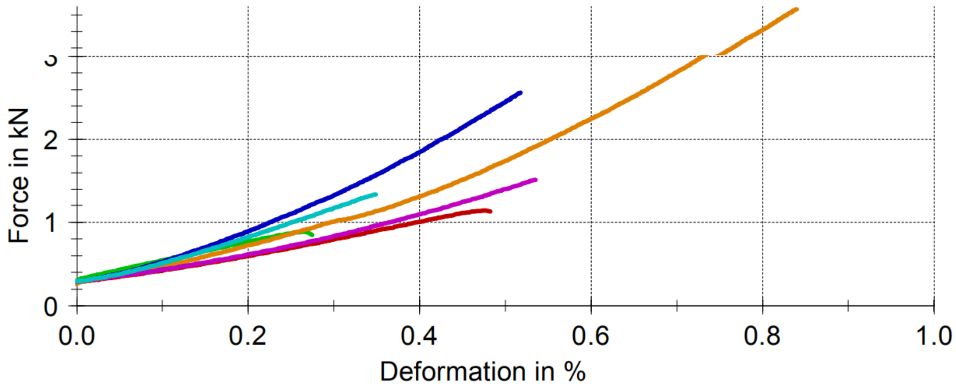
Heading	: Flexural strength. Casted samples 28 d	Specimen type	: Prisms 40 mm x 40 mm x 160 mm
Customer	: Lasia	Pre-treatment	:
Test standard	: SFS EN 196-1:2005 Taivutuskoe	Tester	: Jukka Piironen
Material	: Concrete	Machine data	: Zwick RK 250/50

Pre-load : 300 N
Test speed : 50 N/s

Test results:

Legends	Nr	Specimen no.	Specimen identifier	a_0	b_0	S_0	F_{max}	σ_M	dL at F_{max}	Date
				mm	mm	mm²	N	N/mm²	mm	
(red)	7	1	VTT-1-28d	40,7	41,2	1676,84	1140	2,51	0,2	22.5.2018
(green)	8	2	VTT-2-28d	40,1	41,2	1652,12	889	2,01	0,1	22.5.2018
(blue)	9	3	Ecolan-1-28d	39,8	40,8	1623,84	2570	5,95	0,2	23.5.2018
(orange)	10	4	Ecolan-2-28d	40,9	43,3	1770,97	3670	7,60	0,3	23.5.2018
(magenta)	11	5	Helen-1-28d	39,9	41,2	1643,88	1510	3,46	0,2	23.5.2018
(cyan)	12	6	Helen-2-28d	40,1	40,2	1612,02	1340	3,10	0,1	23.5.2018

Series graph:



Statistics:

Series	Specimen no.	F_{max}	σ_M	dL at F_{max}	a_0	b_0	S_0
n = 6		N	N/mm²	mm	mm	mm	mm²
$\bar{x}$	4	1850	4,11	0,2	40,25	41,32	1663,28
s	2	1060	2,19	0,1	0,4461	1,048	57,38
ν	53,45	57,24	53,32	38,91	1,11	2,54	3,45

24.08.18

Zwick / Roell

Flexural strength 3 m

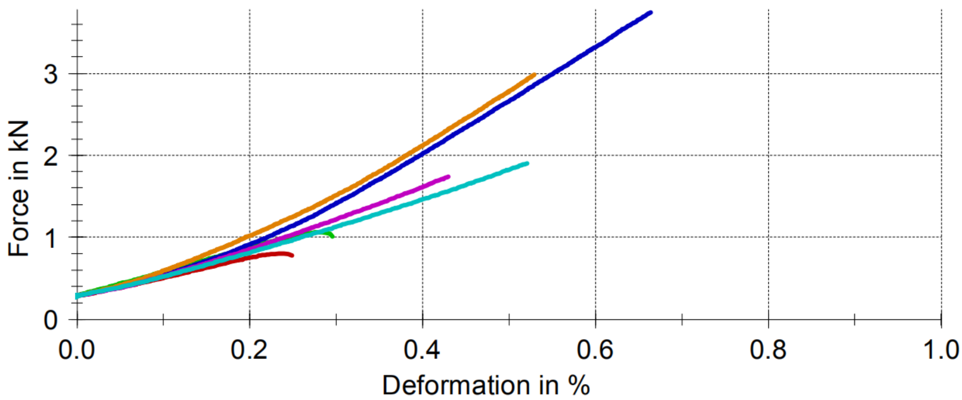
Heading	:	Flexural strength 3 m	Specimen type	:	Prisma 40 mm x 40 mm x 160 mm
Customer	:	Joonas Jaaranen	Pre-treatment	:	
Test standard	:	SFS EN 196-1:2005 Taivutuskoe	Tester	:	Veli-Antti Hakala
Material	:	Concrete	Machine data	:	Zwick RK 250/50

Pre-load : 300 N
Test speed : 50 N/s

Test results:

Legends	Nr	Specimen identifier	a_0 mm	b_0 mm	S_0 mm²	F_{max} N	**σ_M N/mm²**	dL at F_{max} mm	Date
(red)	1	**vtt-1-3m**	40,4	42,3	1708,92	803	**1,74**	0,1	24.7.2018
(green)	2	**vtt-2-3m**	40,1	41	1644,10	1060	**2,42**	0,1	24.7.2018
(blue)	3	**Ecolan-1-3m**	40,5	42,5	1721,25	3740	**8,05**	0,3	24.7.2018
(orange)	4	**Ecolan-2-3m**	40,1	41,9	1680,19	2980	**6,64**	0,2	24.7.2018
(magenta)	5	**Helen-1-3m**	40,1	40,5	1624,05	1740	**4,00**	0,2	24.7.2018
(cyan)	6	**Helen-2-3m**	40,1	40,2	1612,02	1900	**4,41**	0,2	24.7.2018

Series graph:



Statistics:

Series	Specimen no.	F_{max}	σ_M	dL at F_{max}	a_0	b_0	S_0
n = 6		N	N/mm²	mm	mm	mm	mm²
$\bar{x}$	4	2040	4,55	0,2	40,2	41,4	1665,09
s	2	1130	2,42	0,1	0,2	0,9675	45,26
ν	53,45	55,41	53,30	36,24	0,46	2,34	2,72

24.08.18

Zwick / Roell

Compressive Strength of Casted Samples 7d

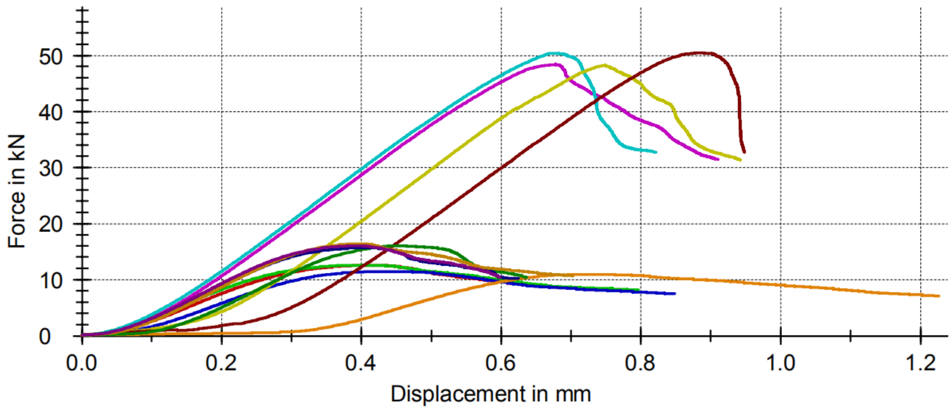
Heading : Compressive Strength of Casted Samples 7d
Customer : Lasia
Test standard : SFS-EN 196-1
Material : VTT, Ecolan
Specimen type : Prism 40x40x160
Tester : Jukka Piironen
Notes... :
Machine data : Kuormituslaite: Zwick RK 250/50
Voima-anturi: HBM U2A NO: D5605

Pre-load : 80 N
Test speed : 0,4 mm/min

Test results:

Nr	Specimen identifier	a_0 mm	b_0 mm	F_{max} kN	σ_M N/mm²	dL at F_{max} mm	Date
1	VTT-1-1-7d	41,40	40,00	12,6	7,58	0,4	2.5.2018
2	VTT-1-2-7d	41,40	40,00	12,6	7,60	0,4	2.5.2018
3	VTT-2-1-7d	40,20	40,00	11,5	7,12	0,4	2.5.2018
4	VTT-2-2-7d	40,20	40,00	10,9	6,80	0,7	2.5.2018
5	Ecolan-1-1-7d	40,80	40,00	48,4	29,65	0,7	2.5.2018
6	Ecolan-1-2-7d	40,80	40,00	50,4	30,87	0,7	2.5.2018
7	Ecolan-2-1-7d	41,60	40,00	48,2	28,99	0,7	2.5.2018
8	Ecolan-2-2-7d	41,60	40,00	50,5	30,32	0,9	2.5.2018
9	Helen-1-1-7d	41,10	40,00	16,0	9,76	0,5	3.5.2018
10	Helen-1-2-7d	41,10	40,00	15,7	9,53	0,4	3.5.2018
11	Helen-2-1-7d	40,30	40,00	16,4	10,16	0,4	3.5.2018
12	Helen-2-2-7d	40,30	40,00	16,1	9,96	0,4	3.5.2018

Series graph:



Zwick / Roell

24.08.18

Statistics:

Series n = 12	σ_u N/mm²	dL at F_{max} mm	a_0 mm	b_0 mm
$\bar{x}$	15,70	0,8	40,90	40,00
s	10,60	0,2	0,55	0,00
v	67,55	32,45	1,34	0,00

Zwick Roell

24.08.18

Compressive Strength of Casted Samples 28 d

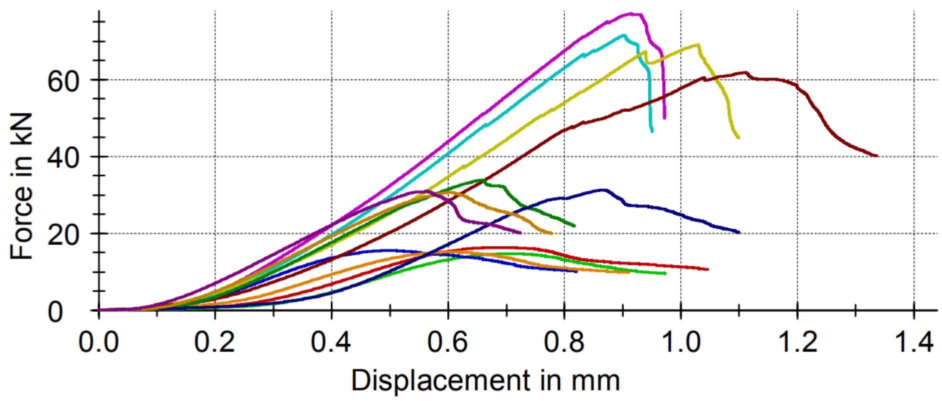
Heading : Compressive Strength of Casted Samples 28 d
Customer : Lasia
Test standard : SFS-EN 196-1
Material : VTT, Ecolan
Specimen type : Prism 40x40x160
Tester : Jukka Piironen
Notes... :
Machine data : Kuormituslaite: Zwick RK 250/50
Voima-anturi: HBM U2A NO: D5605

Pre-load : 80 N
Test speed : 0,4 mm/min

Test results:

Nr	Specimen identifier	a_0 mm	b_0 mm	F_{max} kN	σ_M N/mm²	dL at F_{max} mm	Date
1	**VTT-1-1-28d**	41,20	40,00	16,4	9,92	0,7	22.5.2018
2	**VTT-1-2-28d**	41,20	40,00	14,7	8,93	0,7	22.5.2018
3	**VTT-2-1-28d**	41,20	40,00	15,6	9,46	0,5	22.5.2018
4	**VTT-2-2-28d**	41,20	40,00	15,1	9,19	0,6	22.5.2018
5	**Ecolan-1-1-28d**	40,80	40,00	77,3	47,34	0,9	23.5.2018
6	**Ecolan-1-2-28d**	40,80	40,00	71,6	43,89	0,9	23.5.2018
7	**Ecolan-2-1-28d**	43,30	40,00	69,1	39,88	1,0	23.5.2018
8	**Ecolan-2-2-28d**	43,30	40,00	61,8	35,69	1,1	23.5.2018
9	**Helen-1-1-28d**	41,20	40,00	33,9	20,55	0,7	23.5.2018
10	**Helen-1-2-28d**	41,20	40,00	31,2	18,95	0,9	23.5.2018
11	**Helen-2-1-28d**	40,20	40,00	30,7	19,08	0,6	23.5.2018
12	**Helen-2-2-28d**	40,20	40,00	30,9	19,22	0,6	23.5.2018

Series graph:



Zwick / Roell

24.08.18

Statistics:

Series	σ_N	dl at F_{max}	a_0	b_0
n = 12	N/mm²	mm	mm	mm
$\bar{x}$	23,51	0,8	41,32	40,00
s	14,36	0,2	1,00	0,00
ν	61,06	25,82	2,42	0,00

24.08.18

Zwick / Roell

Compressive Strength of Casted Samples 3 m

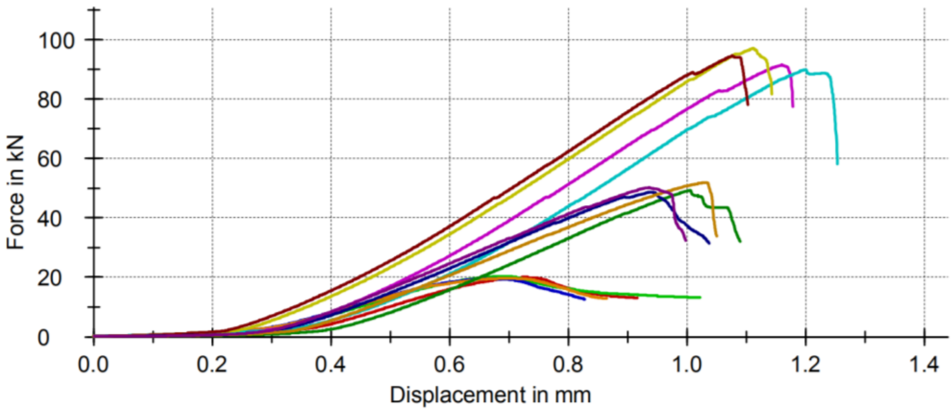
Heading	:	Compressive Strength of Casted Samples 3 m
Customer	:	Lasia
Test standard	:	SFS-EN 196-1
Material	:	VTT, Ecolan, Helen
Specimen type	:	Sementti prisma 40x40x160
Notes...	:	
Machine data	:	Kuormituslaite: Zwick RK 250/50 Voima-anturi: HBM U2A NO: D5605

Pre-load	:	80	N
Test speed	:	1,5	mm/min

Test results:

Nr	Specimen identifier	a_0 mm	b_0 mm	F_{max} kN	σ_M N/mm²	dL at F_{max} mm	Date
1	vtt1-1-3m	42,30	40,00	20,0	11,82	0,7	24.7.2018
2	vtt1-2-3m	42,30	40,00	20,3	11,97	0,7	24.7.2018
3	vtt2-1-3m	41,00	40,00	19,4	11,85	0,7	24.7.2018
4	vtt2-2-3m	41,00	40,00	19,6	11,98	0,7	24.7.2018
5	Ecolan1-1-3m	42,50	40,00	91,5	53,81	1,2	24.7.2018
6	Ecolan1-2-3m	42,50	40,00	89,9	52,89	1,2	24.7.2018
7	Ecolan2-1-3m	41,90	40,00	97,1	57,92	1,1	24.7.2018
8	Ecolan2-2-3m	41,90	40,00	94,5	56,40	1,1	24.7.2018
9	Helen1-1-3m	40,50	40,00	49,4	30,47	1,0	24.7.2018
10	Helen1-2-3m	40,50	40,00	48,6	29,99	0,9	24.7.2018
11	Helen2-1-3m	40,20	40,00	51,9	32,27	1,0	24.7.2018
12	Helen2-2-3m	40,20	40,00	50,2	31,22	0,9	24.7.2018

Series graph:



Zwick/Roell

24.08.18

Statistics:

Series	σ_M	dl at F_{max}	a_0	b_0
n = 12	N/mm²	mm	mm	mm
$\bar{x}$	32,72	0,9	41,40	40,00
s	18,58	0,2	0,92	0,00
ν	56,78	20,77	2,23	0,00

Annex 5. Description of Nordkalk QL 90 T.

Nordkalk QL 90 T

CE EN 459-1

Product:	Quicklime, CaO, Calcium Oxide
Production Plant:	Tytyri, Lohja, Finland
Raw Material:	Finnish limestone
CAS Number:	1305-78-8
REACH Reg. Number:	01-2119475325-36-0026

Typical Chemical Composition

Method: XRF (24 months average)

CaO	83,8 %	Fe_2O_3	0,64 %	Na_2O	0,20 %
SiO_2	7,5 %	MgO	2,1 %	MnO	0,05 %
Al_2O_3	1,7 %	K_2O	0,35 %	P_2O_5	0,04 %

Available CaO	77,0 %	Method: EN 459-2 (12 months average)
Residual CO_2	2,7 %	Method: EN 459-2 (12 months average)

Typical Particle Size

Method: EN 459-2 (12 months average)

mm	%	mm	%	mm	%
< 0,090	83,7	< 0,200	99,7	< 2,000	100

The values in this product description are based on longtime results. Because the raw material of the product is of natural origin the analysis results can vary. All data in this product description is meant as general information for the user. The values should not be interpreted as binding specification and are given for guidance only.

Sales: Nordkalk Oy Ab
Tel. 020 753 7000

www.nordkalk.com

Annex 6. Description of Nordkalk Terra™ KC50 and KC30.

Nordkalk

25.1.2017

Nordkalk Terra™ KC50 ja KC30 seosten tuotekuvaus

Tuotekuvaus
Raaka-aineet: Nordkalk Oy Ab:n Lohjan Tytyrin tehtaan poltettu ja jauhettu kalkki QL90T (CaO) ja Finnsementin Paraisten tehtaan Plussementti CEM II/B-M (S-LL) 42,5 N. Sekä kalkki, että sementti ovat CE-merkittyjä (www.nordkalk.fi/dop ja www.finnsementti.fi)

Nordkalk Terra™ KC50 valmistetaan sekoittamalla raaka-aineet painosuhteissa 1:1 ja Nordkalk Terra™ KC30 painoseossuhteessa 30 % kalkkia ja 70 % sementtiä.

Laadunvarmistus
Tytyrin tehtaan stabilointituotteiden sekoitusasemassa laadunvalvonta tapahtuu erityisten säteilyvaakojen avulla. Jokainen lastaustapahtuma tallentuu tehtaan serverille. Kaikki toimitetut kuormat ovat tarvittaessa jäljitettävissä jälkikäteen kuormakirjan perusteella. Asiakkaille tallenteista lähetetään viikkoyhteenveto, missä ilmoitetaan tuotteen raaka-aineiden prosenttiosuus.

Raportointi
Tulokset (kalkin ja sementin seossuhteet) raportoidaan urakoitsijalle kerran kuukaudessa tai aina tarvittaessa.

Nordkalk Oy Ab

Kari Kuusipuro

Kari Kuusipuro
Myyntipäällikkö
puh. 020 753 7470
kari.kuusipuro@nordkalk.com

Annex 7. Description of fly ash from HELEN.

RWE

Date 22.07.2010
Sample: 2010006718-001

Power AG
Hauptlabor
Dürenerstr. 92
D-50226 Frechen

Helsingin Energia
Mrs. Sanna Ojala
Porkkalankatu 9-11
FIN-00090 Helen

Report for Fly Ash

Place of sampling	Hana
Sampler:	Helsingin Energia
Date of sampling:	
Date received:	28.05.2010
Order number:	2010006717
Sample number:	2010006717-001
Responsible Lab:	Coal laboratory

ANALYSIS OF MAIN CONSTITUENTS, ANNEX 1

Parameter	Value	Unit	Instruction for testing	Comment
Silicon oxide-4	55,6	%(m/m)	DIN 51729 Part 10	*
Alumina	20,8	%(m/m)	DIN 51729 Part 10	*
Iron oxide-3	6,77	%(m/m)	DIN 51729 Part 10	*
Titanium oxide-4	0,85	%(m/m)	DIN 51729 Part 10	*
Calcium oxide	7,54	%(m/m)	DIN 51729 Part 10	*
Magnesium oxide	2,93	%(m/m)	DIN 51729 Part 10	*
Potassium oxide	2,42	%(m/m)	DIN 51729 Part 10	*
Sodium oxide	1,64	%(m/m)	DIN 51729 Part 10	*
Manganese oxide-2	< 0,10	%(m/m)	DIN 51729 Part 10	*
Phosphorus oxide-5	0,56	%(m/m)	DIN 51729 Part 10	*
Sulfur oxide-6	< 0,7	%(m/m)	DIN 51729 Part 10	*
Chlorine	0,001	%(m/m)	EN 196-2	Based on dry matter
Total moisture	0,1	%(m/m)	DIN 51718	As received
Loss on ignition	11,05	%(m/m)	EN 196-2	Based on dry matter
Total Organic Carbon	9,89	%(m/m)	DIN EN 13137	Based on dry matter
Calcium oxide, free	1,82	%(m/m)	EN 451-1	Based on dry matter
pH	12,74		DIN ISO 10390	As received

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DAkkS
Deutsche
Akkreditierungsstelle
D-PL-14144-02-00

RWE

Date 22.07.2010
Sample: 2010006718-001

Power AG
Hauptlabor
Dürenerstr. 92
D-50226 Frechen

ANALYSIS OF TRACE ELEMENTS (SOLID) of ASH, ANNEX 2

Parameter	Value	Unit	Instruction for testing	Comment
Arsenic	29	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Boron	451	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Barium	2160	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Beryllium	4,03	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Bromine	3,3	mg/kg	EN ISO 10304	Based on dry matter
Cadmium	0,5	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Cobalt	40	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Chromium, total	82	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Copper	54	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Fluorine	36	mg/kg	EN ISO 10304	Based on dry matter
Mercury	0,25	mg/kg	EN 1483	Based on dry matter
Manganese	565	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Molybdenum	11,6	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Nickel	70	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Lead	39	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Antimony	4,0	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Selenium	4,2	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Tin	39	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Strontium	1330	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Tellurium	< 0,5	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Thallium	1,2	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Vanadium	113	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Tungsten	79,7	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter
Zinc	120	mg/kg	DIN EN ISO 17294-2 (E29)	Based on dry matter

Date 22.07.2010
Sample: 2010006718-001

RWE Power AG
Hauptlabor
Dürenerstr. 92
D-50226 Frechen

QUANTITATIVE X-RAY DIFFRACTION ANALYSIS OF ASH THROUGH RIETVELD REFINEMENT, ANNEX 3

Parameter	Value	Unit	Instruction for testing	Comments
X-ray-amorphous	63	%(m/m)	DIN EN 13925-2	As received, **
CaO free calcium oxide	3	%(m/m)	DIN EN 13925-2	As received, **
Fe3O4,γ-Fe2O3, magnetite, maghemite	2	%(m/m)	DIN EN 13925-2	As received, **
Al6Si2O13, mullite	13	%(m/m)	DIN EN 13925-2	As received, **
MgO, periklase	3	%(m/m)	DIN EN 13925-2	As received, **
SiO2, quartz	16	%(m/m)	DIN EN 13925-2	As received, **

Annotation to the analysis:
Analysis begin: 28.05.2010; Analysis end: 19.07.2010

Principles for decomposition/ digestion:
DIN EN 17294-2, ICP-MS: HF-decomposition in autoclave at 160-180 °C for 18 h
EN ISO 10304-1, Ion chromatography: HNO_3–digestion at 100 °C for 3 min (acc. EN 14629)

* = The X-ray fluorescence analysis was determined from the 815°C- ignition residue.
** = non-accredited method

The weight fractions of mineral phases (quantitative X-ray diffraction) are rounded to integer values. Shares of <1% (m/m) are not considered.

The applied analysis methods give results equivalent to those obtained with the reference methods, based on experience.

i. A. Poppe
Dr. Klaus Poppe (Head of Laboratory)

i. A. [signature]
Dr. Jens Steidtner (Quality Manager)

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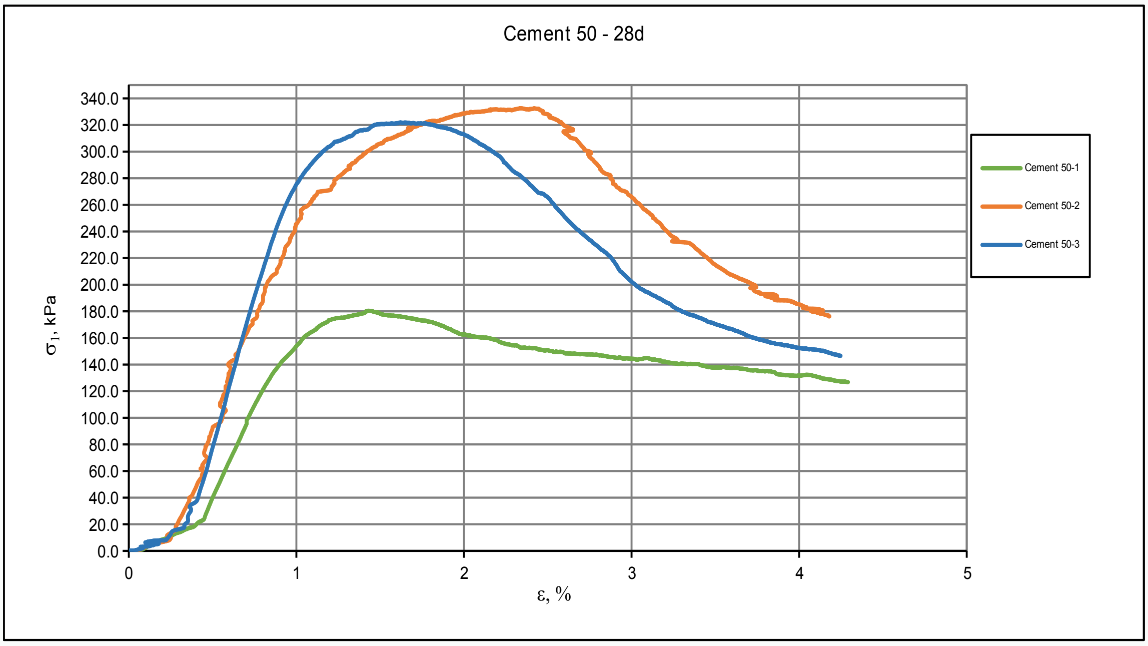
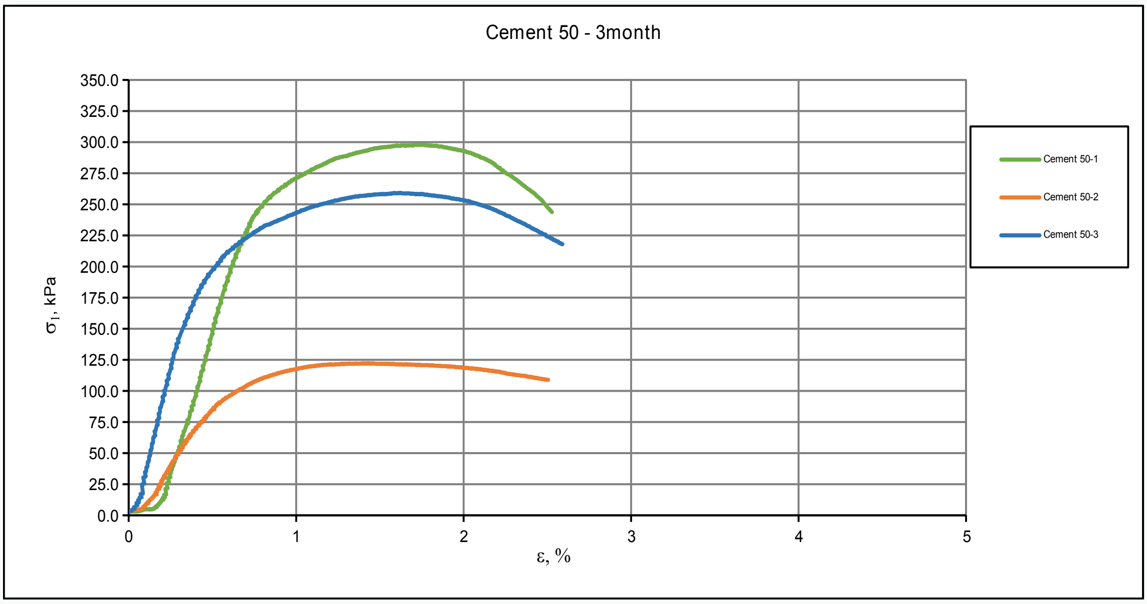
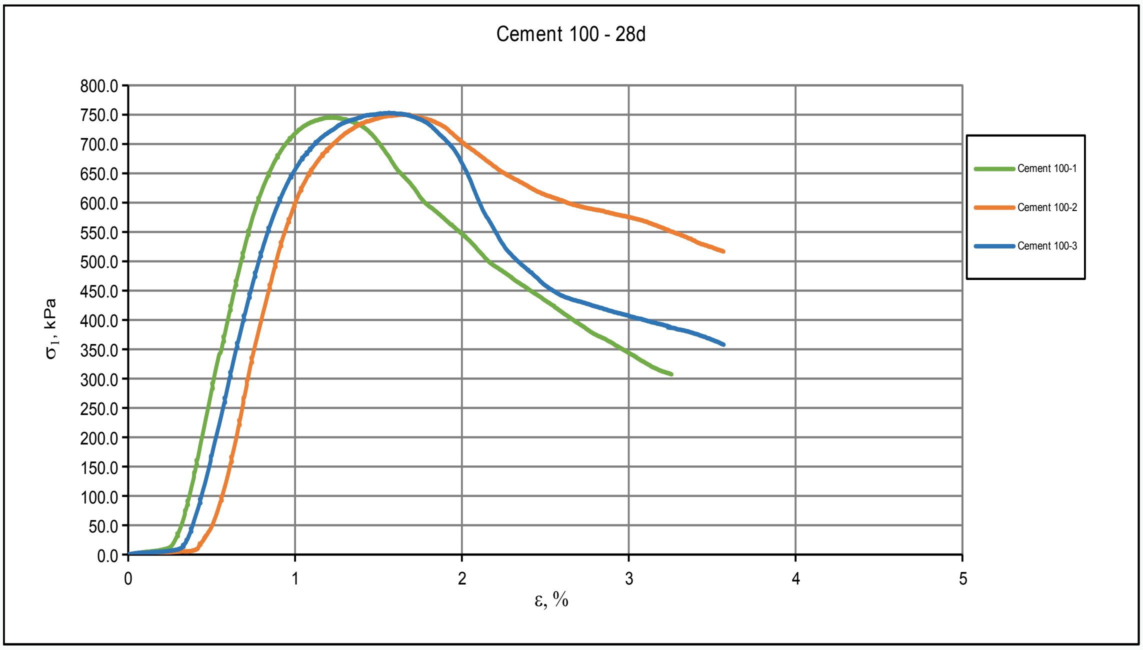
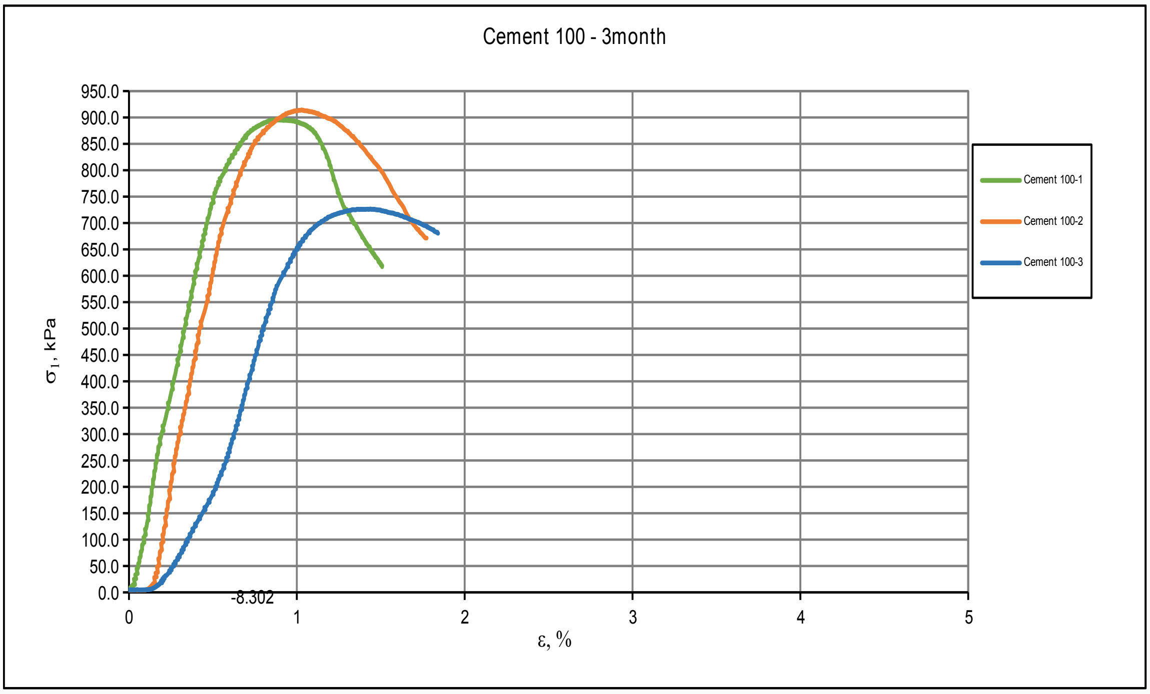
Akkreditierungsstelle
D-PL-14144-02-00

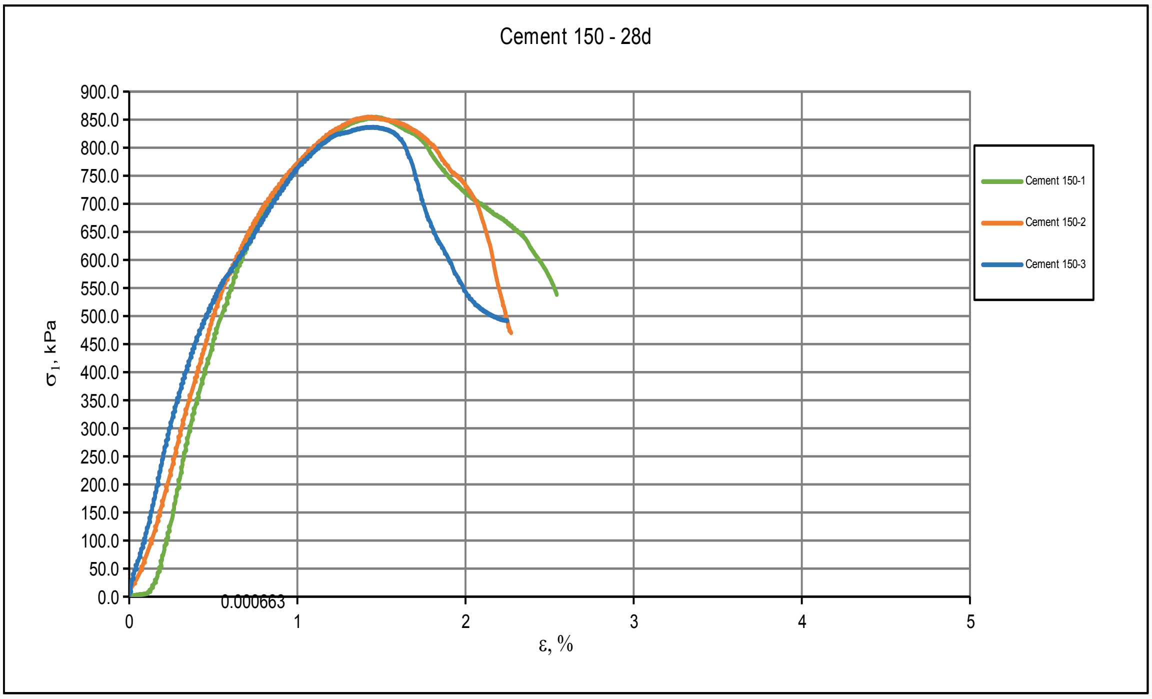
Annex 8. Stress – strain curves from every compression test in UCT.

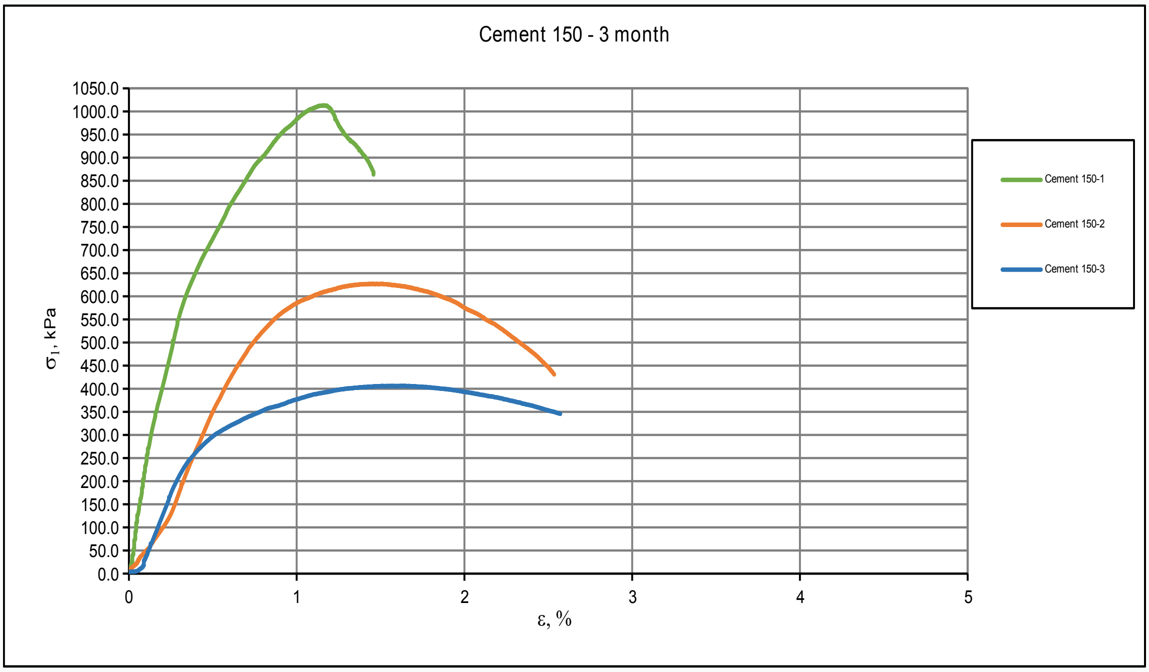


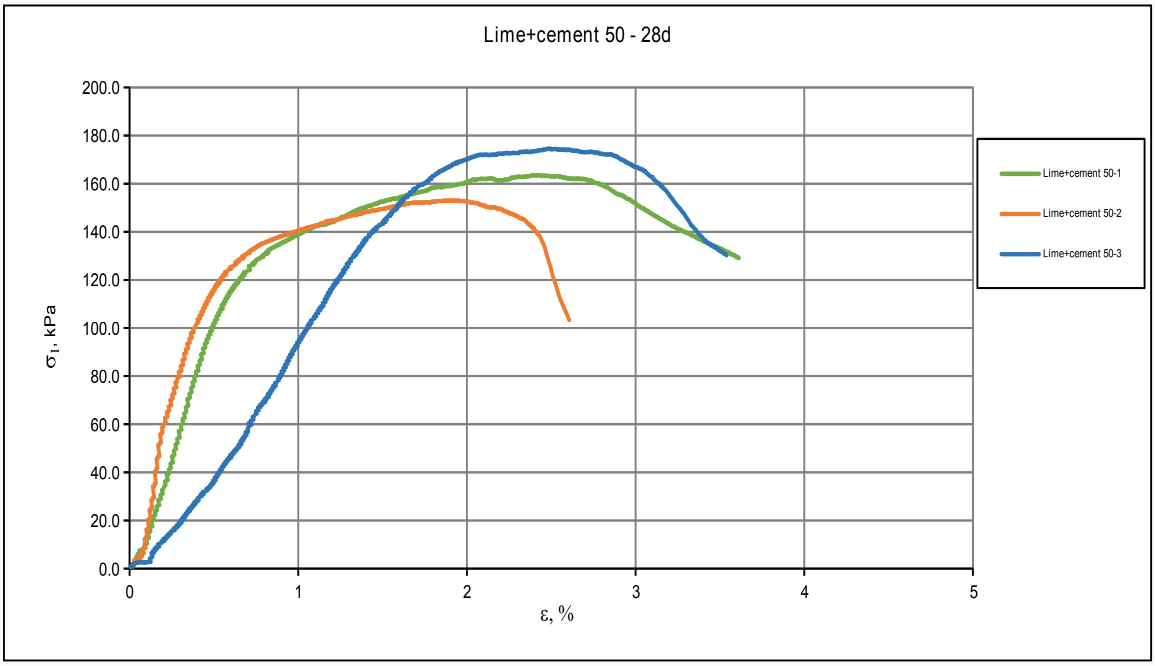


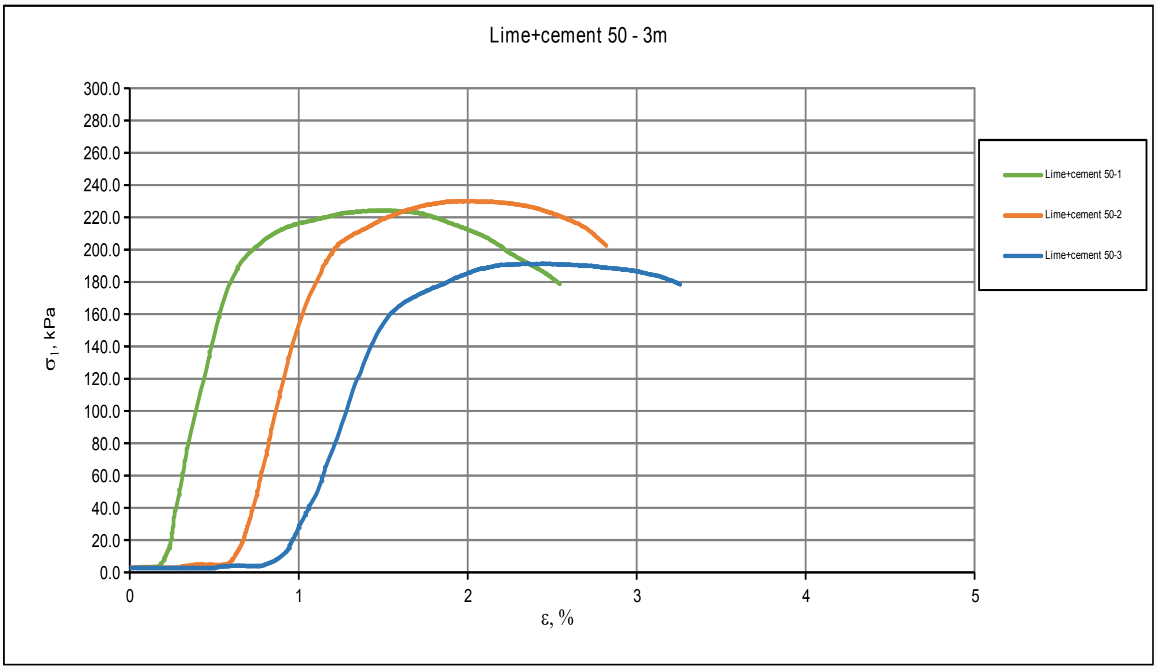

Cement 100 - 28d
800.0
750.0
700.0
650.0
600.0
550.0
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Cement 100-1
Cement 100-2
Cement 100-3

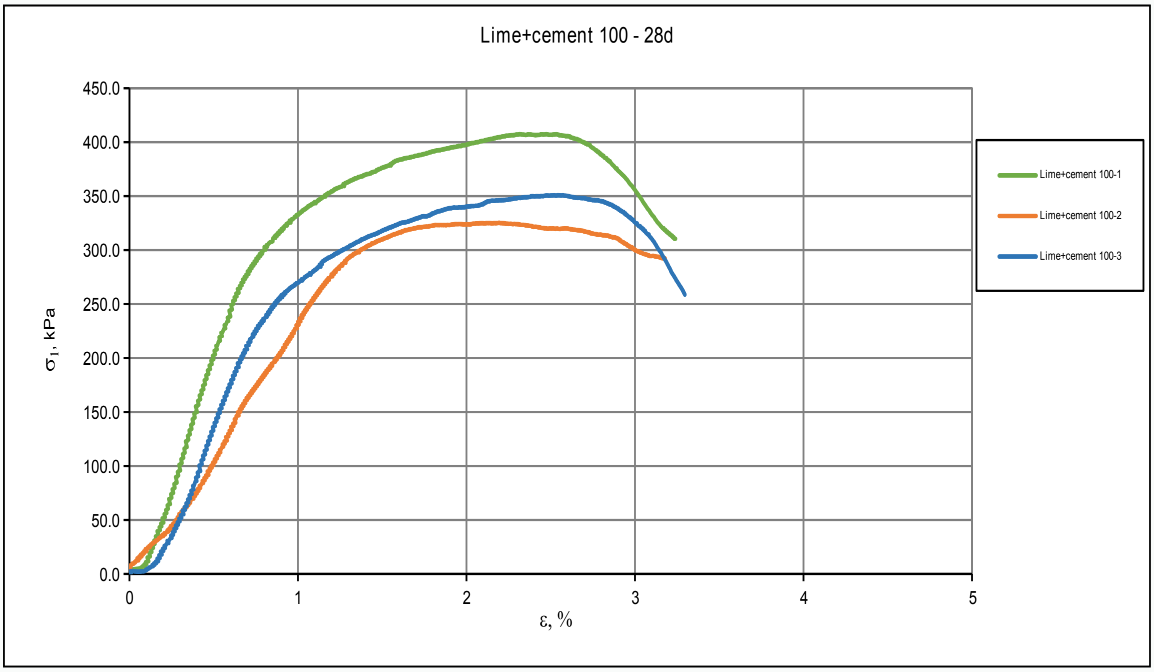

Cement 100 - 3month
950.0
900.0
850.0
800.0
750.0
700.0
650.0
600.0
550.0
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
σ1, kPa
-8.302
0
1
2
3
4
5
ε, %
Cement 100-1
Cement 100-2
Cement 100-3


Cement 150 - 28d
900.0
850.0
800.0
750.0
700.0
650.0
600.0
550.0
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
σ1, kPa
0.000663
0
1
2
3
4
5
ε, %
Cement 150-1
Cement 150-2
Cement 150-3

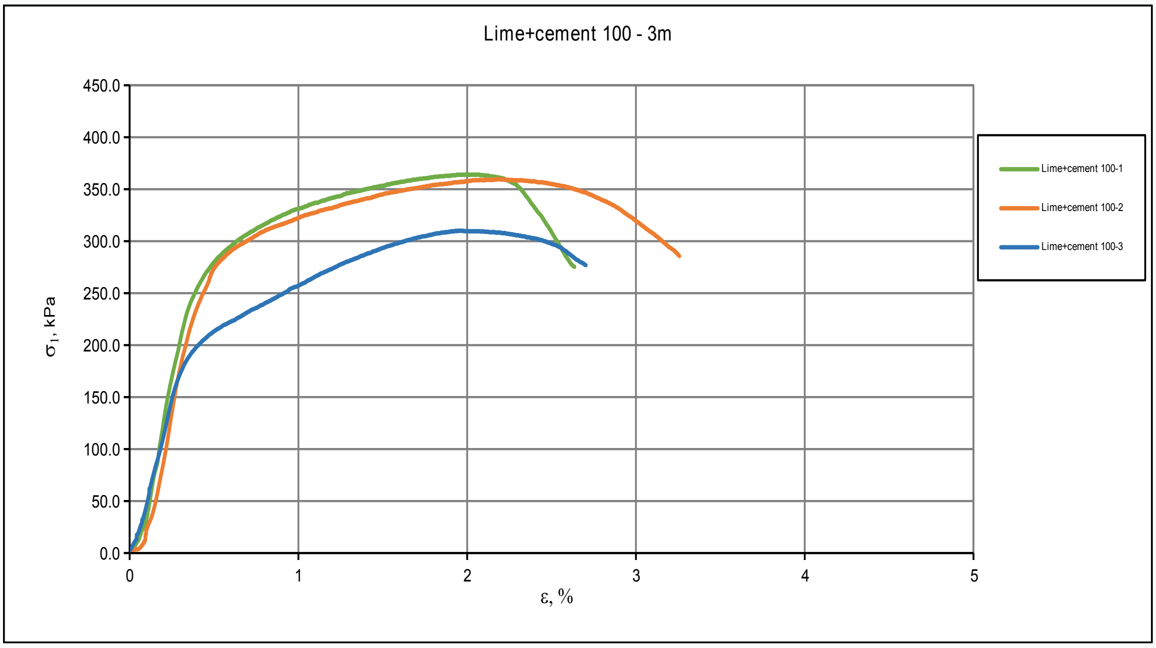

Cement 150 - 3 month
1050.0
1000.0
950.0
900.0
850.0
800.0
750.0
700.0
650.0
600.0
550.0
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Cement 150-1
Cement 150-2
Cement 150-3


Lime+cement 50 - 28d
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Lime+cement 50-1
Lime+cement 50-2
Lime+cement 50-3


Lime+cement 50 - 3m
300.0
280.0
260.0
240.0
220.0
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Lime+cement 50-1
Lime+cement 50-2
Lime+cement 50-3

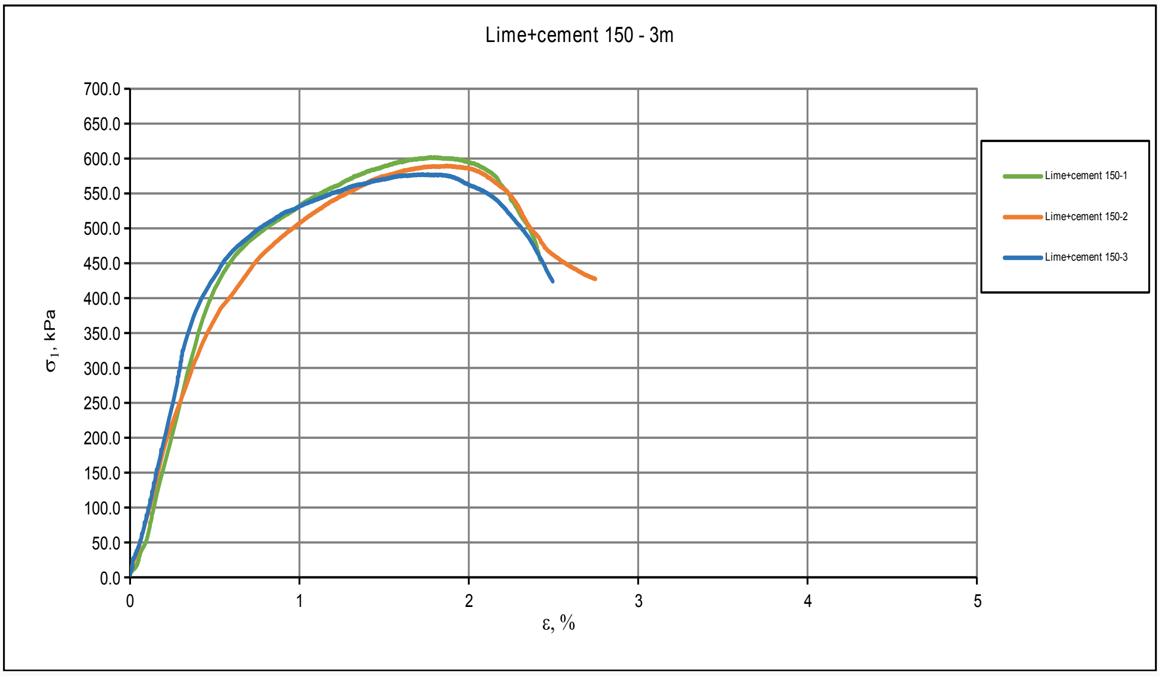


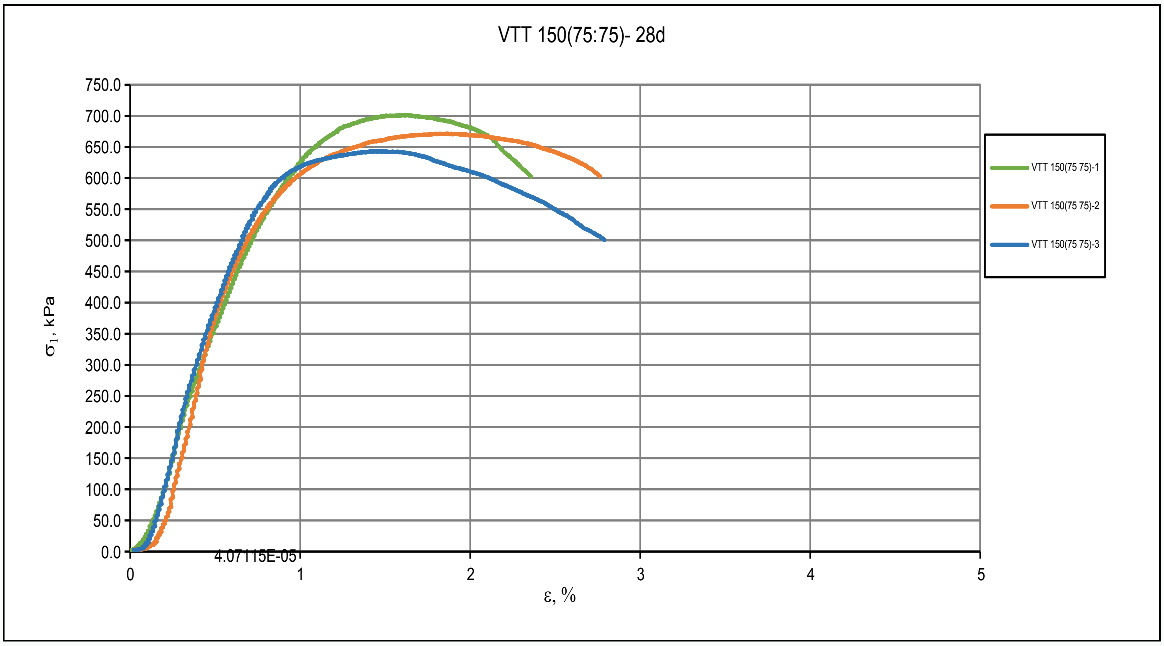
Lime+cement 100 - 28d
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Lime+cement 100-1
Lime+cement 100-2
Lime+cement 100-3

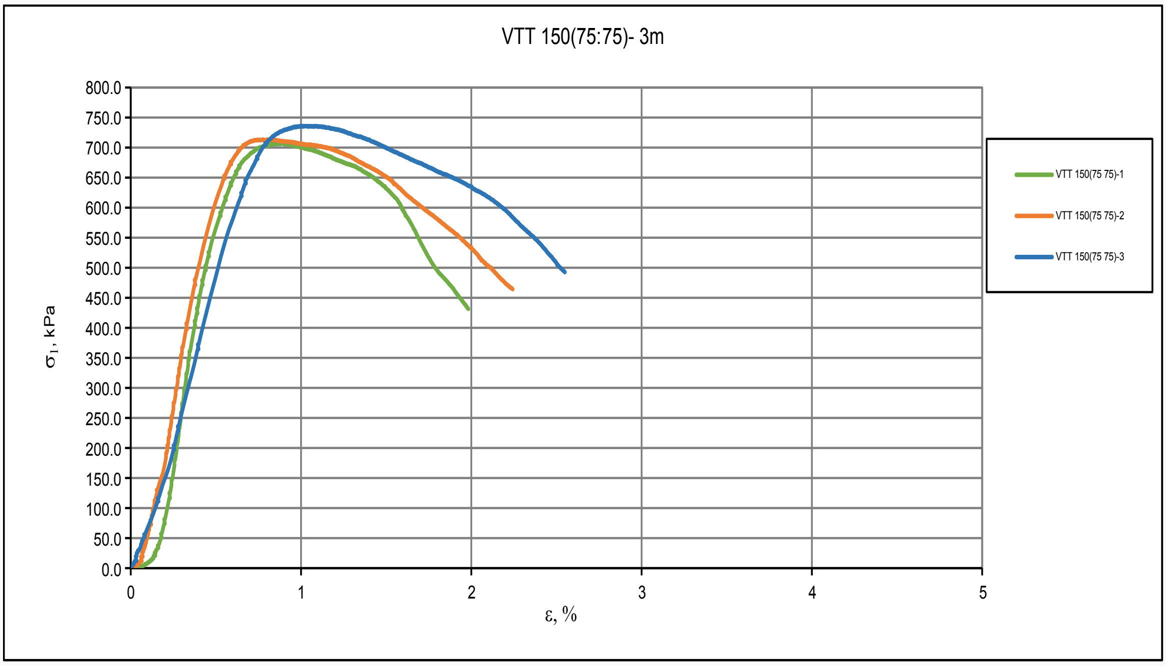


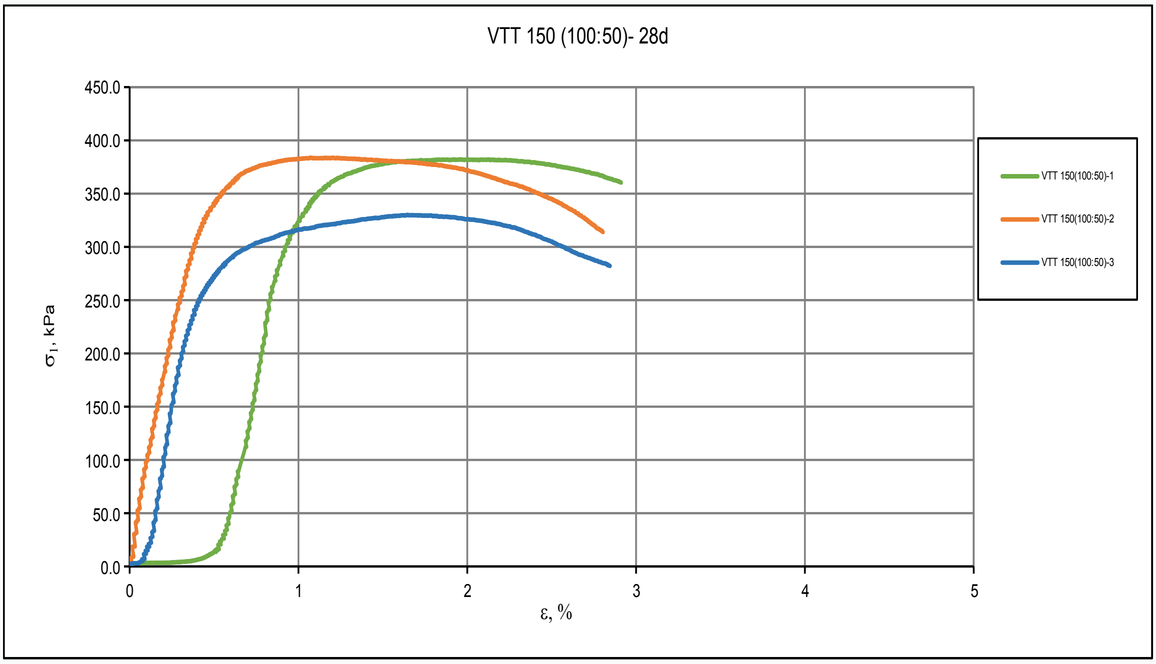
Lime+cement 100 - 3m
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Lime+cement 100-1
Lime+cement 100-2
Lime+cement 100-3

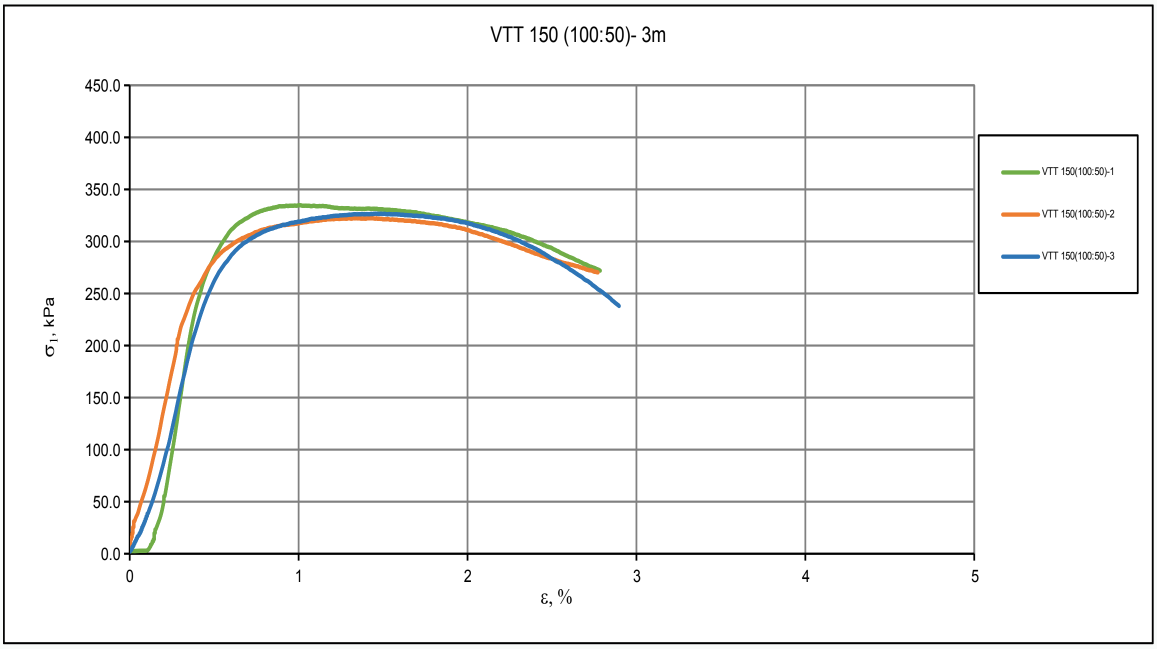

Lime+cement 150 - 28d
600.0
550.0
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Lime+cement 150-1
Lime+cement 150-2
Lime+cement 150-3

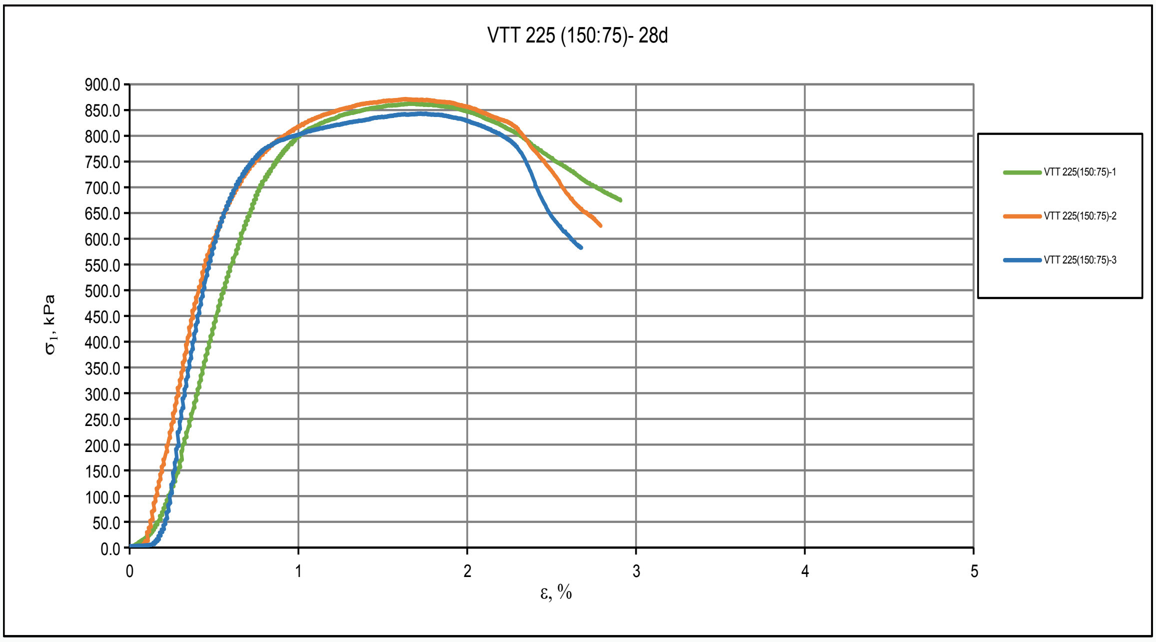

Lime+cement 150 - 3m
700.0
650.0
600.0
550.0
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Lime+cement 150-1
Lime+cement 150-2
Lime+cement 150-3

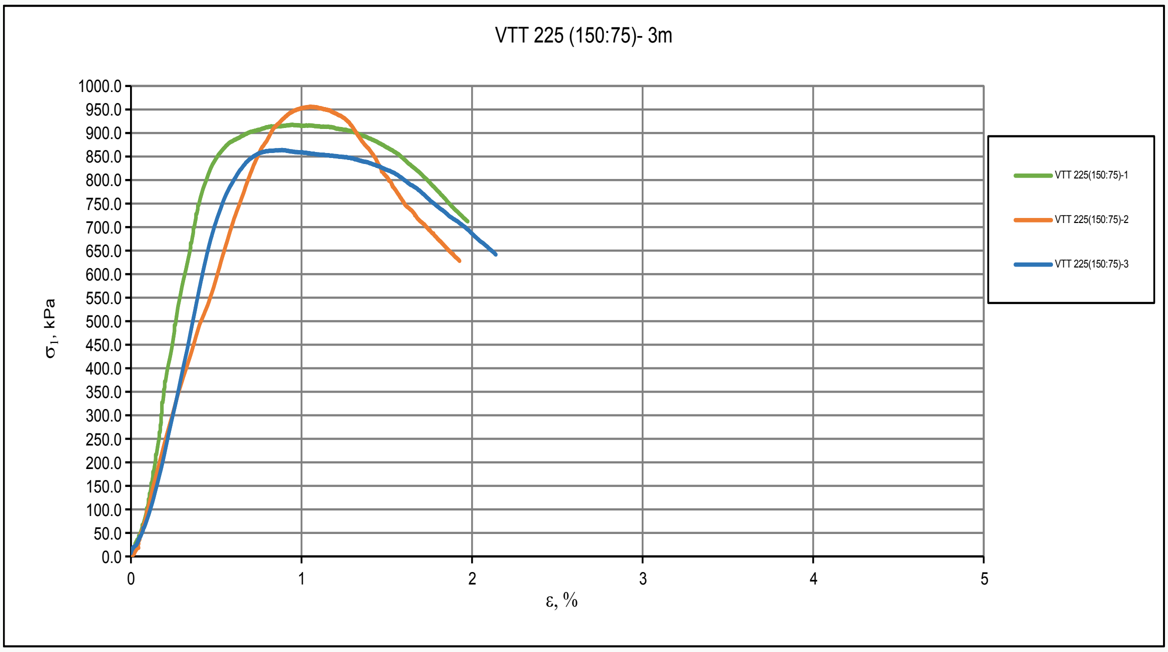

VTT 150(75:75)- 28d
750.0
700.0
650.0
600.0
550.0
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
σ1, kPa
4.07115E-05
0
1
2
3
4
5
ε, %
VTT 150(75 75)-1
VTT 150(75 75)-2
VTT 150(75 75)-3

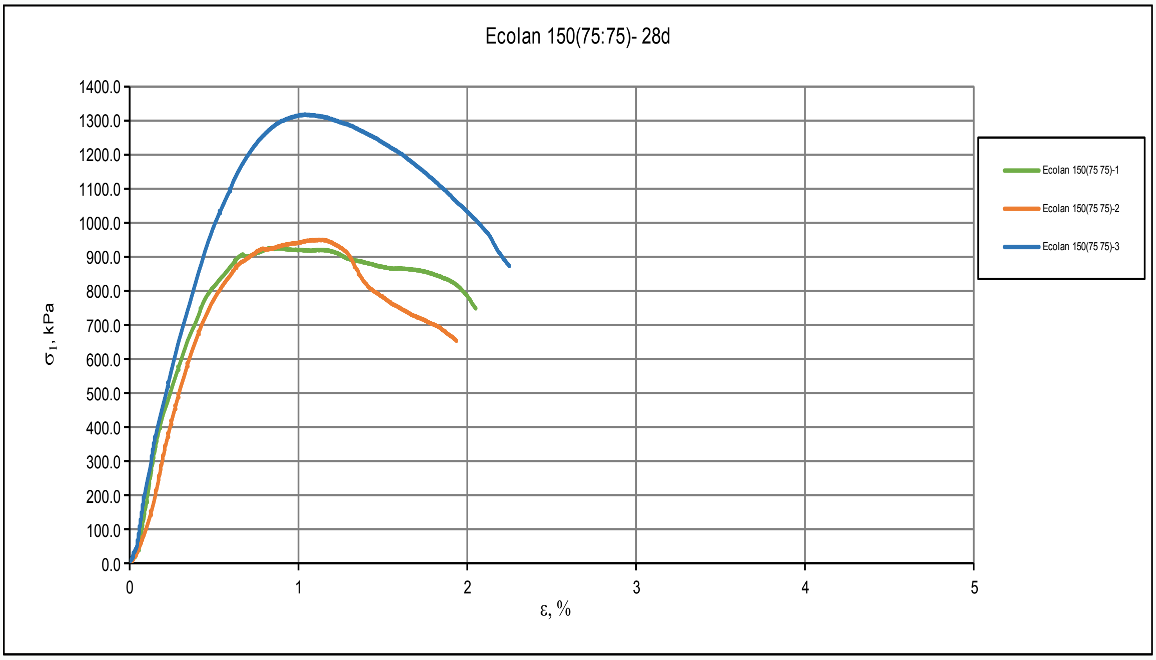

VTT 150(75:75)- 3m
800.0
750.0
700.0
650.0
600.0
550.0
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
VTT 150(75 75)-1
VTT 150(75 75)-2
VTT 150(75 75)-3


VTT 150 (100:50)- 28d
σ1, kPa
ε, %
VTT 150(100:50)-1
VTT 150(100:50)-2
VTT 150(100:50)-3

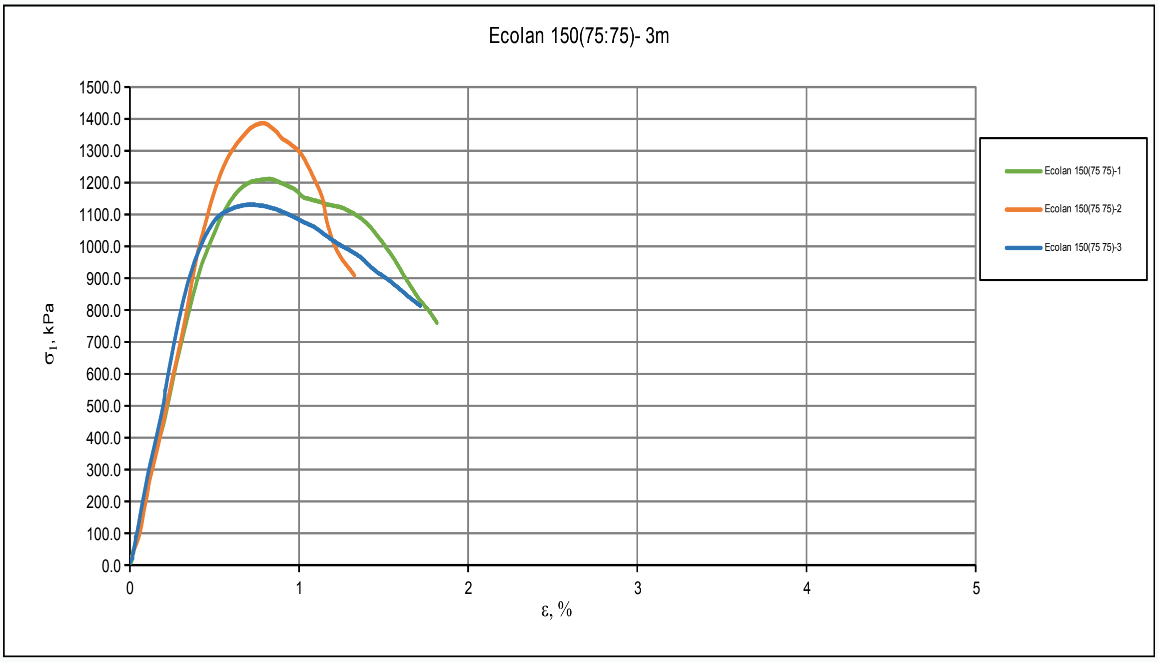

VTT 150 (100:50)- 3m
σ1, kPa
ε, %
VTT 150(100:50)-1
VTT 150(100:50)-2
VTT 150(100:50)-3


VTT 225 (150:75)- 28d
σ1, kPa
ε, %
VTT 225(150:75)-1
VTT 225(150:75)-2
VTT 225(150:75)-3

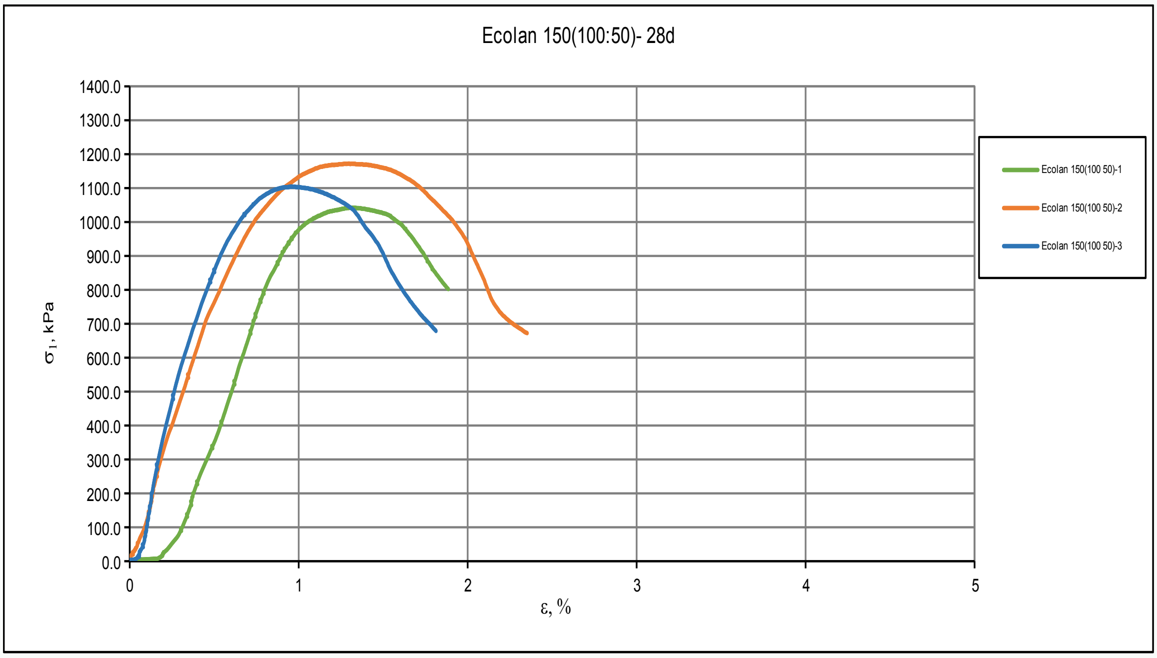

VTT 225 (150:75)- 3m
σ1, kPa
ε, %
VTT 225(150:75)-1
VTT 225(150:75)-2
VTT 225(150:75)-3

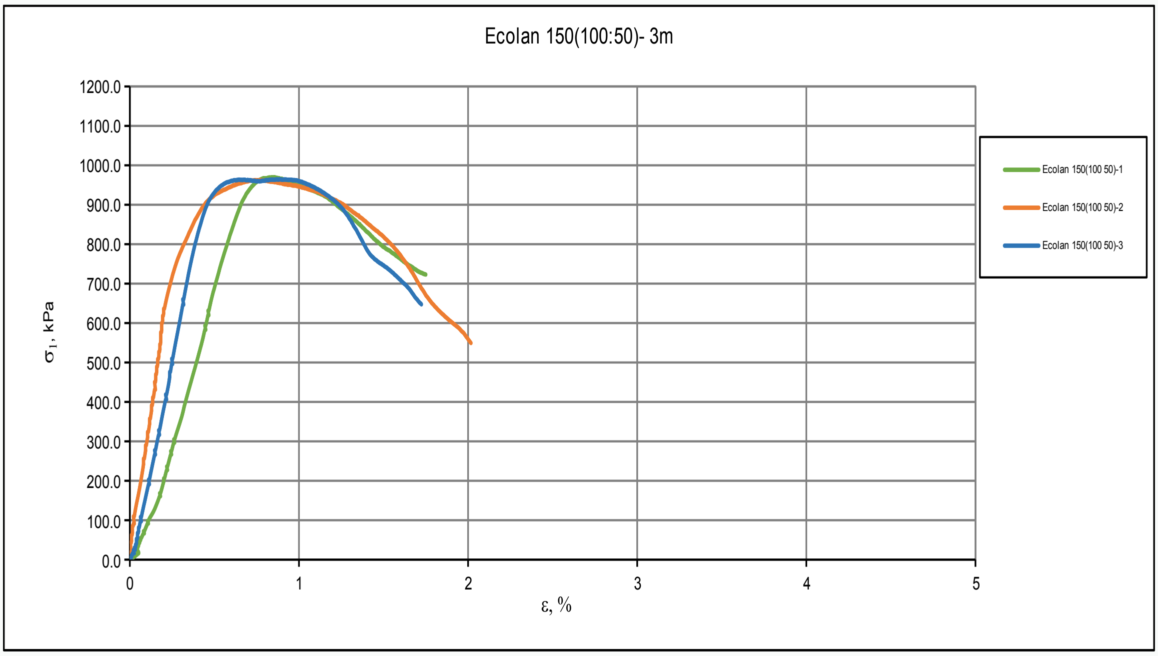


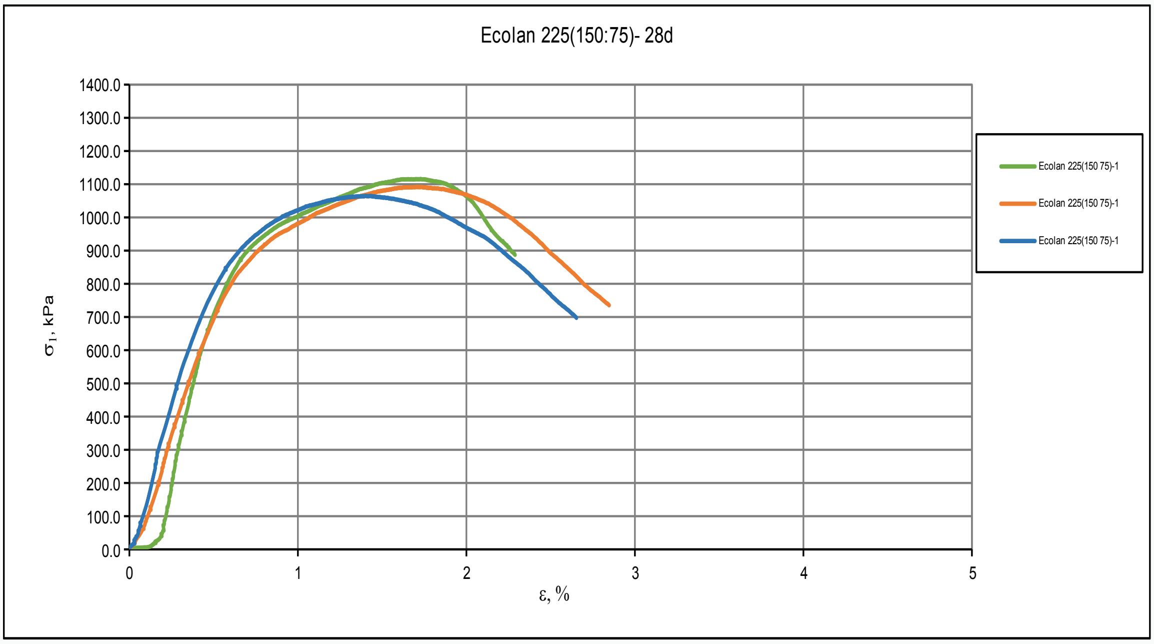
Ecolan 150(75:75)- 28d
1400.0
1300.0
1200.0
1100.0
1000.0
900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Ecolan 150(75 75)-1
Ecolan 150(75 75)-2
Ecolan 150(75 75)-3

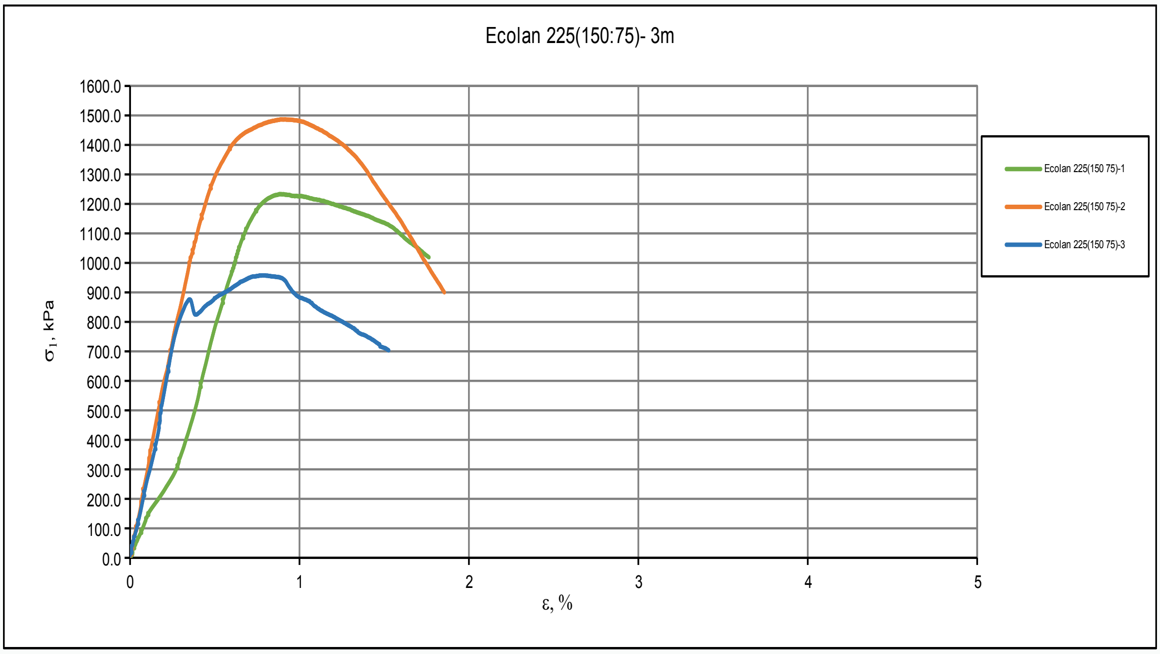


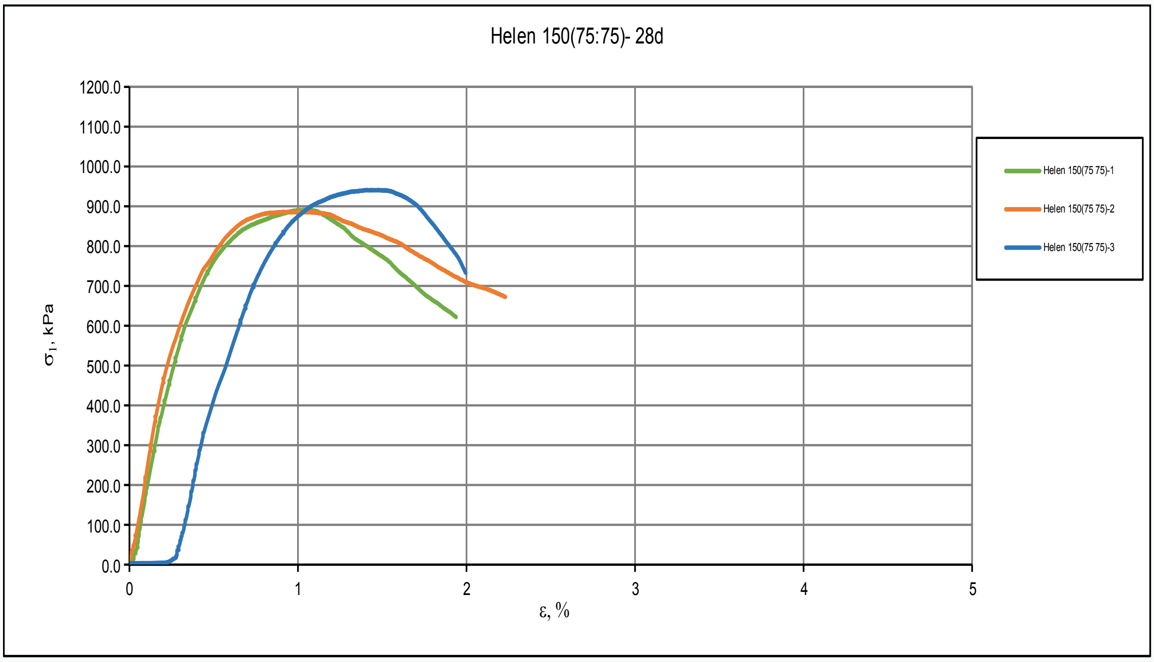
Ecolan 150(75:75)- 3m
1500.0
1400.0
1300.0
1200.0
1100.0
1000.0
900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Ecolan 150(75 75)-1
Ecolan 150(75 75)-2
Ecolan 150(75 75)-3

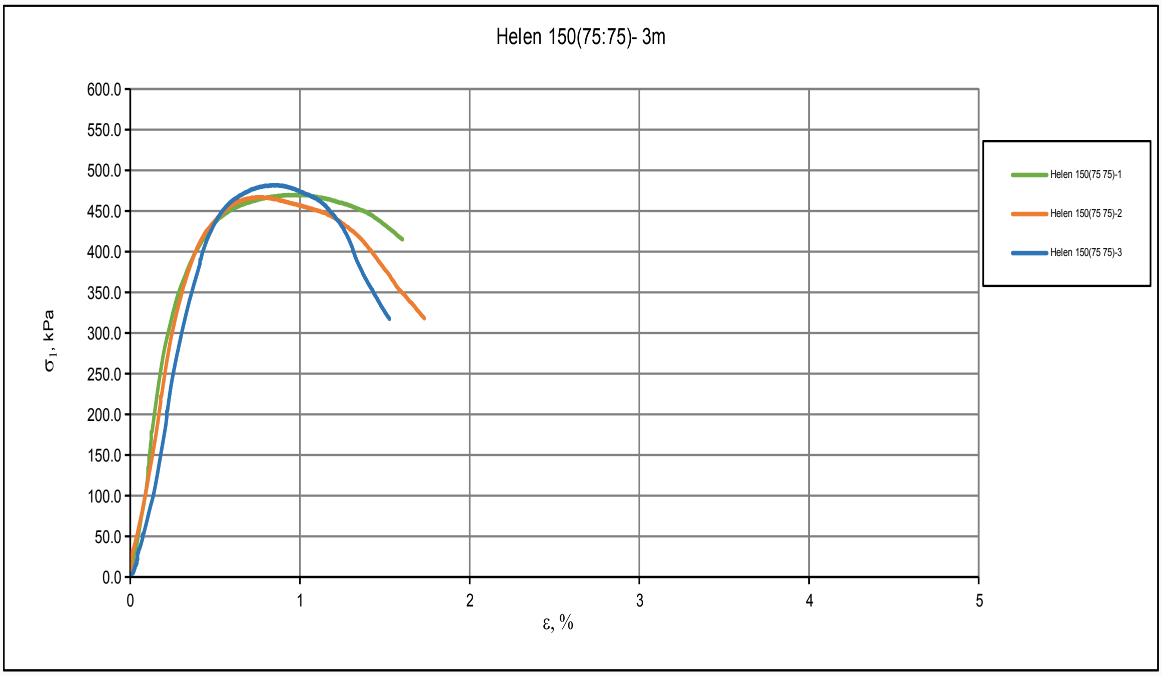

Ecolan 150(100:50)- 28d
1400.0
1300.0
1200.0
1100.0
1000.0
900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
σ I, kPa
0
1
2
3
4
5
ε, %
Ecolan 150(100 50)-1
Ecolan 150(100 50)-2
Ecolan 150(100 50)-3

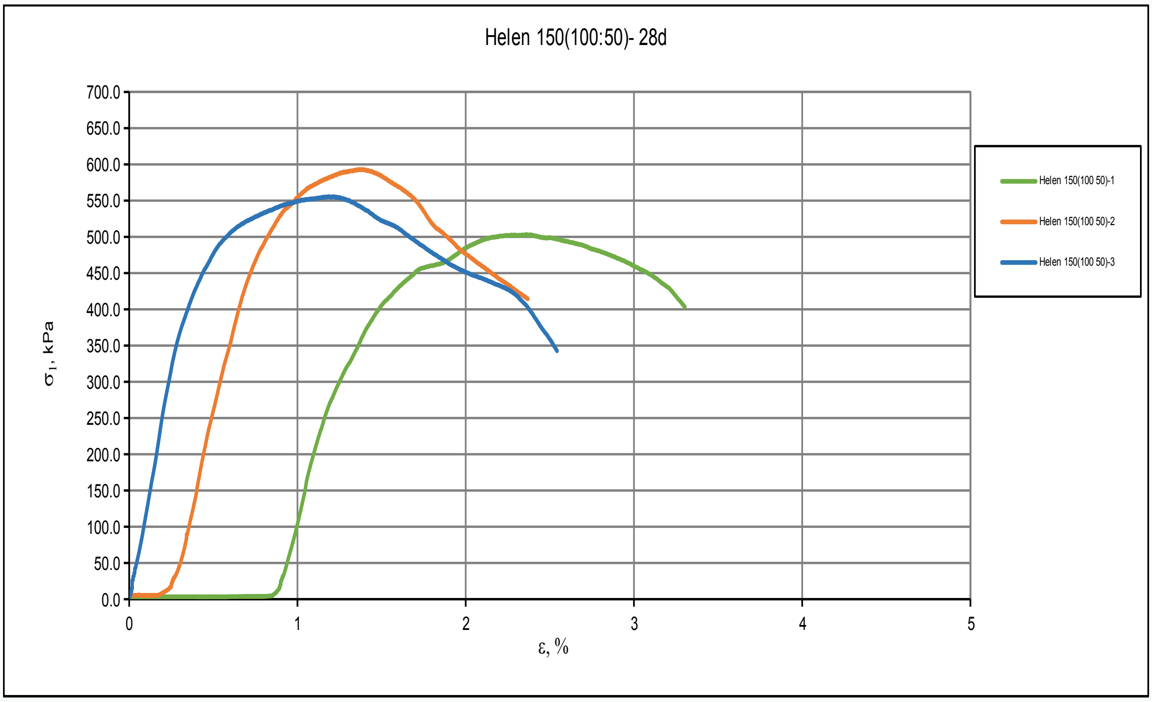

Ecolan 150(100:50)- 3m
1200.0
1100.0
1000.0
900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
σ I, kPa
0
1
2
3
4
5
ε, %
Ecolan 150(100 50)-1
Ecolan 150(100 50)-2
Ecolan 150(100 50)-3

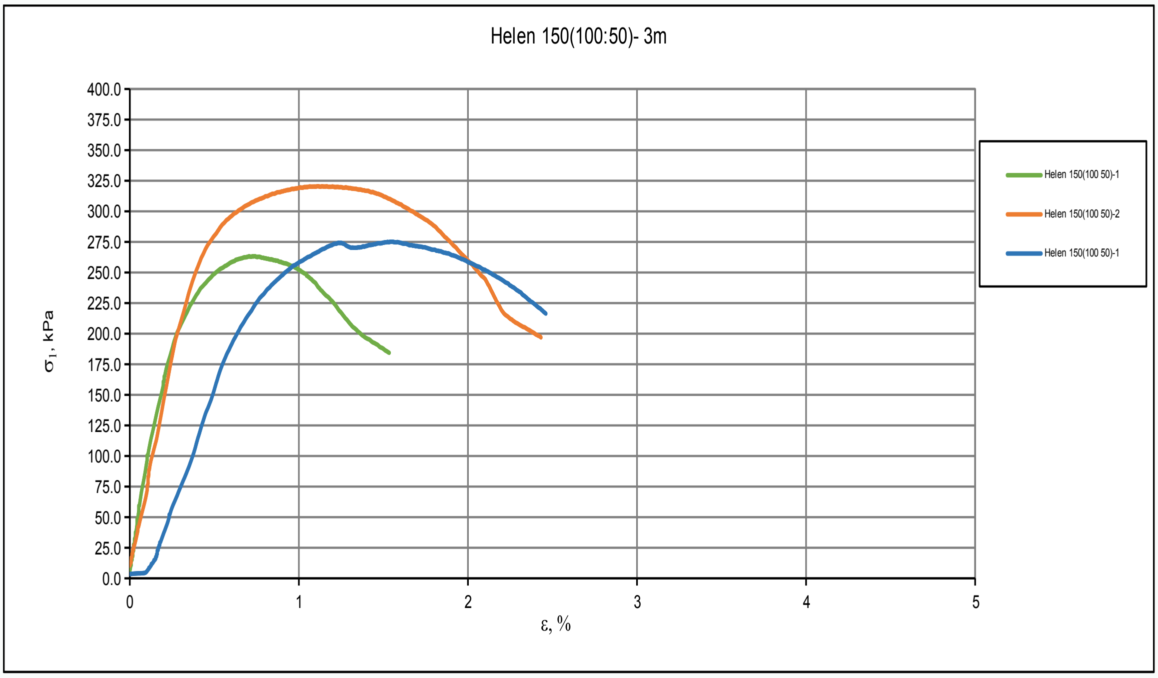

Ecolan 225(150:75)- 28d
1400.0
1300.0
1200.0
1100.0
1000.0
900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
σ₁, kPa
0
1
2
3
4
5
ε, %
Ecolan 225(150 75)-1
Ecolan 225(150 75)-1
Ecolan 225(150 75)-1

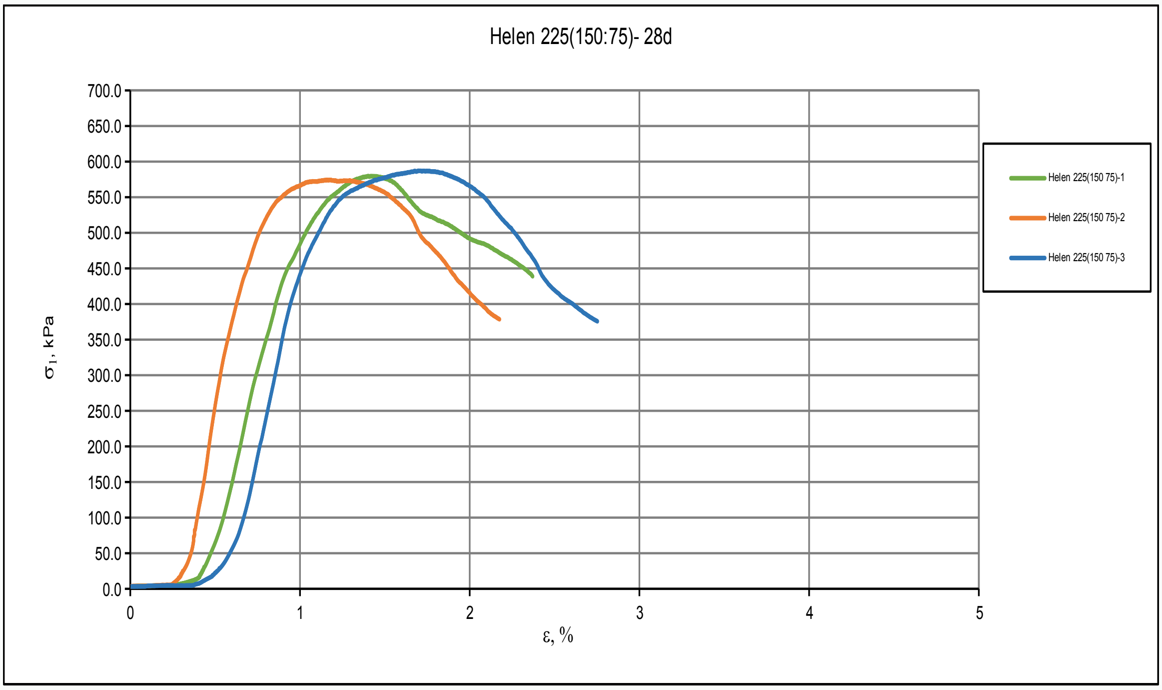

Ecolan 225(150:75)- 3m
1600.0
1500.0
1400.0
1300.0
1200.0
1100.0
1000.0
900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
σ₁, kPa
0
1
2
3
4
5
ε, %
Ecolan 225(150 75)-1
Ecolan 225(150 75)-2
Ecolan 225(150 75)-3

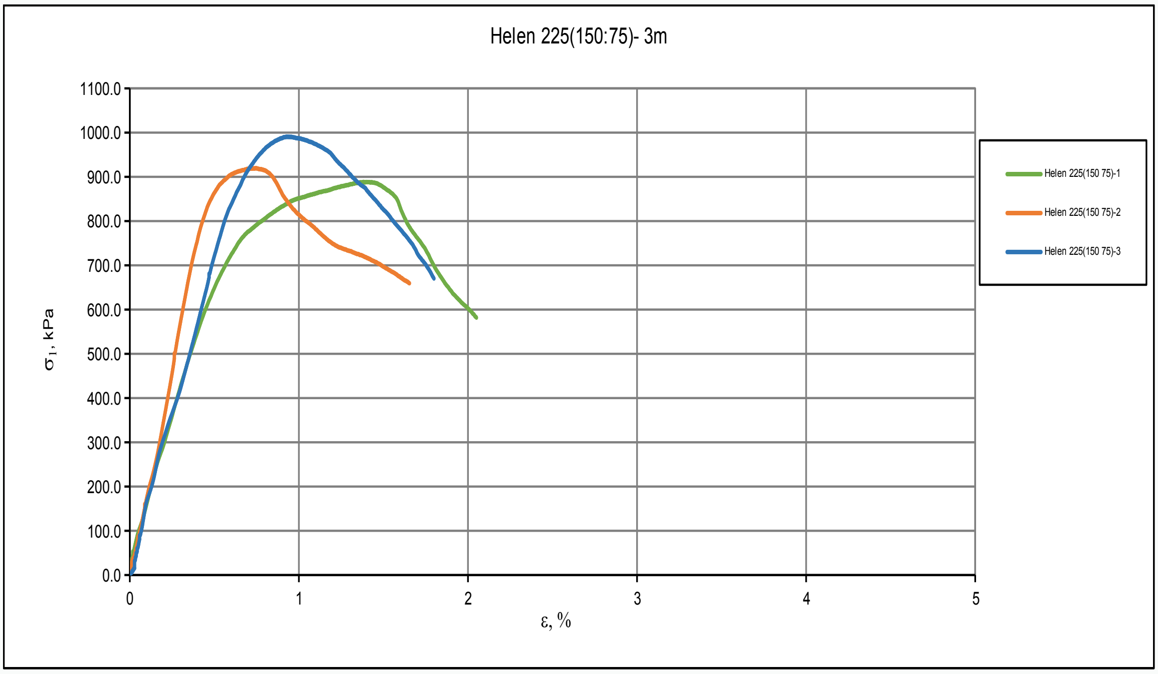

Helen 150(75:75)- 28d
1200.0
1100.0
1000.0
900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Helen 150(75 75)-1
Helen 150(75 75)-2
Helen 150(75 75)-3


Helen 150(75:75)- 3m
600.0
550.0
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Helen 150(75 75)-1
Helen 150(75 75)-2
Helen 150(75 75)-3


Helen 150(100:50)- 28d
σ I , kPa
ε, %
Helen 150(100 50)-1
Helen 150(100 50)-2
Helen 150(100 50)-3
700.0
650.0
600.0
550.0
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0
1
2
3
4
5


Helen 150(100:50)- 3m
σ I , kPa
ε, %
Helen 150(100 50)-1
Helen 150(100 50)-2
Helen 150(100 50)-1
400.0
375.0
350.0
325.0
300.0
275.0
250.0
225.0
200.0
175.0
150.0
125.0
100.0
75.0
50.0
25.0
0.0
0
1
2
3
4
5


Helen 225(150:75)- 28d
700.0
650.0
600.0
550.0
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Helen 225(150 75)-1
Helen 225(150 75)-2
Helen 225(150 75)-3


Helen 225(150:75)- 3m
1100.0
1000.0
900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
σ1, kPa
0
1
2
3
4
5
ε, %
Helen 225(150 75)-1
Helen 225(150 75)-2
Helen 225(150 75)-3