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LIME MODIFICATION OF CLAY TILL
A Case Study

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Geotechnical Engineering

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MASTER'S DISSERTATION

LIME MODIFICATION OF CLAY TILL
A Case Study

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Abstract

This report deals with lime modification of clay till. Lime modification means that the compaction properties of the soil are improved by the addition of lime. The report consists of three main parts: 1) Description of the geotechnical properties of clay till and how lime modification affects the properties; 2) Description of the implementation of lime modification and the tests conducted at a construction site in the northeast part of Lund, Sweden; 3) Evaluation of the test results.

Clay tills are complex soils in earthworks. To be able to pack a clay till, it is required that the soil is in a solid consistency condition. Clay till is rarely found in a solid consistency condition. An ion exchange occurs through the addition of lime where calcium ions replace the existing ions surrounding the clay particles. The ion exchange leads to a structural change, which lowers the plastic limit and makes the soil packable.

The modification has been carried out by Skanska and the measurements have been carried out by geotechnical consultants. The lime used during the modification has been quicklime and the amount of lime was 0.5 % and 1.0 %. The test methods used during the work have been plate load tests (static and dynamic), isotope meter and MCV test.

The most important parameter in lime modification is the moisture content. An optimum moisture content exists for clay till. Quicklime is suitable when the moisture content exceeds the optimum. The porosity increases and results in a low stiffness at low moisture contents. The compaction work becomes easier by adding water before the mixing of lime. The amount of lime affects the result. A lime content of 1.0 % results in a smaller spread of porosity compared to a lime content of 0.5 %. Lime modification is an effective method for improving clay till in earthworks.

Keywords: lime, quicklime, modification, clay till

Sammanfattning

Denna rapport handlar om kalkmodifiering av lermorän. Med kalkmodifiering menas att jordens packningsbarhet förbättras genom inblandning av kalk. Rapporten består av tre huvuddelar: 1) Beskrivning av lermoräns geotekniska egenskaper och hur kalkmodifieringen påverkar egenskaperna; 2) Beskrivning av genomförandet av kalkmodifieringen och vilka markprovningar som gjordes vid ett större byggprojekt i nordöstra delen av Lund; 3) Utvärdering av markprovningsresultaten.

Lermoräner är komplicerade jordar vid markarbeten. För att kunna packa en lermorän krävs det att jordmaterialet befinner sig i ett fast konsistenstillstånd. Lermorän befinner sig sällan i fast konsistenstillstånd. Genom kalkinblandning sker ett jonutbyte där kalciumjonerna ersätter de befintliga jonerna kring lerpartiklarna. Jonutbytet leder till en strukturomvandling som sänker plasticitetsgränsen, vilket gör jorden packningsbar.

Modifieringsarbetet har utförts av Skanska och mätningarna har utförts av geotekniska konsulter. Under modifieringsarbetet användes bränd kalk och kalkmängderna var 0.5 % och 1.0 %. De testmetoder som använts under arbetet har varit plattbelastningar (statisk och dynamisk), isotopmätare och MCV-test.

Den viktigaste parametern vid kalkmodifiering är fuktkvoten där en optimal fuktkvot finns för en lermorän. Då fuktkvoten överstiger den optimala är bränd kalk lämplig att använda. Vid låga fuktkvoter ökar porositeten vilket resulterar i en låg styvhet. Genom att tillsätta vatten innan inblandning av kalk kommer packningsarbetet att underlättas. Mängden kalk påverkar resultatet, en kalkhalt på 1.0 % resulterar i en mindre spridning av porositet jämfört med en kalkhalt på 0.5 %. Kalkmodifiering är en effektiv metod för att förbättra lermorän vid markarbeten.

Nyckelord: kalk, bränd kalk, modifiering, lermorän

Preface

This master's dissertation marks the end of my five-year civil engineering master program at Lund University. Over the years, lots of knowledge have been gathered but the urge for new knowledge has not yet been abated. All the experiences that enriched me over the years in Lund, together with all the new friends I have got, has changed me as a person and I will carry the memories with me for the rest of my life.

This dissertation has been conducted in collaboration with Skanska Väg och Anläggning Syd and I wish to express my gratitude for all the help I have received from the people at ESS. I would also like to thank Petra Andersson (Skanska) who first introduced me to this very exciting subject and who was my supervisor during the work. Another person I would like to thank is my supervisor at the Department of Construction Sciences, Ola Dahlblom, who has been a great help during the work. Finally, I would like to thank my family and friends who have been a great support throughout my education and especially Sofia, who endured me all these years.

Now, my five years at Lund University have come to an end. It has been a personal journey with many new friends. This has been a time I will never forget!

Emil Westesson
Lund, May 2015

Notations and abbreviations

w	Moisture content	%
m_{H_2O}	Mass of water	kg
m_{solid}	Mass of solid material	kg
w_L	Liquid limit	%
w_P	Plasticity limit	%
I_P	Plasticity index	–
V_V	Volume of voids	m^3
V_{lime}	Volume of lime	m^3
E_{v2}	Deformation modulus	Pa
r	Radius	m
σ_{max}	Maximum mean tensile stress	Pa
s	Settlement	m
σ_0	Mean tensile stress	Pa
L_p	Gas volume	%
ρ_d	Dry density	$\mathrm{kg/m}^3$
ρ_s	Compacted density	$\mathrm{kg/m}^3$
ρ_w	Density of water	$\mathrm{kg/m}^3$
c_u	Undrained shear strength	Pa
c'	Cohesion	Pa
ϕ'_k	Friction angle	°
σ_c'	Preconsolidation pressure	Pa
MCV	Moisture condition value	–

Contents

1 Introduction

1.1 Background

In the past, when a site selection was done for a construction project, the decision was heavily based upon the stiffness of the subsoil. When the stiffness of the soil was too low, there were few options for improving the quality. One could either change the design of the construction and/or replace the soil with one with better deformation modulus. If neither one was an option, then the site would have to be abandoned (Makusa 2012).

Due to undesirable soils, there is now a scarcity of desirable areas for construction work in some regions. Even in local projects, there could be undesirable parts. A way to improve those undesirable parts is to remove and replace the soil or modify the existing soil. If the soil is replaced, it means that natural resources will have to be used (Makusa 2012). It could in some places mean an increased amount of transports and a waste of natural resources. The trend today goes towards achieving mass balance and focusing on resource management within the project, which means that modifying the on-site soil is getting more preferable (Franzén et al. 2012).

In-situ modification is used to improve the stiffness of the subsurface in a clay till with a low stiffness. The positive effects of lime modification in road constructions have been known for a long time. There are traces of use in one of the main roads to ancient Rome. The road, the Appian Way, was stabilised with lime and it was created 300 BC (Lindh 2004).

Lime stabilisation was reinvented during the 1920's in the United States. In the 1940's the American military used the method in both road- and runway projects. Lime stabilisation was used in projects with both unperturbed and in disrupted soils (Sandberg 2006).

The method was introduced in Europe during the late 1950's. Since then, the technique has been improved and the equipment likewise. In the beginning, normal farming equipment was used, but in the early 1970's more specialized machines were introduced in the market. The stabilisation method was further refined during the 1980's and 1990's. The improvements of the method were both in the distribution and of the binders that were used (Franzén et al. 2012).

In Sweden, the method was frequently used between the 1960's and the middle 1980's. With the introduction of BYA 84 (1983), incentive for the use of the stabilisation method was reduced. The result was that the method almost vanished in Sweden (Sandberg 2006, Anon. 1983). In late 1990's the guidelines for road construction projects were changed, which made it more preferable to use in-situ stabilisation again. The interest of on-site soil improvement is today high due to raised resource management demands (Franzén et al. 2012).

1.2 Objectives and method

The geotechnical properties of clay till make them problematic when used in earthworks. To reduce the risk of deficiency in the compaction properties of clay tills, modification of the soil by mixing in lime could be used. This dissertation aims to create a better understanding of how the deformation modulus of clay tills depends on various parameters during the modification with low quantities of lime.

Objective

This study has had one main objective:

- Describe the relationship between soil parameters and modification parameters affecting the stiffness of clay till when modified with lime.

The result of the modification process varies due to several different parameters. Among the different parameters, which affect the modification process, there are soil parameters and modification parameters such as the mixing method, how homogenously the soil has been mixed, lime type, amount of lime used and the compaction degree. The soil parameters are for example moisture content, mineral content of the soils, grain-size distribution and these could vary even within a specific project.

In clay tills there are chemical forces acting. At the compaction of an unmodified clay till, problems may occur due to the intermolecular forces that complicate the work to achieve an adequate deformation modulus. The chemical balance of the soil will be altered when the clay till is modified with lime which improves the compaction properties. These parameters need to be taken into account to achieve the desired geotechnical properties in the soil.

Two questions have emerged from the main objective:

- Which measurable soil parameters and modification parameters affect the stiffness of the clay till?
- Can a reduced amount of added lime achieve an acceptable result with the requirements and conditions that prevail at ESS?

Method

The dissertation starts with a literature study in which reports and publications concerning the modification and clay tills are studied. The purpose of this is to provide a good understanding of what happens during the modification and to get an overview of what is already known in the area of modification. A separate literature study was conducted on statistical methods to provide a basis for the subsequent data processing.

Figure 1.1 *Map over Skåne where ESS is located in the northeast part of Lund, taken from Google Maps.*

A case study was conducted at ESS, the European Spallation Source, located in the northeast part of Lund, see Figure 1.1. In order to provide a full understanding of the subject that this dissertation is about, the work has been based on the ESS project as this project uses lime modification. At the construction site, certain areas are modified to provide a more reliable subsurface for constructions which are sensitive to settlements (Anon. 2015a).

The clay till used in the modification at ESS was taken at the construction site. All soil modified originate from the ESS site; the soil was either modified without being excavated, or excavated and transported to a filling area, see Figure 1.2. When the non-transported soil was modified, the top layers were first excavated down to the level where the requirement regarding the stiffness is fulfilled. The excavated soil is treated in the same way as soil excavated elsewhere and distributed using the predefined method (Anon. 2015a).

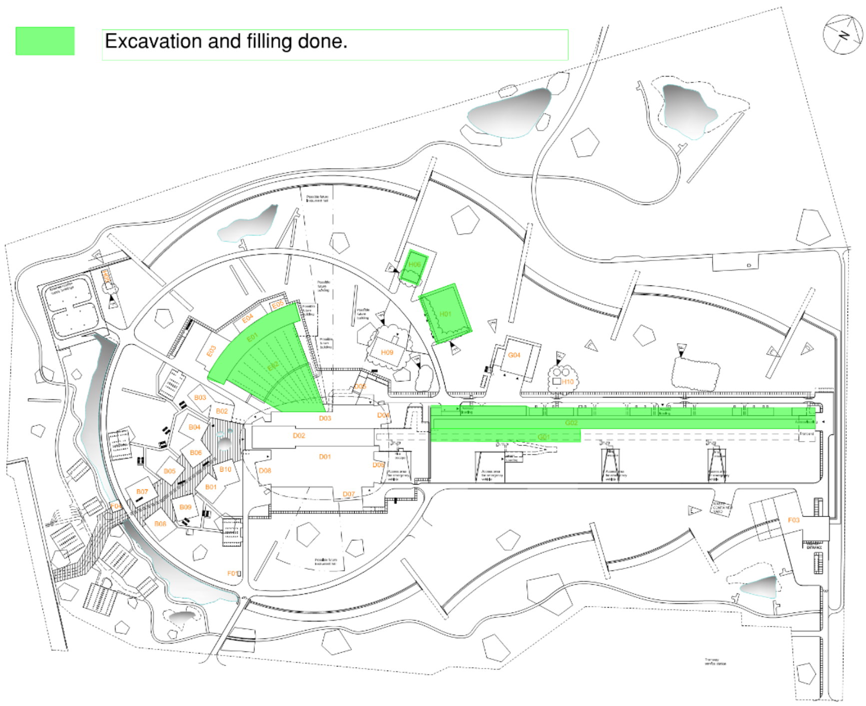

Figure 1.2 *Preliminary design of ESS with areas where modification has been performed highlighted (Anon. 2015a).*

The modification has been carried out by Skanska and the measurements by geotechnical consultants (Anon. 2015a). The already collected data has been processed and analysed in this dissertation.

The methodology to process the data is primarily based on recommendations by Lindh (2004). In order to distinguish between the influence from different parameters they have been investigated individually in a parametric study and the relationship between them was established. The investigated parameters were then compared with the deformation modulus to allow a comparison between different conditions.

Studies of modification with low amounts of lime has previously not been done to a large extent. Most works concerning modification and stabilisation deal with larger amounts of lime. The result of this report could be used as a basis for further studies. The report could also be used as an input to future similar projects, but also as knowledge in the continued modification work at ESS.

1.3 Scope

This dissertation examines the effects of lime modification in clay till. The test site is located in the northeast part of Lund. During the work, primarily two different quantities of lime have been used, 0.5 % and 1.0 %. The measurements have been performed by geotechnical consultants and the analysis has been performed in the present work. The report focuses on the deformation modulus of modified soil.

The distances between the locations of the various tests varies. To combine results from the different test methods the conditions for the soil samples used should be as similar as possible. To achieve this, the distance between the sites of origin for the samples used has been maximum five meters within the scope of this dissertation.

To determine the influence from lime modification on the soil parameters, results from the following testing methods were studied:

- Static plate load test
- Light plate load test
- Isotope meter test
- Moisture condition value test

1.4 Outline of this dissertation

The dissertation consists of three main parts.

Chapter 2 is a literature study of the geotechnical properties of clay till and how lime modification affects the properties and Chapter 3 describes statistical methods used.

Chapter 4 is a description of how the lime modification was carried out and how the tests at the construction site were conducted.

Chapter 5 consist of an evaluation of the measurement data and chapter 6 conclusions of the work are presented.

2 Soil modification in clay tills

2.1 Clay tills

2.1.1 Background geology

The soil in Sweden today originates from the latest inland ice that started to pull back about 18 000 years ago and was completely gone 8000-9000 years ago. During the expansion, the inland ice behaved like a viscous fluid because of the heavy weight in the central parts. Owing to the inland ice expansion, the soil was moved and the rock underneath was crushed. The smallest grain size into which the rock was crushed depend on how hard the rock was. The crushed material was later frozen into the ice and when the inland ice pulled back, the material became the till we have today (Avén 1984).

More than 75 % of the land surface in Sweden is covered by till. Apart from the southern parts of Skåne and a few local places in other parts of Sweden, most of the till is primarily a sandy, silty till (Avén 1984). In the southern parts of Skåne clay till is the dominant soil, due to the fact that the bedrock consists of limestone (Nilsson 2003).

The soil around Lund consists of a clay till with a high content of lime. The till is a so-called low-Baltic clay till which is characterised by a high content of illite and chlorite. The top layer of clay till usually has a brownish colour. This is due to weathering and oxidation of the soil. The layer of clay till below the brownish layer has a greyish colour (Larsson 2000).

Till is characterised by being unsorted and having a wide span of grain sizes. During the glacial period, material could either be transported in the bottom of the ice or higher up. If the material was transported in the bottom of the ice, it became well compacted and as a result gained high compressive strength. Material from a higher level of the inland ice did not become as well compacted and thus gained a lower compressive strength, though still relatively high (Sandberg 2006, Avén 1984).

2.1.2 Soil structure

The properties of soils are based on which materials that are included and how the internal geometry is structured. In general, a soil consists of three phases, a solid phase, a liquid phase and a gas phase. The size of the solid particles is of great importance for the geotechnical properties. Coarse-grained soils are made up of lithological grains, which consist of several different types of mineral. Fine-grained soil, for example silt and clay, usually contains only one mineral (Larsson 2008, Avén 1984).

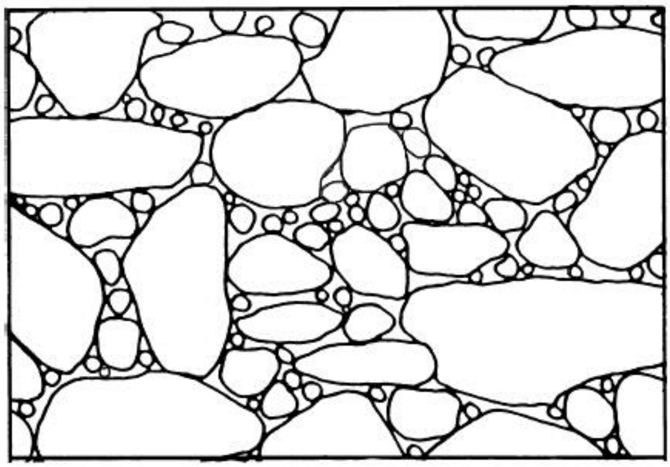

Figure 2.1 *Till with dense structure (after Larsson 2008).*

A till subjected to high pressure exhibits a very dense structure with small pores. The reason for the dense structure of the till is the fact that smaller particles settle in the voids that occur between larger particles, Figure 2.1. The volume ratio between the pore and solid substance is low. The result is that the compressive strength becomes high in tills (Larsson 2008).

In Sweden, several different soil classification systems have existed in modern time. The classification systems have been based on different things; technical properties, composition or creation. Describing the soil from the creation point of view, gives valuable information about the structure and the geotechnical properties of the soil (Larsson 2008).

Since 2004, a common European standard exists for geotechnical classification of soils, SS-EN ISO 14668. In the ISO standard, the mineral soils are classified according to particle size and grain distribution. The standard also consider plasticity, organic content and creation in the classification (Anon. 2005).

The grain size distribution is an important parameter when selecting a stabilising agent (Franzén et al. 2012). The grain size classification in SS-EN ISO 14668 puts mineral soils in different main fractions. The main fractions are displayed in Table 2.1.

Table 2.1 *Classification of mineral soil regarding grain size distribution (Larsson 2008).*

Main fraction	Sub fraction	Designation	Grain size [mm]
Very coarse-grained soil	Large boulder	**LBo**	> 630
	Boulder	**Bo**	> 200 – 630
	Cobble	**Co**	> 63 – 200
Coarse-grained soil	Gravel	**Gr**	> 2.0 – 63
	Sand	**Sa**	> 0.063 – 2.0
Fine-grained soil	Silt	**Si**	> 0.002 – 0.063
	Clay	**Cl**	≤ 0,002

The main fractions are also applicable in mixed grained soils. By measuring the amount of large fraction soil and small fraction soil in weight percent, a classification could be done. The guideline values for the fractions are presented in Table 2.2.

Table 2.2 *Guideline values for the classification of mineral soils in the main groups (Larsson 2008).*

Designation	**Amount of boulder and cobble in weight percent of total amount of soil**	**Amount of fine-grained soil in weight percent of total amount of soil [< 63 mm]**
Very coarse-grained soil	> 40	–
Coarse-grained soil	< 40	< 15
Mixed grained soil	< 40	15 – 40
Fine-grained soil	< 40	> 40

In the AMA-system, soils are classified into material groups depending on the grain size distribution, Table 2.3, (Anon. 2014a).

Table 2.3 *Soil types are classified into material groups (Anon. 2014a).*

Material type	**The amount of specified grain size** [%]				**Example of soil types**
	Very coarse-grained soil [63 – 2000 mm]	*Coarse-grained soil [0.063 – 63 mm]*	*Fine-grained soil [0.002 – 0.063 mm]*	*Organic soil [%]*	
1		< 10		≤ 2	
2	≤ 40	≤ 15		≤ 2	Bo, Co, Gr, Sa, saGr, grSa, GrTi, SaTi
3A		≤ 30		≤ 2	
3B	≤ 40	15 – 30		2	siSa, siGr, siSaTi, siGrTi
4A	≤ 40	30 – 40		≤ 2	clTi
4B	≤ 40	> 40	> 40	≤ 2	Cl, ClTi
5A	≤ 40	> 40	≤ 40	≤ 6	Si, clSi, siCl, SiTi
5B				3 – 6	gyCl, gySi

In Table 2.3 the fine-grained soil is classified as material type 4A, 4B and 5A.

The AMA-system also describes the frost sensibility in different classes where fine-grained soil is the most sensitive soil (Anon. 2014a). The frost sensibility is not taken into account in this report.

2.1.3 Chemical properties in clay

In Sweden, the most common clay mineral is illite. Other minerals that also occur are chlorite, kaolinite and montmorillonite. In the southern parts of Skåne, the presence of calcite in the soil also occurs due to the fact that the bedrock consists of limestone (Larsson 2008).

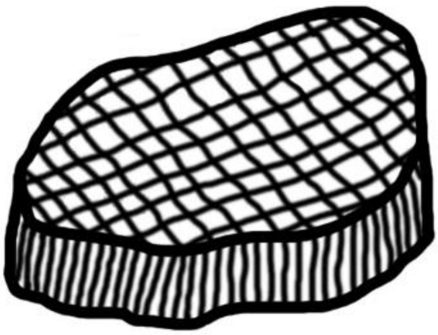

Figure 2.2 *Schematic clay particle (after Larsson 2008).*

The shape of the clay minerals is often thin lamellar, see Figure 2.2. They act both alone and in an aggregate form. As mentioned above, clay particles and in some cases also silt-particles, consist of only one mineral (Larsson 2008). Clay minerals are surface active and surrounded by adsorbed water. The amount of adsorbed water onto the clay mineral depends on the cations in the adsorbed water. The reason is that clay minerals are electrochemically active. Due to their electrochemical activity, the clay minerals are not in contact with each other directly, but bound together by polar bonds or van der Waals forces (Fredriksson 2007, Gunaratne 2014).

In a mixed grained soil, the clay particles form a layer on the surface of the larger particles. At the contact points between larger grains the clay particles form aggregates. When the amount of clay is higher than 15 – 25 % of the total amount of the soil, the coarser grains are entirely separated by the clay particles (Larsson 2008).

2.1.4 Engineering properties of clay tills

When using clay till as an earthwork material, it is important to treat the soil in a way to minimize the risk of negative effects. Clay tills have potential to be good earthwork material and if left untouched the deformation modulus could be naturally high. When touched, the structure of the soil changes. The change could cause negative effects, for example long term settlements, compaction properties and frost sensibility.

The deformation properties depend on the stress history of the soil. If the soil has been exposed to a greater load than the current and consolidated (over-consolidated), the strength of the soil is high. When the pre-consolidation is at the level of the current vertical pressure, the soil is normally consolidated. At the pre-consolidation, the compression properties of the soil change significantly (Avén 1984).

Another important factor is the volume increase of the soil when excavated. The degree of over-consolidation determines the amount of volume increase of the soil and the effort required to excavate in it (Lindh 2004).

Moisture content

Clay tills are sensitive to variation of the moisture content. The sensitivity to variation of moisture content is determined by the amount of fine-grained material in the soil. A clay till has a low permeability and plasticity which makes it harder to dewater (Lindh 2004).

The consistency of a clay till varies with the moisture content. The soil goes from solid to semi-solid, plastic and finally liquid with increasing the moisture content. The limits used to describe the texture of the material change with the moisture content w (Larsson 2008)

$$w = \frac{m_{H_2O}}{m_{solid}} \qquad \textbf{EQ: 2.1}$$

where m_{H_2O} and m_{solid} are the mass of water in the soil and the mass of solid material.

The moisture content w is related to the moisture condition value (MCV); see section 2.4.2 for more information about MCV). To determine the relationship

$$w = a - b \cdot MCV \qquad \textbf{EQ: 2.2}$$

where w is the moisture content (%), a is the interception with the moisture content axis (%) and b is the slope of the line, several MCV-tests in the soil with different moisture contents have to be done, see Figure 2.3 (Lindh 2004).

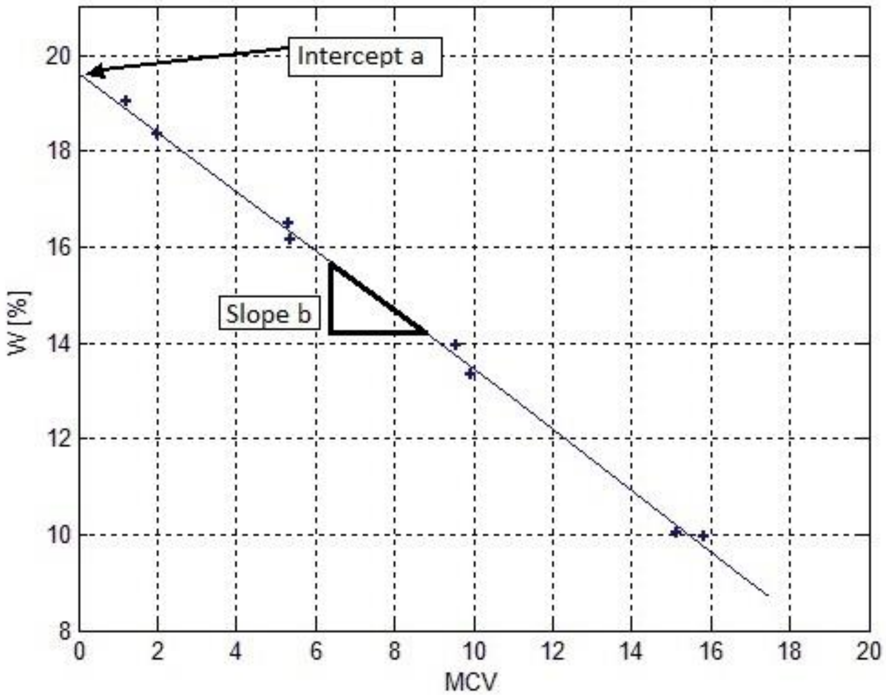

Figure 2.3 *MCV calibration line for a fine fine-grained till (after Lindh 2004).*

Both a and b are soil-dependent factors and therefore need to be determined for each new soil (Lindh 2004). The parameter a is a constant and the parameter b indicates the sensitivity to a change in moisture content. If the b value is small, the soil has a high sensitivity (Lindh 2004).

When a clay till is too wet to use in construction there are several improving methods which could be used to treat the soil. Either through stockpiling or aeration, which demands no additional effort but time to improve the soil. A selfimposed consolidation with additional weight over time reduces the excess pore pressure. Another method that could be used without the time consuming factor is modifying the soil. Modifying the soil using a binder, e.g. lime, involves a great reduction in the consolidation time (Lindh 2004).

Compaction properties

Compaction of a material means that the density of the soil increases and as a result, the engineering properties change. To be able to densify clay till through compaction the most important parameter is the moisture content (Fredriksson 2007, Lindh 2004). In clay tills there are large cohesions, which depend on the van der Waals-bindings that act between the particles. In clay tills, the need for more force in the compaction work may therefore be required as well as a reduced layer thickness compared to a more coarse-grained soil. With increased moisture content, the processing capacity of the clay till increases (Fredriksson 2007).

The compaction of a clay till with high moisture content results in a pore pressure increase. A significant factor in clay till is the low permeability. At a certain compaction level, the continued densification of clay till is not possible before a substantial decrease in the pore pressure, which decreases only slowly due to the low permeability (Lindh 2004).

Apart from the moisture content and the particle size distribution in the soil, the underlying soil also affects the compaction properties of the current ground layer (Lindh 2004).

Codes and standards

In Sweden, several different standards are used when requirements for modification are set (Franzén et al. 2012).

In Eurocode 7, the criteria of suitable material for filling works should be based on the strength, stiffness, durability and permeability properties achieved after compaction. The criteria should take into account the purpose of the fill and on the load that will be placed on the fill. When determining the appropriateness of the filling material, the following aspects need to be taken into account (Anon. 2010):

- Particle size distribution
- Resistance to crushing
- Packability
- Permeability
- Plasticity
- Strength of underlying layer
- Organic content
- Chemical attack
- Pollutant effects
- Decomposability
- Sensitivity to changes in volume
- Sensitivity to low temperatures and frost
- Weatherization
- Effects of excavation, transport and placement

If the material considered is not suitable as a filling material, some of the following measures could be used (Anon. 2010):

- Adjust the moisture content
- Mix with cement, lime or other materials
- Crush, sift or wash
- Protect with appropriate material
- Arrange drainage layer

2.2 Binders

Binder materials could be used in weak soils to improve their geotechnical properties. The improvement could be such as compressibility, strength, permeability and durability. In general, fine-grained tills are best improved with lime, while in a more coarse-grained soil; cement is the more appropriate binder (Makusa 2012). There are other binders, which could be used in interaction with either lime or cement, which improve the result in one way or another.

The process of using lime in the soil to increase the strength is different compared to other binders. The increase in strength comes from an exchange in cations rather than cementing effect, which is a result of the pozzolanic reactions from other binders (Makusa 2012).

In contrast to lime, cement does not depend on the soil mineral. When mixed, the reaction is not between the minerals of the soil and the cement but only between the cement and the water in the soil. The result is that cement is useable with a wide range of soils, though not as effective in fine-grained till as lime. Another difference between lime and cement is the reaction process. The cement reaction does not modify the soil, but stabilises it directly instead (Lindh 2004, Makusa 2012).

There are other kinds of stabilising agents. Pozzolanas have a secondary binding effect. Clay minerals such as kaolinite, montmorillonite and illite are pozzolanic in nature. There are also artificial pozzolanas, which are natural materials that are heated up into an ash (Makusa 2012).

Fly ash is a by-product of coal-fuelled power plants or bio-fuelled power plants. Most fly ashes are secondary binders. A secondary binder cannot produce the desired effect on its own, but instead needs an activator such as cement or the by-products of lime to start the reaction (Makusa 2012).

Blast furnace slag, commonly known as Merit in Sweden, is a by-product in iron production. The chemical composition is similar to the one for cement but Merit is a secondary binder (Makusa 2012).

Organic agents could also be used as a pozzolana; examples of organic agents are rice husk and rice straw. The organic material is treated as artificial pozzolanas (Ali, Adnan & Choy 1992).

Agents used in the stabilisation/modification process could also be used to improve the workability of the soil such as lignosulphonate. To improve the durability of stabilised soil the use of an agent to make the soil hydrophobic is a possibility (Lindh 2004).

2.2.1 Binder functionality

Lime and cement are the two major binder agents. These could be used separately, or together with some other agents. In a general description, lime is preferably used in clay tills with the ability to both modify and stabilise the soil. Cement, which stabilises the soil immediately, works in every grain size though in clay tills the quality control may be difficult. Cement works well in coarse grained soils; see Figure 2.4 (Lindh 2004).

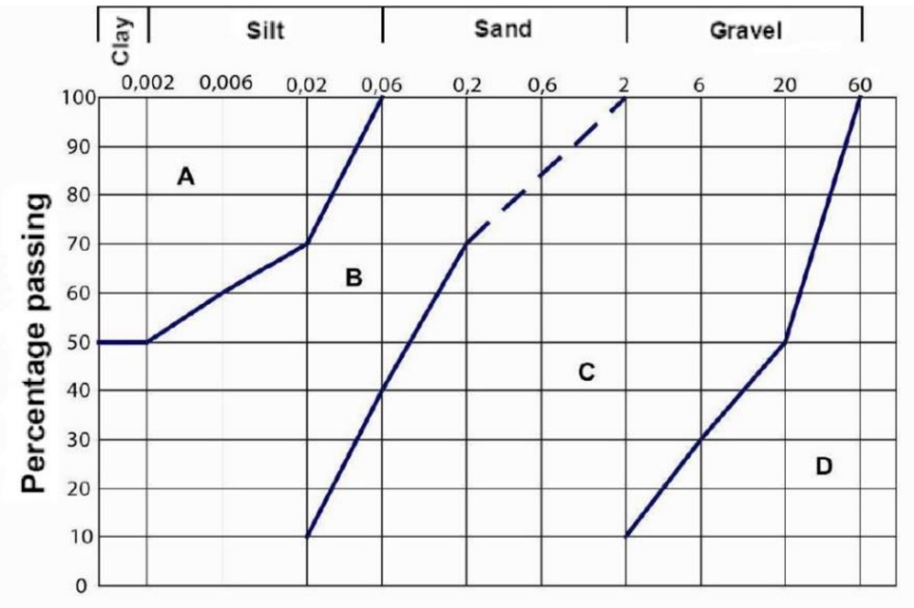

Figure 2.4 *Recommended binders at different grain size distribution (after Franzén et al. 2012).*

Figure 2.4 divides the grain size distributions into four different sections with different suggestions which binders to use. In section A, improving the soil with lime would give a good result, both with quicklime and hydrated lime. Problems could however occur with the mixing (Franzén et al. 2012).

In section B, lime is the most preferable binder, both quicklime and hydrated lime. This is due to the positive effects of lime in clay tills with its modifying abilities. The major application area for improving soils with lime is thus soils with the granulometric composition in section B (Franzén et al. 2012).

In section C, cement is the most suitable binder, which will create a stabilising effect on the soil. In section D, it is inappropriate to improve the soil (Franzén et al. 2012).

This report is focused on soil modification using lime.

2.2.2 Lime

Lime is a collective expression for quicklime CaO, hydrated lime $Ca(OH)_2$ and carbonated lime $CaCO_3$. The three varieties of lime are related by the creation, which is illustrated in the following equations (Lindh 2004):

$$CaCO_3 + heat \rightarrow CaO + CO_2 \qquad \textbf{EQ: 2.3}$$

$$CaO + H_2O \rightarrow Ca(OH)_2 + heat \qquad \textbf{EQ: 2.4}$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad \textbf{EQ: 2.5}$$

When using lime as a binder in soil modification, it is delivered in one of three different ways, as quicklime, hydrated lime or as slurry. The slurry is hydrated lime mixed with water while both quicklime and hydrated lime are delivered as a dry powder (Lindh 2004, Gustafsson 1999).

The most commonly used lime is quicklime CaO. It is produced from carbonated lime (limestone) $CaCO_3$ by heating. There are several positive aspects of using quicklime compared to hydrated lime or a slurry:

- More economical
- Higher available free lime content per mass unit
- Denser than hydrated lime, which results in less required transport space
- Immediately reduces water from the soil (up to 32 % of its own mass)
- Exothermic reaction which accelerates strength gain and evaporates excess water
- A slurry is less usable when the soil is wet

There are negative effects of using quicklime instead of hydrated lime or slurry. One negative effect is that if the soil is dry it will need to be watered. Quicklime is also highly reactive and is thus harmful to the people who work with it. Extensive safety measures must therefore be established to ensure the personnel's safety (Makusa 2012, Lindh 2004, Gustafsson 1999).

When using lime as a binder in the modification process, whether it is quicklime or hydrated lime, an increase in pH will occur. An increased pH will result in a chemical reaction between calcium and clay minerals in the soil, such as siliceous and aluminous compounds. Due to raised pH, calcium silica and calcium alumina hydrates will be created, similar to those of cement paste, which will increase the strength of the soil (Ghobadi, Abdilor & Babazadeh 2014, Makusa 2012)

Soils in which sulphur and organic material are present may inhibit the strengthening process if the binder agent is calcium. The use of lime in a sulphate-rich soil could cause the calcium in the lime to react with the sulphate in the soil. The reaction between sulphate and lime will cause the soil to swell, which may affect the strength of the soil negatively (Makusa 2012).

2.3 Soil modification

2.3.1 History

Lime is one of the oldest developed construction materials. Lime has been used in soil-lime mixtures in the construction of roads for more than 2000 years. The Romans used a soil-lime mixture in their road construction to improve the stiffness. The most famous road improved with lime by the Romans is the Appian Way (Dash, Hussain 2012, Lindh 2004).

The method of modifying the soil with lime was not used in Sweden until the late 1950's where it was met with great doubt. Modification of the soil (and stabilisation) was used more frequently during the 1970's and the early 1980's (Lindh 2004, Franzén et al. 2012). According to Gustafsson (1999), the use of modification and stabilisation disappeared in Sweden during the 1980's due to:

- Health and safety problems that arose in connection with the spreading of lime
- Mixing problems with settlements as a result
- BYA 84, incentive to use shallow soil stabilisation disappeared
- The market was not large enough to justify buying and maintaining the equipment required

Skanska, previously Skånska Cementgjuteriet, had possession of a milling machine until the end of the 1980's, when it was no longer financially viable to maintain it due to lack of demand (Gustafsson 1999).

Due to changes in the guidelines, modification of soils is today getting more common. Improvements have been made since the 1980's, such as development of the equipment and the binders. The new equipment has increased the efficiency and the quality of the process. Today, modification and stabilisation can be performed both in-situ and ex-situ (Lindh 2004).

2.3.2 Procedures

Modifying a soil can be done in different ways. The modification process could be done in-situ or ex-situ depending on what is more preferable.

In-situ

In-situ stabilisation involves both modification and stabilisation of soil on-site. By applying binder agents without removing the bulk soil, the stiffness increases. In-situ modification could be performed by several different methods (Lindh 2004).

In-situ modification is roughly divided into three phases, spreading, milling and compaction. The surface to be modified is prepared according to need and then the binder is spread onto the soil. When the binder has been spread in an even layer, the mixing phase begins (Lindh 2004).

Figure 2.5 *A tractor spreading lime at ESS.*

Mixing is done for two reasons; Mixing the soil and the binder into a homogeneous mixture and to break up large lumps and thus improve the compaction properties. To get a satisfactory mixing between the soil and binder, the milling should be performed into the underlying layer.

Figure 2.6 *A machine mixing the lime with the soil at ESS.*

Finally, the modified soil should be compacted. Compaction is important to attain the desired quality of the modified soil (Gustafsson 1999, Lindh 2004).

There is equipment that allows the stabilising agent to be added when the soil is mixed. That would mean improved working environment and environmental impact due to reduced dusting (Gustafsson 1999).

Figure 2.7 *Compaction work with a vibrating smooth drum at ESS.*

Ex-situ

The method of ex-situ modification involves moving the soil from its original position to another place with the purpose of improving its quality by modification using a binder. The soil could later, when modified, be used as a filling material (Makusa 2012).

2.3.3 Modification process

When strengthening a clay till using lime, the process could be divided into two phases; the modification phase, which takes part during the first few hours, and the stabilisation phase. The stabilisation phase starts after the modification phase and is defined as a long-term process, which strengthens the soil through chemical processes (Lindh 2004). The modification process is an electrochemical change, which changes the properties of the soil. This electrochemical change occurs when calcium ions are added to the pore water in the soil (Olofsson Augustsson 2010).

The process of modification could be described as the following process:

Depending on the amount of soil moisture, either quicklime or hydrated lime is used. When using quicklime, the initial process is a chemical process between water and quicklime, which hydrates the lime, see EQ: 2.4 (Avén 1984).

For every 100 g CaO used, 32 g H_2O is bound and additional water evaporates due to the exothermic reaction. The result is a clay till with less water, which increases the compaction properties in the soil (Assarson 1972, Lindh 2004).

Figure 2.8 *Steam rises due to the exothermic reaction which occurs between quicklime and the water in the soil.*

The hydrated lime (includes quicklime after the slaking process) acts as a source of calcium cations. In the water, except distilled water, there is a presence of dissolved ions. Around the clay particles in clay tills, cations together with water are adsorbed onto the surface. When the amount of calcium cations increases, they have a tendency to replace the normally adsorbed cations on the surface of the clay particles (Lindh 2004, Avén 1984).

The reason for the change of cations adsorbed to the clay particles is explained by the Lyotropic series, also named Hofmeisters series. In general, the cations with higher valence replace those with lower valence (Lindh 2004, George, Ponniah & Little 1992). The Lyotropic series is based on the charge of the ions and is described as

$$NH_4^+ < K^+ < Na^+ < Li^+ < Ca^{2+} < Mg^{2+} < Al^{3+}$$

Generally, Na^+ and K^+ ions are attracted to the clay particles. With an increase of Ca^{2+} ions, which got a higher charge, the existing ions are replaced. The amount of Ca^{2+} ions needed to start the ion exchange is approximately 0.1 g $Ca(OH)_2$ /kg clay (Dr. Neumüller 1973, Parker 2002).

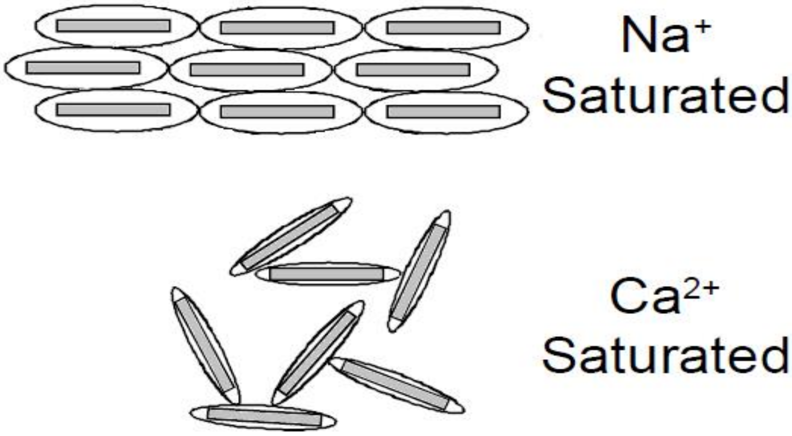

Figure 2.9 *Textural change due to modification (after Little 1987).*

The positively charged Ca^{2+} ions can bind to two particles and create a bridge through ion correlation. When bridges are formed, waterproof conglomerate are produced which leads to a decrease of the specific surface of the clay particles. The adsorptively bound water to the clay minerals can be through structural transformation capillary enclosed. This structural change leads to an increase in the plastic limit and the result is improved compaction properties, facilitated milling and more easily evaporated excess water (Åhnberg et al. 1995, Avén 1984, Lindh 2004, Dr. Neumüller 1973, Assarson 1972).

To obtain a complete exchange of cations in the clay mineral only about 1 % of hydrated lime, based on the dry weight of the clay till, is needed (Assarson 1972, Gustafsson 1999).

When the compaction work has been done, together with the ion exchange, the stiffness has increased. The engineering properties of the clay till will be improved with improved water resistance and reduced settlements (Avén 1984).

The improvements by soil modification are completed within a couple of hours. The definite time of completion differs between different soils depending on the mineral content. The time varies from half an hour up to 72 hours, though the main part of the modification is done in the beginning (Avén 1984, Lindh 2004).

The stabilisation phase, which is a chemical process, starts after this modification phase. The process is dependent on temperature, pH and the availability of silicates and aluminates. The chemical processes are finished after a long time and successively increase the stiffness. Another positive effect is reduced capillary suction (Avén 1984).

2.3.4 Parameters affecting the strength of improved soil

There are several different factors influencing the lime-soil reactions such as the moisture content, organic matter, clay minerals and the ion content in the soil. This results in a complex dimensioning system, which will be unique to each different soil (Gustafsson 1999, Franzén et al. 2012, Makusa 2012).

In contrast to dealing with concreate, there are no well-formed dosage methodologies when working with soil improvements. The reason a method like the criterion for concreate such as water/cement ratio does not work is the complex behaviour of the soil (Consoli, da Silva & Heineck 2009). The result of modifying the soil with lime is affected by many factors. There are both soil factors; chemical-physical properties of the soil, its porosity and moisture content, and modification factors; amount of lime, compaction and mixing (Consoli, da Silva & Heineck 2009, Åhnberg et al. 1995).

Several studies have been made to evaluate frost susceptibility in clay tills. The results vary though there are some indications that a clay till with a little amount of lime added could be more susceptible to frost than an untreated soil. Other studies indicate that there is no difference in frost susceptibility between treated or untreated clay till (Sandberg 2006, Lindh 2004).

The effect of soil temperature when improving a clay till with lime varies. In the modification phase, there are no indications of the temperature influence the strength development (George, Ponniah & Little 1992, Lindh 2004, Makusa 2012). In the stabilisation phase, the reaction rate between the Ca^{2+} ions and silicates or aluminates is dependent on the temperature in the soil. The reaction rate is increased by a higher temperature and if the temperature is below 7℃ the reaction rate is very slow (Lindh 2004, Kujala 1984).

Mixing

To obtain an even increase in strength, when modifying clay till with lime, it is important to make sure that the binder is homogeneously mixed with the clay till (Åhnberg et al. 1995).

When quicklime is used as a binder, there will be an immediate increase of temperature in the close vicinity around accumulations of lime grains. The consumption of water in the hydration of the lime together with the evaporation of water in the exothermic reaction could lead to an uneven water distribution in the soil. The water distribution together with the ion exchange results in that the soil gets coarser, drier and harder to process, which could result in that the lime gets unevenly distributed (Åhnberg et al. 1995).

In a clay till it is important to get the mixing evenly performed. At a micro level, the hydrated lime dissolves into the water and the ions are transported to the clay particles. The Ca^{2+} ions could be unevenly distributed if not mixed with the clay till properly which could cause strength problems (Åhnberg et al. 1995).

The amount of lime mixed into the clay till increases the unconfined compressive strength approximately linearly (Consoli, da Silva & Heineck 2009).

Moisture content

In a modification process, it is essential to have enough moisture to make the hydration of the lime complete. It is also important to achieve an efficient compaction. In a soil with insufficient moisture content, the lime will compete with the soil to get the needed water. In a clay till, often containing lots of soil water, the hydration process could be delayed if the moisture content is insufficient. A delayed hydration will affect the final strength (Makusa 2012).

When improving a clay till with lime, the relationship between moisture content and MCV changes. With constant moisture content, the treated soil gets a higher MCV. The difference in MCV-value does not change remarkably when adding more lime, the change happens during the modification process (Lindh 2004).

There is a relationship between the moisture content and the cohesion in the soil. When the soil is improved with lime, this relationship is changed and when the moisture content is the same of untreated soil, the cohesion is much higher. As with the MCV, the change happens during the modification process and remains relatively constant when more lime is added (Lindh 2004).

Depending on moisture content, a cohesive soil could either be solid, semi solid, plastic or liquid, see Figure 2.10. The moisture content when the soil passes from plastic to liquid condition is known as liquid limit w_L. The moisture content when the soil passes from plastic to solid state is known as plasticity limit w_P. These limits could be determined through laboratory testing and the difference between them is called plasticity index (I_P) (Assarson 1972).

$$I_P = w_L - w_P \qquad \textbf{EQ: 2.6}$$

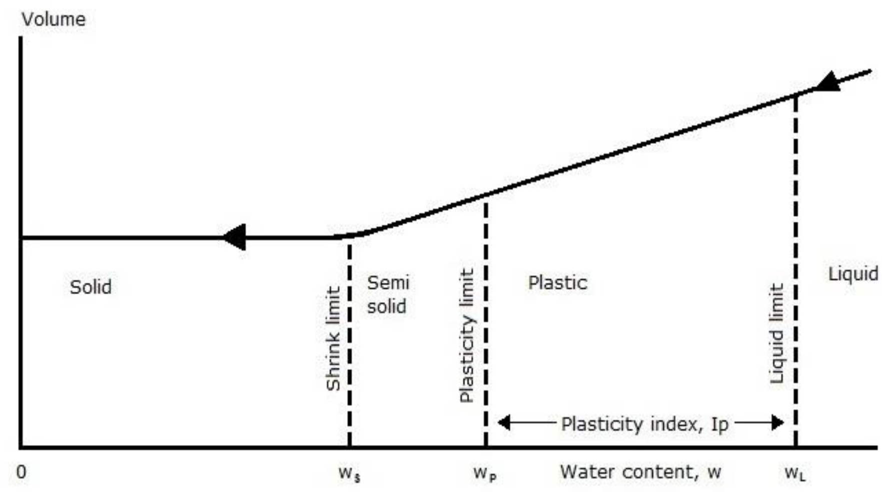

Figure 2.10 *Different states of consistency in fine-grained till (after Larsson 2008).*

In order to compact a cohesive soil it must be in its solid state consistency. In a normal clay till it is rarely the case that the soil is in a solid state. Through the modification process, the structural change and the internal dehydration that occurs, leads to an increase in the plasticity limit and thus changes the soil into a more solid state (Assarson 1972, George, Ponniah & Little 1992).

According to Consoli, da Silva & Heineck (2009) there is no relationship between unconfined compressive strength and water/lime ratio.

Compaction

Compaction of modified soil is essential to achieve the desirable quality for the subsurface of a construction. Modification changes the compaction properties of a clay till. To achieve the desired results when compacting the modified soil, sufficient compaction energy is needed and the moisture content must be within a certain range (Lindh 2004).

A delay in time between compaction and modification, with hydrated lime, could be advantageous to the strength in the soil. The hydrated lime requires time to diffuse through the soil to produce maximum homogeneity and maximum effect on the plasticity (Makusa 2012).

To improve the strength greatly in a modified soil the reduction of porosity through compaction is essential. It was shown that the relationship between the unconfined compressive strength and porosity is approximately linear in a compacted modified clay till (Consoli, da Silva & Heineck 2009).

A relationship between unconfined compressive strength and a voids/lime ratio adjusted by an exponent unique to the soil and lime used has been observed, see Figure 2.11. The voids/lime ratio is defined by the voids volume of the compacted soil divided by the lime volume i. e. (Consoli, da Silva & Heineck 2009).

$$\frac{V_V}{V_{lime}} = \frac{Volume\ of\ voids\ (water + gas)}{Volume\ of\ lime} \qquad \textbf{EQ: 2.7}$$

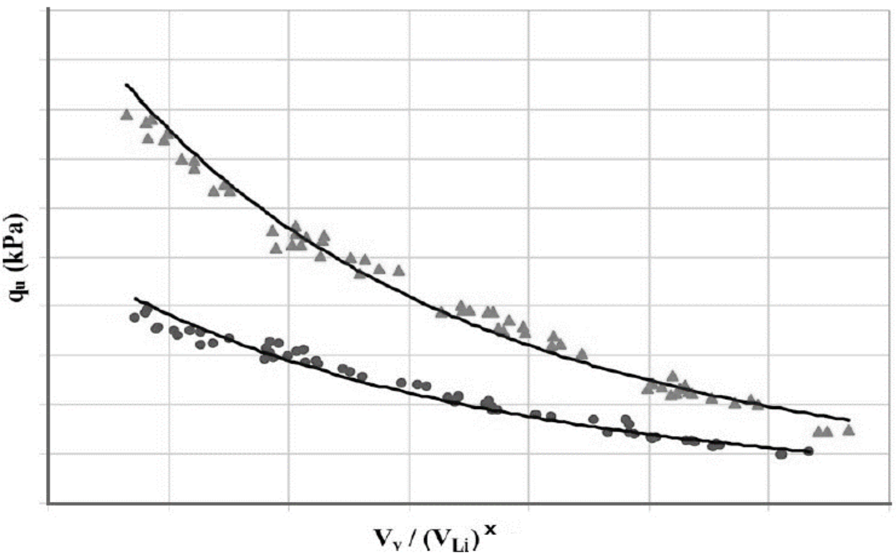

Figure 2.11 *Adjusted voids/lime ratio (after Consoli, da Silva & Heineck 2009).*

Organic matter

Organic content in a clay till could in varying degree retard or reduce the modifying process. Organic content may include retarding substances such as humus and humic acids. The humic acids react with the hydrated lime and form a product, which cannot be dissolved and precipitates out on the clay particles. The acids could cause the pH to drop (Axelsson, Johansson & Andersson 2002, Franzén et al. 2012).

Clay mineral and ion content

The modification process is strongly dependent on the ion content and the minerals in the clay till. The difference in strength when modifying a clay till could be significant. To transfer experience between projects with different soil types is thus difficult. (Franzén et al. 2012).

When the soil is modified with lime, the clay particles flocculate. The flocculation results in a decrease of plasticity in the soil. This effect is also dependent on the mineral compositions. The differences between different clay minerals are illustrated in Table 2.4.

Table 2.4 *Cations-exchange capacities of clay minerals (Drever 1982)*

Clay mineral	Cations-exchange capacity ($meq/100$ g clay mineral)
Vermiculite	$120 - 200$
Smectite	$80 - 150$
Illite	$10 - 40$
Kaolinite	$1 - 10$
Chlorite	< 10

In Sweden, the most common clay mineral is illite. Other minerals that also occur are chlorite, kaolinite and montmorillonite. Montmorillonite has a higher cation-exchange capacity compared to kaolinite (Larsson 2008).

The basis for the pH is water. Water is in some degree divided into H^+ and OH^-, these are in equilibrium with each other and it is this ion concentration, which creates the basis for the pH. The pH will rise drastically when adding lime to the soil due to the OH^- groups in the hydrated lime (Johansson, Åhnberg & Pihl 2006).

During the modification phase, the pH is not as relevant as in the stabilising phase. To start the stabilising phase with lime a high pH is required ($pH > 10$) (Åhnberg et al. 1995, Johansson, Åhnberg & Pihl 2006). In acidic soils, it could be necessary to add more lime to raise the pH-level to make the stabilising reaction begin (Johansson, Åhnberg & Pihl 2006).

Lime modification of a clay till is sensitive to sulphate and sulphide concentrations above 1 %. Phosphates and nitrates are compounds other than sulphate or sulphide, which could interfere in the curing process and provide a reduced strength growth (Franzén et al. 2012).

2.4 Test methods

When using clay tills in earthwork, the acceptability criteria are usually set in relation to the engineering properties that affect the volume change characteristics of compacted fill (Lindh 2004). Lindh (2004) presents the most important criteria as:

- Particle size distribution
- Moisture content
- Plastic limit
- Undrained shear strength
- Compaction characteristics
- Moisture condition value (MCV)

2.4.1 Field tests

Static plate load test

Static plate load is a testing method to determine the stiffness of the soil and how well the underlying layers are packed. The static plate load test is performed by a circular plate loaded with a force in two load cycles. The first load cycle has a maximum load of 0.5 MPa. The second load is carried out with a load of about 90 % of the first load cycle. In both load cycles, the elastic and plastic settlements are measured. The deformation modulus E_v is used to characterize the stiffness of the soil. The relationship between the mean tensile stress and the measured settlements of the two load cycles results in two load modules, E_{v1} and E_{v2} (Hellman 2011, Anon. 1993).

The value E_{v2} is the deformation modulus from the second plate load test. The ratio between E_{v2} and E_{v1} tells how well the modified layers are packed. The deformation modulus is calculated as (Anon. 1993)

$$E_v = 1.5r \frac{1}{a_1 + a_2 \cdot \sigma_{1,max}} \quad \textbf{EQ: 2.8}$$

where

$r =$	Radius of the plate	mm
$\sigma_{1,max} =$	Maximum mean tensile stress in the first load cycle	$\mathrm{MN/m^2}$

and the constants a_1 and a_2 are defined through

$$s = a_0 + a_1\sigma_0 + a_2\sigma_0^2 \quad \textbf{EQ: 2.9}$$

where

$s =$	Settlement at the load plate centre	mm
$\sigma_0 =$	Mean tensile stress at the centre of the plate	$\mathrm{MN/m^2}$
$a_0, a_1, a_2 =$	Constants in the second-degree polynomial	$-$

The static plate load test is easy to perform, though relatively slow. The method is sensitive to the arrangement of the equipment. The plate must have a good contact over the entire surface, otherwise the results of the deformation modulus will be too low (Hellman 2011). The static plate load test should be performed according to the guidelines in (Anon. 2014b).

It should be noted that the E_{v2} value is not the same deformation modulus as obtained in a triaxial test, however, Vägverket (1993) uses the term deformation modulus for the E_{v2} value. The E_{v2} value will for convenience in this report be referred to as deformation modulus.

Light drop weight test

The light drop weight test is a non-destructive way to use for compaction verification in a modified and compacted soil. It is a quick and an easy method to carry out in the field, which allows a large number of tests to be performed (Olofsson Augustsson 2010, Hellman 2011).

The light drop weight tester could vary in size and weight. Normally it is a 10 kg weight which is dropped along a rod down onto a damped plate. The load plate on which the weight is dropped is usually 300 mm in diameter and the load is approximately 7 kN (Hellman 2011).

Due to the relatively low weight of the tester, the method has limited depth in which it is effective. Normally linear elastic theory is used to calculate the deformation modulus in the soil from the light drop weight tester. Light drop weight test presented by Orrje (1968) gave a deformation modulus 2 – 3 times that obtained by a static plate load test which gives an indication of the error if the tester is not adjusted to the static plate load test (Bergdahl 1984).

To obtain the deformation modulus, using a light drop weight tester, is only approved if it can be proven that the obtained values correspond to results obtained from a static plate load test (Fredriksson 2007).

Isotope meter (Troxler)

Isotope meter is commonly referred to as Troxler after the trademark Troxler. In this report, the isotope meter will be referred to as Troxler. The Troxler measures the density of the soil by inserting a probe into the soil. The probe emits radiation, which is dampened in intensity when it passes the ground. The radiation is measured and used to calculate the density and moisture content. The results, which can be calculated from the test are; moisture content, dry density, gas volume and degree of compaction (Hellman 2011).

The results in gas volume and density given by the Troxler method are acceptable values when making a control over the compaction results (Berggren et al. 2004).

The gas volume L_p (in percent) is determined by (Fredriksson 2007)

$$L_p = 100 \cdot \left(1 - \frac{\rho_d}{\rho_s}\right) - \frac{w \cdot \rho_d}{\rho_w} \qquad \textbf{EQ: 2.10}$$

where

$\rho_d =$	Dry density	t/m^3
$\rho_s =$	Compacted density	t/m^3
$\rho_w =$	Density of water	t/m^3
$w =$	Moisture content	%

The Troxler must be regularly calibrated against moisture content determinations.

Visual inspections

When a clay till is modified, visual inspections of scattered amount of binder, milling depth, decomposition degree and homogeneity should be performed.

The milling depth is controlled by hand and measured using a ruler. When the milling is too shallow, adjustments could be made with a second milling. If the milling gets deep, the binder is diluted. For large deviations, additional binders may be needed with subsequent milling (Franzén et al. 2012).

The homogeneity of the modified soil is controlled by a visual inspection after the milling. If the homogeneity is considered insufficient, an additional milling could be necessary. The degree of decomposition could be used as a method to measure the homogeneity of the modified soil (Franzén et al. 2012).

Measurement of the decomposition rate is important for fine-grained tills with high clay content. The test should be carried out according to SS EN 12386-48: 2005 (Franzén et al. 2012).

2.4.2 Laboratory tests

MCV (Moisture Condition Value)

MCV is a measurement of the lowest amount of compaction energy required to achieve maximum compaction of a soil at a specific moisture content. The value is material specific and needs to be determined for each type of soil (Fredriksson 2007).

The MCV method has great advantages compared to other methods when deciding the compaction properties of a soil. The method is easy to use and may easily be correlated to the initial shear strength of the soil. Another advantage is that the method could be used in the field, which allows the modification process to be adjusted with regard to the compaction properties (Franzén et al. 2012).

When determining the MCV of a soil, a device called moisture condition apparatus (MCA) is used. The apparatus has a cylinder shape with the internal diameter 100 mm. The compaction of the soil is achieved by a rammer, which drops freely from a height of 250 mm. The rammer has a diameter of 97 mm and the mass is 7 kg. To avoid extrusion between the rammer and the cylinder a lightweight disc is placed on top of the soil (Lindh 2004).

The soil sample used in the MCV test is first sieved through a 20 mm sieve to remove the largest particles. After the sieving, a sample of 1500 g is used and put in the cylinder (Fredriksson 2007).

The difference in penetration between n and $4n$ strokes (for example, first and fourth, second and eighth) is noted. The difference is plotted against 10 times the logarithm of the number of blows n, $[10 \cdot Lg\ n]$, see Figure 2.12. The definition of MCV is 10 times the logarithm of the number of blows required to achieve a difference in penetration of 5 mm in the plotted curve. When the difference is less than 5 mm the soil is considered to have no significant density increase. (Lindh 2004, Fredriksson 2007).

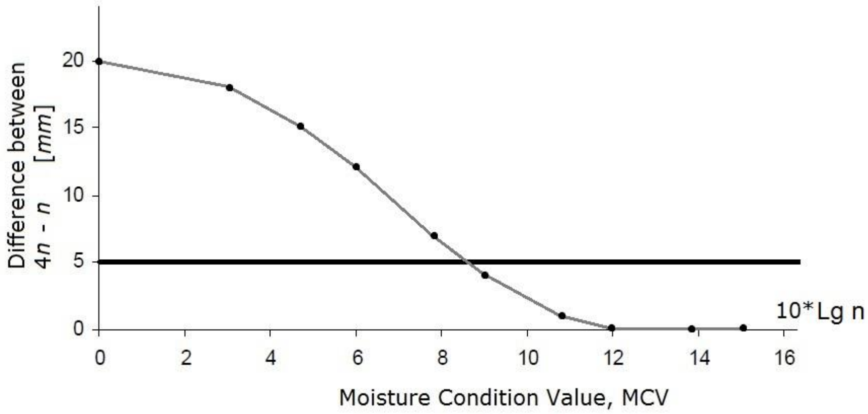

Figure 2.12 *A MCV curve (after Sandberg 2006).*

There are linear relationships between the moisture content and MCV in specific soil types. A decrease in moisture content results in an increase of the MCV (Fredriksson 2007). There is a similar relationship between the moisture content and the shear strength of the soil. An increase of moisture content results in a decrease in shear strength, see Figure 2.13 (Lindh 2004).

There is a relationship between the porosity and the MCV, Figure 2.13. Since the deformation modulus is related to the porosity, the deformation modulus could be determined through an MCV test. To ensure that the porosity is less than 5 % in the soil, the MCV should be MCV $\leq$ 12 (Franzén et al. 2012).

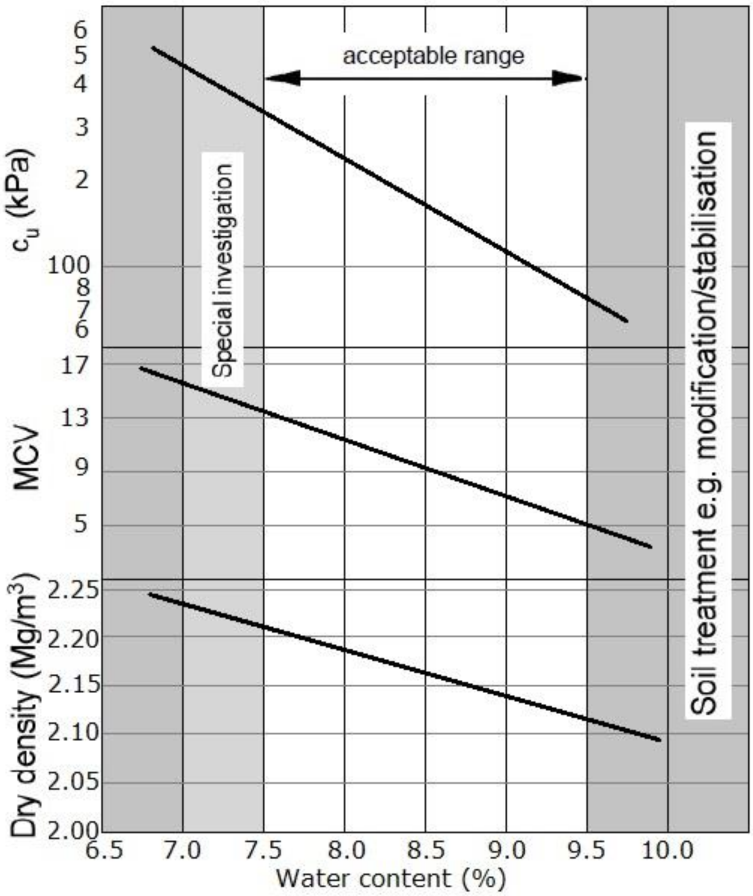

Figure 2.13 *Relationship between moisture content, dry density, MCV and shear strength in modified soil (after Lindh 2004).*

3 Experimental design

3.1 Basic principles

The methodology in this report is largely based on Lindh (2004) recommendations. The main objective is describing the relationship between the modification process and both soil- and modification- factors. Since several factors affect the strength of the soil, these factors will have to be isolated by keeping those parameters that are not studied constant (Montgomery 2001).

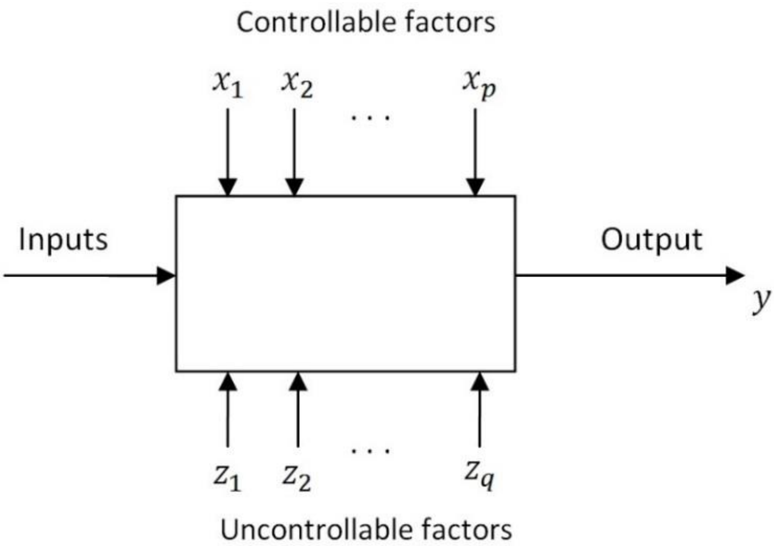

Figure 3.1 *Schematic representation of experimental design (after Montgomery 2001).*

Experimental design is a useful method to compare and evaluate the effect of different parameters on a product, Figure 3.1. The result of experimental design methods could improve the field performance, lower production costs and increase the reliability of the modification process in clay till (Montgomery 2001).

When implementing experimental design, a statistical approach is suitable to use, which allows the appropriate data to be evaluated, and results in objective and valid conclusions. Since all data in this study are subject to experimental errors, the only objective approach to analysis is with statistical methods (Montgomery 2001).

There are two aspects to an experimental analysis, the design of the experiment and the statistical analysis of the data. The design of the experiment is closely related to the analysis method. Experimental design follows three basic principles; *replication*, *randomization* and *blocking* (Montgomery 2001).

Repeating a basic experiment (replication) gives an estimation of the experimental error. This estimation of error becomes a parameter for determining whether an observed difference in the data is statistically different or not (Montgomery 2001).

Randomization is very important when using statistical methods in experimental design. It is important that a parameter is tested with a randomization between the observations and independently distributed. The randomization is done to average out the effects of extraneous parameters that may be present (Montgomery 2001).

In experimental designs, blocking is a technique used to improve the precision with which comparisons among the parameters are studied. A block is a set of experiments with relatively homogeneous conditions. Blocking is an efficient way to reduce the variability created by other parameters, which are not of interest (Montgomery 2001).

3.2 Difficulties mitigated by statistical methods

Statistical methods are used to fit a model to a set of parameter values. The parameter values are described as a data set of x and y values. To describe the uncertainty of the model, standard error and confidence intervals are used. To describe the uncertainty, the least square method is normally used. Problems with the least square method could occur when several explanatory variables with relationship between each other exist. Another problem with the least square method is if a few measured values differ considerably from the rest, it could have an inappropriate huge effect on the linear regression (Anon. 2015b).

There are a few points that should be considered when implementing statistical methods in experimental designs. An important factor when an experiment is analysed is to make sure that as much information as possible is available concerning the data received; this includes non-statistical knowledge about the subject (Box, Hunter & Hunter 1978).

Variations produced by disturbing parameters, both known and unknown, are called experimental errors. These experimental errors always occur during experiments and should not be seen as a negative aspect but as a variation that is often unavoidable. Experimental errors could be both errors in measurement and in the soil due to the heterogenic nature of clay tills. Other experimental errors could be unknown factors, which affect the result (Box, Hunter & Hunter 1978).

Statistical analysis gives a measure of precision and could give an indication in change of rate and mean values. By using statistical analysis, the probability that the produced relationship is truthful is greatly increased (Box, Hunter & Hunter 1978).

A relationship between two parameters could occur because of a third parameter, which affects both of them. This could lead to misguiding in an analysis between different parameters. By using experimental designs with sound principles and randomization, data can be generated with a sound basis for deducing causality (Box, Hunter & Hunter 1978).

Through well worked experimental designs, effects between different parameters could be described by different expressions more complex than linear relationship. Effects of interactive and non-linear relationships could be estimated by statistical methods, which could lead to decreased transferring of experimental errors (Box, Hunter & Hunter 1978).

To demonstrate the effect of different parameters of a probability distribution or the parameters of a model, a statistical hypothesis could be used. The hypothesis is based on conjunction between different parameters and results. The difference is demonstrated by rejecting a null hypothesis and could be stated formally as

$$H_0: \mu_1 = \mu_2 \qquad \textbf{EQ: 3.1}$$

$$H_1: \mu_1 \neq \mu_2 \qquad \textbf{EQ: 3.2}$$

where μ_1 and μ_2 are mean values of the comparison parameter when different variables are tested. The equation H_0 is called the null hypothesis and H_1 is called the alternative hypothesis. If the null hypothesis is rejected by tests, it could then be called statistically significant (Montgomery 2001).

Errors could occur when performing hypothesis testing. One of them occurs when the null hypothesis is rejected when it is true and is defined as a type I error. A type II error occurs when the null hypothesis is not rejected when it is false. These two errors are defined as α and β and the probability is given as

$$\alpha = P(type\ I\ error) = P(reject\ H_0|H_0\ is\ true) \qquad \textbf{EQ: 3.3}$$

$$\beta = P(type\ II\ error) = P(fail\ to\ reject\ H_0|H_0\ is\ false) \qquad \textbf{EQ: 3.4}$$

When performing a hypothesis test, the normal procedure is to specify a value of the probability of type I error α, which is often called significance level. In this study α is decided to be $\alpha = 0.05$. With a predecided α-value the experimental test is then designed to make the probability of type II error β value as suitably low as possible (Montgomery 2001).

The *p*-value is the probability of type I error in a test, in other words, the probability of finding data samples with the same results or "more extreme" results, when the null hypothesis is actually true. One way to decide the reliability of a result given by a test is with the *p*-value α_0. When the *p*-value is equal to or smaller than the significance level ($\alpha_0 \leq \alpha$), it implies that the result of the observed data is not in agreement with the null hypothesis. When the null hypothesis is untrue it must be rejected and the alternative hypothesis is accepted as the true one. The p-value is a tool for deciding whether to reject the null hypothesis or not and does not in itself support the probability of the hypothesis (Montgomery 2001).

4 Case study – ESS

This master's dissertation is based on the soil modification process at the ESS, the European Spallation Source, located in the northeast part of Lund in the southern part of Sweden, see Figure 4.1. The European Spallation Source is a pan-European project and is going to be a world-class research centre. The modification at the ESS has been done to receive sufficient stiffness in the soil. The requirements of the deformation modulus is given to provide a more reliable subsurface to certain constructions which are sensitive to settlements (Anon. 2015a).

Figure 4.1 *Map over Skåne where ESS is located in the north-east part of Lund taken from Google Maps.*

4.1 Soil conditions at the ESS

The clay till used in the modification at the ESS originates from the construction site; it was either modified without being excavated, or it was excavated and transported to a filling area. Figure 4.2 illustrates the areas where the modification has been carried out. When the existing ground has been modified, the soil has firstly been excavated down to the level where the requirement of the deformation modulus is fulfilled. The excavated masses are then treated as the masses excavated elsewhere and laid out in the predetermined modification method. The deformation modulus has been studied to control the stiffness of the subsurface. The required deformation modulus imposed on the modified subsurface of the facility is an E_{v2} value above 40 MPa (Anon. 2015a); see Section 2.4.1 for more information on E_{v2}.

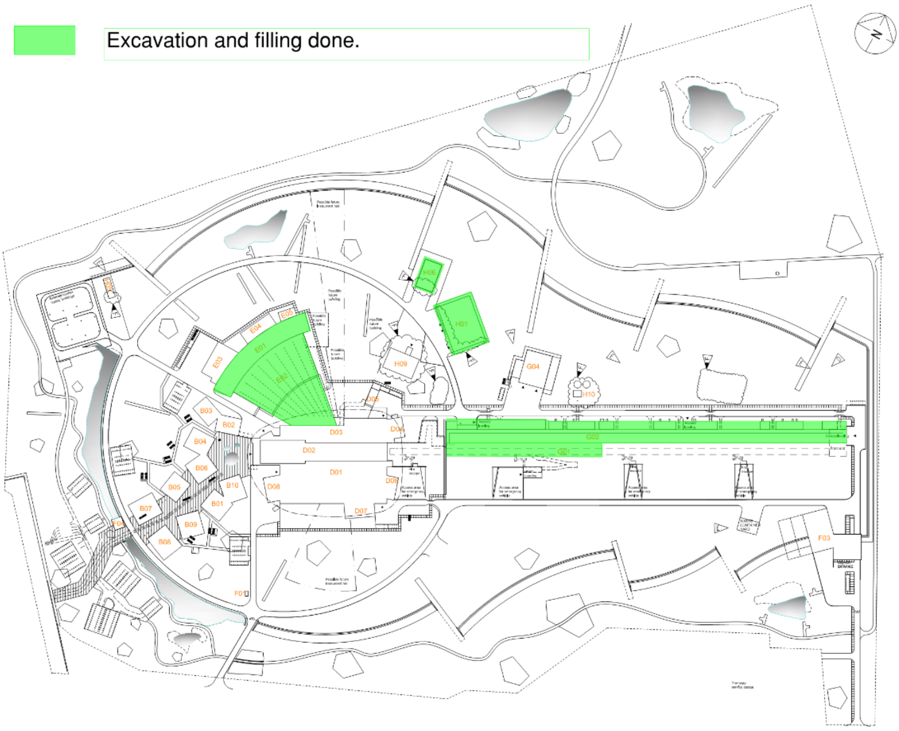

Figure 4.2 *Preliminary design of ESS with highlighted areas where modification have been performed (Anon. 2015a).*

The site is situated in a cultivated landscape where the soil is dominated by clay till. The thickness of the clay till extends all the way down to the bedrock, which results in that the work will be performed solely in clay till.

The clay till could be divided into three layers, a shallow layer of clay till which is sandy and silty. The shallow layer is followed by an upper and a lower clay till with high deformation modulus. The upper clay till is brownish in colour while the lower clay till is greyish. Both the brown and the grey clay till have been modified (Anon. 2015a). The clay till belongs to material type 4B according to AMA Anläggning 13 (2014), see Table 2.3.

The shallow clay till has a limited deformation modulus with a E_{v2} value of 20 – 30 MPa. The thickness of this layer is about one meter and it is not approved to use as subsurface to the modification. This layer has been removed down to an acceptable level and later modified. The upper and lower clay till with a higher deformation modulus has an E_{v2} value of 40 – 60 MPa; see Table 4.1. The values in Table 4.1 are provided by geotechnical consultants.

Table 4.1 *Soil parameters, average value (Anon. 2015a).*

Soil layers	Shear strength	Deformation modulus	Preconsolidation
Upper clay till	$c_u = 100\ kPa$ $c' = 20\ kPa$ $\phi'_k = 32°$	$E_{v2} = 20 - 30\ MPa$	$\sigma_c' = 800\ kPa$
Lower clay till	$c_u = 250\ kPa$ $c' = 45\ kPa$ $\phi'_k = 32°$	$E_{v2} = 40 - 60\ MPa$	$\sigma_c' = 800\ kPa$

4.2 Soil modification at the ESS

During the modification, quicklime has been used. The choice of the amount of quicklime used was made after the moisture content of the clay till. The modification was carried out between late September and late November and the test values were taken in connection to the modification (Anon. 2015a).

To minimize undesired effects, the soil modification process was halted during precipitation and when the average temperature was below 5°C. When the clay till was stored, treatment to minimize the effects of precipitation was performed (Anon. 2015a).

The working procedure has been as described below throughout the modification process. There was an improvement, which was carried out halfway through the modification process. The improvement was more frequently adding water, and that the added amount of water was increased. Another improvement was a general increase of the added amount of lime. Additional quantities of water were added when the greyish clay till was processed and the mixing was performed twice (Anon. 2015a).

Figure 4.3 *Ongoing modification at ESS.*

The working procedure used in the modification process at the ESS was as follows (Anon. 2015a):

1. Laying of 0.3 meter layers of clay till
2. Loosening of the surface with crawler tractor
3. Removal of boulders and visual inspection of the soil
4. Visual inspection of moisture content, possibly adding water
5. Spreading of lime
6. Milling of the surface
7. Smoothing of the surface with crawler tractor
8. Compaction with vibrating smooth drum
9. Controls of compacted surface

The modification has been carried out by Skanska and the measurements have been performed by geotechnical consultants.

Figure 4.4 *The appearance of the mixed modified clay till before compaction occurs.*

4.3 Test methods at the ESS

The following tests were made during the modification process (Anon. 2015a).

- Moisture content
- MCV
- Light drop weight test
- Static plate load test
- Measure of density and gas volume (Troxler)
- Visual controls

MCV tests were performed right after the compaction of the modified soil was completed, about one hour in average after the modification. The light drop-weight test and the Troxler tests were made a few hours after modification has been completed. Light drop weight test must be regularly correlated against static plate load. The Troxler must be calibrated against moisture content determinations (Anon. 2015a).

The distances between the locations of the various tests varies. To combine results from the different test methods the conditions for the soil samples used should be as similar as possible. To achieve this, the distance between the sites of origin for the samples used has been maximum five meters within the scope of this dissertation (Anon. 2015a).

Tests were conducted on unmodified compacted surfaces. The results on these unmodified surfaces exhibited a wide spread and the deformation modulus did not reach the requirements imposed on the surfaces to be modified. The requirements made on the porosity are not reached in the unmodified clay till due to the variation in the results that are highly variable, see Figure 4.5 and Figure 4.6.

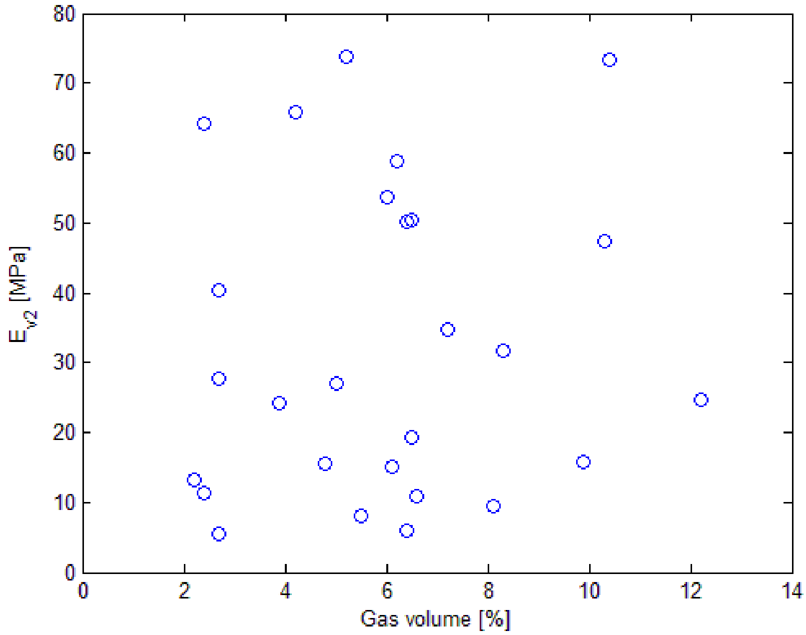

Figure 4.5 *Deformation modulus and gas volume in an unmodified soil with values taken from the Troxler.*

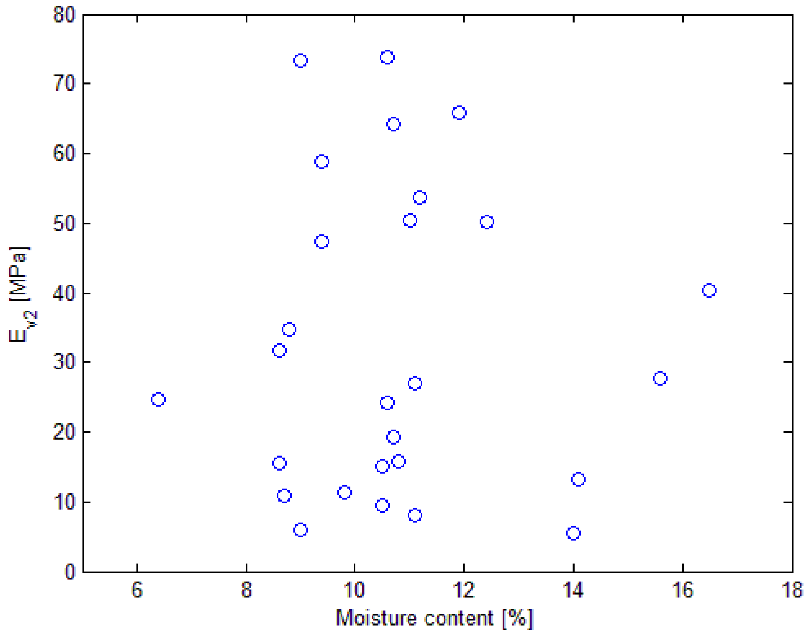

Figure 4.6 *Deformation modulus and moisture content in an unmodified soil with values taken from the light drop weight test and the Troxler.*

5 Analysis

The data used in the report originates from the ESS fieldwork, and was sampled during varying conditions. The modification and collecting of data, which was used in the dissertation, was carried out by Skanska and geotechnical consultants (Anon. 2015a).

To increase the understanding of how the modification process with smaller quantities of lime behaves in clay tills, different quantities of lime have been tested, especially 0.5 % and 1.0 %. Tests with different amounts of lime, other than 0.5 % and 1.0 %, were tested only to a limited extent and are thus excluded from the analysis. A limited amount of testing has been performed in unmodified clay till.

This chapter is divided into several different sections. Each section covers a parameter that may affect the deformation modulus in the modified soil. In these sections, the results are illustrated through different diagrams.

The distances between the locations of the various tests varied. When the different test methods were combined, the distance between the sites of origin for the samples used has been maximum five meters within the scope of this analysis. Only tests that were spaced with a distance between each other of about five meter or less were combined and used for the dissertation analysis. The values of the deformation modulus in the modified soil have demonstrated a very large spread, which has led to great uncertainty. The deformation moduli used in this section are taken from the light drop weight test, apart from a comparison between MCV and the static plate load.

Attempts to control time effects have been made. However, the exact time after the modification process was a little uncertain and of varying accuracy. As the modification process begins immediately and is expected to be complete after a few hours, the precision is important.

As the dissertation has only focused on results given during field work, it provides the opportunity to study problems arising with the mixing method used in production. The opportunity to investigate the sensitivity of the compaction work of various parameters has been made possible during this case study. Under more controlled conditions, in a laboratory environment, the various parameters could be studied in a more controlled manner to provide a more accurate result.

Parameters that could not be measured:

- The deformation modulus of the underlying layers, which has led to complications.
- The relationship between deformation modulus and the thickness of each layer, since each layer had the same thickness.
- The homogeneity in the mixing.
- The relationship between the number of passes with a vibrating smooth drum and the deformation modulus.

5.1 Moisture content

The distribution of moisture content in the tested modified soil has been normally distributed with a mean value of just below 20 %. The moisture content was measured during both the MCV test and Troxler measurements, both of which have shown similar distribution curves.

Figure 5.1 illustrates the different distribution curves of moisture content. The top diagram shows the combined distribution curve where moisture contents from both MCV and Troxler are included. The two diagrams below show the distribution curves from each field test. All three distribution curves tend to be normally distributed with a mean value just below 20 %. The moisture content has been considered normally distributed during the analysis.

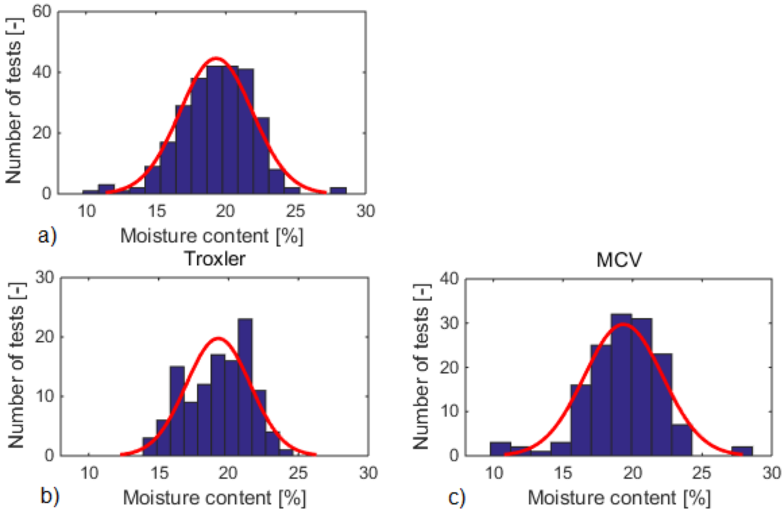

Figure 5.1 *Histograms of the distribution of moisture content in the modified soil. a) The total moisture content distribution. b) The moisture content distribution of the Troxler. c) The moisture content distribution from the MCV.*

Figure 5.2 illustrates the relationship between the deformation modulus and moisture content with test samples taken from the Troxler. Both lime quantities of 0.5 % and 1.0 % are included.

The relationship between moisture content and deformation modulus are difficult to interpret. At low moisture contents (below 16.0 – 16.5 % in this soil type), the deformation modulus tends to be low. At high values (for this soil type > 22 %), the deformation modulus also tends to decrease with increasing moisture content. The optimum moisture content is about 20 % after the modification has occurred in the clay till; see Figure 5.2.

The slope is steeper when the moisture content is lower than the optimum value compared to the slope given by moisture contents higher than the optimum value, see Figure 5.2. To reduce the risk of a low deformation, it is better to have a higher moisture content compared to the optimum moisture content. Since the quicklime consumes water when mixed with the soil, a higher moisture content is needed to reach the optimum deformation modulus.

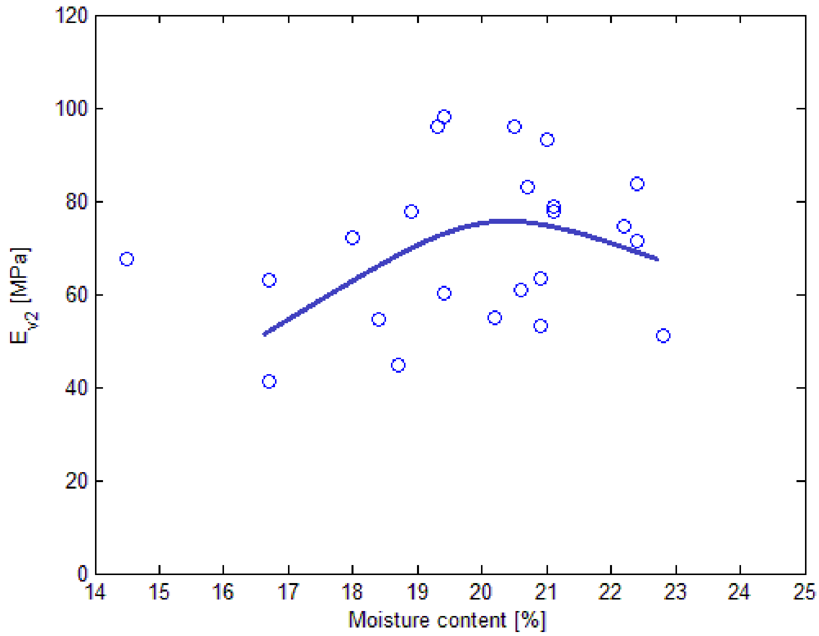

Figure 5.2 *Deformation modulus and moisture content with values taken from the light drop weight test and the Troxler, values from both 0.5 % and 1.0 % are included.*

The low deformation modulus at low moisture contents could be explained by the lime reactions that require water. The water continues to react with lime until a porosity has been encountered that does not allow further reactions with lime. The increased porosity also contributes to the low deformation modulus.

As mentioned in section 2.1.4, the compaction energy required to reach a certain compaction is increased with increased moisture content due to the van der Waals-bindings acting between the clay particles. Since the number of passes is constant, the result of the compaction decreases with increased moisture content. This could be a part of the reason to why the deformation modulus decreases after the optimum moisture content.

The amount of lime added (in kg) is calculated by a predecided average density in the soil. The concentration of the lime will thus decrease with increasing moisture content and with high moisture content, the lime concentration will be diluted. This diluted lime concentration could also have affected the result in a negative way.

5.2 Gas volume

The pore volume will be expressed as gas volume in this report, similar to the description given in section 2.1.2. By plotting the relationship between moisture content and gas volume, the results tend to be a linear relationship. The variation of the gas volume was large in the first period of the modification. During the second half of the modification, with a refined basic mixing method, a linear relationship occurred between the moisture content and the gas volume, see Figure 5.3. In the selected tests, both before and after the improvement of the mixing method, the amount of lime was 1.0 %.

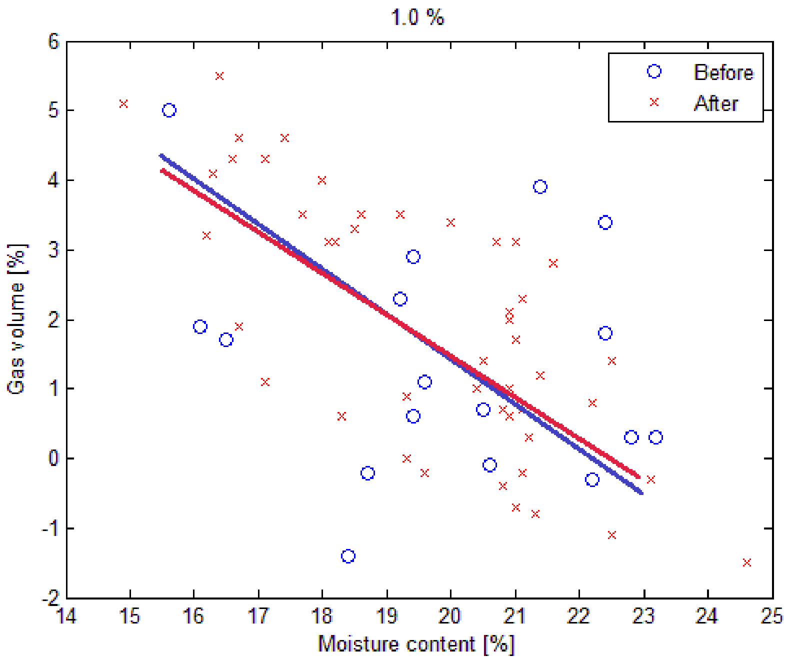

Figure 5.3 *Gas volume and moisture content before and after the refinement of the mixing method with values taken from the Troxler.*

Figure 5.4 illustrates the relationship between gas volume and moisture content with samples taken from the Troxler.

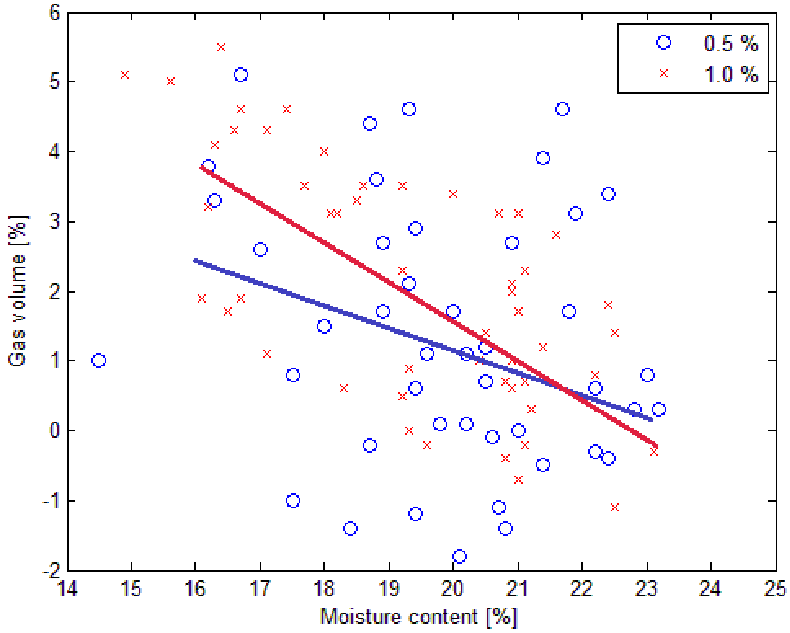

Figure 5.4 *Gas volume and moisture content for different lime content with values taken from the Troxler.*

A clear relationship is detected between the moisture content and the gas volume when the lime content is 1.0 %. No relationship can be proven when the lime content is 0.5 %. Why the variation of the gas volume is larger when the amount of lime is 0.5 % compared to 1.0 % when plotted against moisture content may be due to several reasons. Most of the samples with a lime content of 0.5 % were made during the initial phase of the modification. During the initial period, the experience and expertise of those who carried out the work was lower and the human factor may thus have influenced the work.

During the modification, it was more difficult to create a homogeneous mixture with a lime content of 0.5 % compared to when a lime content of 1.0 % was used. As difficulties arose with a lime content of 0.5 %, a reduced amount of lime in the future work would thus not be beneficial to ensure that the requirements of the porosity are met.

Figure 5.5 illustrates the difference in relationship between gas volume and the deformation modulus with samples taken from the Troxler.

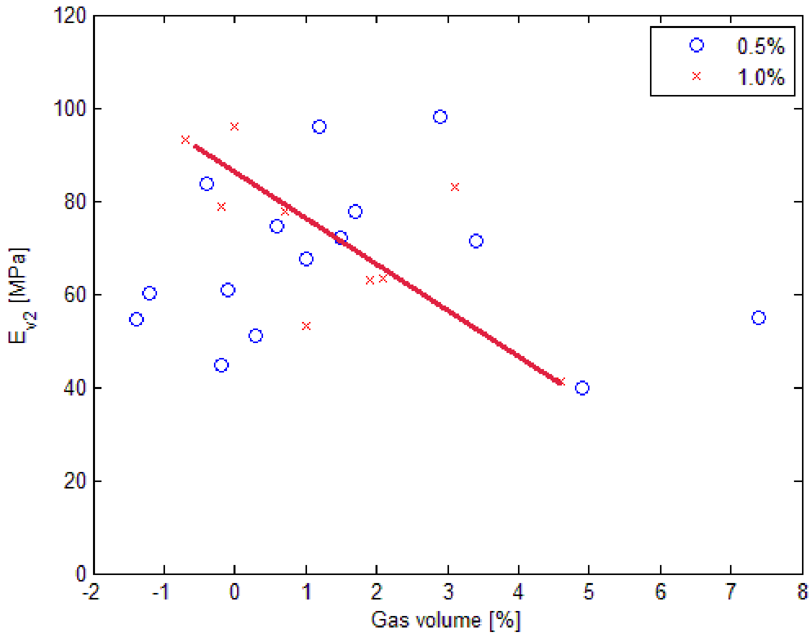

Figure 5.5 *Deformation modulus and the gas volume with values taken from the light drop weight test and the Troxler.*

A linear relationship occurs between the deformation modulus and gas volume at a lime content of 1.0 %, with a reduced deformation modulus with increased porosity. With a lime content of 0.5 %, a wide variation occurs with the highest deformation modulus provided at 2 – 3 % and then does the deformation modulus decrease.

The most obvious conclusion is regardless of the amount of lime that large gas volumes are unfavourable for the deformation modulus. The nonlinear relationship for a lime content of 0.5 % could be due to chance because the variation in gas volume is large.

When the variation of the gas volume is studied in the unmodified clay till (see Figure 4.5), a till with the lime content of 0.5 % (see Figure 5.5) and till with a lime content of 1.0 % (see Figure 5.5), one can see a clear tendency that an increased amount of lime gives control over the gas volume. It should be noted that at higher quantities of quicklime, a significant increase in gas volume would occur. The increase is caused by the hydration that occurs when the quicklime reacts with water in the clay, leaving behind voids. To compensate the voids that occur, water needs to be added in corresponding amounts.

When compacting a soil, it is not possible to get a gas volume of 0 %, nor negative values. Negative gas volume values in the figures depend on varying soil density, which creates an error. Instead of a continued linear tendency at low gas volumes, the slope could instead be seen to level out and go towards a gas volume of 0 % at a very high moisture content.

5.3 Volume of void

Volume of void (*Vv*) is defined as the volume of water and gas in the soil and its distribution curve in the soil is illustrated in Figure 5.6.

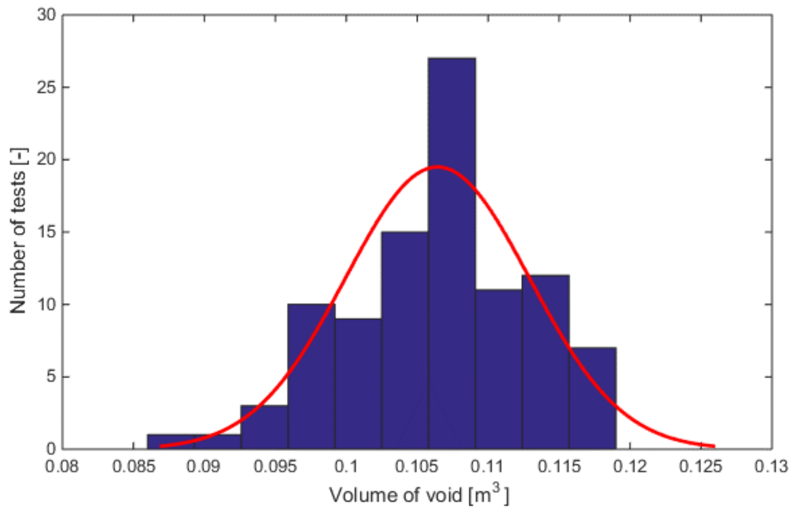

Figure 5.6 *Distribution curve of the volume of voids in the modified soil with values taken from the Troxler.*

The histogram shows that the volume of void is normally distributed in the modified soil with a mean value of 0.106 m^3 where the thickness, 0.3 m, of the layers is taken into account and the volume is per square meter.

The relationship between moisture content and volume of void in the modified soil is illustrated in Figure 5.7.

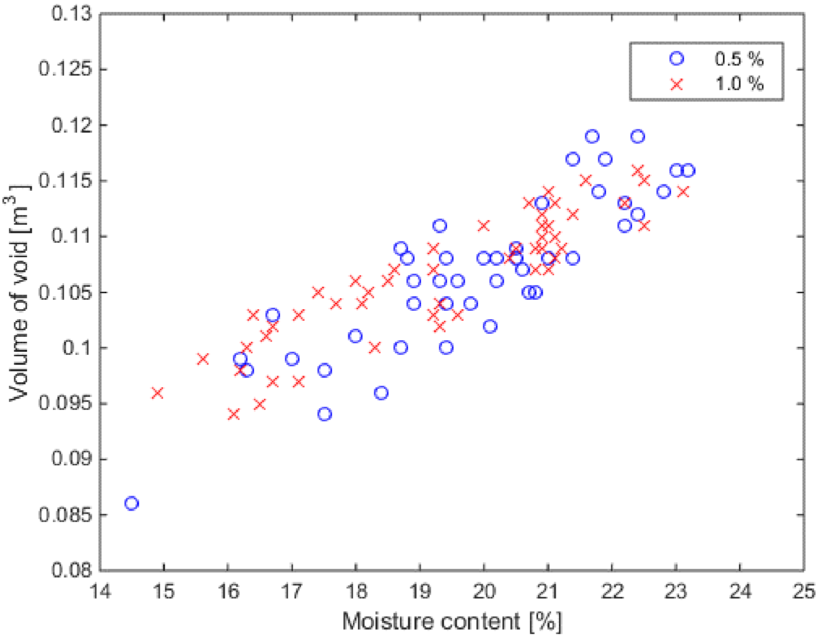

Figure 5.7 *Volume of void and moisture content with values taken from the Troxler.*

The distribution curve of the volume of void is largely due to the distribution curve of the moisture content. A clear relationship between moisture content and volume of void is illustrated in Figure 5.7. The relationships for lime concentrations of 0.5 % and 1.0 % are illustrated in the same figure.

By studying the slopes for the different lime contents in Figure 5.7, a steeper trend is demonstrated when the lime content is 0.5 % compared to 1.0 %. This is due to the relationship between the moisture content and gas volume for the different amounts of lime. In Figure 5.4, a larger spread is illustrated when the lime content is 0.5 % compared to 1.0 %. This spread determines the slope of the relationship between moisture content and volume of void.

Figure 5.8 illustrates the relationship between the volume of void and the deformation modulus. It includes both lime concentrations of 0.5 % and 1.0 %.

In comparing the deformation modulus and the volume of void in Figure 5.8, a nonlinear distribution is obtained. At low and high values, the deformation modulus becomes low. A volume of void value of around 0.105 – 0.110 m^3, where the thickness, 0.3 m, of the layers is taken into account and the volume is per square meter, will give the optimum deformation modulus results in this clay till.

A risk with the volume of void is that a combination of low moisture content and high gas volume could be difficult to identify. This risk combination could result in that the volume of void value ends up in the optimum range, which could be misguiding.

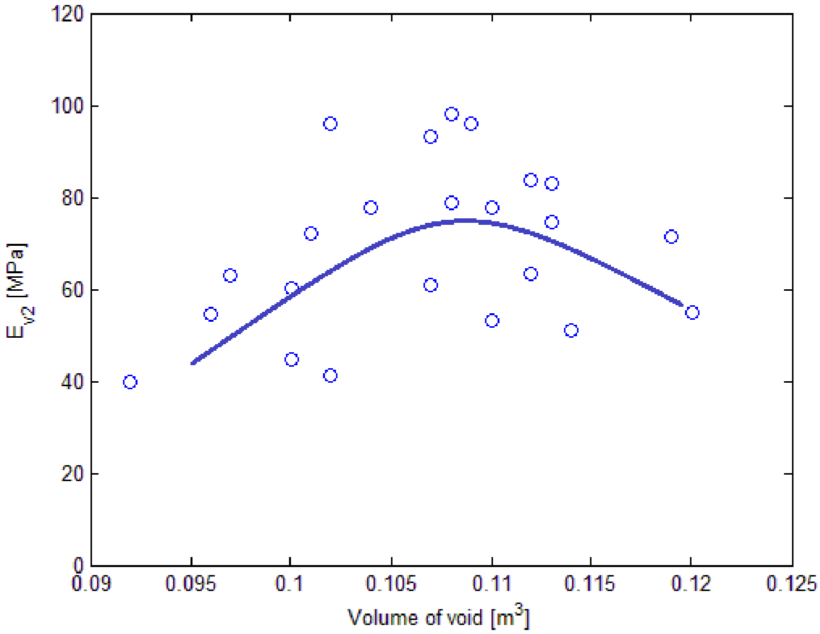

Figure 5.8 *Deformation modulus and the volume of void in the soil with values taken from the light drop weight test and the Troxler, values from both 0.5 % and 1.0 % are included.*

When studying the lower volume of void values, they have a moisture contents of 18 % or lower. By comparing the moisture content of the lower volume of void values with Figure 5.2, a decreasing deformation modulus could be seen to occur. At even lower moisture contents, the gas volume tends to be higher, which increases the volume of void.

At high moisture content, the porosity will approach zero, leading to a volume of void value that is directly dependent on the moisture content. High volume of void values will thus give low deformation modulus, similar to when the moisture content is high. A high volume of void value may also be due to poor compaction in a modified soil with normal moisture content.

The relationship between moisture content, volume of void and gas volume is illustrated in Figure 5.9.

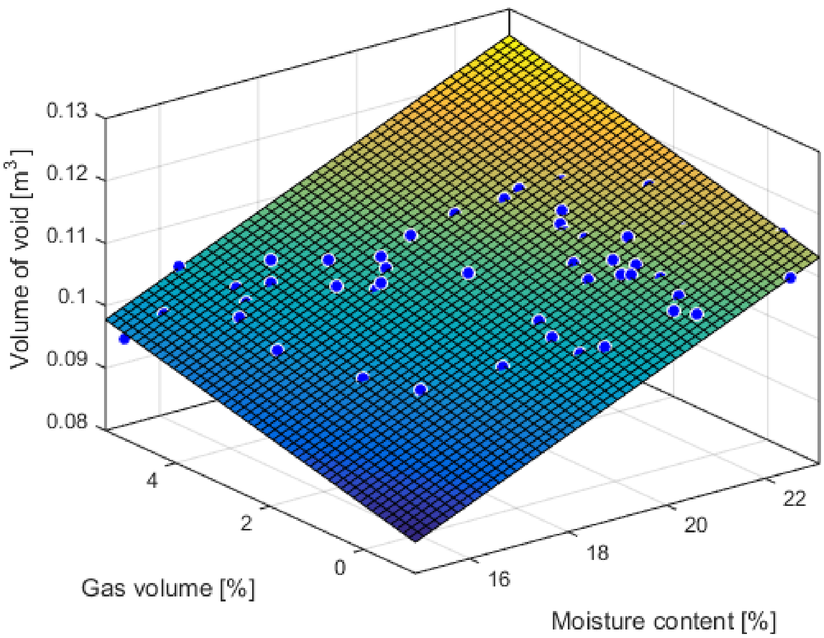

Figure 5.9 *The relationship between volume of void, moisture content and gas volume with values taken from the Troxler, values from both 0.5 % and 1.0 % are included.*

5.4 Dry density

Figure 5.10 illustrates the relationship between the dry density and deformation modulus in test samples taken from the Troxler, both with lime content of 0.5 % and 1.0 % are included in the diagram.

The relation between dry density and deformation modulus has a curve-like shape similar to those for both moisture content and volume of void. The deformation modulus increases with increasing dry density up to a dry density of about 1700 kg/m^3. After the optimum dry density of 1700 kg/m^3, the deformation modulus tends to go down with increased dry density. As the relationship between dry density and the deformation modulus is similar to the one between the moisture content and deformation modulus, it would be easier to use moisture content as a prediction tool instead of dry density.

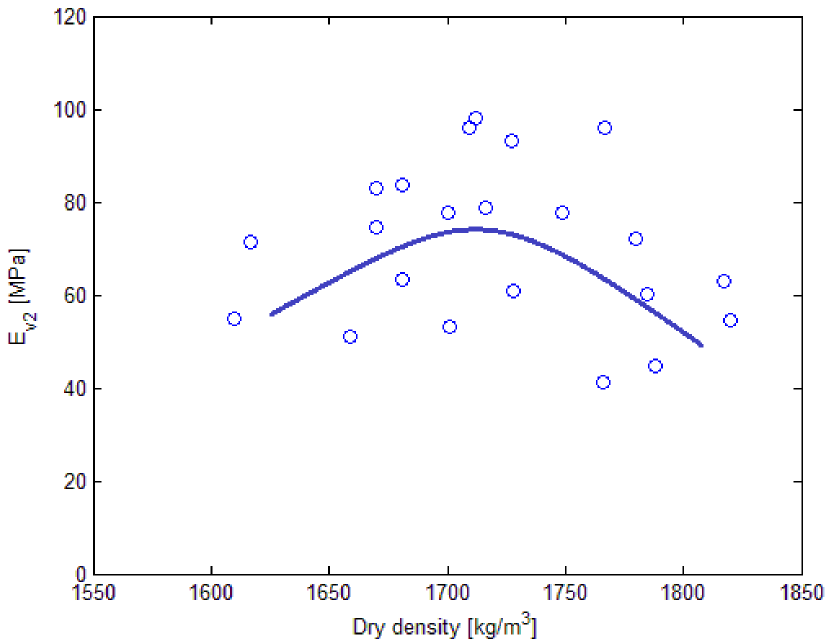

Figure 5.10 *Deformation modulus and dry density with values taken from the light drop weight test and the Troxler, values from both 0.5 % and 1.0 % are included.*

5.5 Mixing method

During the modification process at the ESS site, the mixing method was changed to adjust to external conditions. When the moisture content of the unmodified soil was too low, water was added during the modification to reduce the risk of a high gas volume and to obtain an easier compaction work. Precipitation in connection to the modification process was not included in the definition of added water. The amount of added water varied, but mainly it was about 5 – 10 l/m^2.

The applied basic working method used during the modification process was refined halfway through the process, see section 0. After the improvement, there was a clear relationship between gas volume and moisture content. Before the improvement, the variation was larger and no clear relationship could be discerned. This improvement in the basic method also gave a clear relationship to the gas volume as illustrated in Figure 5.3.

In Figure 5.11 the relationship between moisture content and MCV value is illustrated. A difference is made between samples with added water and no added water. The left diagram shows results for samples with 0.5 % added lime and the right diagram shows results for samples with 1.0 % added lime.

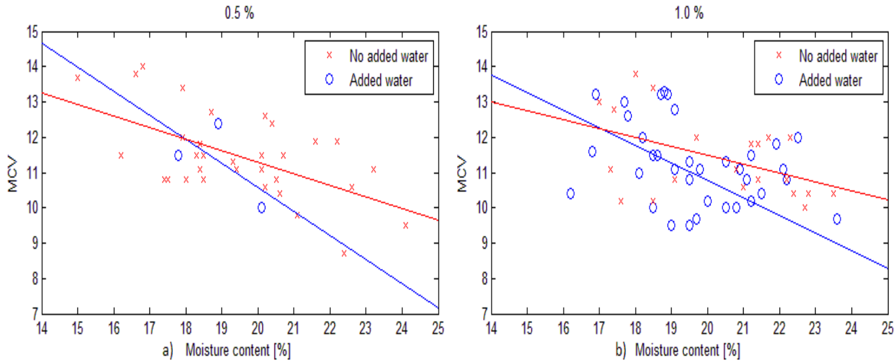

Figure 5.11 *The relationship between moisture content and the MCV when water is added in the mixing process or not. a) A lime content of 0.5 %. b) A limecontent of 1.0 %.*

In the comparison of moisture content and MCV values taken from samples without added water and with added water it was found that the slope was steeper when the soil was watered during the modification process. There were only four samples taken when water was added and the lime content was 0.5 % and one of the samples was strongly deviant and thus excluded.

The soil tend to be easier to pack by adding water during the modification process. This is shown in Figure 5.11, where it generally becomes lower MCV values for masses that are watered compared to non-watered masses with the same moisture content.

5.6 Soil type

A relationship between moisture content and the MCV was made for the deeply located greyish clay till and the brownish upper clay till, see Figure 5.12. The relationship illustrates that the MCV value is generally higher for the greyish clay till than for the brownish clay till at the same moisture content. The amount of lime used in the comparison was 1.0 %.

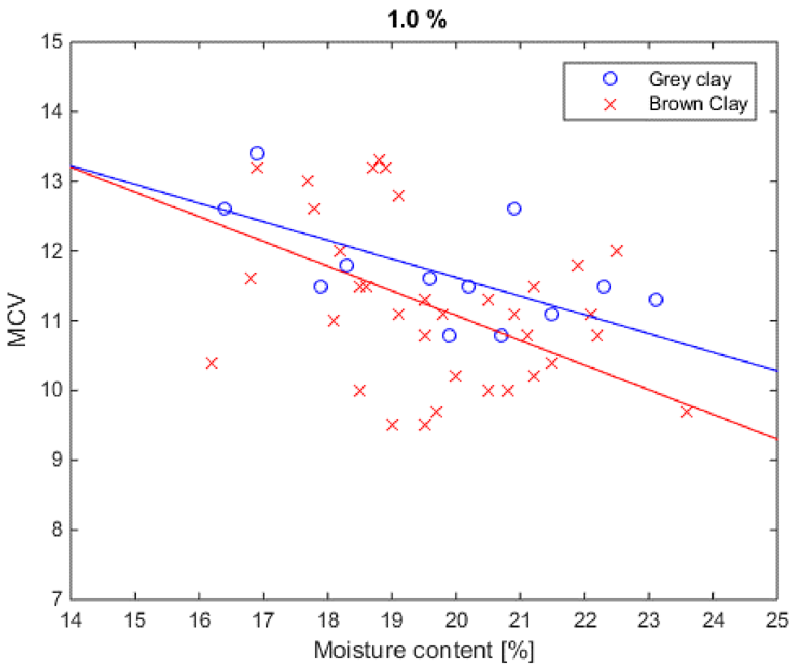

Figure 5.12 *Moisture content and MCV for two kinds of clay till with values taken from the MCV test.*

The greyish clay till requires much more compaction work than the brownish. This could be due to the chemical properties that exist in the unoxidized grey soil. It could also be that the consolidation ratio is higher in the greyish clay than in the brownish clay.

5.7 MCV

In the comparison between MCV and Troxler, only five measuring points could be used and one of them was deviating and was thus excluded. The credibility in the comparison between the MCV and the Troxler was low due to the few measurement points that could be used. Since both the Troxler and the MCV measures the moisture content, a comparison between the desired parameters and the moisture content was performed. The moisture content enabled a comparison between large amounts of measurement points. This enabled the relationship to be determined between the MCV and dry density and *Vv*. The relationships are illustrated in Figure 5.13.

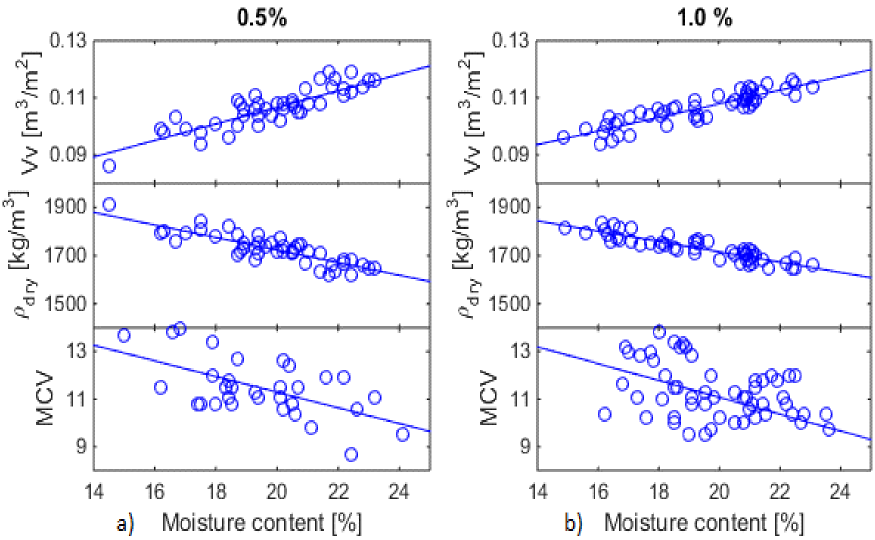

Figure 5.13 *The relationship between moisture content, MCV, dry density and volume of void in a modified fine-grained till. a) A lime content of 0.5 %. b) A lime content of 1.0 %.*

The relationship between deformation modulus and MCV is illustrated in Figure 5.14. Measurement points have been selected from the same modification batches to give as equal conditions as possible in the analysis between MCV and deformation modulus. A linear relationship can be interpreted from Figure 5.14 where an increased MCV value indicates an increased deformation modulus. This relationship applies to MCV values of 8 – 13.

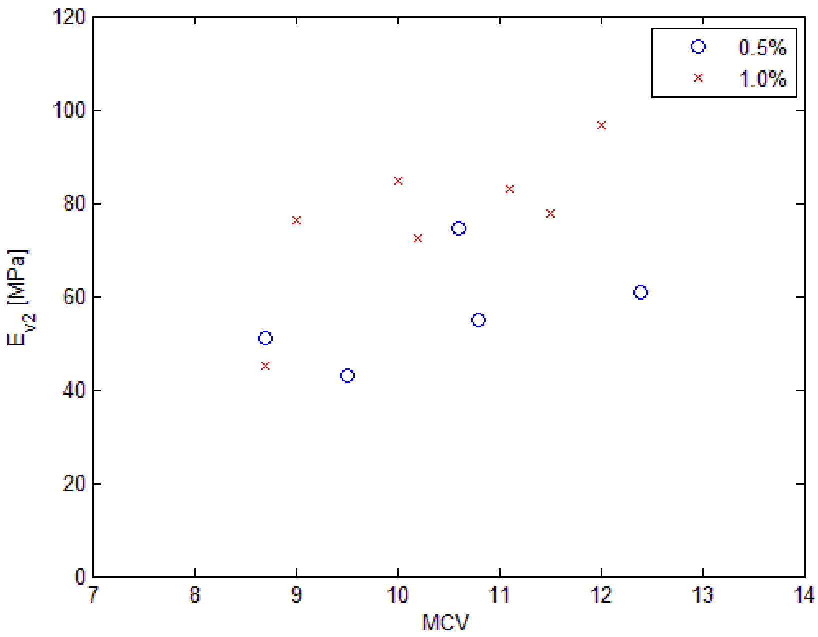

Figure 5.14 *Deformation modulus, MCV and amount of lime with values taken from the light drop weight test and the MCV test.*

A comparison between deformation modulus, given by static plate load, and MCV provides measuring points in Figure 5.15. No relationship can be demonstrated between the deformation modulus and static plate load.

When samples were made in exactly the same modification batches, a relationship could be discernible where an increased MCV value gave an increased deformation modulus (this is not illustrated in this report, though tests were made). One reason for the lack of clarity when multiple tests were made could be the time after the modification that the tests were taken, which was not consistent.

Since the modification process takes only a few hours, a slight difference in time between the tests would make a difference.

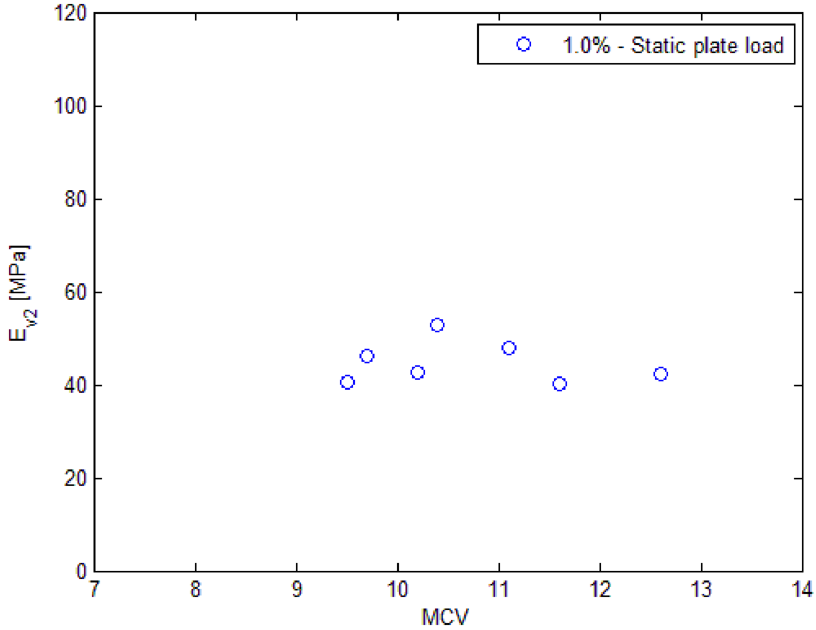

Figure 5.15 *Deformation modulus and MCV with values taken from the static plate load test and the MCV test.*

Another error that might have occurred is that the light drop weight test was often performed at a later stage, which means that the current MCV value might have changed after the completion of the modification. As the uncertainty is so great, the MCV value is not a suitable parameter to use when controlling the deformation modulus.

5.8 Voids/Lime ratio

A comparison between the deformation modulus and the relationship between voids/lime ratio (defined in EQ: 2.7) has been made, see Figure 5.16. The method Consoli, da Silva & Heineck (2009) used in their report to determine the voids/lime ratio has been used.

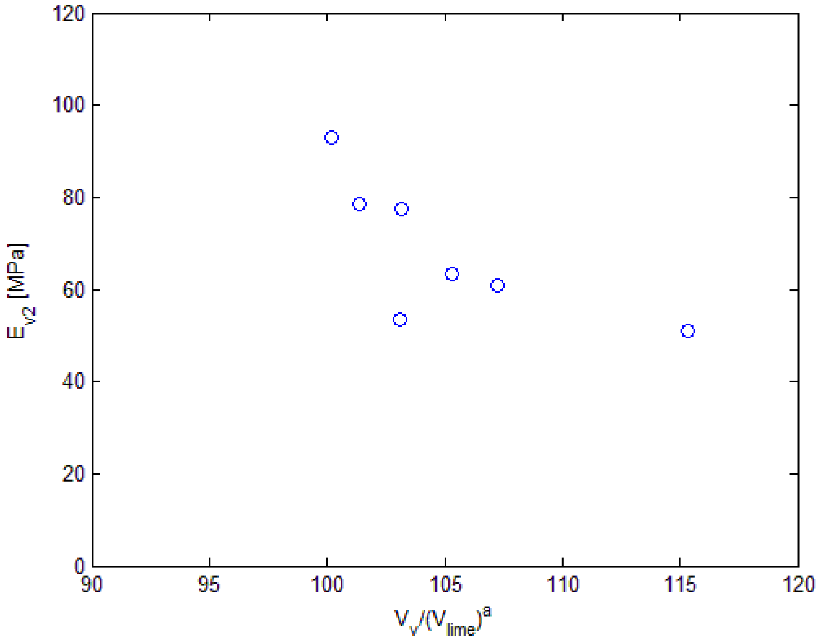

Figure 5.16 *Deformation modulus and the adjusted voids/lime ratio, a was set to 0.1. The values are taken from the light drop weight test and the Troxler.*

To create a fit between the different amounts of lime, a potency was added to the volume of lime. The potency, *a*, was set to 0.1 in this curve. To get a better value of *a*, more lime quantities need to be tested.

A problem encountered during the study has been that in this work, it has not been possible to keep the various soil parameters fixed. A relationship could not be established between the deformation modulus and the voids/lime ratio as it was a lack of different amounts of lime. A relationship could be distinguished for the deformation modulus, but further studies are required.

Uncertainty and variability in compaction that occurs during the modification process, with lesser amounts of lime, can be compared to the behaviour of unmodified clay till. It could be that the voids/lime ratio has a lower limit for the amount of lime when the method is no longer reliable.

5.9 Sources of error

By studying the moisture content from the MCV test and Troxler test, the modification was not completed when the MCV test was taken. This might have affected the outcome of the MCV value. Since the plate load tests were performed a further time after the modification process compared to the MCV test, the result may have been different compared to if the tests were conducted simultaneously.

The time is a source of error. As the modification process is completed within a few hours and the stabilisation commences immediately after, there is a risk of varying deformation modulus, both because of unfinished modification and of commenced stabilisation. This is due to the time after the modification process that the tests were conducted varied slightly.

One factor that has influenced the results throughout the entire modification is varying weather. In periods of heavy rain, the ground has been in a wetting phase, while during periods of dry weather, the soil has been in a drying phase. The pore water in the soil has a different structure depending on in which phase the soil is.

6 Discussion and conclusions

6.1 Discussion

As shown in this work, the modification method becomes more stable and secure with a higher amount of added lime. When a larger amount of lime (quicklime) is used, an increased amount of water needs to be added. The addition of water is made to compensate for water bound and evaporated in the modification phase. As shown in the report, the added water helps to achieve a reliable and stable process in the compaction work.

If the modification process would have been carried out with hydrated lime, a reduced risk of uncontrolled moisture variation would occur. The gas volume that occurs because of the reaction between the quicklime and the moisture in the soil would disappear as well.

The Ca^{2+} ion is the part of the lime that is sought during the modification phase, which is done with both quicklime and hydrated lime. From the amount of ions per kg, the quicklime is more efficient compared to the hydrated lime. To achieve a complete modification, an amount of approximately 1.0 % hydrated lime is needed as mentioned in section 2.3.3. The amount of lime needed during the modification process would not be much larger compared to quicklime.

During the winter when the soil has plenty of moisture in itself, it can be helpful to reduce the moisture by adding quicklime. During the summer, the moisture content is generally slightly lower in the soil, which could affect the modification result negatively. In the summer season, it would definitely be beneficial to reduce the reduction of moisture in the soil through the use of hydrated lime instead of quicklime.

6.2 Conclusions

There is a relationship between moisture content and the deformation modulus, as in accordance to previous work. When a modified clay till is compacted, there is an optimum moisture content where the deformation modulus drops significantly with lower moisture content. The deformation modulus also drops at a moisture content higher than the optimum, although not as much as for low moisture content. To achieve an optimum modification, the moisture content should be slightly above the optimum moisture content when the modification is started, as the modification process with quicklime requires water. The moisture content is the most important parameter affecting the modification process.

The porosity is an important parameter that affects the deformation modulus. An increased amount of lime makes the relationship between gas volume and moisture content clearer. This allows the gas volume to be predicted, as the moisture content in the soil is known. An increased porosity gives a reduced deformation modulus. The relationship becomes less clear at lower lime content.

The compaction work will be easier when water is added during the modification. An increased amount of lime gives a more stable modification process, which makes it easier to predict the results. Even when there is no need to add water to the soil, it may be beneficial to add both water and additional lime for the result to be more homogeneous. The deeper located greyish clay till, which is unoxidized, requires more compaction work in order to achieve satisfactory results as compared to the overlying oxidized brownish clay till.

If studying a particular type of soil, the main parameters that influence the deformation modulus are:

- the amount of lime added
- the moisture content
- the gas volume
- the amount of supplied compaction work

The gas volume is directly influenced by the amount of compaction work and the workability of the soil. The moisture content affects how workable the soil is and is needed to complete the chemical reactions required for the modification process.

There are additional parameters that affect the deformation modulus that could not be examined in this report. Soil parameters such as clay minerals, ion content and the amount of organic content are parameters that could not be examined. The soil parameters make each soil unique and an investigation needs to be done at each new construction site.

Problems arise when low amounts of lime are used. When a lime content of 0.5 % is used, the soil tends to be not homogeneously mixed which could lead to both a low deformation modulus and a high gas volume. The uncertainty would have been very large if a lime content of less than 0.5 % had been used. The requirements for the deformation modulus could be achieved through adequate compaction work in optimum moisture conditions.

The modification process, with lime as a binder, is carried out to establish a stable and reliable method when clay till is used in earthworks with high demands. Reducing the amount of lime during the modification would have been inappropriate with the conditions that existed during the period when the modification was performed.

Recommendations to ESS

Recommendations made to the continued modification at ESS:

- Ensure that the soil has sufficient moisture content, as the modification process is sensitive to low moisture content. The soil will be easier to process by adding water, which causes the soil to behave in a more predictive manner.
- To avoid the loss of moisture in the soil due to hydration, consider testing hydrated lime if the modification will continue during warmer periods.

6.3 Future research

During the work, a number of suggestions for future studies have emerged:

- A continued study of tests conducted in controlled laboratory conditions to determine how the various critical parameters react to different quantities of lime.
- A continued study on the voids/lime ratio where several different amounts of lime are used. This relationship could be used to determine the amount of lime that would be preferable to use in soils with abnormal moisture content.
- An interesting study would have been to examine how the hydrated lime would behave during the modification process. The hydrated lime would reduce the amount of moisture content evaporation and thus lower the moisture variation.
- An interesting study would be to examine various forms of mixing methods. An improved modification process could possibly allow a lower lime content and still achieve satisfactory results. Both the number of mixings and various types of rollers could be examined.
- Modified soil may need to be used in smaller areas where it would be cost-inefficient to perform modification. It would be interesting to investigate if it is possible to compact a modified clay till at a storage location and then move it to the area in question within the construction site.

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