Svensk Djupstabilisering
Swedish Deep Stabilization Research Centre

Report 3

Stabilization of Organic Soils by Cement and Puzzolanic Reactions
– Feasibility Study

Karin Axelsson
Sven-Erik Johansson
Ronny Andersson

National Deep Mixing Program
NDM

English Translation
July 2002

Swedish Deep Stabilization Research Centre

The Swedish Deep Stabilization Research Centre coordinates research and development activities in deep stabilization of soft soils with lime-cement columns. A joint research programme based on the needs stated by the authorities and the industry is being conducted during the period 1996 – 2004. Members of the Centre include authorities, lime and cement manufacturers, contractors, consultants, research institutes and universities.

The work of the Swedish Deep Stabilization Research Centre is financed by its members and by research grants.

The Swedish Deep Stabilization Research Centre is located at the Swedish Geotechnical Institute and has a Steering Committee with representatives choosen from among its members.

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Foreword – English Translation

Translation of this document was made possible through collaborative effort of Swedish Deep Stabilization Research Centre and the US National Deep Mixing (NDM) program. The mission of both organizations is to facilitate advancement and implementation of deep mixing technology through partnered research and dissemination of international experience.

The Swedish Deep Stabilization Research Center with its headquarter at the Swedish Geotechnical Institute (SGI) coordinates research primarily on dry mix methods. An international conference on "dry mix methods for deep soil stabilization" was held in Stockholm in 1999. The findings from research and state-of-the practice in Europe, particularly on stabilization of organic soil, were presented and published in the proceedings. SGI is also a partner of EuroSoilStab, the R&D project focusing on organic soils and infrastructure applications.

The National Deep Mixing program coordinates a program of deep mixing research in the US. The international workshop on "Deep mixing technology for infrastructure development" was held in Oakland, California in 2001. A forum of users and experts from industry, government and academia examined the current practice and research needs; and identified the challenges ahead for implementation of deep mixing technology.

We hope dissemination of international experience serves as a step toward our better understanding and promotion of this innovative technology in the construction industry.

July 2002

Göran Holm, Linkoping, Sweden

Ali Porbaha, California, USA

Foreword

The present feasibility study, “Stabilization of Organic Soils by Cement and Pozzolanic Reactions”, was carried out as a project at the Swedish Deep Stabilization Research Centre (SD) in summer 1996 and reports the state of our knowledge at that time. The findings have since been actively applied at the Centre and within the EU project EuroSoilStab. The work comprises an investigation of the strength of stabilized mud and peat. The report has served as a basis for SD’s continued study of the properties of stabilized earth—relevant parameters.

The work of the feasibility study is divided into laboratory trials, evaluation, and comparison with previously reported projects. The trials were done on mud and peat from two locations, Arlanda airport and the Örebro–Arboga motorway, where reinforcement works including deep stabilization were in progress at the time.

The authors wish to thank Helen Åhnberg of the Swedish Geotechnical Institute and Elina Parkkinen of Lohja Rudus Oy AB for their assistance with the work.

The report was edited by Jan Lindgren of the Swedish Geotechnical Institute.

Danderyd (Stockholm), 11 August 2000

Björn Paulsson *Karin Axelsson* *Sven-Erik Johansson* *Ronny Andersson*
Chair, SD

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Summary

The purpose of this report is to point out the possibility of stabilizing gyttja and peat by determining the shear strength of samples stabilized in the laboratory. The report has also served as a basis for an in depth study at the Swedish Deep Stabilization Research Centre.

Samples of stabilized soil were produced in the laboratory. The soil consisted of gyttja and peat from two sites and the strength of the stabilized samples was determined with unconfined compression tests. Different binders were used, consisting of cement (four different types), lime and residual material from industry.

The main conclusions are as follows:

- Strength both in gyttja and peat can be considerably improved by the use of stabilizers.
- Density tends to increase in the stabilized samples. Increased density also tends to give increased strength.
- The storage temperature is of varying importance for different stabilizing agents. To make the best comparison between laboratory stabilization and in situ stabilization, the laboratory samples must be stored at the same temperature as is expected in the soil in situ.

The results from the stabilization tests show that different types of cement and different mixes with cement and other stabilization agents vary with respect to effect. Swedish rapid hardening cement gave the best results in gyttja, but in some samples Swedish standard cement gave equivalent results at 26 days. Cement mixed with ground granulated blast furnace slag gave gave the next best results after cement alone.

Cement mixed with ground granulated blast furnace slag gave the best results in peat. Stabilization with cement alone also gave a good result. Lime has a poor effect in peat.

In almost every case, mixes with fly ash gave the worst results of all residual materials.

The results correspond well with those that can be expected from the theoretical evaluation in Chapter 4.

Based on the theoretical valuation and the results in the report, Chapter 6.2 recommends that the binding effect of the stabilizing agent should be based on cement and puzzolanic reactions. With respect to technical demands, a preliminary investigation is always made. Today, it is proposed that Portland cement, lime and ground granulated blast furnace slag be approved. Suitable amounts of binder are suggested.

The characteristics and composition of the residual material vary partly with the type of raw material and the fact that various industrial processes are not designed to produce the best residual material. Other materials, including new types, should therefore always be reviewed for each project in accordance with environmental regulations.

A number of projects for further research are presented below:

- Establish and clarify performance and methodology when samples with stabilized soil are being prepared and tested.
- Examine the importance of the robustness of the stabilizing agents (Chapter 4.6).
- Develop methods and criteria for evaluating the environmental effects of new stabilizing agents.
- Study the chemical and physical parameters affecting reactions that increase strength.

1. Introduction

1.1 PURPOSE

The purpose of this feasibility study was to demonstrate the feasibility of stabilizing mud and peat by determining the shear strength of laboratory-stabilized samples. A second purpose of the study is to serve as a guide to methodology and trial planning for the further development of mass stabilization and for a further study planned at the Swedish Deep Stabilization Centre (SD).

1.2 BACKGROUND

In late 1995 the Swedish Geotechnical Institute (SGI) published its report on a major project on the effects of cement and lime in the deep stabilization of different soils [5]. The project yielded results that should permit the stabilization of organic soils such as mud and peat. At the same time, mass stabilization has been introduced in Sweden.

Mass stabilization is a new technique for the stabilization of loose soil layers such as peat and mud. In mass stabilization, unlike the deep mixing method, binder is blended into the whole layer, resulting in a stabilized “block”.

The mass stabilization method has been developed over the last five years and applied with good results in a number of projects in Sweden and Finland [10, 15]. In Finnish projects using mass stabilization, shear strength has been increased by factors of up to 40 in mud and up to 20 in peat.

SD is carrying on R&D efforts for the further development of deep stabilization technology using columns of lime cement. In view of the growing interest in the new mass stabilization technique and its high development potential, it was decided to draw up a separate R&D plan for this technique. The plan [12] mentions the need to demonstrate and further investigate the effectiveness of stabilization of organic soils such as mud and peat.

The work presented herein was carried out in 1996 and the report reflects the state of our knowledge at that time. Since then the findings have been actively applied at SD and in the EU project “EuroSoilStab”.

2. Mass stabilization

When a road or railway embankment is to be constructed on clay soil, some form of soil improvement is usually needed to avoid settlement and stability problems. The traditional solution is deep stabilization of the clay. However, the clay is often overlaid by loose layers of peat and mud in which it is difficult to achieve adequate bearing capacity by deep mixing. A conventional solution here is e.g. soil substitution, which involves excavating the loose soil layers and replacing them with frictional material of higher bearing capacity.

Soil substitution is expensive and frequently also problematic, as the replaced material must be disposed of and new filling material hauled to the site. There has therefore been a need to develop a functional, economical, and more environmentally friendly method for stabilizing mud and peat. The recently developed mass stabilization technique meets these requirements.

Mass stabilization is a soil reinforcement technique in which stabilizing agents are blended into the entire soil layer. Unlike the deep mixing method, this results in a stabilized “block”. Stabilization reduces subsidence and improves the stability of the soil. Mass stabilization enables loose soil layers to be used instead of being disposed of. It also reduces extraction and haulage of natural gravel and other fill.

Hitherto, mixing has been done by means of a tool mounted on an excavator. A geotextile is then spread over the stabilized surface, followed by a 0.5 m layer of gravel e gravel bed compacts the stabilized material and is also used to form a working surface for the excavator.

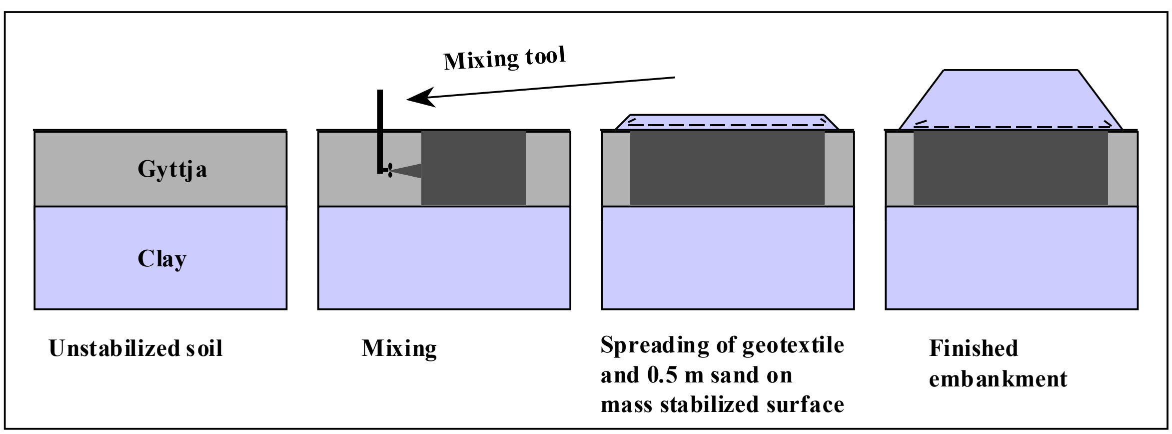


Fig. 1. Mass stabilization.

As at 1997 the method had been used in more than ten projects in Sweden and Finland, primarily in road and railway embankments. The binders used in these projects consisted of cement and mixtures of cement and various types of industrial residues. Inert soils such as sand can also be mixed with cement, and various salts can be added to control the stabilization reactions.

Other possible applications for the mass stabilization technique include stabilization of intractable excavated material to render it usable as fill or to produce an artificial "crust".

3. Stabilization trials in mud and peat – execution

The present feasibility study began in April 1996 with mixing trials in the SGI Laboratory at Linköping. Soil samples of mud and peat were taken from two locations and a number of binders used for mass stabilization.

Distinct mixing and storage procedures were used for the mud and peat samples. The mud was mixed and stored in the conventional way in sample tubes of inside diameter 50 mm, while the peat samples were stored in sample tubes of inside diameter 68 mm and with a vertical load. The mixing and storage procedure for the peat samples conformed to procedures developed in Finland, which were demonstrated by Elina Parkkinen of Lahja Rudus Oy Ab. The new test equipment was fabricated in the SGI workshop on the same principles as the Finnish equipment.

After storage for periods of 14 and 26 days (mud) and 28 days (peat), SGI determined the density of the samples and carried out unconfined compression tests which were evaluated by SGI Laboratory for shear strength. Altogether 84 mud samples and 68 peat samples were studied.

3.1 CLASSIFICATION AND PROPERTIES OF MUD AND PEAT

The properties of the unstabilized soils are shown in Table 1. The samples represent mud and peat from the third runway at Arland airport and mud and peat from the site of the Örebro–Arboga motorway.

The most prominent difference between the peats is their water content. That of the Arlanda peat is 442 % and of the Örebro peat 1308 % and 1413 %. Since the water content of peat varies widely it is difficult to state a “normal” value. However, the water content of the Arlanda peat can be considered unusually low.

Besides the differences in water content the peats also differ notably in their content of organic material. The Arlanda peat is lower in organic material and more highly humified than the Örebro peat.

As well as the characteristics reported in Table 1, the chemical composition of the water phase of the original soils was determined. This was done by expression of the pore water followed by chemical analysis.

Table 1. Properties of unstabilized soil. Density of peat was assumed to be 1.0 ton/m^3 and of gyttja 1.2 ton/m^3

	According to 1981 system*	Org. cont %	Water content w %	Cone liquid limit w_L%	Humi-fication von Post	Soil classifiction
Örebro						
G1	Grey-green clayey gyttja with plant parts	8,0[1]	151	140		le Gy vx
T1	Brown-black low-humified peat	99[2]	1308		H2–H3	Tl
T2	Brown-black peat	97[2]	1413		H2–H6	T_L / T_M
Arlanda						
G2	Grey-green clayey gyttja with plant parts	17[1]	205			le Gy vx
T3	Black highly humified peat with plant parts and wood remnants	73[2]	442	259	H8	Th

1) Determined by the colorimeter method
2) Determined by the ignition method

* Based on visual soil classification adjusted for existing measurement data.

3.2 PORE WATER ANALYSIS

Before deep stabilisation is applied in a project, routine laboratory tests are done using various stabilizing agents in order to predict the effectiveness of stabilization. The geotechnical properties of the unstabilized soil are also determined, including its water content, density, liquid limit, sensitivity, shear strength and soil type. In some cases its organic content and degree of humification are also studied.

Studies show that soils with apparently similar mechanical properties can give widely differing effectiveness of stabilization with the same agents. This is probably due to the effect of different chemical substances in the soils. Chemical analyses of the unstabilized soil can therefore provide useful additional information.

One method for the chemical analysis of soil is pore water expression, in which the ion concentrations in the water phase of a stabilized or unstabilized soil are determined. In this feasibility study pore water expression and analysis were done on the unstabilized soil. The results are shown in Appendix 5.

The chemical laboratory analysis of stabilized and unstabilized soils is described in more detail in /ref 5/. The report describes, among other things, the changes in the ionic composition of the water phase on addition of various stabilizing agents and their effects on strength-enhancing reactions.

3.3 STABILIZING AGENTS

The stabilizing agents (Table 2) comprised four types of cement, lime, ground granulated blast furnace slag, fine sand, and various industrial residues. See further Chapter 4.1. In addition, a chemical addition, Glorit, was tried. All the materials were from sources in the Nordic countries, but not all of them are commercially available.

The choice of stabilizing agents was based on the results of previous trials in Sweden and Finland. Altogether 11 stabilizing agents and one chemical addition were used in 19 combinations (see Appendix 1).

Table 2. Stabilizers used.

BINDERS		**ADDITIVE MATERIALS**		
	Puzzolanic materials	**Latent hydraulic materials additive**	**Fillers**	**Chemical**
CEMENTS	By-pass ash (B)	**GROUND GRANULATED**	Fine sand (FS)	Glorit (G)
Cem SH P (SH)	**ASH**	**BLAST FURNACE SLAG**		
Cem Std P (Std)	Fly ash 1 (F1)	Granulated blast furnace slag 1 (M1)		
Pikasementti (FSH)*	Fly ash 2 (F2)	Granulated blast fuurnace slag 2 (M2)		
Cement 4 (C4)				
LIME				
Quicklime (CaO)				

* Finnish rapid hardening cement

3.4 TEST PROGRAMME

The combinations of binding agents and soils that were tested are shown in summary in Fig. 2. The test programme in its entirety will be found in Appendix 2.

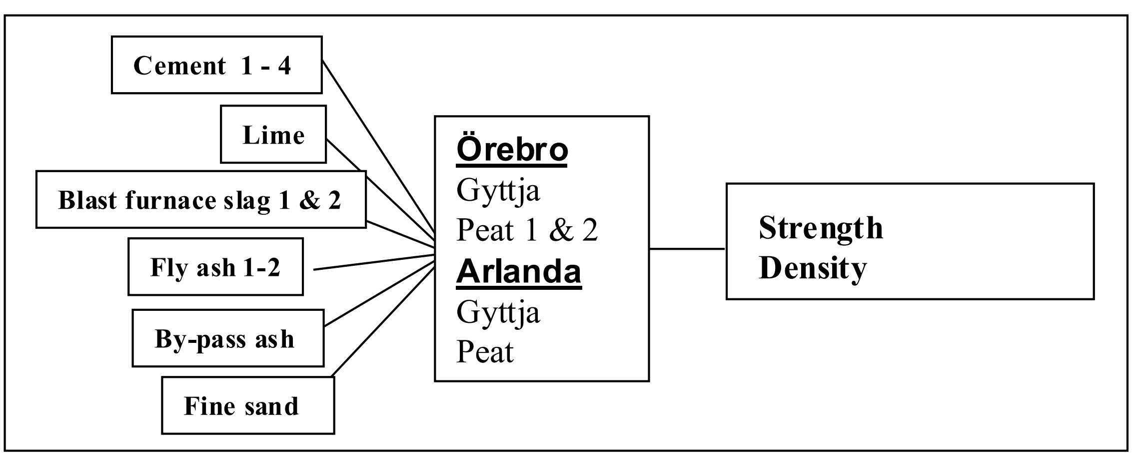


Fig. 2. Test programme.

The quantity of stabilizing agent used in all the mud samples was 200 kg/m^3. The quantity of stabilizing agent added to the peat samples was in most cases 250 kg/m^3, but this was varied in some samples as may be seen from the test programme in Appendix 2.1.

The Arlanda peat was found to be very dry during admixture of stabilizing agent, which made the stabilized mass crumbly and difficult to mix. Water was therefore added to some of the samples in order to enhance mixing and to observe the effect on stabilization effectiveness.

3.5 SAMPLE PREPARATION AND TESTING

To reduce the differences in soil properties between samples, each soil was blended until the mass was relatively homogeneous. After homogenization, which was done by the SGI Laboratory, addition of stabilizers took place.

Mixing and storage of the mud samples was carried out by the normal procedure for mixing and storage of clay samples. Under this procedure, the soil and the stabilizing agent were mixed to a homogeneous mass by means of a household mixer and then compacted and stored in tubes of inside diameter 50 mm. In the case of the Örebro mud each layer was compacted by hand, which is the compacting procedure normally used in Finland. The Arlanda mud was compacted with a constant pressure for approximately 10 seconds after each layer, this being the usual method in Sweden. The test results were evaluated by the same method used in unconfined compression testing of stabilized clay samples. The shear strength is calculated as half of the compressive strength, corrected for deformation according to Swedish standard.

The samples were stored at 8 ºC, after which the shear strength was determined by unconfined compression testing. To provide an idea of the change in the shear strength of the mud over time, compression tests were carried out after 14 and 26 days. The test at 14 days was done on one sample and the test at 26 days on dual samples.

Mixing and preparation of the peat samples was done by a different method than the mud samples. The tubes used had an inside diameter of 68 mm and the samples were subjected to a vertical load during storage. The procedure is described in Fig. 3.

1. A net was taped over the bottom of the tube to permit the peat specimen to take up water during storage.

2. The peat was mixed with stabilizer to form a "homogeneous" mass and then compacted into the sample tubes by hand.

3. The specimen was subjected to a dispersed pressure of ~18 kPa by means of an iron cylinder.

4. The stabilized specimens were then placed in a specially design sample box consisting of a plastic tray positioned so that the specimens could be stored vertical. The bottom of the tray was then filled with water to a depth of ~50 mm.

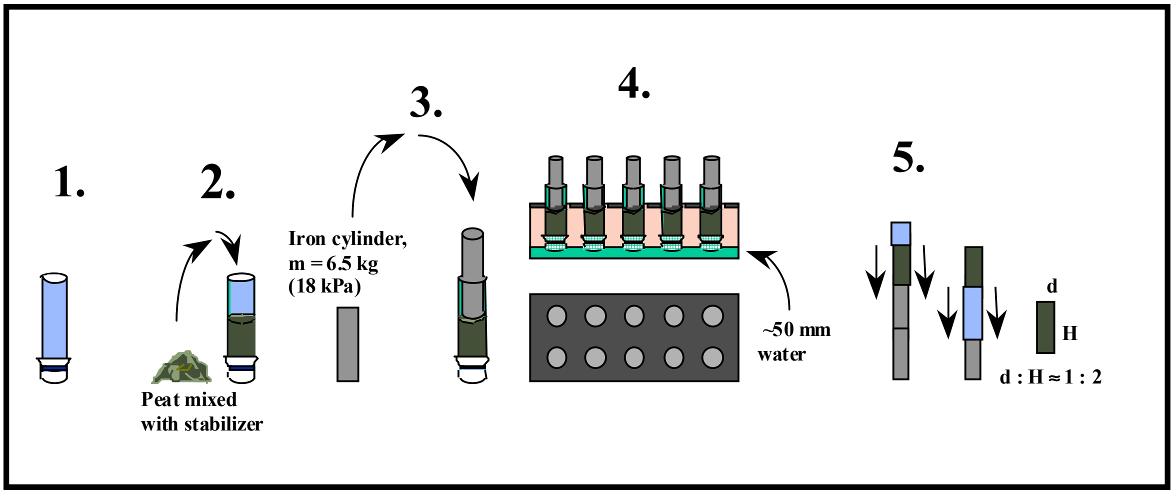


Figure 3. Mixing and storage ppproceduure in peat tests.

5. After 28 days at room temperature the specimens were expelled from the tubes and unconfined compression tests performed.

The peat specimens were stored for 28 days and the compression tests were done on dual specimens. Most of the specimens were stored at room temperature (~21 ºC), as has been the practice in Finland, but because the temperature in the ground is normally ~8 ºC a number of parallel peat specimens were prepared and stored at 8 ºC.

This method of mixing and storing peat specimens, developed in Finland, is the one that is now used for testing. The test method is intended to resemble the field conditions of mass stabilization. The larger diameter of the specimens is intended to provide a more representative sample of the heterogeneous peat material. The loading imposed after mixing is intended to correspond to a field loading ~1 m of frictional material. The stabilized peat is enabled to absorb water through the net at the bottom of the tube. This resembles the field conditions of the stabilized peat at the edge of the stabilized volume, which can absorb water from adjacent unstabilized peat.

4. The influence of various factors on stabilization effectiveness

Numerous factors affect the strength obtained on stabilization. The variation in stabilization effectiveness between different types and quantities of stabilizer is normally greater in stabilized muds and peats than in stabilized clays.

This chapter describes briefly how various factors in principal can influence stabilization effectiveness.

4.1 EFFECT OF STABILIZERS

When stabilizers are added to a soil layer, various reactions take place whereby the soil is bound together and its strength is increased. Different stabilizers build up strength in different ways. The main admixtures used for the deep mix stabilization of clays in Sweden are lime and cement. However, other binders/fillers may be appropriate, just as in other types of soil stabilization. The stabilizers discussed in connection with mass stabilization are divided into the following groups:

- binders: cement and quicklime
- latent hydraulic admixtures, e.g. ground granulated blast furnace slag
- pozzolanic admixtures, e.g. fly ash
- fillers, e.g. fine sand

The group to which a stabilizer belongs depends, in simple terms, on its $CaO:SiO_2$ ratio, its general mineralogical composition, and its particle size and shape (see Table 3).

Table 3 Properties affecting reactivity of stabilizers (after /ref 4/).

Classification sition CaO/SiO_2	Chemical compo- structure	Mineraological	Particle
Binders			
Portland cement	~ 3	crystalline	~ 300 – 500 m^2/kg
Quicklime	> 40		0 – 0.1 mm
Latent hydraulic additives			
Ground granulated blast fuuuurnace slag	~ 1	amorphous	~ 400 – 600 m^2/kg
Puzzolanic additives			
Coal fly ash	~ 0.1 – 0.5	amorphous/crystalline	~ 300 – 500 m^2/kg
Fillers			
Fine sand	<< 0.1	kristallin	0.006 – 0.002 mm

4.1.1 Cement and lime

Cement and lime are binding agents. They bind and strengthen the soil without the need to add an activator. The strength enhancing reactions are briefly discussed below:

• Lime is produced by burning limestone. It reacts immediately on contact with water in the soil to form slaked lime or calcium hydroxide ($Ca(OH)_2$). This reaction generates heat and the pH value increases to approximately 12.5. It is a condition for the subsequent pozzolanic reactions, in which clay particles in the soil react with the calcium hydroxide forming strength enhancing reaction products.

• Cement consists of numerous minerals and is manufactured by combining cement clinker (a sintered material of limestone and clay) with gypsum. Cement mixed with water forms calcium silicate hydrate and calcium hydroxide ($Ca(OH)_2$). Calcium silicate hydrate, generally referred to as CSH gel, forms on the surfaces of the cement particles and because it has a strongly cementing effect it binds the soil together and increases its strength. Since the hydraulic reaction takes place considerably faster than the pozzolanic reaction, cement stabilized soil normally attains higher strength than lime stabilized soil, particularly in the first few months.

Since some $Ca(OH)_2$ is formed during cement stabilization, pozzolanic reactions will also take place, though to a lesser extent than in lime stabilization. Hence in cement stabilization, in addition to the cementation reaction, the same strength enhancing reaction products are formed as in lime stabilization in about one fifth of the quantity.

• In conventional deep stabilization by deep mixing, the binder combination cement and lime has been bound to give good stabilization effectiveness. Cement provides rapid, high and "robust" growth in strength. The slaking of the lime also provides momentary drying and heat evolution which accelerates the reaction of the cement, while the pozzolanic reactions provides a further increment of strength in the longer term.

Examples of the chemical composition of cement and lime will be found in Table 4.

Table 4. Examples of percentage chemical composition of standard Portland cement, lime, and granulated blast furnace slag.

	Portland cement (Slite Std)	Quicklime	Granulated blast furnace slag
SiO_2	21	2	36
Al_2O_3	4	0.8	9
Fe_2O_3	2	—	1
CaO	63	92	40
MgO	3	1.6	11
SO_3	3	—	—
Loss on ignition	1	1.6	—

4.1.2 Fly ash

Fly ash is obtained as a residue from power stations and heating plants fuelled with pulverized fuel. The properties and reactivity of the ash vary depending on e.g. the coal and the combustion process.

Almost all the fly ash obtainable and used in Nordic countries comes from coal combustion. This ash is low in CaO and gives pozzolanic reactions when used as a stabilizer. Pozzolanic stabilizers do not react by themselves during stabilization, but they can form strength enhancing materials very slowly on addition of water and some form of calcium hydroxide ($Ca(OH)_2$). Calcium hydroxide is normally added in the form of Portland cement in order to obtain faster "normal" strength enhancement.

Since fly ash is a residue from a process whose primary purpose is to produce energy, even ash from a single plant can have widely varying properties. A plant will not always use the same grade of coal, or even coal from the same deposit, which naturally results in wide variations in the technical and environmental properties of the residue. Each batch must therefore undergo technical and environmental quality assessment.

4.1.3 Granulated blast furnace slag

During the refining of ore into metal various types of slag are formed as by-products. Granulated blast furnace slag, a by-product of iron smelting, is the slag most frequently used for mass stabilization and is therefore the main focus of the present discussion. Examples of chemical compositions of granulated blast furnace slag will be found in Table 4.

The mineralogical composition and reactivity of the slag vary depending on the rate of cooling after leaving the blast furnace (1500 ºC). Slow cooling results in a crystalline, quite unreactive slag, while rapid cooling produces an amorphous, glassy, latent reactive slag. Granulated blast furnace slag is a product of fast cooling and is thus a latent reactive slag.

Granulated blast furnace slag used as a stabilizer has latent hydraulic properties. This means that, like pozzolanic materials, the slag can form strength-enhancing products with calcium hydroxide ($Ca(OH)_2$). The difference is that the slag contains rather more reactive lime. However, the reaction rate of the slag itself is so slow as to be negligible. Some form of activitation is therefore necessary if it is to be used as a binder. The most commonly used activator for slag is Portland cement. Other substances can be used as activators, but their reactions are quite different and the reaction products have different properties and durability. The use of other activators should therefore be discussed and clarified in advance.

As with other pozzolanic materials, the strength-enhancing reactions that occur during stabilization with granulated blast furnace slag are highly temperature-sensitive. Higher temperatures normally increase the reaction rate and hence the strength. Conversely, the strength enhancement normally falls drops rapidly if the temperature falls.

Availability of usable slag is usually dependent on proximity to a smelting works. Since granulated blast furnace slag is merely a by-product, one has to accept the composition supplied. There is normally little variation in quality in slag from the same smelting works if the raw material is constant. However, product declarations and even quality are an essential condition for the use of granulated blast furnace slag. Swedish engineers have a long record of good experience with the product Merit 5000, binder M1 in the present report.

4.1.4 Filler materials

To increase the number of solid particles a filler, such as fine sand, may be added in soil stabilization. The filler itself does not react but increases the strength of the soil by acting as a “stiffener”.

The filler material will be of greatest relevance in the stabilization of peat and mud, as these soils often require large quantities of stabilizers (see Chapter 4.2). Replacing part of the stabilizer with inexpensive filler can save costs. The filler may also be expected to fill any voids formed during stabilization.

In practice, fillers do differ in effectiveness since no filler is completely inert. Thus, for example, high-silica sand is likely to have a greater effect than limestone filler. However, the effect of fillers of whatever type is considerably less than that of the same quantity of binder.

4.2 STABILIZER QUANTITIES

Peat and mud normally require greater quantities of stabilizer than does clay. This is partly because peat and mud contain fewer solid particles to stabilize. Since it is the solid particles that provide structure, a greater quantity of stabilizer needs to be added. Moreover, mud and peat have a considerably higher water:soil ratio than clay. The large amount of water in the soil implies larger voids, requiring more stabilizer.

4.3 EFFECT OF SOIL TYPE

Mud and peat, unlike clay, have high organic content. The organic material may include retarding substances such as humus and humic acids. During stabilization the humic acids react with ($Ca(OH)_2$) to form insoluble reaction products which precipitate out on the clay particles. The acids may also cause the soil pH to drop. This negatively affects the reaction rate of the binders, resulting in a slower strength gain in mud and peat than in clay.

Studies in Finland /ref 16/ indicate that in soils with high organic contents, such as mud and peat, the quantity of binder needs to exceed a “threshold”. As long as the quantity of binder is below the threshold the soil will remain unstabilized. A reason for this may be that the humic acids are neutralized when sufficient binder is added.

A recent study at the University of Oulu, Finland, /ref 7/ shows the negative effect of humus and humic acids on the effectiveness of soil stabilization. However, the results of the study indicate that the humus and humic acid content of the soil is only one of several factors affecting stabilization effectiveness. Hence the stabilization outcome of a binder cannot at present be definitely predicted merely by determining the organic content and humus content of the soil.

Cement is often a more effective stabilizer than lime in mud and peat soils. This is probably due to the effect of humic acids as discussed above and to the inhibition of one of the most important strength-enhancing mechanism of the lime (pozzolanic reactions). In pozzolanic reactions the lime reacts with clay particles in the soil to form binding materials. In peat and mud the organic material occupies so much of the soil volume that the stabilizer fails to come in contact with the few clay particles that are present, with the result that pozzolanic reactions do not take place. Cement gives a more robust strength gain as the cement forms binding materials with water and clay particles play no role.

4.4 EFFECT OF STORAGE TEMPERATURE

The heat evolved when a soil is stabilized depends on the stabilizer used (see Fig. 4). Heat accelerates the reaction rate of stabilization.

The temperature in the soil is normally around 8 ºC. At this temperature most stabilizers react slowly. The strength enhancing reactions that are least affected by ambient temperature are the hydraulic reactions.

One difference that exists between stabilizers is that those with high heat evolution (e.g. lime and cement) are less dependent on the temperature of the ambient soil than those having slow and low heat evolution in themselves (e.g. granulated blast furnace slag). Hence in a soil stabilized with low exothermic agents the reaction rate, and hence the short-term strength, will fall if the ambient temperature drops. Similarly, the strength will increase if the ambient temperature rises. Hence for best comparison with real conditions laboratory samples should be stored at temperatures corresponding to field temperatures, i.e. different storage temperature for different types of stabilizers.

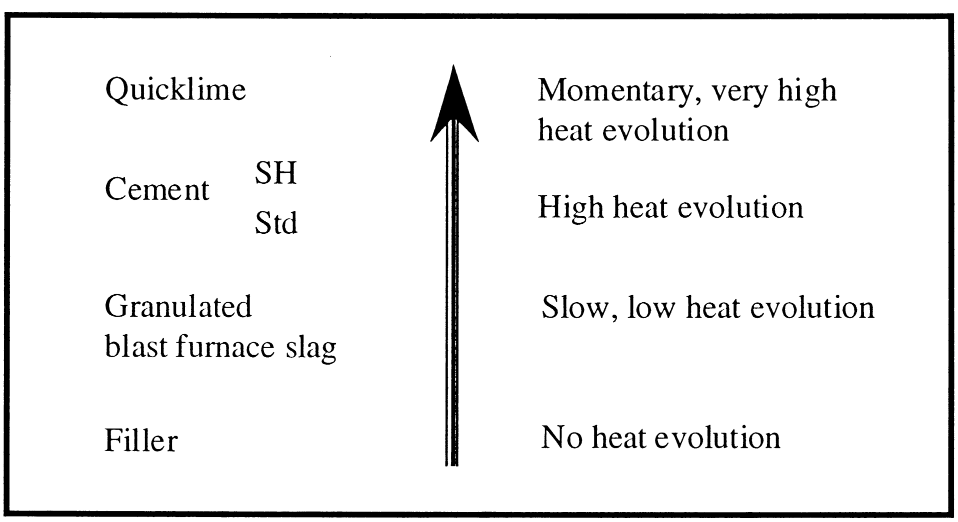


Fig. 4. Heat development in soil after stabilization with variout stabilizers.

4.5 EFFECT OF DEGREE OF COMPACTION

The bulk density of mud and peat is normally very low, i.e. the ratio of voids to solids is relatively high. The voids are mostly filled with water. The density of mud and peat normally tends to increase on stabilization since some of the water in the soil is replaced by the stabilizer. This also reduces the voids fraction, particularly in the case of peats containing large amounts of water.

Since strength of stabilized material generally increases as the voids fraction decreases (other conditions being equal), the effectiveness of stabilization in peat and mud is likely to depend on how well compacted the material becomes. Laboratory mixing tests show large differences in stabilization effectiveness between peat specimens stored under load and specimens stored without load. One reason is that peat often gets very sticky during mixing, making it difficult to compact. Storage under load expels any air pockets and hence higher strength is attained.

In order for the stabilizer to react completely it is also important for the stabilizer to be homogeneously mixed with the soil. In general, stabilization effectiveness increases with the homogeneity of the stabilized material.

4.6 EFFECT OF CONSISTENT QUALITY

To ensure homogeneity of the mass stabilized volume it is important that the stabilization method is relatively insensitive to variations in e.g. soil and execution. Stabilizers vary in their ability to yield a product of consistent and reliable quality.

The commonest stabilizing agents today, cement and lime, have been found to yield a product of consistent and reliable quality in "normal soils", see e.g. /5/. Given that mass stabilization is often done in organic soils in which a certain amount of water flow may occur, the consistent quality, reaction rate and environmental properties of a stabilizer are of still greater importance than in conventional deep stabilization of clay.

5. Results

This chapter reports the results of the stabilization tests on mud and peat. At the end of the chapter we compare our results with those of some earlier experiments.

5.1 SAMPLE PREPARATION

With mud the addition of stabilizer and preparation of specimens was relatively straightforward. There was no noticeable difference in sample preparation between the Arlanda and Örebro muds or between the different stabilizers.

The peats were more difficult than the muds to mix into a homogeneous mass. While the Örebro peat, with a water:soil ratio of over 1300 %, was relatively easy to mix and compact, the Arlanda peat, with a water:soil ratio of ~ 400 %, was crumbly and dry even before stabilization. Adding stabilizer made the sample still drier, which strongly affected the result. Mixing and compaction proceeded considerably more smoothly in the Arland peat samples to which water was added.

5.2 SOIL DENSITY AND STRENGTH

Chapter 5.2 reports the density and the results of unconfined compression tests on the mud and peat. The complete results are presented in Appendices 3 and 4. Strength testing of the mud was done after storage for 14 and 26 days and of the peat after 28 days. In general, the stabilization effectiveness achieved was very good.

5.2.1 Density of stabiilized mud

The density of both the Arlanda mud and the Örebro mud increased somewhat after stabilization, see Figs 5a and 5b. The density increase was slightly greater in the Örebro mud, which was compacted manually, than in the Arlanda mud, which was compacted by constant pressure. There is no discernible difference in the density increase depending on the stabilizer added.

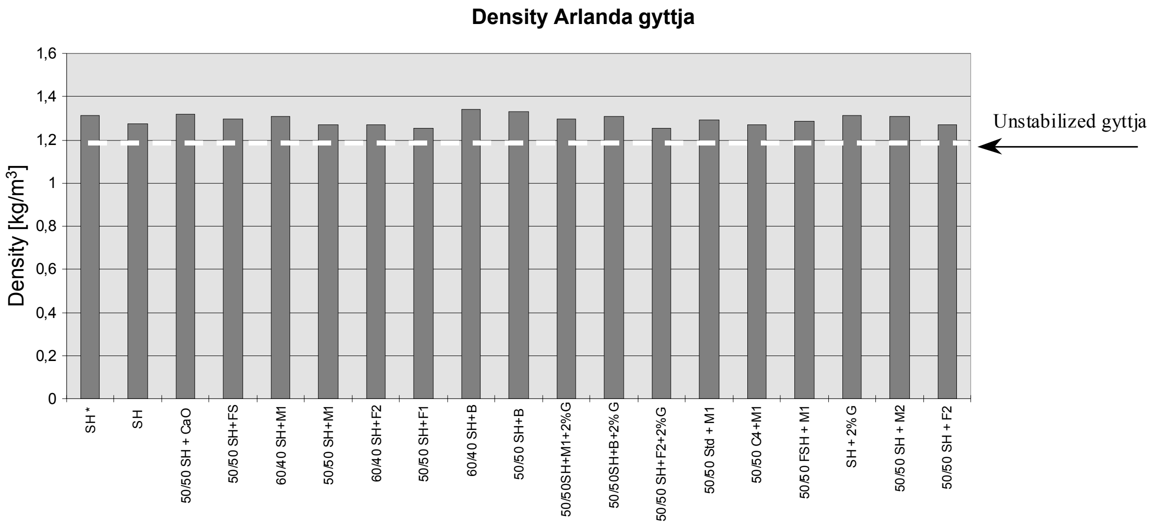
5.2.2 Strength of stabilized mud

Conventional binders

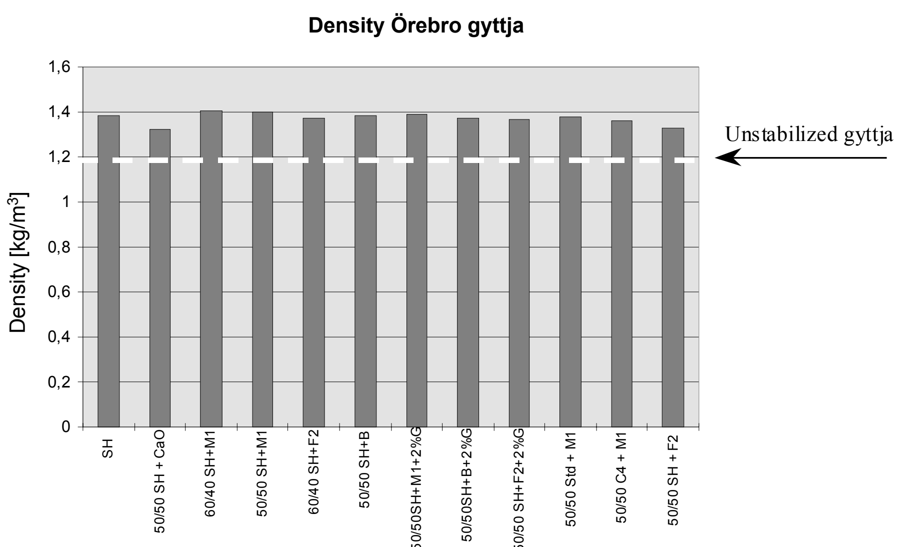
Jet cement by itself results in the best strength in both Arlanda and Örebro mud, see Figs 6 and 7.

A stabilizer consisting of jet cement mixed with lime gives relatively low shear strength at 14 days. The shear strength at 26 days is somewhat higher in the Arlanda mud but is still considerably lower than that obtained by stabilization with jet cement alone, see Fig. 6.

Results similar to those reported above are also reported in /ref 5/. However, /ref 13/ recommends a mix of 50 % cement and 50 % lime for the deep mix stabilization of mud. This is justified by the

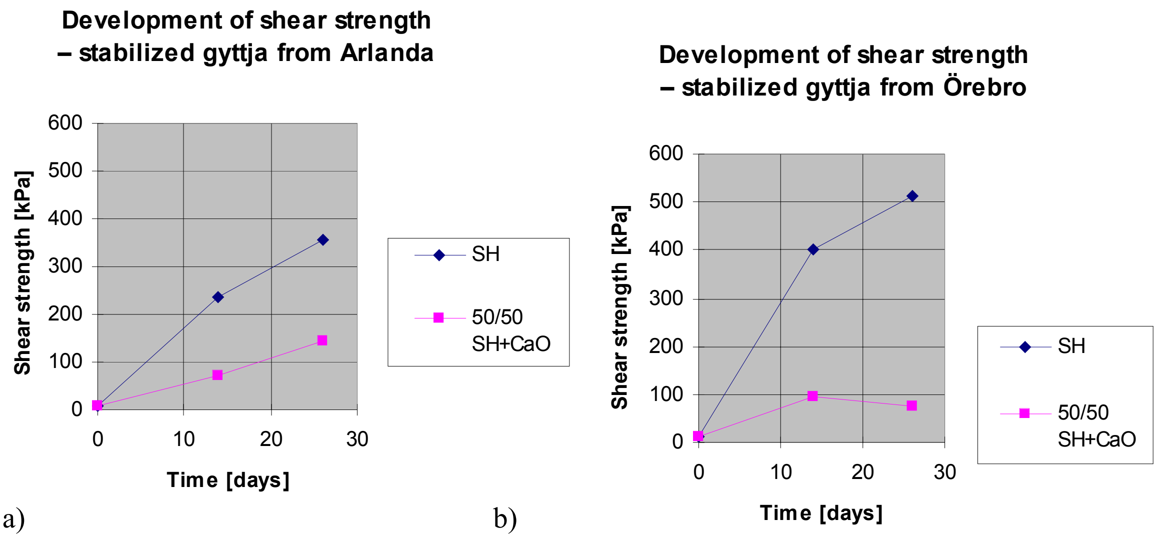


a) * Compaction manually



b)

Fig. 5. Density of stabilized gyttja. The 26 day results are averages of two specimens. 200 kg stabilizer per m³ was used in all specimens.
(a) Arlanda (compacted by constant pressure unless otherwise indicated)
(b) Örebro (compacted manually)



a) b)

Fig. 6. Strength evolution on stabilization with rapid hardening cement alone and with rapid hardening cement and lime. 200 kg stabilizer per m^3 was used in all specimens.
a) Arlanda gyttja b) Örebro gyttja

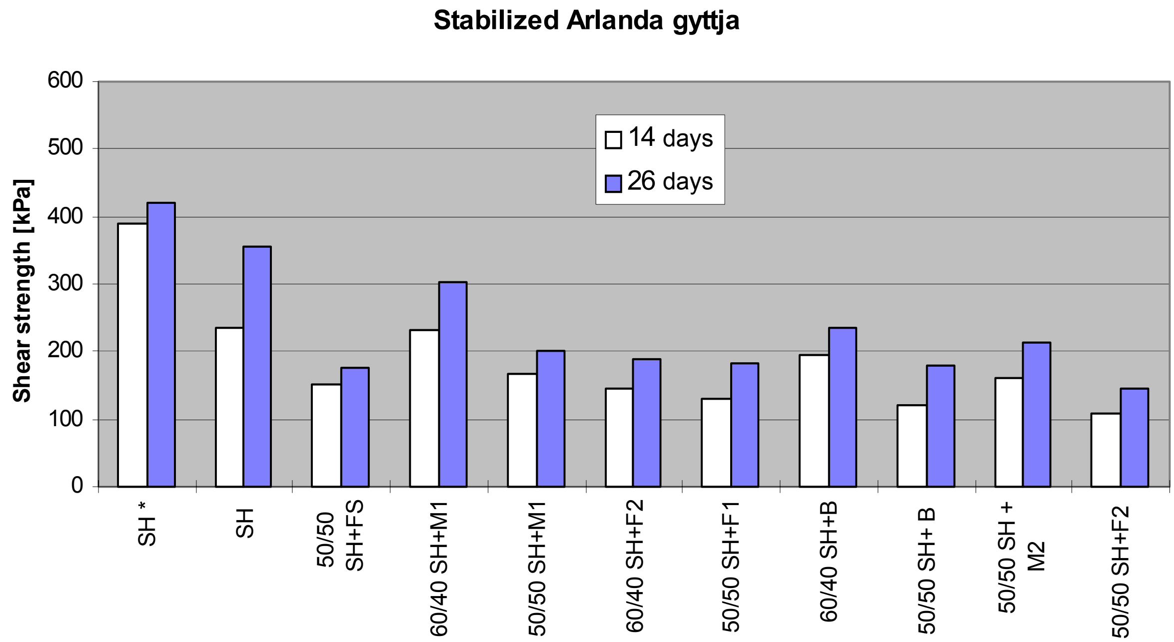
extensive fund of experience of deep mix stabilization and the robustness of the mixture.

Other stabilizers
By comparing samples stabilized with jet cement alone (reference samples) and mixtures of jet cement with other materials the relative effects of different stabilizers can be determined. Such a comparison is shown is Fig. 7.

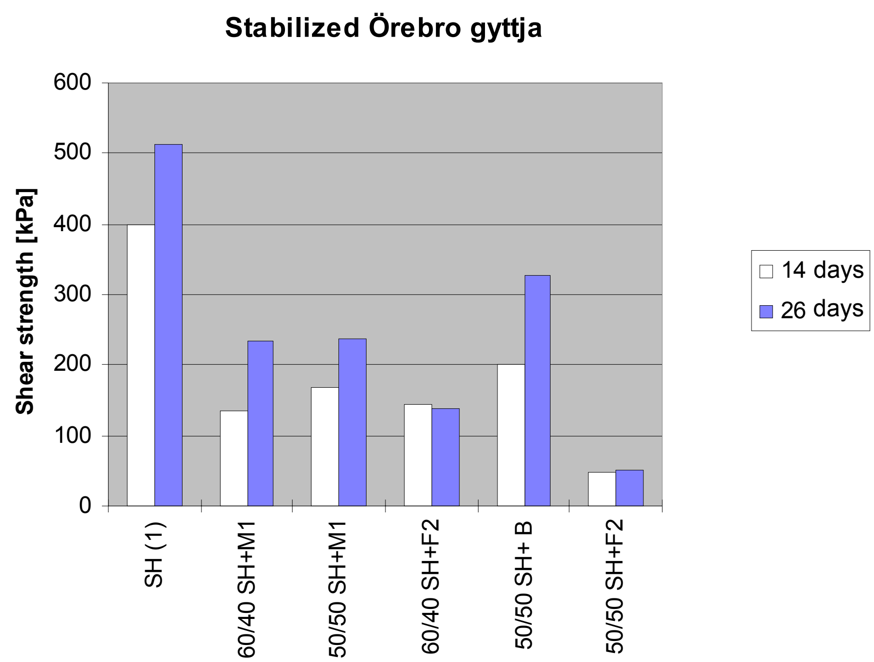
The best stabilization effectiveness in both Arlanda and Örebro is obtained with jet cement alone. The results with mixtures are inferior to those with jet cement alone in every case. Of industrial residues, best results are obtained with ground granulated blast furnace slag and bypass ash.

Comparison of different cements
Different cements can be compared with each other in the same way as the industrial residues. Fig. 8 shows a comparison of stabilization tests using 1:1 mixtures of different cements with ground granulated blast furnace slag.

The results indicate that stabilization effectiveness varies with the cement. The cement that gave best and most reliable results with both the Arlanda and the Örebro mud was Swedish jet cement. With Arlanda mud, Swedish jet cement and standard cement and Swedish jet cement gave equal stabilization effectiveness at 26 days, while cement 4 gave poorer results. The Örebro mud is most effectively stabilized by Swedish jet cement, Fig. 8.

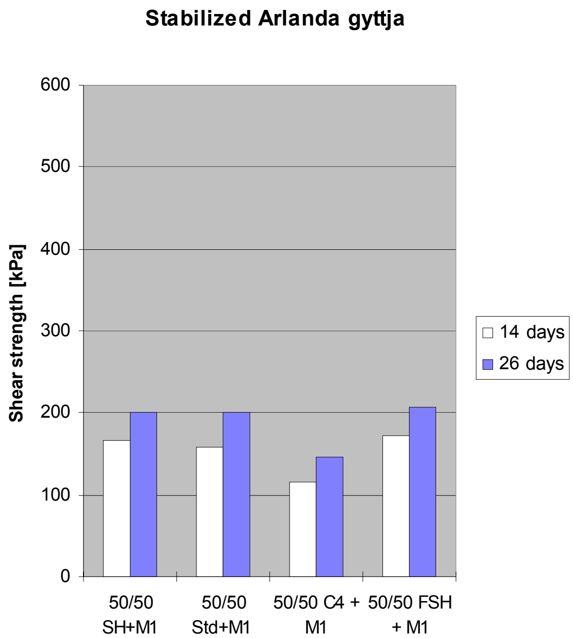


a) * Compacted manually

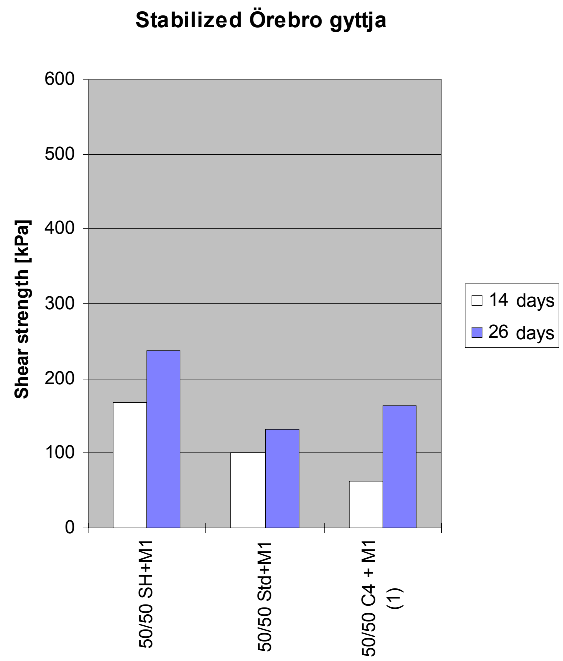


b) (1) Wide dispersion between specimens.

Fig. 7. Shear strength of gyttja after storage for 14 and 26 days. The 26 day results are averages of two specimens. 200 kg stabilizer per m^3 was used in all specimens.
a) Arlanda (compacted by constant pressure unless otherwise indicated)
b) Örebro (compacted manually)



a)



b) (1) Wide dispersion between specimens.

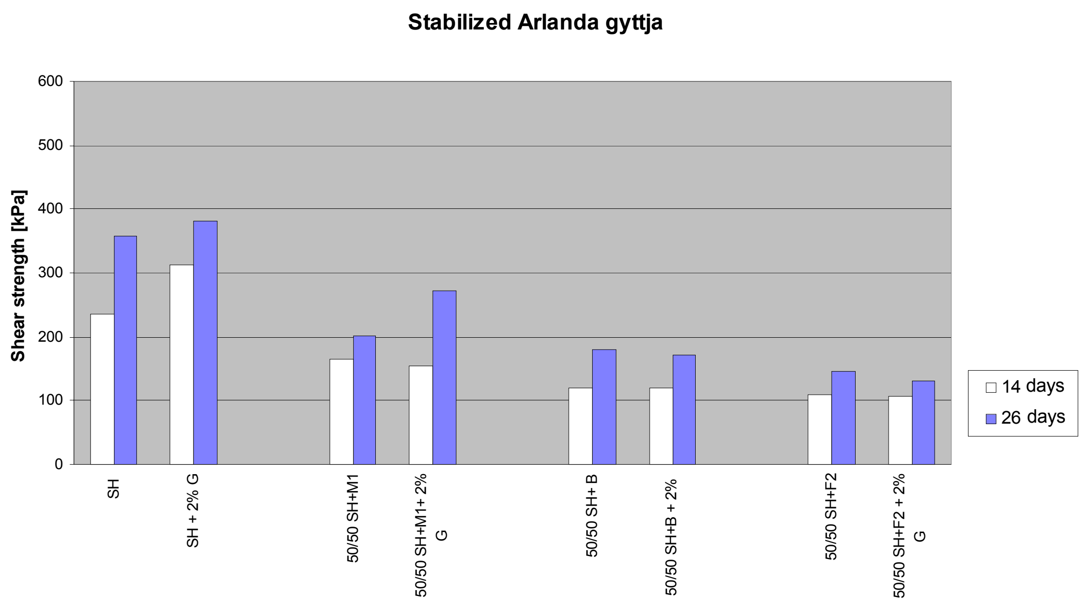
Fig. 8. Shear strength of gyttja after storage for 14 and 26 days. The 26 day results are averages of two specimens. 200 kg stabilizer per m^3 was used in all specimens
a) Arlanda (compacted by constant pressure)
b) Örebro (compacted manually)

Glorit chemical admixture

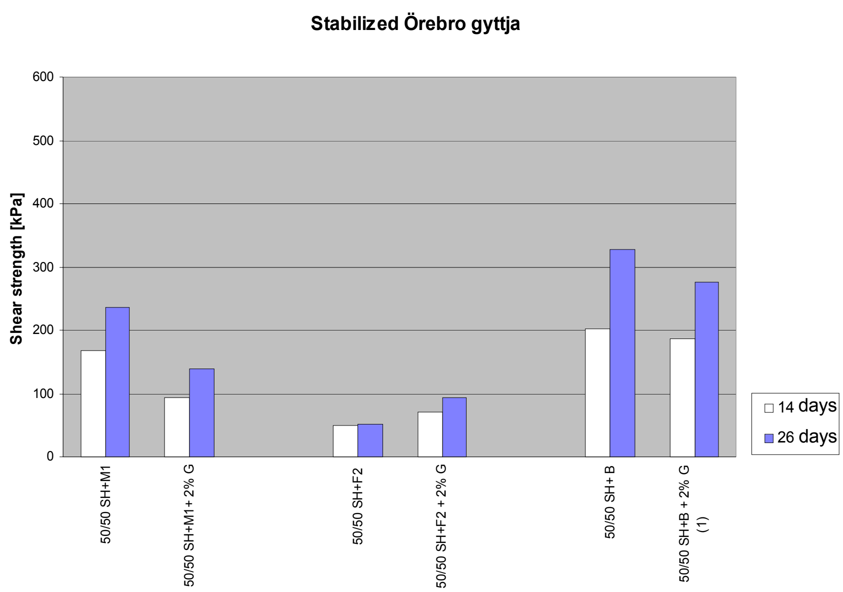
A number of parallel specimens were prepared with a chemical admixture of 2% Glorit (the trade name of an inorganic salt), Fig. 9. The results show no absolute difference between specimens with and without Glorit in many cases. In other cases strength values with Glorit are slightly better or worse. Overall, based on these results, Glorit seems to have no effect.

5.2.3 Density of stabilized peat

The stabilized Örebro peat specimens showed a uniform density increase regardless of what stabilizer was added, Fig. 10b. The density of the Arlanda peat specimens, on the other hand, tended to decrease or remain unchanged after stabilization, Fig. 10a. Exceptions were the Arlanda peat specimens to which water was added: the density of these specimens increased.

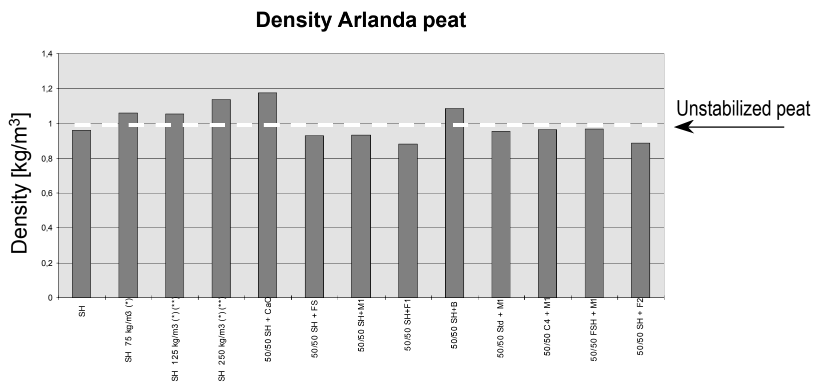


a)

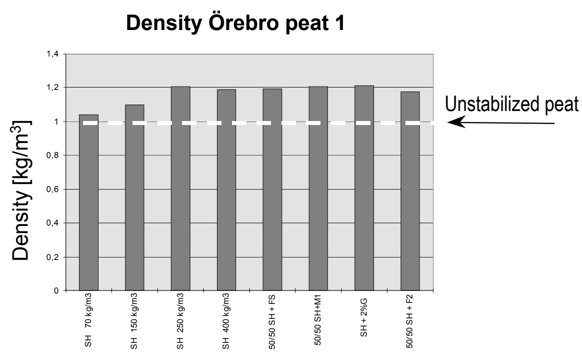


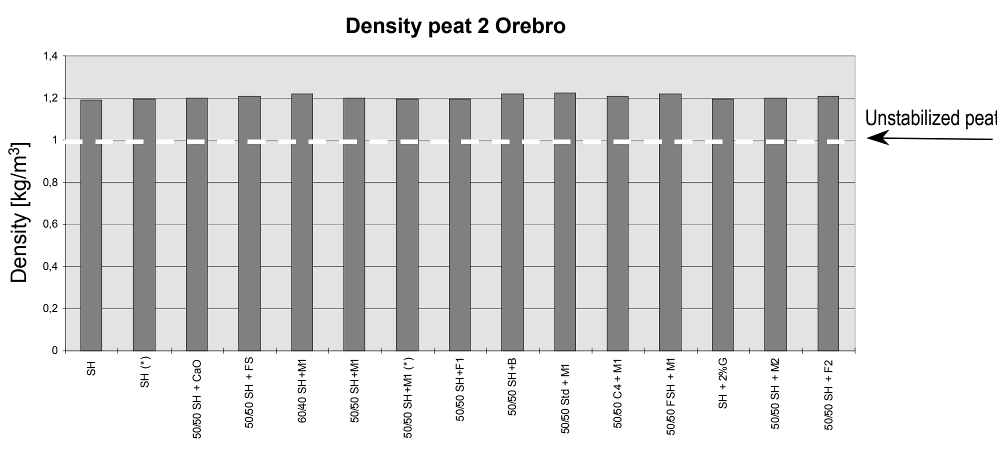
b) (1) Wide dispersion between specimens.

Fig. 9. Effect of Glorit (G) on stabilization effectiveness in gyttja. The 26 day results are averages of two specimens. 200 kg stabilizer per m^3 was used.
a) Arlanda b) Örebro



a) (*) Stored at 8 ºC (other specimens were stored at 21 ºC) (**) Water added





b) (*) Stored at 8 ºC (other specimens were stored at 21 ºC).

Fig. 10. Density before and after stabilization. 250 kg stabilizer per m^3 was used unless otherwise indicated. Results normally represent the average of two specimens.
a) Arlanda peat b) Örebro peat 1 and 2

5.2.4 Strength of stabilized peat

The Arlanda peat was “crumbly” in the unconfined compression tests. The results show very low shear strength regardless of what stabilizer was added. The hypothesis was formed that too little water was present for all the binder to react. The specimens to which water was added showed good stabilizing effectiveness, Fig. 11, confirming the presence of unreacted binder (cement) in the specimens. The water addition enabled hydraulic reactions to take place.

Conventional binders

In the Örebro peat high shear strength is obtained with most stabilizers. However, a mixture of jet cement with lime gives relatively low strength, Fig. 12.

Other stabilizers

Fig. 13 compares the relative effectiveness of different stabilizers. Samples stabilized with jet cement alone (reference samples) are compared with samples stabilized with 1:1 mixtures of jet cement with other materials.

The best stabilizing effectiveness in the Örebro peat is obtained with a mixture of jet cement and granulated blast furnace slag. Stabilization with jet cement alone is also very effective. Other mixtures yield poorer results.

Storage temperatures

The specimens that were stored at 8 ºC instead of 21 ºC confirm that the storage temperature plays a greater role in stabilization with granulated blast furnace slag than with jet cement alone. After storage at 8 ºC, better stabilization effectiveness was obtained with jet cement alone than with mixtures of jet cement and granulated blast furnace slag. In specimens stored at 21 ºC, somewhat better stabilization effectiveness is obtained with mixtures of jet cement and granulated blast furnace slag, Fig. 14.

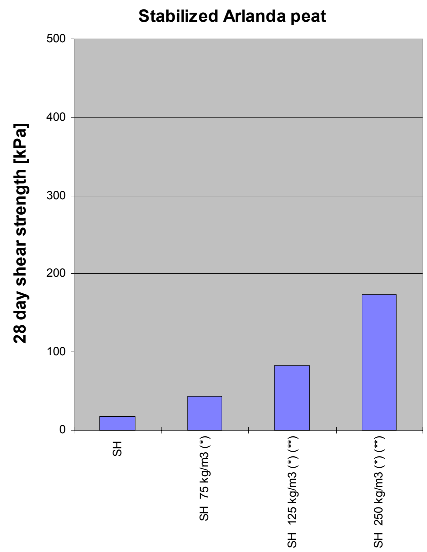
Comparison of different cements

Fig. 15 compares different cements. The specimens were stabilized with 50:50 mixtures of various cements with granulated blast furnace slag No. 1.

The results show that the stabilization effectiveness varies with the cement. With the Arlanda peat, jet cement was somewhat more effective than other cements. With the Örebro peat standard cement gives somewhat better stabilization effectiveness than jet cement. Swedish standard cement and jet cement are both more effective than Finnish jet cement and cement 4.

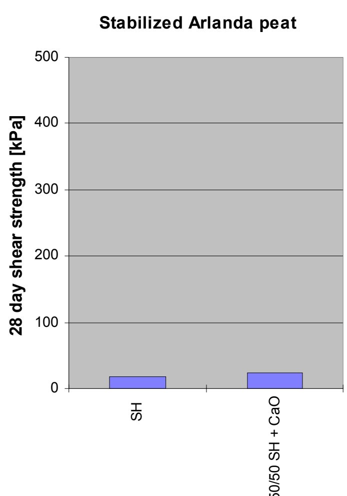
Glorit chemical admixture

To investigate whether the chemical admixture of Glorit affects stabilization effectiveness with peat, parallel speciments were prepared with jet cement alone and jet cement plus 2 % Glorit. On the basis of the results in Fig. 16, Glorit does not appear to have any positive effect.

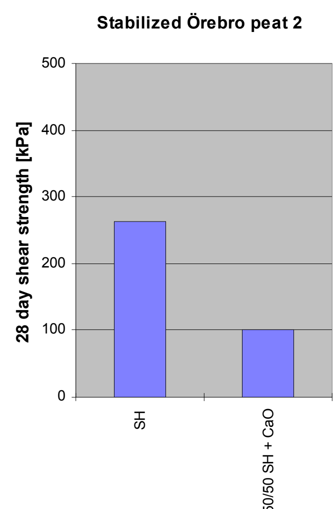


(*) Stored at 8 ºC (other specimens were stored at 21 ºC)   (**) Water added

Fig. 11. Effect of water addition to Arlanda peat. 250 kg stabilizer per m³ was used unless otherwise indicated. Results normally represent the average of two specimens.

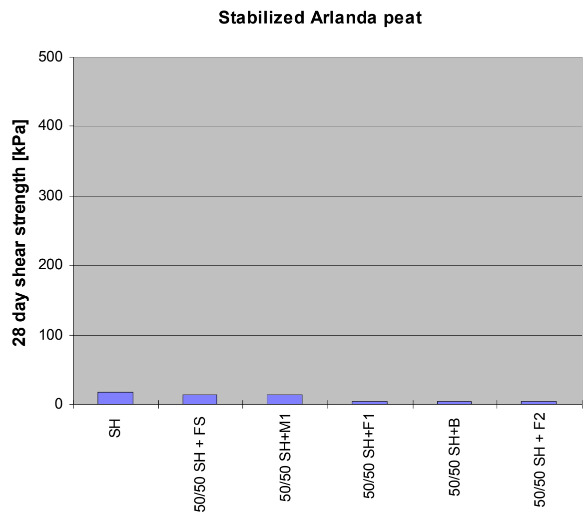


a)

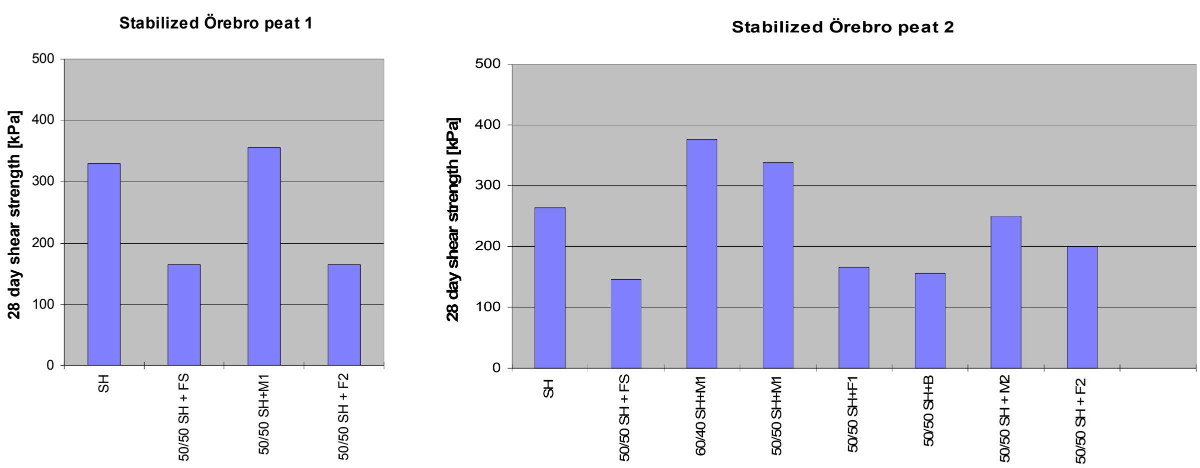


b)

Fig. 12. Shear strength on stabilization with jet cement alone and with rapid hardening cement and lime. 250 kg stabilizer per m³ was used unless otherwise indicated. Results normally represent the average of two specimens
a) Arlanda peat   b) Örebro peat 2



a)



b)

Fig. 13. Shear strength after storage at 21 ºC for 28 days. 250 kg stabilizer per m^3 was used unless otherwise indicated. Results normally represent the average of two specimens
a) Arlanda peat b) Örebro peats 1 and 2

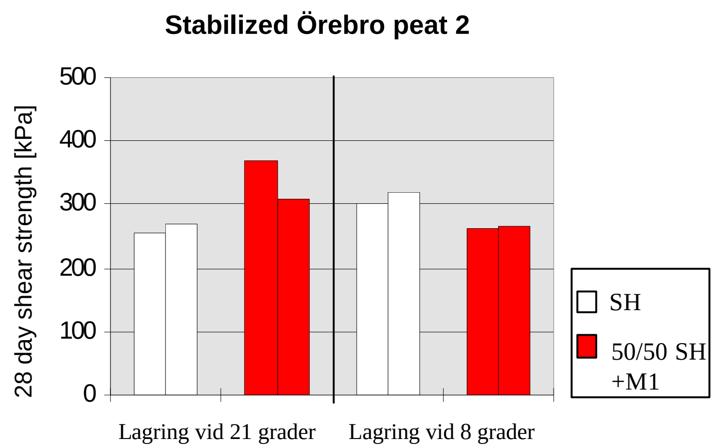
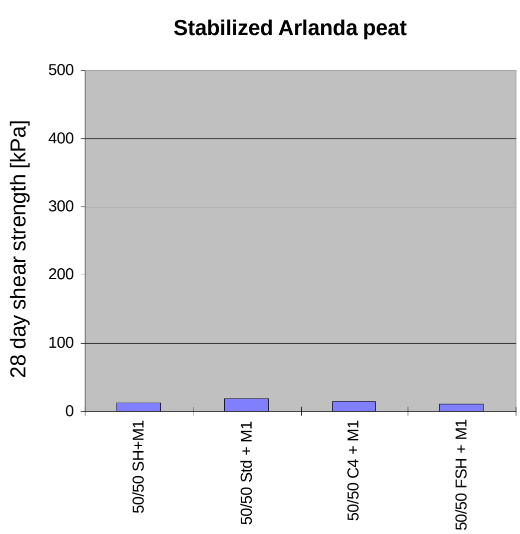
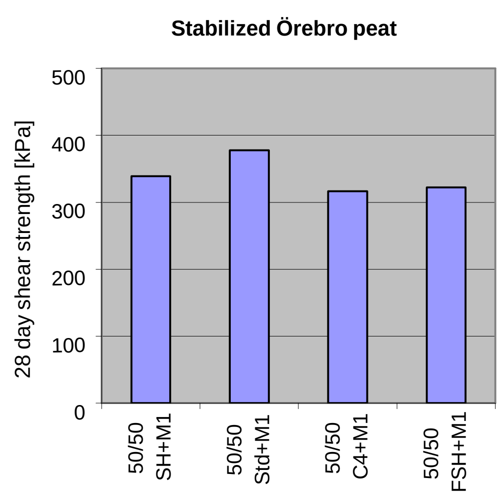


Fig. 14. Comparison of stabilized Örebro peat stored at 8 ºC and at 21 ºC. 250 kg stabilizer per m^3 was used unless otherwise indicated.

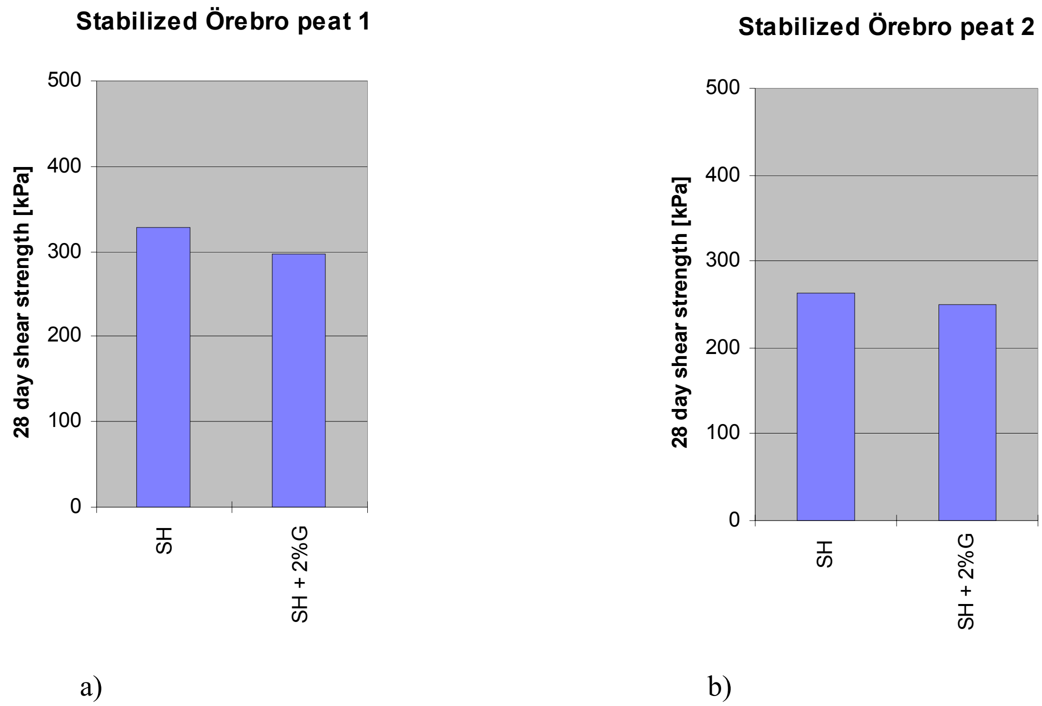


a)



b)

Fig. 15. Shear strength after storage for 28 days. 250 kg stabilizer per m^3 was used unless otherwise indicated. Results normally represent the average of two specimens.
a) Arlanda peat b) Örebro peat 2



Figur 16. Effect of Glorit on stabilization effectiveness in peat. 250 kg stabilizer per m^3 was used. Results normally represent the average of two specimens.
a) Örebro peat 1 b) Örebro peat 2

Different stabilizer quantities

Specimens of the Örebro peat were prepared with different quantities of stabilizer (jet cement alone), Fig. 17. The 28 day shear strength of these speciments shows an increase over the range of addition rates from 70 kg/m^3 to 250 kg/m^3. However, an addition rate of 400 kg/m^3 gives lower strength than 250 kg/m^3, indicating that the water:binder ratio has an effect on the shear strength.

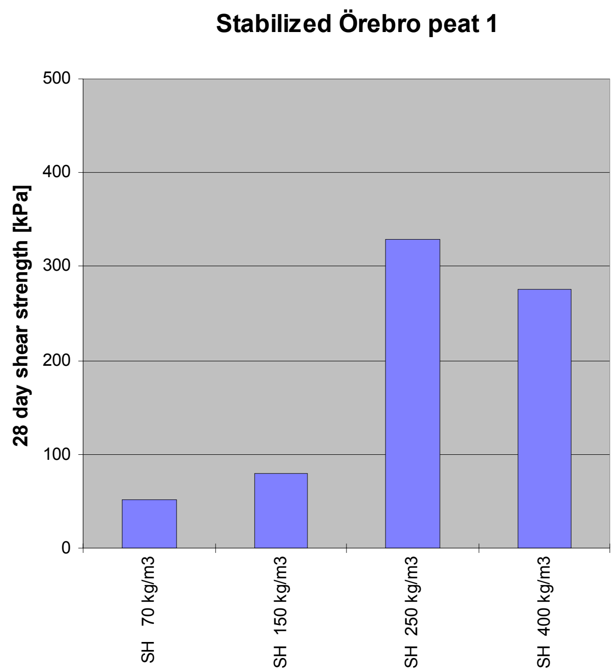


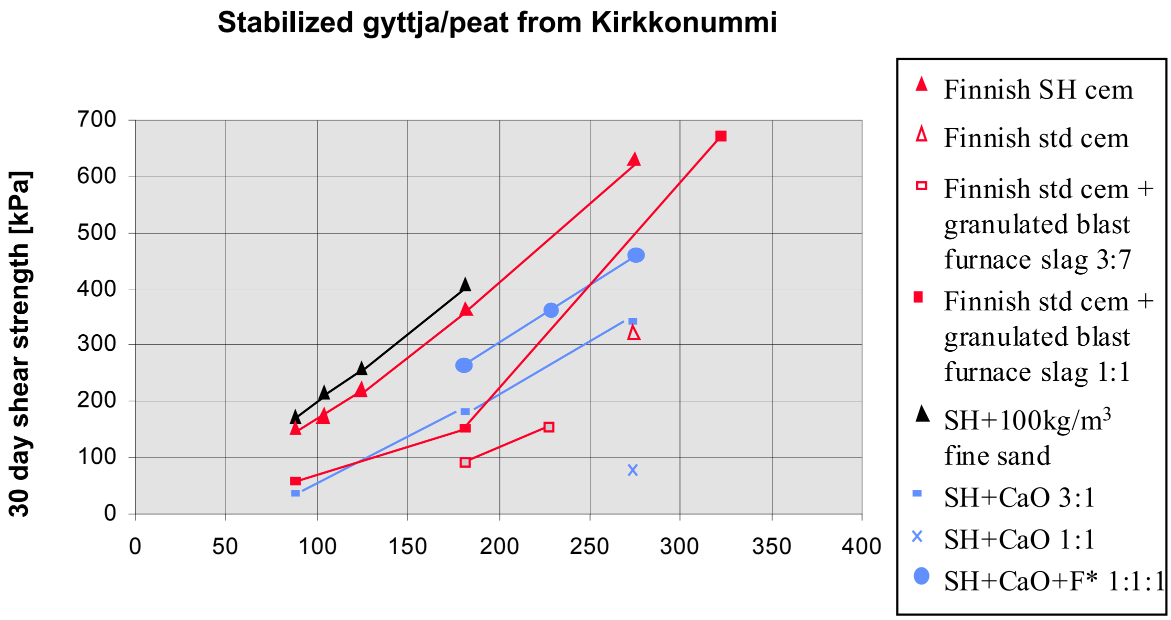
Fig. 17. Shear strength after storage for 28 days. Tests using 250 kg stabilizer per m^3 were done on two parallel specimens, the results above representing the average. Other tests were done on single specimens.

5.3 COMPARISON WITH EARLIER RESULTS

5.3.1 Kirkkonummi

Ahead of a road construction project at Kirkkonummi, west of Helsinki, stabilization trials were done on clay, mud and peat from the site. Selected results of unconfined compression tests on the mud and peat are reported in Appendix 6 and Fig. 18.

The best stabilization effectiveness was obtained with jet cement mixed with 100 kg/m^3 of fine sand and with jet cement alone. The addition of filler (100 kg/m^3 fine sand) to the jet cement gives an increment of ~30 kPa in shear strength, Fig. 18. This confirms that the number of solid particles in the peat has an influence on the effectiveness of stabilization, since the shear strength increases when fine sand (i.e. solid particles) is added. Of other stabilizers tested, a 50:50 mixture of Finnish standard cement and granulated blast furnace slag also gives good stabilization effectiveness, Fig. 18.



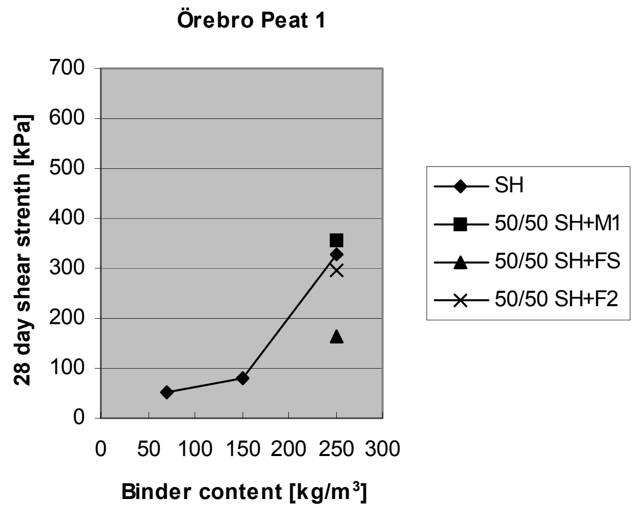
F* = Finnstabi, special binder from Kemira pigments.

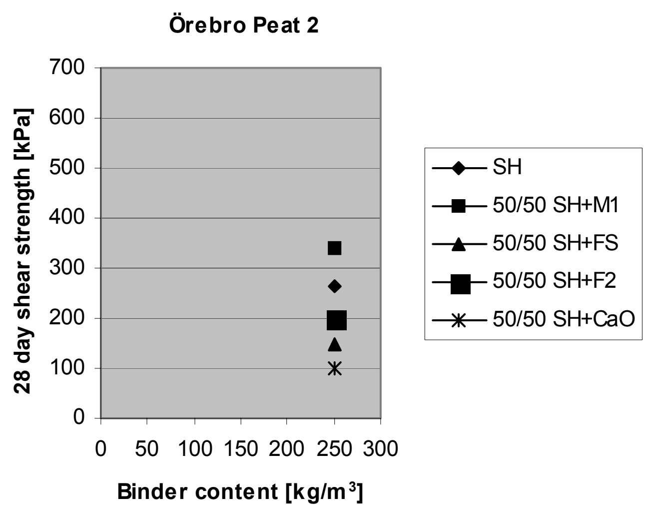
Fig. 18. Shear strength with different stabilizer quantities. Results are from tests ahead of a stabilization project at Kirkkonummi, Finland. From Finsementti.

5.3.2 Örebro – Arboga

The feasibility study used mud and peat from a motorway construction site between Örebro and Arboga. Ground improvement in the form of deep and mass stabilization is planned in a number of clayey and peaty areas, and stabilization tests were therefore carried out. Selected results are reported in Appendix 6. Fig. 19 compares the results from this feasibility study (peats 1 and 2) with those of the preliminary investigation (peats A and B).

The results differ in absolute level, which is certainly to be explained by differences in sampling methods and probably also by differences in the original peats. However, the results do show that in both cases a mixture of cement and lime gives the poorest outcome, while cement mixed with ground granulated blast furnace slag and cement alone give the best outcome.



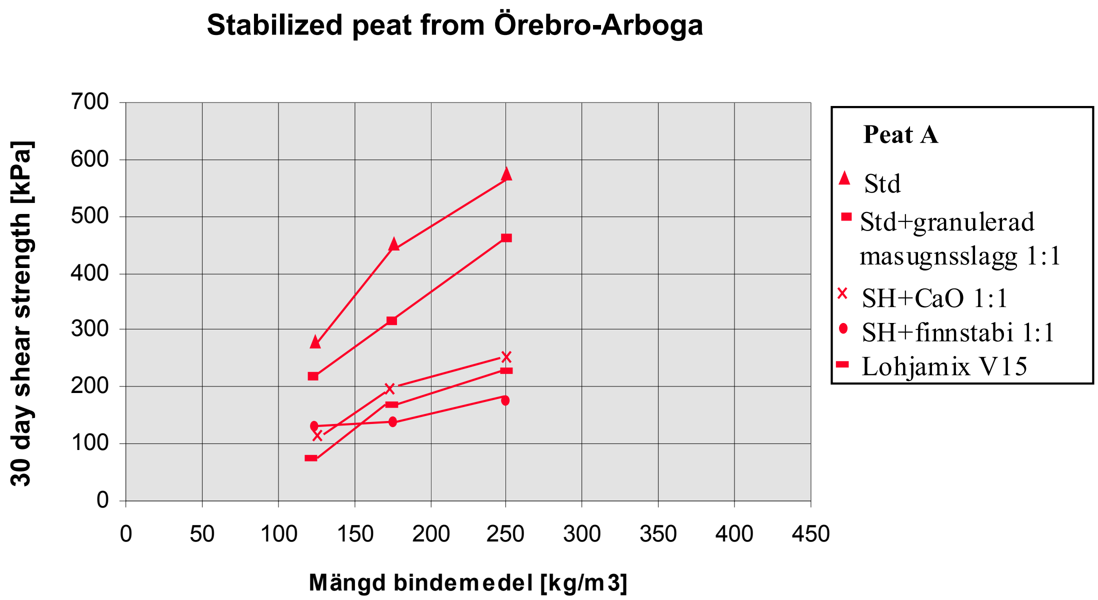


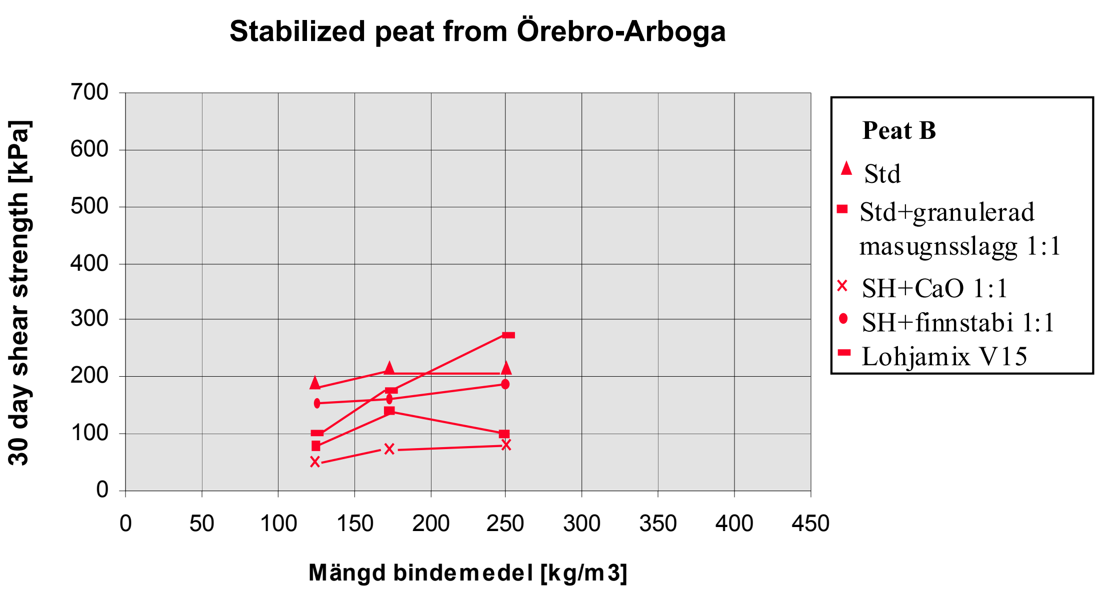
a) Peats from feasibility study

Peat 1 = Water content: 1308 % Organic content: 99 %

Peat 2 = Water content: 1413 % Organic content: 97 %

Fig. 19. Results from earlier stabilization tests at Örebro compared with results from this feasibility study. Shear strength determined by unconfined compression test after storage for one month.
a) Stabilized peats 1 and 2 from this feasibility study. 250 kg stabilizer per m³ was used.





b) Previously tested peats from Örebro–Arboga:
Peat A = Density 0.98 t/m^3 Water content: 1350 % Organic content: 99,1 %
Peat B = Density 0.98 t/m^3 Water content: 1290 % Organic content: 98,9 %

Fig. 19b. Shear strength with different stabilizer quantities. Results are from previous tests from Orebro – Arboga.

6. Conclusions and recommendations

6.1 CONCLUSIONS

The studies show that the strength of peat and mud can be considerably improved by stabilization. The strength attainable depends on the composition of the added stabilizer and on the choice of filler, if used.

New method for preparation and storage of stabilized peat specimens
A special method was used for the tests on peat (Chapter 3.6), which was developed and is currently in use in Finland. The special test equipment that it requires was constructed by the SGI workshop after studies of the Finnish equipment. Both compaction and storage proceeded relatively smoothly. Extraction of the speciments from the tubes was considerably more difficult than with conventional tubes. However, this should be possible to improve.

Density

With the exception of the Arlanda peat, the density tends to increase after stabilization (Figs 6 and 11). A relationship can be seen between the increase in density and an increase in the strength of the specimens. A possible explanation of this might be that the specimens whose density increased were well compacted, resulting in reduced pore volume and hence greater strength. No relation can be seen between the change in density and the stabilizer used.

Shear strength

Unconfined compression tests give very high values of shear strength for a number of stabilizers, both with Örebro mud and peat and with Arlanda mud. The Arlanda peat, however, gave low shear strength values. A reason for this may be the low water:soil ratio of the peat and its crumbly consistence. The hypothesis was formed that not enough water was present for all the binder to react. Good stabilization effectiveness was measured in the specimens to which water was added, confirming that unreacted binder (cement) was present in the specimens. Adding water permitted hydraulic reactions to take place.

Stabiilizers

The results of the stabilization tests show that different cements and mixtures vary considerably in effectiveness. In mud, Swedish jet cement alone was gave the most effective stabilization, but in some cases Swedish standard cement was equally good. All mixtures gave poorer results with mud than did cement alone. In peat, mixtures of cement and ground granulated blast furnace slag gave the best results. Stabilization with cement alone (standard cement and jet cement) also gave good results.

Mixtures containing fly ash gave in almost every case the worst results of all the industrial residues. In peat, lime gives poor stabilization effectiveness. The results are in good agreement with those that may be expected on theoretical grounds (see discussion in Chapter 4).

Storage temperature

The role storage temperature varies with different stabilizes. For the best comparison with field conditions, specimens should be stored at temperatures similar to those that can be expected to occur in the field.

6.2 RECOMMENDATIONS

The recommendations below are based on currently well-known binder reactions and on current thinking on traditional deep-mix stabilization.

Stabilizers

Based on the review in Chapter 4 and on the results of this feasibility study, we recommend that binding effect of stabilization should be based on hydraulic or pozzolanic reactions. A pilot study is always done in accordance with technical requirements. Materials used today are Portland cement, lime, inert fillers and ground granulated blast furnace slag. They are provided with product declarations and the environmental characteristics are also well-known. Documentation of these can be found e.g. in the "building product declarations" (*byggvarudeklaration*) developed by the Swedish construction industry, see e.g. /ref 17/.

The properties and composition of industrial residues vary, due among other things to different raw materials and to the fact that industrial processes are not driven by requirements on the composition of residues. Other materials and new materials should therefore always be reviewed under the Swedish Environment Act and their reactions, reaction products and their properties should be investigated in each individual project.

Stabilizer quantities

On the basis of the present study and other experience the authors recommend following binders and quantities for mud, peat and hydraulic fill:

Soil	Binder	Typical quantity
Gyttja	Cement or mixtures of cement and granulated blast furnace slag	100 – 200 kg/m^3
Peat		150 – 250 kg/m^3
Hydraulic fill		70 – 200 kg/m^3

The above ranges are the normal ones. The final choice of binder and quantity is made on the basis of a technical pilot study and the conditions of the project.

Proposed projects

A number of projects are proposed below for further work.

- Develop a standardized test method. Today a variety of test methods are in use for peat, resulting in wide variations and difficulty of comparing results.

- Investigate the importance “robustness” (Chapter 4.6) of a stabilizer, i.e. its ability to maintain its reaction rate and provide consistent and reliable quality notwithstanding variations in soil and work methods. Soil layers containing peat and mud require more “robust” stabilizers than clay soils due to the presence of humus and the wide variation in their properties.

- Develop methods and criteria for evaluating the environmental effects of new stabilizers.

- Study in detail the chemical and physical parameters that affect strength-enhancing reactions. Ideally it would be possible to determine the most appropriate stabilizer from a simple chemical assay of the unstabilized soil.

- Study the effect of natural fillers, such as sand, on the strength of stabilized soils.

- Study the effect of water content on strength. Is there a minimum water:soil ratio below which stabilization of peat with a dry stabilizer is not possible?

- The mixing, compaction and homogeneity of dry peats may well be improved by adding the stabilizer as a slurry rather than in dry form. Is it possible to add slurry to dry muds and peats? Since the water content of peaty soils is subject to seasonal variation, the mixing method (dry or as slurry) might itself be varied.

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Combination of stabilizing agents

Designation	Proportion stabilizing agent											
	SH	Std	FSH	C4	CaO	M1	M2	F1	F2	B	G	FS
SH	100											
SH + CaO	50				50							
SH + FS	50											50
SH + M1	60					40						
SH + M1	50					50						
SH + F2	60								40			
SH + F1	50							50				
SH + B	60									40		
SH + B	50									50		
SH + M1 + G	50					50					2	
SH + B + G	50									50	2	
SH + F2 + G	50								50		2	
Std + M1		50				50						
C4 + M1				50		50						
FSH + M1			50			50						
SH + G	100										2	
SH + M2	50						50					
SH + F2	50								50			

Cement

SH	=	Cem SH P
Std	=	Cem Std P
FSH	=	Pikasementti (Finnish rapid hardening cement)
C4	=	Cement 4

Lime

CaO	=	Quicklime

Tillsatsmaterial

B	=	By-pass ash
F1	=	Fly ash 1j
F2	=	" 2
FS	=	Fine sand
M1	=	Ground granulated blast furnace slag 1
M2	=	– " – 2

Chemical additive

G	=	Glorit

Test programme

Binder	Arlanda gyttja Binder content kg/m³	Arlanda gyttja Unconfined compr. test 14 & 26 days	Örebro gyttja Binder content kg/m³	Örebro gyttja Unconfined compr. test 14 & 26 days
SH	200	x x	200	x
SH + CaO	200	x		x
SH + FS	200	x		
60/40 SH+M1	200	x	200	x
50/50 SH+M1	200	x	200	x
60/40 SH+F2	200	x	200	x
50/50 SH+F1	200	x		
60/40 SH+B	200	x		
50/50 SH+B	200	x	200	x
50/50SH+M1+2% G	200	x	200	x
50/50SH+B+2% G	200	x	200	x
50/50SH+F2+2% G	200	x	200	x
50/50 Std + M1	200	x	200	x
50/50 C4 + M1	200	x	200	x
50/50 FSH + M1	200	x		
SH + 2% G	200	x		
50/50 SH + M2	200	x		
SH + F2	200	x	200	x

Binder	Peat Arlanda Binder content kg/m³	Peat Arlanda Unconf. comp. test 28 days	Peat 1 Örebro Binder content kg/m³	Peat 1 Örebro Unconf. comp. test 28 days	Peat 2 Örebro Binder content kg/m³	Peat 2 Örebro Unconf. comp. test 28 days
SH	250	x	250	x	250	x x(*)
SH	75(*)	x	70	x		
SH	125(**)(*)	x	150	x		
SH	250(**)(*)	x	400	x		
SH + CaO	250	x				x
SH + FS	250	x	250	x	250	x
60/40 SH+M1					250	x
50/50 SH+M1	250	x			250	x x(*)
50/50 SH+F1	250	x			250	x
50/50 SH+B	250	x			250	x
50/50 Std + M1	250	x			250	x
50/50 C4 + M1	250	x			250	x
50/50 FSH + M1	250	x			250	x
SH + 2% G			250	x	250	x
50/50 SH + M2					250	x
SH + F2	250	x	250	x	250	x

(*) Storage at 8 °C (other peat samples stored at 21 °C)
(**) Water added (see table next page)

Water added in peat samples from Arlanda

Binder	Binder content 1 [kg/m^3]	Unconf. compr. test 28 days	Peat [g]	Water added [g]	Water ratio "natural" w [%]	Water ratio after water added w_{ny} [%]
Arlanda peat						
SH	75	x	460	0	434	434
"	125	x	460	50	434	492
"	125	x	450	67	434	502
"	250	x	450	50	434	483
"	250	x	446	50	434	479

Strength properties in gyttja

Arlanda gyttja

Original density assumed to be 1.2 ton/m³	Gyttja	Arlanda	(Compaction by constant pressure unless otherwise indicated)			
	14 d		26 d			
Binder content 200 kg/m³ = 167 kg/t	Density [t/m³]	Shear str.(**) [kPa]	Density [t/m³]		Shear str. (**) [kPa]	
SH	1.32	389(*)	1.3	1.33	436(*)	405(*)
	1.28	236	1.29	1.26	365	349
50/50 SH + CaO	1.29	74	1.32	1.32	148	137
50/50 SH + FS	1.28	153	1.29	1.3	175	175
60/40 SH+M1	1.31	233	1.31	1.31	293	311
50/50 SH+M1	1.21	166	1.27	1.27	225	178
60/40 SH+F2	1.25	146	1.28	1.26	184	191
50/50 SH+F1	1.3	129	1.29	1.21	175	189
60/40 SH+B	1.3	194	1.34	1.34	243	228
50/50 SH+B	1.32	120	1.33	1.33	195	165
50/50SH+M1+2%G	1.3	154	1.29	1.3	287	257
50/50SH+B+2%G	1.32	121	1.31	1.3	162	180
50/50 SH+F2+2%G	1.25	107	1.26	1.25	146	117
50/50 Std + M1	1.3	158	1.29	1.29	201	202
50/50 C4 + M1	1.28	116	1.26	1.28	149	144
50/50 FSH + M1	1.3	172	1.29	1.28	205	207
SH + 2%G	1.31	312	1.31	1.32	369	395
50/50 SH + M2	1.31	162	1.31	1.31	211	218
50/50 SH + F2	1.26	109	1.26	1.28	135	158

Örebro gyttja

Original density	Gyttja	Örebro	(Compaction manually unless otherwise indicated)			
assumed to be 1.2 ton/m³	14 d		26 d			
Binder content 200 kg/m³ = 167 kg/t	Density t/m³	Shear str.(**) [kPa]	Density t/m³		Shear str. (**) [kPa]	
SH	1.34	400	1.38	1.39	463	562
50/50 SH + CaO	1.39	95	1.3	1.34	64	90
60/40 SH+M1	1.4	135	1.4	1.41	230	240
50/50 SH+M1	1.39	167	1.4	1.4	234	239
60/40 SH+F2	1.37	143	1.37	1.37	139	139
50/50 SH+B	1.42	202	1.37	1.4	310	344
50/50SH+M1+2%G	1.37	93	1.39	1.39	152	127
50/50SH+B+2%G	1.39	186	1.36	1.39	276	59
50/50 SH+F2+2%G	1.37	70	1.37	1.36	92	93
50/50 Std + M1	1.41	100	1.38	1.38	149	113
50/50 C4 + M1	1.39	62	1.34	1.38	255	74
50/50 SH + F2	1.34	49	1.33	1.33	54	48

(*) Compaction by hand
(**) Unconfined compression test according to SS (Swedish Standard)

Strength properties in peat

Original density: 1 ton/m³ Binder content 250 kg/m³	Peat Arlanda 1 28 days Density t/m³		Shear str. (**) [kPa]	
SH 250 kg/m³	0.92	1	25	11
SH 75 kg/m³ (*)	1.06		44	
SH 125 kg/m³ (*) (***)	1.05	1.06	79	85
SH 250 kg/m³ (*) (***)	1.12	1.15	178	168
50/50 SH + CaO	1.18	1.17	25	21
50/50 SH + FS	0.96	0.9	18	11
50/50 SH+M1	0.95	0.92	19	7.7
50/50 SH+F1	0.93	0.83	5	3.1
50/50 SH+B	1.09	1.08	5	4.7
50/50 Std + M1	0.96	0.95	19	17
50/50 C4 + M1	0.96	0.97	13	16
50/50 FSH + M1	0.95	0.99	7.6	14
50/50 SH + F2	0.87	0.9	3.5	4.3

Original density: 1 ton/m³ Binder content 250 kg/m³	Peat 1 Örebro 1 28 days Density t/m³		Shear str. (**) [kPa]		Peat 2 Örebro 1 28 days Density t/m³		Shear str. (**) [kPa]	
SH 250 kg/m³	1.2	1.21	313	344	1.19	1.19	257	270
SH 250 kg/m³ (*)					1.19	1.20	300	319
SH 70 kg/m³	1.04		51					
SH 150 kg/m³	1.1		79					
SH 400 kg/m³	1.19		276					
50/50 SH + CaO					1.2	1.2	104	96
50/50 SH + FS	1.19	1.2	171	160	1.2	1.22	137	156
60/40 SH+M1					1.22	1.22	377	376
50/50 SH+M1	1.21	1.2	369	344	1.23	1.17	370	308
50/50 SH+M1 (*)					1.19	1.20	261	265
50/50 SH+F1					1.22	1.17	192	141
50/50 SH+B					1.23	1.21	157	155
50/50 Std + M1					1.22	1.23	391	366
50/50 C4 + M1					1.21	1.21	317	316
50/50 FSH + M1					1.22	1.22	359	288
SH + 2%G	1.21	1.21	313	281	1.23	1.16	260	239
50/50 SH + M2					1.18	1.22	193	308
50/50 SH + F2	1.17	1.18	163	167	1.21	1.21	212	190

(*) Storage at 8 °C (other peat samples stored at 21 °C)
(**) Unconfined compression test according to SS (Swedish Standard)
(***) Water added

Pore water analysis

Ion concentrations in mM(mmol/l)

	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	SO_4^{2-}	Cl^{-}	**sum +**	**sum -**	**ion balance**	**pH**
ÖREBRO										
G1 le Gy vx	1.732	0.900	0.441	0.294	3.066	0.66	5.999	6.795	-0.796	5.6
T1 Tl	0.295	0.064	0.144	0.149	0.160	0.49	1.011	0.814	0.198	5.6
T2 T	0.376	0.078	0.199	0.171	1.192	0.54	1.278	0.920	0.358	5.6
T1 unfiltered	0.393	0.070	0.167	0.146	0.212	0.49	1.239	0.918	0.321	5.6
T2 unfiltered	0.956	0.163	0.233	0.234	0.319	0.54	2.705	1.174	1.531	5.6
ARLANDA										
G2 le Gy vx	6.679	3.271	0.838	0.826	11.098	0.78	21.564	22.971	-1.407	5.6
T3 Th	1.342	0.276	0.426	0.300	1.062	0.90	3.962	3.026	0.936	5.9

Earlier tests performed at Kirkkonummi, Finland

Peat

Stabilizing agent	28 day shear strength (**) [kPa]	
	172 kg/m^3	199 kg/m^3
SH	159	
Finnish std cem+ granulated blast furnace slag 1:1		112

Gyttja

Stabilizing agent	28 day shear stregnth (**) [kPa]
	200 kg/m^3
SH	290
Finnish std cem+granulated blast furnace slag 1:1	330

Peat + gyttja 1:1

Stabilizing agent	30 day shear strength (**) [kPa]						
	100 kg/m^3	120 kg/m^3	140 kg/m^3	200 kg/m^3	250 kg/m^3	300 kg/m^3	350 kg/m^3
SH	153	187	212	369		626	
Finsk std cem						313	
Finsk std cem + granulated blast furnace slag 3:7				86	149		
Finsk std cem + granulated blast furnace slag 1:1	54			150			677
SH + 100 kg/m^3 fine sand	158	206	246	396			
SH + CaO 3:1	33			169		321	
SH + CaO 1:1						73	
SH + CaO + F (*) 1:1:1				263	353	450	

Earlier tests performed for Örebro/Arboga project

Stabilizing agent	30 day shear strength (**) [kPa]					
	Peat A (density δ = 0.98 t/m^3 water ratio w = 1350 % organic content 99.1 %)			Peat B (density δ = 0.98 t/m^3 water ratio w = 1290 % organic content 98.9 %)		
	125 kg/m^3	175 kg/m^3	250 kg/m^3	125 kg/m^3	175 kg/m^3	250 kg/m^3
Std	284	455	573	198	210	207
Std + granulated blast furnace slag 1:1	214	312	469	78	145	98
Std + CaO	110	197	247	59	86	89
Std + Finnstabi (*)	130	131	171	157	160	189
Lohjamix V15	85	172	222	102	175	271

(*) Finnstabi = special binder from Kemira pigments
(**) Unconfined compression test according to Finnish Standard

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