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PER LINDH[1,2], POLINA LEMENKOVA[3*]

BEHAVIOUR OF MORAINE SOILS STABILISED WITH OPC, GGBFS AND HYDRATED LIME

This paper aims to evaluate the effects of blended binders on the development of strength in moraine soils by optimising the proportion of several binders. We tested three types of soil as a mixture of moraine soils: A (sandy clay), B (clayey silt) and C (silty clay), collected in southern Sweden. The soil was compacted using a modified Proctor test using the standard SS-EN 13286-2:2010 to determine optimum moisture content. The particle size distribution was analysed to determine suitable binders. The specimens of types A, B and C, were treated by six different binders: ordinary Portland cement (OPC); hydrated lime ($Ca(OH)_2$); ground granulated blast furnace slag (GGBFS) and their blends in various proportions. The strength gain in soil treated by binders was evaluated by the test for Unconfined Compressive Strength (UCS) against curing time. For soil type A, the strength increase is comparable for most of the binders, with the difference in behaviour in the UCS gain. The OPC/lime, GGBFS and hydrated lime showed a direct correlation, while OPC, OPC/GGBFS and GGBFS/hydrated lime – a quick gain in the UCS by day 28th. After that, the rate of growth decreased. Compared to soil type A, $Ca(OH)_2$ performs better on the stabilisation of soil type B. Besides, the hydrated lime works better on the gain of the UCS compared to other binders. The GGBFS/$Ca(OH)_2$ blend shows a notable effect on soil type A: the UCS of soil treated by $Ca(OH)_2$ performs similarly to those treated by OPC with visible effects on day 90th. Cement and a blend of slag/hydrated lime demonstrated the best results for soil type B. An effective interaction was noted for the blends GGBFS and hydrated lime, which is reflected in the UCS development in soils type A and B. Blended binder GGBFS/hydrated lime performs better compared to single binders.

Keywords: civil engineering; UCS; soil; cement; slag; lime

[1] SWEDISH TRANSPORT ADMINISTRATION, DEPARTMENT OF INVESTMENTS TECHNOLOGY AND ENVIRONMENT, NEPTUNIGATAN 52, BOX 366, SE-201-23 MALMÖ, SWEDEN

[2] LUND UNIVERSITY, LUNDS TEKNISKA HÖGSKOLA (LTH), FACULTY OF ENGINEERING, DEPARTMENT OF BUILDING AND ENVIRONMENTAL TECHNOLOGY, DIVISION OF BUILDING MATERIALS, SWEDEN

[3] UNIVERSITÉ LIBRE DE BRUXELLES (ULB), ÉCOLE POLYTECHNIQUE DE BRUXELLES (BRUSSELS FACULTY OF ENGINEERING), LABORATORY OF IMAGE SYNTHESIS AND ANALYSIS (LISA) BELGIUM

* Corresponding author: polina.lemenkova@ulb.be

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1. Introduction

In this paper, we present an efficient approach that exploits the effects of the three different binders on the stabilisation of moraine soils. The stabilising agents include the following three binders: ordinary Portland cement (OPC); hydrated lime (calcium hydroxide, $Ca(OH)_2$); ground granulated blast furnace slag (GGBFS) and their mixtures in various proportions. The choice of these binders is explained by the physicochemical properties of lime, slag and cement, for which they are widely accepted as conventional stabilising agents for shallow stabilisation [1-4] and for horizontal stabilisation where they are used as single binders [5-7].

The blends of cement with pozzolanic materials are often used in the deep mix method of soil stabilisation [8-9]. The examples of blended binders used for soil stabilisation prove their applicability and effects on the variation of microstructure and development of soil strength [10-14]. There is a variety of blends of binders available on the commercial market, from many binder suppliers [15-18]. An inventory list of the existing powder binder blends was presented earlier [19]. Such blends have been specially designed to adopt the stabilising agents to the different soil types with the main aim to be suitable to a specific individual environmental setting of each soil type, as well as the technical goals of the works.

In general, the researchers agree that mixed binders can be more efficient, compared to single binders. This is explained by the combined effects from various physicochemical effects of the single binders, such as the content of silicon dioxide (SiO_2) in cement, or calcination reaction from lime due to the effects of calcium oxide (CaO), or pozzolanic reaction from fly ash. Together, these processes in soil particles increase their bearing capacity, due to there being less space in pores, increased stiffness and compaction [20-21].

However, the effects of percentage on blended binders and its impact on strength development are not straightforward. This can be explained by the individual properties of soil, grain size, moisture and the impact of pH on the stabilisation/solidification process in a blended soil-binder mixture which are limited by the studies on the physicochemical behaviour of soil. These include measuring strength by the standard procedure of loading specimens in a testing chamber by an apparatus for UCS tests until failure [22-24]. The UCS test is one of the most straightforward and frequently employed methods to evaluate soil strength, which is why it was used in this study to test the development of soil strength in stabilised samples.

A different approach that enhances the classic UCS testing and enables testing of soil strength and porosity by the non-destructive advanced methods includes seismic tests, which use propagated elastic waves [24-25]. Other examples include geochemical studies on soil purification, where a literature review concluded that adding binders generally decreases the level of soil contamination and leaching along with the increasing content of cementitious agents. Although pH and the content of heavy metals also play a large role. Thus, evaluating soil contamination upon stabilisation with binders is reported earlier [26-27]. Soil strength is also evaluated in the context of environmental assessment of frozen soil behaviour [28-31].

Nevertheless, the main challenge of the geotechnical works consists of the complexity of soil as a study object, owing to its different types and the variety of practical applications. This is particularly relevant for engineering cases that involve transportation infrastructure, including the construction of roads, highways, tunnels or building foundations [32-34]. With this regard, it becomes clear that no standard universal solution exists, and the soil specimens should be tested individually in each project case. The soil in this project has been collected in southern Sweden and is presented by silty clay and moraine. The moraine includes soil glacier material, such as glacial tills, unconsolidated debris and fine-grained clayey soil, which is typical for the formerly glaciated regions of southern Sweden.

This study contributes to the existing experiments on mixing binders for analysis of their effects on soil strength. The approach is based on the statistical method of mixing binder blends. The main research question is whether a mixture of different binders may result in different effects on soil stabilisation and whether the gain of strength performs more effectively compared to the process by the single binder. The goal of this study is twofold. First, we demonstrated the functionality of blended binders and their effectiveness in the stabilisation of silty clay and moraine soils. Second, we assessed the performance of the laboratory testing experiments and the behaviour of tested soil specimens.

2. Methodology

We first performed experimental studies on dry density/water content relationship analysis on the soil. Afterwards, we evaluated particle soil distribution to analyse the type of tested soil according to its structure. Then we performed the compaction tests according to the Moisture Condition Value (MCV) method. We continued with the strength tests according to the Unconfined Compressive Strength (UCS) testing. Using the results of the tests, we analysed the performance of different types of soil stabilised by different blends of binders with regard to the development of strength.

2.1. Materials

The soil material used in this investigation was excavated from three different trial pits in southern Sweden. The three different soils are denoted A, B and C in the following text. The moraine soil types are classified as follows: soil A is sandy clays, soil B is clayey silt, and soil type C is silty clay. According to the Unified Soil Classification System (USCS), soils type A (sandy clays) categorised to class CL – fine-grained inorganic clays of low to medium plasticity, sandy clays, silty clays, lean clays; soils of type B categorised to class MH – inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts; soil of type C (silty clay) is categorised by type OL – organic silts and organic silty clays of low plasticity. The soil contents used in the investigation are presented in Table 1. The soil specimens were fabricated and prepared by vibratory compaction using the compaction equipment, modified from the DYNAPAC laboratory compactor (HYPERLINK "https://dynapac.com/") [35], following the guide

TABLE 1

Characteristics of soil types tested in the laboratory experiments*

Soil type	**Particle density, ρ_s (Mg/m^3)**	**OMC mod. Proctor (%)**	**Dry density, ρ_s Mg/m^3**	**W_n (%)**	**Liquid limit, W_L (%)**	**Plasticity index**
A	2.70	6.1	2.26	9.8	19.3	<10
B	2.71	9.2	2.12	14.6	23.9	11.9
C	2.67	—	—	13.0	—	<10

* Table notes: ρ_s – Particle density, OMC – Optimum Moisture Content in modified Proctor compaction test; ρ_s – Dry density; W_n – Water content (number) in percentage; W_L – Liquid limit.

of Proctor compaction tests by the Swedish Institute for Standards (SIS) [36] modified from international standards [37].

2.2. Proctor compaction test

The Proctor compaction procedure was performed in three layers where the surface of each compacted layer was first scarified, then the next layer was added, and the procedure was repeated. Here we did not assess the curing period of single binders, but only the cumulative effects from blended mixtures. The results of the Proctor compaction are presented in Fig. 1. The compaction procedure includes the following workflow. The 4500 g of each soil specimen was compacted for one hour after mixing with the binders in a polyvinyl chloride (PVC) tube supported by an outer steel tube. The specimens were cropped to the height of about 2.06 m, sealed tight with paraffin and kept closed within the PVC tube. The temperature of curing was kept at a constant temperature of 20°C.

The relative humidity (RH) of soil shows its water content, which includes measured water content both on the surface of the particles and in pores. In this case, it was evaluated as 85%. The determination of liquid limit in soil has been performed using the guidance of the Swedish Institute for Standards [38-39] by a cone penetrometer. The complete period of curing lasted three months, while control measurements were taken on days 7, 28 and 90 to evaluate the dynamics of the stabilisation process. During this period, no weight loss was recorded in specimens, which excluded external possible bias effects.

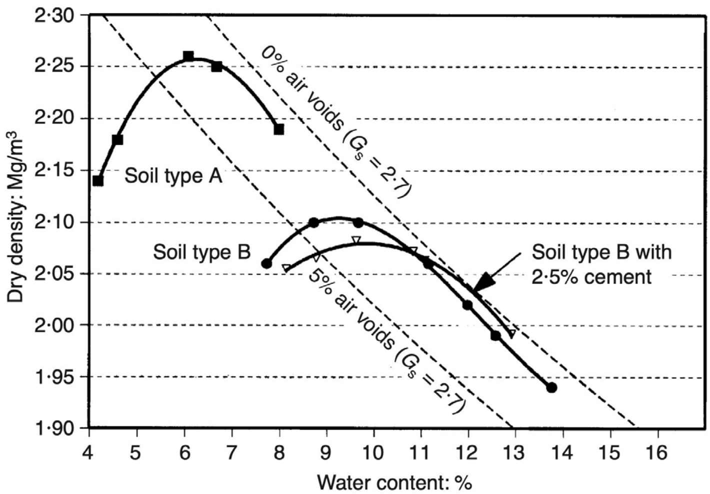

Fig. 1. Dry density/water content relationship for soil type A and B unstabilised, and soil type B stabilised with 2,5% cement, according to the Proctor test

2.3. Particle size distribution

The grain size distribution curves are plotted for all three soil types of sandy clays, clay and silty moraine in Fig. 2. This graph shows the distribution of the evaluated soil samples according to the repeatability of the particle size with the aim of assessing the grading limits for the foundation material. According to the standards of General Technical Construction Specifications for Roads [40], the acceptable quality of the foundation soil should have a grain size distributed between the dash-dotted lines, which shows the extreme acceptable limits for the foundation material, which is illustrated in Fig. 2.

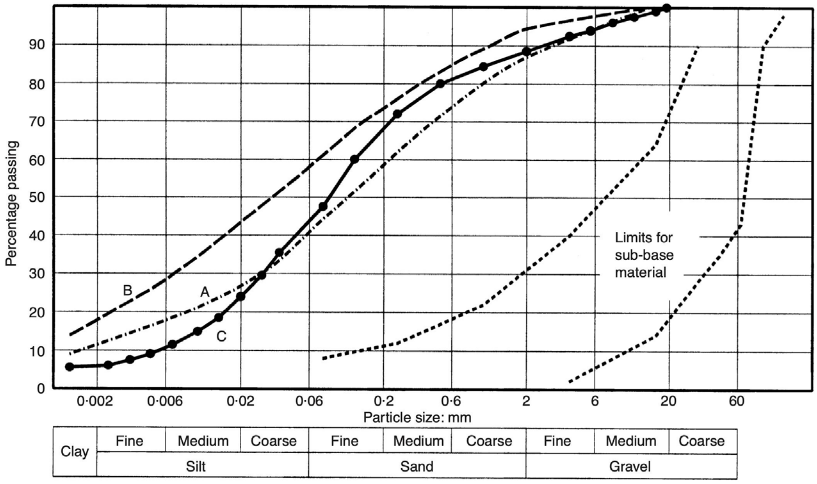

Fig. 2. Particle size distribution for soils A, B and C compared to limits for the sub-base material according to the Swedish National Road Administration (SNRA, 1996)

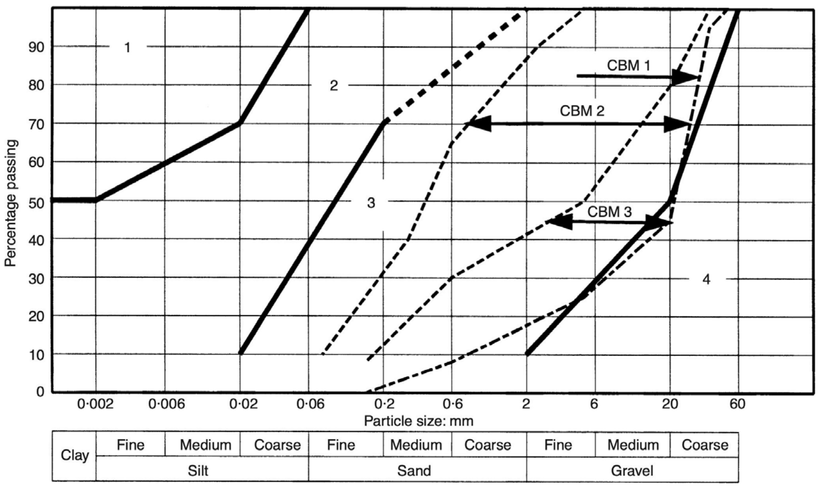

Fig. 3. Requirements for stabilised sub-base and cement-bound material. CBM 1 only has a coarse limit

As mentioned above, various stabilisation agents should be used for the effective stabilisation of different soil types. Therefore, the recommended boundaries for the applications of these binders for soil with various particle sizes are summarised in Fig. 3. Here, one can note that region 1 (upper left part of Fig. 3) represents the soils with a high percentage of fine-grained particles (0.001 to 0.06 mm), where shallow stabilisation is hardly possible. In rare cases, quicklime or hydrated lime may be used in such cases. Region 2 is presented by coarse silt and all types of sand (fine, medium and coarse) with particle sizes from 0.02 to 2 mm. It can be stabilised with quicklime or hydrated lime.

Further, binder materials OPC, asphalt or methods of mechanical stabilisation such as compaction used to bond soil-aggregate particles are recommended for region 3, which is represented from coarse silts to fine gravel (particle size from 0.06 to 6). Region 4 is represented by the most coarse fractions of gravel soil (grain size from 2 to over 60 mm), Fig. 3. Coarse fractions of gravel soil are unsuitable for stabilisation and were excluded from the experimental tests in this work. Upon the examination of soil particles, the content clay in the tested specimens ranged from 6% to 18%, i.e., we had a soft clayey type of fine-grained soil for testing, Fig. 3.

Thus, all three types of soil tested in this study (a mixture of sandy clays, clay and silty moraine) are classified as in regions 2 and 3 in Fig. 3. For such types of soil, the stabilisation works well with lime and cement (when selecting single binders), which were selected as binders for this reason. The OPC, GGBFS and hydrated lime were used as commercially available binder materials. The chemical analyses of all three binders showing the specific content of components are presented in Table 2.

TABLE 2

Chemical analysis of binders used in this experiments

Chemical compound	Portland cement, %	GGBFS, %	Hydrated lime, %
CaO ($Ca(OH)_2$)	61.9	36	72.9*(92)
SiO_2	19.8	36	0.8
Al_2O_3	4.1	10	0.6
Fe_2O_3	2.6	0.4	0.2
MgO	3.4	13	1.2
K_2O	1.3	0.6	0.1
Na_2O	0.3	0.4	0.1
SO_3	3.6	2.5	—
Loss on ignition	2.5	—	24
Cl	0	—	—
P	—	—	0.01
Total	99.8	98.9	99.9
Glass content	—	97	—
Specific surface	3753 cm^2/g	5000 cm^2/g	160000 cm^2/g

* Equivalent value, hydrated lime contains no CaO.

2.4. Binders for soil stabilisation

The stabilising agents react differently depending on the soil type. This is caused by a variety of reasons, of which the most important are the chemical content, processes of bonding with soil particles, followed by the temperature and period of curing as well as equipment and methods of curing. For example, upon the reaction with water, cement produces a mixture of gel composed of CaO, SiO_2 and H_2O. A total of 100 kg of cement, upon the reaction with 25 kg of water, will produce 100 kg of gel (CaO, SiO_2, H_2O) and 25 kg of hydrated lime ($Ca(OH)_2$).

Likewise, 25 kg of hydrated lime ($Ca(OH)_2$) reacts with Al_2O_3 and SiO_2 and results in ca. 75 kg C_2AS*8H_2O. For instance, $Ca(OH)_2$ may produce the most significant amount of binder, while GGBFS – the smallest. The difference in reaction products from six various binder blends used in this research is summarised in Table 3. Here one can notice that the cement performs better than the other stabilised agents in the stabilisation of coarse-grained soil. For instance, compared to hydrated lime, it does not require any external minerals as additives in a binder, Table 3.

TABLE 3

Amounts of reaction products in kg produced from different binder combinations after complete reaction

Recipe type	Binder ratios	Binder fabricated	Pozzolanic binder	Total binder content
1	Cement (100)	100	75	175
2	Cement (50) + slag (50)	100	37	137
3	Slag (100)	100	—	100
4	Slag (50) + lime (50)	50	152	202
5	Lime (100)	0	305	305
6	Lime (50) + cement (50)	50	190	240

Apart from the soil type with different particle size distributions, the reaction of the binder varies with the time of progress. For instance, cement has the fastest stabilisation effects, which start to react within as quickly as two hours after mixing with soil. Moreover, a large part of the soil-cement reaction is complete in less than one month (28 days). Compared to cement, the effects of lime were notable after a longer time, that is, the reaction of lime with soil performs slower. However, the complete chemical reaction with clay is achieved after 18 months for both binders. However, the mixture of lime/clay results in more reaction products against the cement/clay, which is also dependent on the soil temperature as an additional factor.

We selected the mixtures of suitable binders to achieve the improvement of the physiochemical properties in the stabilised soil specimens. To this end, we used the existing guidance for the stabilising agents that best suit a specific fine-grained soil type, Table 4. Specifically, the selection of binders considers the response from different particle sizes of soil on various binders used for soil treatment, as shown in Table 4. Therefore, in silty and clay moraine, hydrated lime changes particles, which results in the increased workability of the stabilised soil. In contrast, quicklime may improve the strength of the coarse-grained soil due to the decreased water amount in a soil specimen during slaking.

For example, lime is the best suitable binder for clayey fine-grained soils, because it facilitates clayey minerals to produce products with pozzolanic reactions. Here we can note that coarse silt, based on its properties, is ranked between hydrated lime and cement, as per Table 4. This illustrates that a blend of lime/cement reacts better with soil, compared to pure binders used for the stabilisation of the same soil specimens. The classification of binders according to their effects on strength development in soil, using standard laboratory methods, equipment and tools for compacted soil, is presented in Table 5. These trial experiments are designed for the deep mix method of stabilisation.

TABLE 4

Suitability of stabilisation approaches for various soils* (modified after [22])

Designation	Fine clay	Coarse clay	Fine silt	Coarse silt	Fine sand	Coarse sand
Grain size, mm	<0.0006	0.0006-0.002	0.002-0.01	0.01-0.06	0.06-0.4	0.4-2.0
Soil volume stability	Very poor	Fair	Fair	Good	Very good	Very good
Lime	++	++	++	–	–	–
Cement	+	+	+	+	++	++
Bitumen/asphalt	–	–	–	–	++	++
Polymeric-organic	–	+	++	++	++	–
Mechanical	–	++	++	++	++	++
Thermal	++	++	–	–	–	–

* Explanation of values: ++ Maximal effective; + Effective, but quality may vary; – Not effective.

TABLE 5

Classification of strength development in fine-grained soils stabilised through the addition of different binders*

Soil type	Stabilising agent		
	Lime	Lime and cement	Cement
Clayey silt	v	+	++
Silty clay	+	+	++
Clay	v	+	+
Clay (quick)	+	+	++
Clay (saline)	+	+	+
Clay (sulphide)	–	+	+
Clay (organic)	v	+	+
Clayey mud	v	v	+
Gyttja	–	v	+
Peat	–	v	+

* Explanation of suitability effects: – None or poor; v Acceptable; + Good; ++ Excellent.

2.5. Soil strength (UCS)

The Unconfined Compressive Strength (UCS) test was performed [41]. Evaluating the UCS is a crucial step in soil quality assessment, as it well represents the mechanical and physical properties of stabilised soil. The process of stabilisation improves the main characteristics of soil, such as liquid limit, plasticity, shrinkage, compactness, stiffness and strength. Therefore, stabilised soil specimens were tested on strength. In the following section, Figs. 4 to 7 show the changes in the strength values of soil-binder mixtures for 7, 14, 28, and 90 days of curing. Overall, the UCS values increase along with the curing period for all the binder contents. The higher UCS values are a result of soil particles sticking together more tightly in soil-binder mixtures that are more dense. Increased bonding between the grain particles results in a greater load resistance of the tested soil specimen, as well as reflected in its improved strength.

3. Results and discussion

Fig. 4 shows the development of strength (UCS) in the soil of type A (sandy moraine clays) stabilised by various binders: lime, GGBFS, GGBFS/lime, OPC/lime, OPC/GGBFS and pure OPC. The strength increase for OPC/hydrated lime is parallel to the strength increase of GGBFS but GGBFS gives lower values in UCS. After seven days the mixture of GGBFS and hydrated lime performs similarly to pure hydrated lime. However, on day 90th of the curing period there is a clear advantage for the blend GGBFS/hydrated lime.

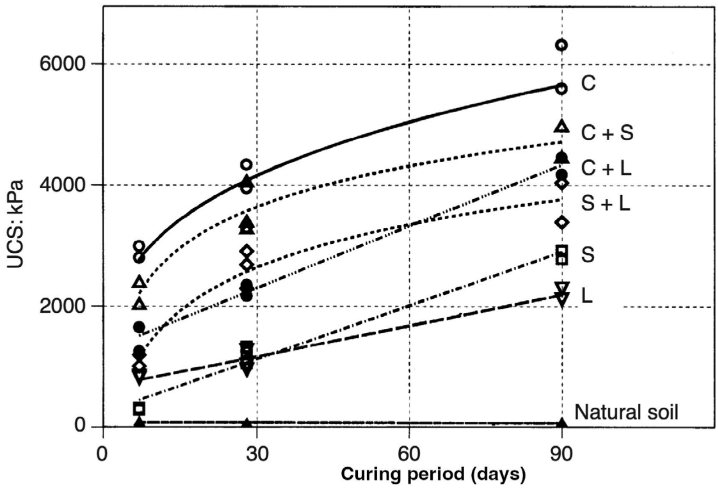

Fig. 4. The variation in UCS values based on different curing agents and time period for soil type A. Abbreviations: C = 2.5% cement; S = 2.5% slag; L = 2.5% lime; S + L = 1.25% slag + 1.25% lime; C + S = 1.25% cement + 1.25% slag; C + L = 1.25% cement + 1.25% lime

The analysis of Fig. 4 shows that cement (OPC) contributes to higher levels of strength in soil, compared to the other types of binders. Likewise, specimens treated with GGBSF demonstrated the lowest UCS on day 7th of the curing period. However, on day 28th soil performs similarly to specimens stabilised by the hydrated lime, see Fig. 4. This phenomenon can be explained by the low clay content in soil type A, which might be responsible for a low increase in UCS for soil treated by $Ca(OH)_2$.

Besides, the results also demonstrate a larger interval of variations in UCS, compared to the soil type B (clayey silt), as in Fig. 4 and Fig. 5. Here, the UCS for soil type A varies from 2 to 6 MPa, while the one of soil type B lies within the range of 0.8 to 2.7 MPa. When using the same binders and combinations, the sandy and silty moraine is more stabilised than the clay moraine. Furthermore, the OPC demonstrated the largest impact on the UCS of soil on day 90th (5.8 MPa), followed by the blend OPC/GGBFS (4.7 MPa), OPC/lime (4.5 MPa), GGBFS/hydrated lime (3.85 MPa), GGBFS (2.9 MPa) and hydrated lime (2.1 MPa), Fig. 4. The GGBFS has the lowest impact on UCS for both soil types, which is notable on day 7th (200 kPa), as shown in Fig. 4.

Fig. 5 shows the behaviour of soil type B (clayey silt) upon stabilisation with various binders. The UCS of soil type B after the 7th day of the curing period results in a linear model for GGBFS

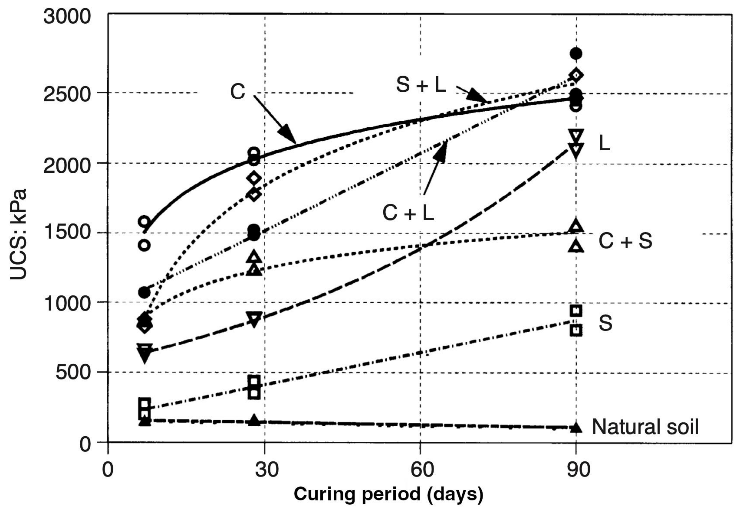

Fig. 5. The variation in UCS values based on different curing agents and time period for soil type B. Abbreviations: C = 2.5% cement; S = 2.5% slag; L = 2.5% lime; S + L = 1.25% slag + 1.25% lime; C + S = 1.25% cement + 1.25% slag; C + L = 1.25% cement + 1.25% lime

and natural soil, which also show the lowest values of UCS (250 and 180 kPa, respectively). The correlation has quadratic curves for the binder combinations lime / GGBFS (dotted line) and cement with a rapidly increased strength by day 28th with values of 1700 kPa and 2100 kPa, respectively. The UCS demonstrated a straight line by using blended cement/hydrated lime, rapidly increasing linearly: 1100 kPa (day 7th), 1500 kPa (dat 28th), 2600 kPa (day 90th). The stabilisation by pure hydrated lime shows a hyperbolic curve with increasing strength: UCS on day 7th is 570 kPa, on day 28th is 850 kPa and on day 90th is 2200 kPa, Fig. 5.

As per Fig. 5, it can be noted that using blend hydrated lime/GGBFS as stabilisers in a ratio 50/50 gives the quadratic curve with a more notable impact on strength development, compared to the 100% lime. For instance, the values of UCS for a blend lime/slag versus lime are as follows (Fig. 5): the UCS for the lime/slag on day 7th is 800 kPa, for day 28th is 1750 kPa, on day 90th is 2600 kPa, while for 100% pure hydrated lime the UCS for the day 7th is 600 kPa, on day 28th is 900 kPa and on day 90th is 2200 kPa, Fig. 5. This proves the effectiveness of the blended binder (lime/slag), compared to the pure lime for the development of strength (UCS) in tested soil specimens of type B (clayey silt).

Fig. 6 shows the development of strength (UCS) for the sandy clay (type C), stabilised by the same binders, as described above. Here one can note that cement (OPC) is still the dominating factor in UCS gain, compared to hydrated lime, and in this case, the pure OPC component works better than the blend of cement/lime. The strength for sandy clay treated with four binders shows that specimens stabilised with OPC and lime (5% for each in ratio) gives a lower UCS value compared to soil stabilised with only cement (5%). For instance, the comparison of UCS for the OPC versus cement/lime gives the following values: on day 7th – 3600 for C10 while 1850 for C/L, on day 14th – 4100 kPa for C10 while 1900 for C/L, on day 28th – 4700 kPa for cement C10, while 2050 kPa for C/L and on day 90th – 5400 kPa for C10 while 2100 for C/L. For soil type B (Fig. 6), the UCS in specimens measured on day 28th of the curing period showed similar

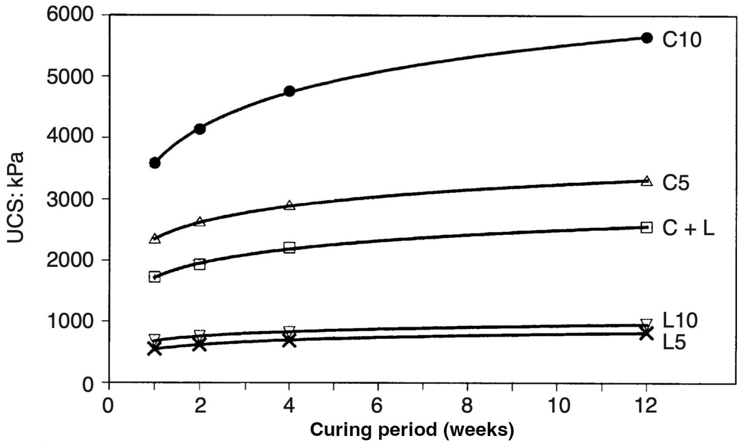

Fig. 6. UCS after different curing periods and binder types for a sandy clay (type B).
Notations: C = 10% cement; C5 = 5% cement; L5 = 5% lime; L10 = 10% lime; C + L = 5% cement + 5% lime

effects in strength gain as the one in samples measured on day 7th, but the effects from the blended mixture of lime/cement are more notable, if compared to other binders. This indicates that lime is suitable as a binder for the treatment of sandy clay.

Fig. 7 shows clayey silt, chosen as a reference material for the comparison with soil types A and B. Blended binders lime/OPC and single binder lime and OPC were used for soil stabilisation. The analysis of Fig. 7. shows that a mixture of the OPC/hydrated lime leads to a quick increase in UCS of soil, which reaches its maximum by day 28th, then stabilises and does not exceed 1000 kPa for the complete curing period. The contributions from the pozzolanic reaction to UCS for the blends that contain $Ca(OH)_2$ are rather insignificant. In contrast, the effects from

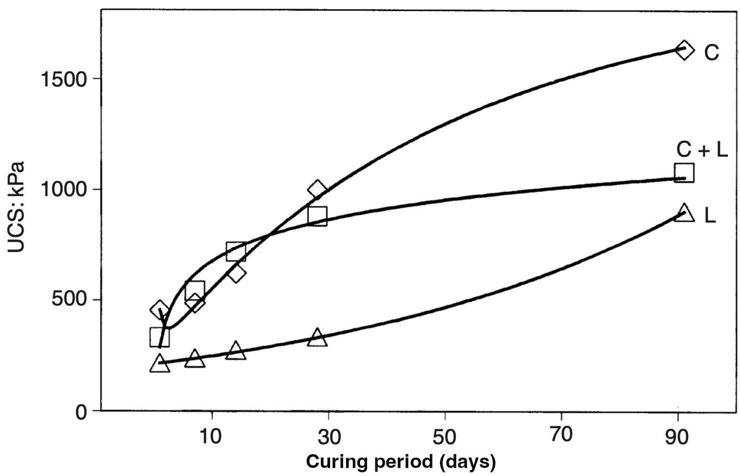

Fig. 7. The UCS at different curing periods and binder types for a clayey silt (type B).
Notations: C = 4% cement; L = 4% quick lime; C + L = 3% cement + 1% quick lime

the OPC and hydrated lime show clear increase in strength for the complete period, with cement dominating in values. Compare the values of UCS for the final day of curing: 1700 kPa for cement, 950 kPa for blended mixture and 750 kPa for lime. The performances of $Ca(OH)_2$ and the mixture of OPC/$Ca(OH)_2$ are comparable after 90 days of curing.

The mixture of the GGBFS and hydrated lime as binders perform better in comparison to pure OPC. It is because a blend of GGBFS and hydrated lime does not affect soil compactness as much as OPC. Second, the content clay in soil type B is enough to produce the maximum amount of stabilised material. As for soil type A, the clay content here is lesser and not enough to produce reaction products by cement binder.

4. Conclusion

This paper presents a novel series of soil tests using silty and clay moraine, collected in southern Sweden. The stabilisation of soil by binders is necessary in cases when the soil has characteristics that are not sufficient for construction works: poor in quality and soft texture or having lower UCS values. This is a case for clayey expansive soils. Investigating the effects of various binders and their combinations on soil behaviour during the stabilisation process can be useful in increasing soil strength and bearing capacity. This is because soil treatment with different binders can further enhance its properties. It is possible to use single binders and to combine them in various proportions. To this end, we have demonstrated the effects of various binders for the stabilisation of soil specimens using three main types of binders (1) OPC; 2) hydrated lime ($Ca(OH)_2$); 3) GGBFS) and their blends in various combinations and ratios.

In this paper, we have proposed a novel approach to the stabilisation of a Swedish mixture of moraine soils (sandy clay, clayey silt and silty clay) using six different binders: ordinary Portland cement (OPC); hydrated lime ($Ca(OH)_2$); GGBFS and their blends in various proportions. The method is efficient and can handle significant mining engineering problems related to the fundamental soil performance following soil-binder chemical interactions. To effectively stabilise different types of moraine soil, standard binders in fixed proportions are not sufficient. Therefore, we experimentally tested the combinations of these binders and observed the effects of binder ratios on soil behaviour, i.e. soil strength parameters, which indicate bearing capacity.

Specifically, we tested ordinary Portland cement, GGBFS, and hydrated lime, in various proportions (%) and evaluated the effects of the percentage of stabilising agents, including pozzolanic binders, on the results of soil stabilisation. Because the reaction of binder varies with the time of curing progress, limiting binder content received using the existing methods of soil stabilisation does not consider the most influencing inherent clay mineralogy of the materials, which is the case for moraine soils of southern Sweden. Therefore, we additionally evaluated the particle size distribution for soils A, B and C compared to limits for the sub-base material, as well as estimated the dry density/water content relationship for soil types A, B and C with the use of the Proctor test.

This study confirmed the effectiveness of traditional methods for stabilising soil, particularly in determining the strength parameters of Swedish moraine soils. These soils are difficult to work with due to their fine-grained nature, but the study experimented with different binders to find solutions. It has been demonstrated that the effects of various binders on soil parameters using conventional techniques of stabilisation are controlled by the combined influence of chemical and mineralogical properties of binders reacting with soil particles. Thus, the usage of various binders for soil treatment implies the improvement of soil properties: strength, workability and bearing capacity, which is necessary for the construction of critically important objects of transport infrastructure, roads and foundations.

A suitable combination of binders has been made using the information on soil particle size and grain distribution analysis since fine-grained and coarse-grained soils should be stabilised using different binders for the best effects, as demonstrated in this paper. Our method has several advantages. It can easily be applied to clay soils, specifically moraine tills in southern Sweden. Additionally, it is cost-effective in engineering projects due to the flexible combination of binders. While there are several binders available on the market, their use in real projects can have some disadvantages. Thus, to make a correspondence between the long-term performance and rational workflow of the construction process in real projects, commercial producers propose diverse blends of binders, specifically adjusted for the specific soil types, considering regional properties and available materials.

However, a significant disadvantage of using novel commercial blends of binders is that the information regarding the ratio and exact proportions of chemical components constituting a mixture is not always available. Instead, the manufacturers tend to apply trade names to the novel binders rather than explaining their chemical content and proportions of blends. Accordingly, novel methods and approaches are tested in real projects for improving the workflow of the binder stabilisation process and to evaluate the effects of the binders on soil strength [42-44]. However, since soil stabilisation is of utmost importance for civil engineering due to its direct effects on the safety of constructions and roads, novel approaches should be tested to define the optimal binder blends designed for effective soil stabilisation. To handle such constraints, we used the available binders and performed a series of tests on soil stabilisation, using a combination of binders in various proportions, to define the best parameters of binders which have the most effective effects on soil stabilisation, specifically for the regional type of moraines of southern Sweden with a fine-grained structure of the soil. Thus, as a response to the need to determine the most optimal combination of binders for fine-grained soil stabilisation, and to fill in the gap in the existing trials on binder components and their effects on soil strength, we presented in this study a series of trials on soil strength on silty and clayey moraine from southern Sweden, stabilised by various binders in different compositions and their blends.

Our method can be applied to various soil types by combining binders and assessing the impact of the mixtures on soil characteristics. Moreover, the method of soil stabilisation, as demonstrated in this paper, presents solutions that can be repeated on other specimens of fine-grained soil, because it is based on the use of the existing binders (cement, slag, lime), which were mixed in various proportions and applied for stabilisation of several types of Swedish clayey moraine. It is crucial to test the strength of soil in real engineering geologic projects to achieve solidification. Theoretical computations cannot replace this process as the soil is a complex object with unique properties that are formed as a result of regional long-term geologic development and landscape-climatic local setting.

More complex recommendations for selecting stabilising agents may be applied for the treatment of various soil types, depending on their regional properties, for instance, prone to freeze-thaw effects in cold regions, e.g., similar to those in Sweden. Although general standards of soil stabilisation exist, it is always necessary to perform experimental testing of soil specimens in real engineering projects as a requirement for the safety and stability of civil constructions and engineering objects. The behaviour of strength in specimens stabilised by different binder blends has been illustrated through statistical plotting. We believe that our experiments, as a contribution to the development of effective methods in practical soil engineering and geotechnical constructions, will find applications in future similar projects as a reference study. Thus, this report provides new solutions for the use of binder blends on soil solidification and stabilisation of fine-grained moraines collected in southern Sweden and can be used as a case study in future works.

As a recommendation for future studies, the extended experimental tests may include additional investigation of shear strength parameters of soil, such as the variations of cohesion and internal friction angle of soil, which are important parameters in the evaluation of its bearing capacities. For instance, specimens treated by various binders as curing agents may be tested for internal friction based on differences. Besides, various additives, for instance, granite powder, can improve the angle of internal friction and decrease cohesion values which improves the overall performance of the stabilised soil. Such additional laboratory experiments are considered as future directions of the study with extended applications of improvement of soil parameters. In this case, soil specimens should be subjected to a variety of geotechnical experiments in the laboratory and in-situ conditions, following the existing standards.

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