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Article

Simplex Lattice Design and X-ray Diffraction for Analysis of Soil Structure: A Case of Cement-Stabilised Compacted Tills Reinforced with Steel Slag and Slaked Lime

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Abstract: Evaluating the structure of soil prior to building construction is valuable in a large variety of geotechnical and civil engineering applications. To build an effective framework for assessing the strength of the stabilised soil, the presented workflow includes a complex approach of simplex lattice design and X-ray diffraction for the analysis of soil structure. Different from the traditional in situ measurements, we propose a statistical framework for effective decision-making on binder combination to stabilise soil collected in three localities of Southern Sweden—Bromölla Municipality (Skåne County), Petersborg (Östergötland County) and Örebro (Örebro County). A practical solution is presented that includes the evaluation of strength properties of various types of soil using ordinary Portland cement (OPC), slaked lime and steel slag as pure agents and blended binders. The specimens were collected in Southern Sweden and included sandy silty tills and clay till (clay content 6–18%). The preprocessing included the mineralogical analysis of mineral composition and soil structure by X-ray diffraction (XRD) and a sieve. The soil samples were fabricated, compacted, rammed, stabilised by six binder blends and assessed for uniaxial compressive strength (UCS). The moisture condition value (MCV) and water content tests were done for compacted soil and showed variation in the MCV values for different binders. The study determined the effects from binder blends on the UCS gain in three types of soil, measured on days 7, 28 and 90. Positive effects were noted from the steel slag/lime blends on the UCS gain in sandy silty tills. A steel slag/slaked lime mixed binder performed better compared to the pure binders. The effectiveness of the simplex lattice design was demonstrated in a series of ternary diagrams showing soil strength evaluated by adding the stabilising agents in different proportions.

Keywords: steel slag; simplex lattice design; ordinary Portland cement; slaked lime; X-ray diffraction; compressive strength; soil stabilisation; civil engineering

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1. Introduction

Cementitious materials have positive effects on the development of strength and the hardening of clayey soil during stabilisation. Many traditional binders often are used for



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soil stabilisation, among which cement is widely accepted [1–4]. Apart from cement, many other stabilising agents can be added to binder blends. Replacing the cement by other materials aims to enhance the technical performance of soil stabilisation, to increase the economic efficiency of the construction process through cheaper materials and to reduce the environmental impacts from CO₂ discharges [5–7]. Moreover, blends fabricated from various binders have more durable and notable effects on soil [8–10]. The stabilisation of soil is due to the ability of binders to decrease the space between the pores in soil through the bonding of particles during the period of curing [11,12]. The decrease of volume in the pores of soil develops over the time of curing and results in the decreased porosity and permeability of soil [8–10]. Cementitious binders increase the compactness and strength of soil, which increases its workability and bearing capacity, the key requirements for soil quality in road construction.

Many various binders have notable beneficial effects on the development of strength in binder–soil blends in the process of stabilisation. For instance, adding slaked lime and steel slag increases the uniaxial compressive strength (UCS) of soil, as reported in many studies [11–13]. As for the impact from the mixtures of binders on soil compactness, earlier works have shown their positive effects on various types of soil intended for the construction of roads [14–16]. An industrial waste with pozzolanic properties, ground granulated blast furnace slag (GGBS) is obtained as a by-product from the steelmaking process [17].

The fundamental physical properties of metallurgical slag include viscosity and rheological parameters, formed through chemical composition, which includes SiO₂ (silica), Al₂O₃ (aluminium oxide) and MgO (magnesium oxide) [18]. This makes steel slag a widely used binding component in soil stabilisation for roadbed structures [19–21], as it has benefices on pore structure of soil, due to its physio-chemical properties. Because soil as a porous material which experiences shrinkage and decrease in voids with the inclusion of cementitious binders, the compaction and stabilisation processes significantly decrease porosity and increase the bulk density of soil [22]. This suggests positive effects from the additives in soil, which increase its strength and decrease permeability and porosity when added in optimal amounts [23,24]. Another often-studied environmental parameter that is closely related to climate setting is the freeze-thaw durability of soil used as roadbeds, which is actual for countries with cold climate conditions [25,26].

The stabilisation of soil takes into account chemistry of the stabilising agents which provides the effects of binders on soil strength [27]. Thus, the UCS of soil is improved with binders due to the beneficial effects from reinforcing materials. Moreover, the resistivity of soil is enhanced by stabilisation against seasonal climate cycles, such as freeze–thaw processes. Earlier works reported that added binders, such as cement pastes, improved the microstructure and geotechnical parameters of soil: shear modulus and compaction). This is caused by the increased bonds between the soil's particles, which chemically reinforce its inner structure [28–30]. Steel slag binds soil particles effectively in contaminated soil polluted by heavy metals, and decreases leaching [31–33]. In turn, steel mill sludge can be used for the reinforcement of clay bricks, to decrease negative environmental consequences and to optimise its utilisation [34].

The effects from blended binders and their influence on the development of soil strength are not as straightforward. If we consider the general inclusion of stabilising agents, it increases the UCS of soil. However, the effects may vary individually, depending on the types of binders and soil, as well as the effects from external factors such as the curing period and temperature). For example, slaked lime and fly ash reduce the permeability and improve the strength in a cohesive soil due to the pozzolanic reaction from the siliceous and aluminous materials [35]. The incorporation of cement decreases the porosity in the pore microstructure of soil due to the bonding of particles [36,37]. However, the effects from different pH in various soil types are also important: strength increases with a higher pH [38,39]. Finally, the important parameter is the mineralogy and structure of soil: fine-grained, medium-grained or coarse-grained [40].

Although rates in strength development generally increase along with the increasing content of binders in a cement–soil mixture, external factors such as moisture content and temperature also play a significant role. Thus, since the effects of pore refinement in soil and compaction act simultaneously during curing, it is always necessary to determine the effects from binders in each case, since they may vary in different binders used for soil stabilisation. In general, binders reduce the permeability of soil, ensure a gain in strength and eliminate environmental effects (decreased leaching, reduced pH).

The existing literature and case studies on soil stabilisation tend to focus on the final stage when assessing the gain in strength. It includes the effects from various binders, both traditional [41–43] or novel ones [44,45], and the evaluation of workability of the stabilised soil [46]. These methods are effective to evaluate the general stabilisation results and to obtain a rough estimate of the soil strength over a curing period. However, a comparative analysis of blended mixtures needs special attention, to provide adequate data regarding the analysis of the effects from particular binders and their ratios, when mixed in proportion, on soil strength. Apart from the traditional UCS testing, more advanced techniques that allow for accurate and nondestructive measurements include seismic waves and X-rays [47,48]. One such technique uses elastic P-waves propagating through a soil specimen. The soil strength is calculated from the measured P-wave velocities, which directly correlate with the stiffness, hardness and density of the microstructure in a porous medium [49,50].

The accurate and systematic evaluation of strength in clayey tills from Southern Sweden is lacking. Such soils are subject to harsh environmental and climate conditions and require individual testing of their behaviour. This especially concerns experimental tests on stabilisation by various binders using blended mixtures in various proportions. Therefore, the objective of this study was to fill in this gap by presenting a study with a special focus on Swedish soils collected in three localities: Bromölla Municipality (Skåne County), Petersborg (Östergötland County) and Örebro (Örebro County). The study presents a statistical evaluation of the effects from various proportions of binders on soil strength. To this end, we evaluated these effects over a period of curing and presented data as a series of ternary diagrams plotted by the simplex method. Besides, the influence of binders on the moisture condition value (MCV) of soil was evaluated to show their effects on soil improvement. The binders should be selected for each type of soil individually, because various binders are better adjusted to various soil types. Therefore, the effects from diverse binders should be tested and evaluated separately using a statistical approach to optimise the workflow. To this end, we performed a series of statistical simplex tests to define the best relationships of soil–binder mixtures with regard to the strength of soil.

This study evaluated the effects from stabilising agents on the long-term strength gain in three types of soil measured on days 7, 28 and 90. The binders included ordinary Portland cement (OPC), slaked lime and ground granulated blast furnace slag (GGBFS). Additional geotechnical characteristics were tested for each type of soil stabilised by various binders: dry density, water content and MCV. In order to perform the tests more effectively, we performed a statistical optimisation of these processes using existing experimental approaches [51,52]. The research was performed using the available tools and equipment of the Swedish Geotechnical Institute (SGI). The methodology followed the standards on soil quality testing defined by the Swedish Institute for Standards (SIS). The dynamics in strength and changes of soil structure stabilised by various binders were examined by the UCS and moisture and compactness were evaluated using the Proctor compaction test during curing. The variations were visualised, compared and analysed as a series of ternary plots showing the correlations between binders and the strength of the stabilised soil.

2. Materials and Methods

2.1. Approach

To evaluate structural and physicochemical parameters of the soil, we applied two types of tests: the moisture condition value (MCV) for the compaction characteristics of

specimens and the uniaxial compressive strength (UCS) for strength properties of the stabilised soil.

2.2. Sample Preparation

The samples were fabricated using raw material originated from three localities of Southern Sweden—Bromölla Municipality (Skåne County), Petersborg (Östergötland County) and Örebro (Örebro County). Tested soil included types A, B and C with varied physiochemical characteristics, described as follows. The clay content of these specimens varied from 6 to 18%. Based on the dominating size of the particles within the tested specimens, sandy silty tills characterised soils of types A and C, and clay till characterised soil type B. The material characteristics is summarised as follows.

- Soil type A had the following characteristics: particle density $\rho_s = 2.70 \text{ mg/m}^3$; the optimum moisture content (OMC) according to the modified Proctor compaction test was 6.1%; the dry density was $\rho_d = 2.26 \text{ mg/m}^3$; the natural water content was (W_N) = 9.8%; the liquid limit measured by a cone penetrometer (W_L) was 19.3%; the plasticity index was <10.
- Soil type B had the following characteristics: particle density, $\rho_s = 2.71 \text{ mg/m}^3$; OMC according to the modified Proctor compaction test, 9.2%; dry density, $\rho_d = 2.12 \text{ mg/m}^3$; natural water content, (W_N) = 14.6%; liquid limit by cone penetrometer, (W_L) 23.9%; plasticity index < 11.9.
- Soil type C included only measurements of the particle density and W_N . Thus, the particle density ρ_s for soil type C was 2.67 mg/m^3 and $W_N = 13.0\%$; plasticity, index < 10. The Table 1 summarises the performed tests.

Table 1. Summary of tests for soil samples stabilised by OPC, hydrated lime and GGBFS.

Soil Type A											
Recipe	0	1	2	3	4	5	6	7	8	9	10
OPC	0.00	2.50	1.25	0.00	0.00	0.00	1.25	0.83	1.67	0.42	0.42
Lime	0.00	0.00	0.00	0.00	1.25	2.50	1.25	0.83	0.42	0.42	1.67
GGBFS	0.00	0.00	1.25	2.50	1.25	0.00	0.00	0.83	0.42	1.67	0.42
Soil Type B											
Recipe	0	1	2	3	4	5	6	7	8	9	10
OPC	0.00	2.50	1.25	0.00	0.00	0.00	1.25	0.83	1.67	0.42	0.42
Lime	0.00	0.00	0.00	0.00	1.25	2.50	1.25	0.83	0.42	0.42	1.67
GGBFS	0.00	0.00	1.25	2.50	1.25	0.00	0.00	0.83	0.42	1.67	0.42
Soil Type C											
Recipe	0	1	2	3	4	5	6	7	8	9	10
OPC	0.00	2.50	1.25	0.00	0.00	0.00	1.25	—	—	—	—
Lime	0.00	0.00	0.00	0.00	1.25	2.50	1.25	—	—	—	—
GGBFS	0.00	0.00	1.25	2.50	1.25	0.00	0.00	—	—	—	—

Notations for Table 1. Grain size distribution, particle density, natural water content and XRD tests performed for all soil types recipe 0. Optimum moisture content was tested for type A recipe 0 and type B recipes 0 and 1. Liquid limit was tested for types A and B, recipe 0. The UCS tests were performed on days 7 (types A and B, recipes 0 to 6, twice in each case), 28 (A: recipes 0 to 6, thrice; B: all the recipes, twice; C: recipes 1 to 6, twice) and 90 (twice for all cases for A: all recipes; B: recipes 0 to 6; C: 0 to 7).

2.3. X-ray Diffraction (XRD)

Diverse behaviours of various types of soil during stabilisation can be analysed based on mineral soil properties, which are related to the compositional characteristics of soil. The analysis of soil by X-ray diffraction (XRD) may facilitate the explanation of the mechanisms underlying the responses of soil specimens to hardening with binders. Therefore, XRD enables one to better understand soil properties and to estimate the compositional content of particles and minerals contained in the soil samples. To this end, we estimated the mineral composition and structure of the solid phases of soil using the difference in

XRD patterns, to understand their response to the addition of binders during the stabilisation process.

The X-ray diffraction (XRD) method was applied to identify the mineral compositions of soil specimens and to observe soil specimens. The quantitative evaluation was conducted with an electron microscope to obtain structural and microstructural information (crystallite size and lattice pattern) for soil specimens prepared for stabilisation and hardening. The principle of soil hardening consists in the adsorption of binders during reactions with soil and transport of the stabilising materials through the pores of soil, which performs at the interfaces of soil with various physiochemical properties that are different for the soil components. Soil types A and B contained clay minerals in a mixed layer of smectite montmorillonite), illite and kaolinite. Soil type C contained chlorite $\text{ClO}-_2$, illite and kaolinite.

2.4. Binders

Binders can be rated according to their effects on the strength development in soil (Table 2). For example, the suggested binders containing sand, cement and lime were suitable for illite and kaolinite. This explained the choice of lime and cement as binders for the stabilisation of soil types A and B. The chlorite in soil type C responded well to stabilisation by cement, which is why OPC was selected for soil type C. For these reasons, the following commercially available binders were used for the soil treatment: OPC, GGBFS and a slaked lime.

Table 2. Suitability of binders in stabilisation of soil (Unified Soil Classification System, USCS).

Stabilising Agent *	G	GW	GM	S	CS	CH
A	++	++	++	+	+	—
B	++	++	++	++	++	+
C	++	++	++	++	++	—
D	+	+	++	—	+	++
C (CaO + GP cement)	—	—	+	—	+	++
C (CaO + GGBFS)	—	++	++	—	+	+
E	++	++	+	+	—	—
F	++	++	+	+	—	—
G	+	++	++	—	++	+

Notations for Table 2. Definitions of symbols, according to USCS: G: gravel (crushed rock); GW: well-graded gravel; GM: silty/clayey gravel; S: sand; CS: sandy/silty clays; CH: fat heavy clay. Suitability: ++ perfectly suitable; + satisfactory; — not suitable. * Symbols for binders: A—GP cement AS3972; B—GB cement AS3972; C—cementitious blend of pozzolanic binders (fly ash + GP cement + GGBFS + CaO in triple and quaternary mixtures); D—slaked lime or calcium hydroxide (CaO); E—asphalt/bitumen, standard AS2008; F—GP cement/asphalt; G—insoluble polymers.

The blends of the standardised binders were used in blending operation, which was performed in a mixing with soil, according to the SGI standards for soil composition and recommended binders. It was controlled through records used for the ternary plots for the UCS estimation. We selected different types of binders for each type of soil, because these binders reacted differently with soil particles. The reaction products were based on six different binder recipes, which were as follows (in kg): (1) OPC (100); (2) OPC (50) + GGBFS (50); (3) GGBFS (100); (4) GGBFS (50) + lime (50); (5) lime (100); (6) lime (50) + OPC (50); Figure 1. The soil was treated with these binders or their blends. The quantity of binder was equal to 2.5% of the dry density of soil, because it enabled us to reach the maximum UCS value of 5 MPa after 3 months of curing period. The structure of the three soil types varied from clay to coarse sand particles and were treated with lime and cement. There were differences in the effects from various binders (Table 3). For instance, OPC quickly started to react with soil particles within 2 h after mixing. Most of the reaction was finished in 2 months, Figure 1. In contrast, the effects from lime were more consequent and similar to a straight line.

The argumentation for the use of these materials is as follows. Organic matter increases in soil compaction due to the molecular bonds between the particles. Sand contributes to the increase of mechanical stability, density, cohesion and gain in strength. Allophane increases the pozzolanic strength, compaction and densification of soil. Kaolinite has effects on the stability, contributes to early strength and workability, as well as later strength gain of soil. Illite and montmorillonite add an early strength gain to the soil.

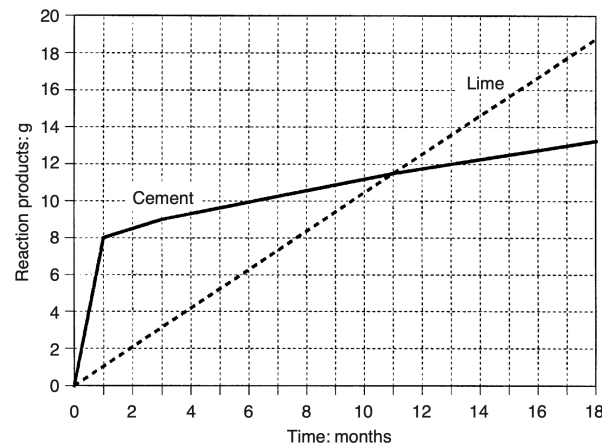


Figure 1. The effects from OPC and lime on soil particles (10 g binder/100 g dry soil).

Table 3. Reaction on stabilisation from main soil compounds and suggested binders.

Soil Component	Chemical Formula	Binders
Organic matter	–	Mechanical
Sand	SiO_2	Clay loam; asphalt
Allophane	$Al_2O_3(SiO_2)_{1.3-2}(2.5-3)H_2O$	Lime (CaO)
Kaolinite	$Al_2(OH)_4Si_2O_5$	Sand; cement; lime
Illite	$K, H_3O(Al, Mg, Fe)_2(Si, Al)_4O_{10}[(OH)_2, (H_2O)]$	Cement; lime
Montmorillonite	$(Na, Ca)_{0.33}(Al, Mg)_2(Si_4O_{10})(OH)_2nH_2O$	Lime (CaO)

To add workflow effectiveness in geotechnical works, various commercial producers present binders with trade names. However, often the exact content and the proportions might not be available, which requires testing binders for soil stabilisation. For example, lime and OPC mixed with clay react during one and half year of stabilisation period. However, the combination of lime with clay has more productivity compared to the one of cement with clay with regard to the products, which depends on the temperature. The OPC works better for coarse material, while lime is more suitable for fine-grained soil. Again, contrary to lime, OPC does not require external materials to result in a binding blend. The coarse silt type of soil can be stabilised by lime and cement better than by the pure binder.

2.5. Compaction

The soil specimens were treated by surface compaction using the devices available at SGI to compact the granular material of soil. A quantity of 4.5 kg of each specimen was compacted in layers, using plastic and steel equipment with a levelled surface for each corresponding layer. The samples were mixed with binders and compacted for one hour. Thereafter, the specimens were cut to a height of ca. 2.06 m, sealed and stored within a plastic tube. The specimens did not lost weight during the curing period. Each layer was compacted with a 5 kg rammer with 25 blows, which resulted in a decrease of 30 cm. To sift out large lumps, the soil was sieved, with pieces bigger than 19 mm removed. The suitable specimens were moulded again and located into a sealed container. The containers were kept at a constant temperature of 20 °C and relative humidity of 85%. The MCV of the

mixture, was determined in one hour of soil compaction, while the UCS tests were taken on days 7, 28 and 90.

2.6. Moisture Condition Value (MCV)

The MCV of the soil–binder mixture was determined because compaction is a key procedure of soil improvement with regard to strength and durability. The advantage of the MCV consists in its simplicity and availability to measure the least compaction needed to reach the highest soil density at a given water content for the assessment of the fitness of soil for geotechnical works. The MCV was determined in accordance with the EN 13286-46 standards and the UK Standard 1377 [53,54], adapted for the current case. This MCV is based on the repeated compaction of a specimen with a rammer until the limited compaction is reached.

The technical procedure was as follows. A free-falling 7 kg and 97 mm diameter rammer was attached to the equipment. A specimen of 1500 g was placed at 2.50 m. The upper limit for the MCV was set at 14, to ensure the OMC of the stabilised soil. The dry densities of specimens stabilised by 6 types of binders described in the previous section were processed and evaluated by the moisture condition apparatus (MCA), a device developed by the TRL in Scotland for the evaluation of the MCV (<https://www.hixtra.com/services/moisture-condition-value-mcv/> (accessed date: 13 November 2022)). The performance of the dry density of the compacted samples was evaluated for the different soil types (Figure 2), where it demonstrated higher values for type A compacted by the MCA, compared to the vibratory compaction (Figure 2). In contrast, soil type B demonstrated lower values for the MCA compaction, compared to the vibratory compaction. The MCV for soil A was enhanced compared to B, due to the vibratory compaction, which affected the dry density differently than the MCA.

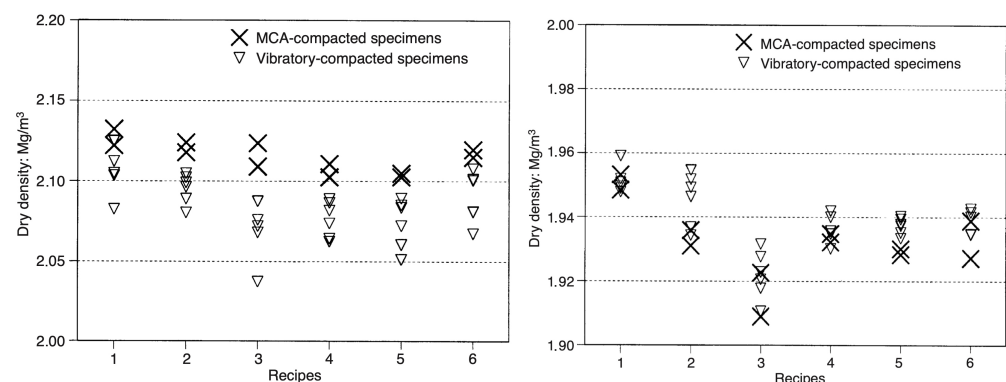


Figure 2. Comparison of the dry density values for various compaction methods and binder blends: types A (left) and B (right).

Due to the variations in the mineralogical content of the soil samples (clay, quartz), the natural water content differed significantly in various soil types within the same group (Figure 3).

Nevertheless, the vibratory compaction resulted in values of the dry density identical to those of the MCA compaction, which were <14 for all the samples. For the case of $MCV < 14$, the soil is workable and becomes homogeneous and dense with normal compaction equipment. Each soil type was homogenised; however, small variations in the water content remained between each specimen due to the individual properties of soil, which was within the normal distribution. The natural water content in a stabilised soil is an important variable for groundwater discharge and the evaluation of soil chemistry (Figure 3). Thus, if the moisture content of a soil is at optimal values, the soil is suitable for construction works.

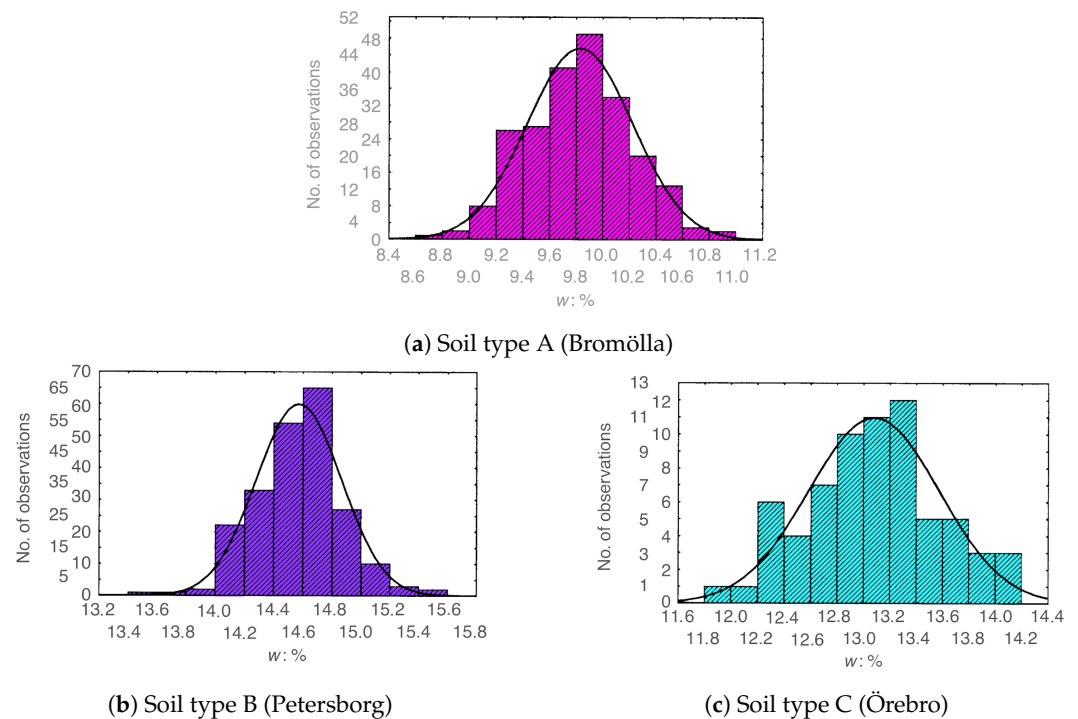


Figure 3. Variations in natural water content by soil types.

2.7. Simplex Lattice Design

The mixture design was adopted from existing studies to evaluate the effects from the individual binders and their blends using a simplex lattice design with three binders: OPC, GGBFS and slaked lime. We used six components of the recipes for the normal simplex lattice design. The scheme in Figure 4 presents three single blends and binder mixtures.

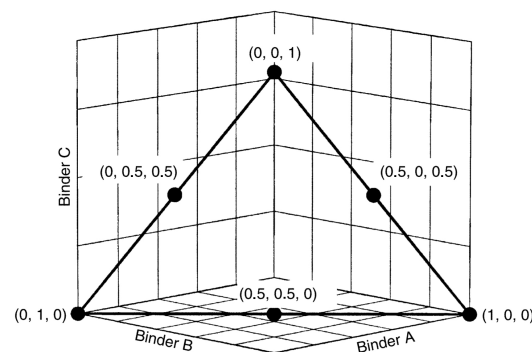


Figure 4. Equilateral triangle showing a simplex lattice mixture design for binder selection (3, 2).

Three statistical regression models characterised the material, depending on the test design. These included linear, quadratic and special cubic models as in Equations (1)–(3), respectively.

(a) Linear model:

$$y = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \epsilon \quad (1)$$

(b) Quadratic model:

$$y = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \epsilon \quad (2)$$

(c) Special cubic model:

$$y = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{123} x_1 x_2 x_3 + \epsilon \quad (3)$$

where β is the regression coefficient; ϵ is the residual error; x_i is the value of factors; y is the dependent variable.

The variable y contained the effects from the linear model and the interactions of the quadratic model and special cubic models, respectively. We included only the significant effects from the last two regression models. The regression models were evaluated using an ANOVA to test the significance level $p > 0.05$. The null hypothesis H_0 was that the mean of MCV or UCS of soil was equal for all stabilising agents. The alternative hypothesis H_1 implied the contrary, i.e., at least one binder differed from the others. Testing the equality of binders led to Equations (4) and (5):

$$H_0 = \mu_1 = \mu_2 = \dots = \mu_a \quad (4)$$

$$H_1 : \mu_i \neq \mu_j \quad (5)$$

for at least one pair of (i, j) .

If H_0 was true, then all treatments had a common mean μ . The p-level indicated we could reject H_0 . H_0 was statistically tested.

3. Results

In this section, we quantitatively evaluate our method on real case data for the three soil types stabilised by various binders. All the statistical experiments were performed using the dataset on three soil types and implemented in MATLAB. For quantitatively evaluating the simplex lattice design, three different datasets on soil materials were used. The results are illustrated as a series of plotted ternary plots showing the response surfaces for the UCS and MCV (Figures 5–8). The circles on the borders of these figures signify the content of the binders: single binder, binary blend or a complex mixture. The results are shown in Figure 5. The isoline indicates the interaction between the binders as factors. The response surfaces in Figures 5–8 show the effects from the binders on soil stabilisation.

3.1. MCV

Equations (6) and (7) refer to the response surface equation for binder blends tested for various soil types. Here, C , L and S stand for cement, lime and steel slag, and the combinations LS and CLS for their mixes, respectively. The numbers represent the quantities of binders taken for stabilisation.

$$MCV = 13.2C + 11.4L + 8.9S + 3.7CS + 2.2LS \quad (6)$$

$$MCV = 12.4C + 10.5L + 8.6S + 7.4CL + 22.5CLS \quad (7)$$

The total amount was adjusted for 100%, that is, the boundary conditions satisfied the following assumption: $0 \leq C, S, L \leq 1$ and $C + L + S = 1$, with the sum of the independent factors equal to one for all cases. One can derive from Equations (6) and (7) that the OPC had the strongest effect on soil compaction after one hour of curing. There were correlations between various binders for all the soil types with positive values indicating the enhanced MCV.

Nevertheless, binder blends contributed significantly to the MCV. Thus, the combination of blend OPS/GGBFS 50/50% increased the MCV up to 0.925 at a maximum for type A (Equation (6)). The blend of binders OPC/lime 50/50% contributed to the increase of MCV to 1.85 for soil B (Equation (1)). For soil type A, there was an adjusted R^2 value of 0.999, i.e., a very low variability. The GGBFS had the least effects on soil compaction (Figure 5).

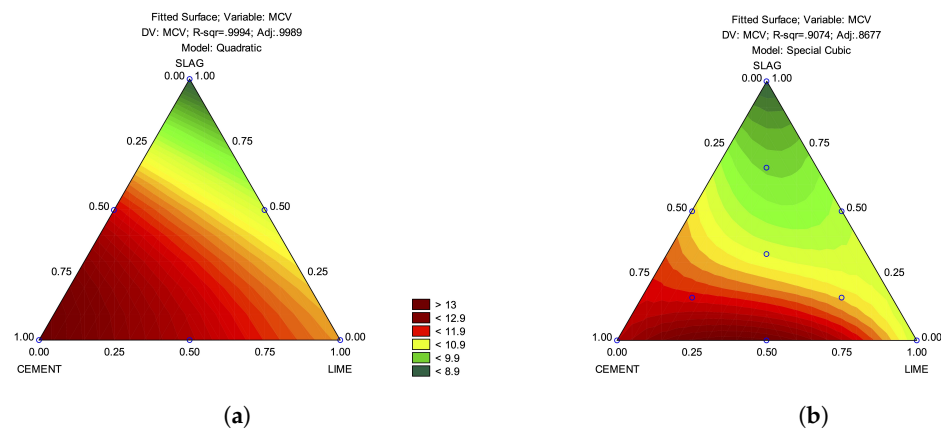


Figure 5. MCV for various binders blended with soil: (a) type A (Bromölla); (b) type B Petersborg.

3.2. UCS

The UCS was tested for types A and B on days 7, 28 and 90, while soil type C was tested on days 28 and 90.

3.2.1. Measurements of UCS on 7th Day

Because the soil types varied in clay content, we assumed that the performance of lime differed in soil types A, B and C, which was proved by Figures 6–8. The 7-day UCS values evaluated for types A and B are given in Equations (8) and (9).

$$UCS = +2930C + 850L + 310S + 1640CL + 2500CS + 2150LS \quad (8)$$

$$UCS = +1500C + 640L + 240S + 1650LS \quad (9)$$

The UCS for soil A and B cured for 7 days is shown in Figure 6. The comparative analysis of soil types showed that type A had a higher strength compared to that of B and C. Furthermore, it also demonstrated a significantly larger extent of variations in UCS values compared to type B.

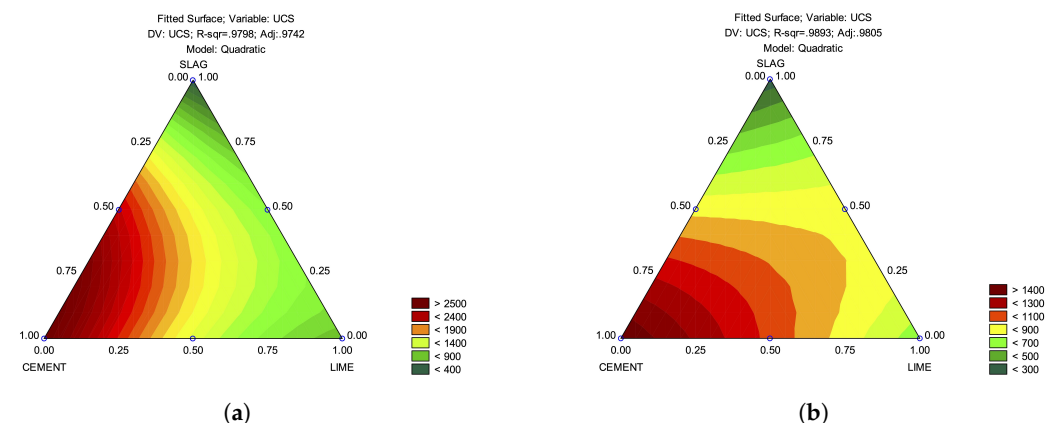


Figure 6. UCS strength for soil–binder mixtures cured for 7 days: (a) A (Bromölla); (b) B (Petersborg).

Indeed, soil of type A had the UCS varying within 2–6 MPa, while the UCS of type B ranged from 0.8 up to 2.7 MPa. The 7-day UCS for type A showed a significant full quadratic regression model, i.e., all effects from all binders were considerable. We also noted that OPC had the largest impact on the UCS of soil, while GGBFS had the lowest impact on UCS for both soil types (Figure 6). After a 7-day curing period, the OPC–lime blend had a negative effect on UCS, i.e., this part of the blend reduced the UCS. For soil of type B, the UCS on the 7th day of curing resulted in a linear model and had a quadratic significant term lime–GGBFS. With a 50:50% blend of lime–GGBFS, the quadratic term had more impact on the UCS compared to the effects from single slaked lime.

3.2.2. Measurements of UCS on 28th Day

The UCS of stabilised soil of types *A*, *B* and *C* on the 28th day of the curing period are presented in the subplots of Figure 7. The UCS of soil in kPa for soil types *A*, *B* and *C* on the 28th day of curing is summarised in Equations (10)–(12). Here *C*, *L* and *S* indicate OPC, lime and GGBFS, and the combinations *CS* and *LS* are their mixes.

$$UCS = +3800C + 1030L + 1210S + 4270CS + 6030LS \quad (10)$$

$$UCS = +2080C + 810L + 410S + 4440LS \quad (11)$$

$$UCS = +1090C + 180L + 430S + 2360CS \quad (12)$$

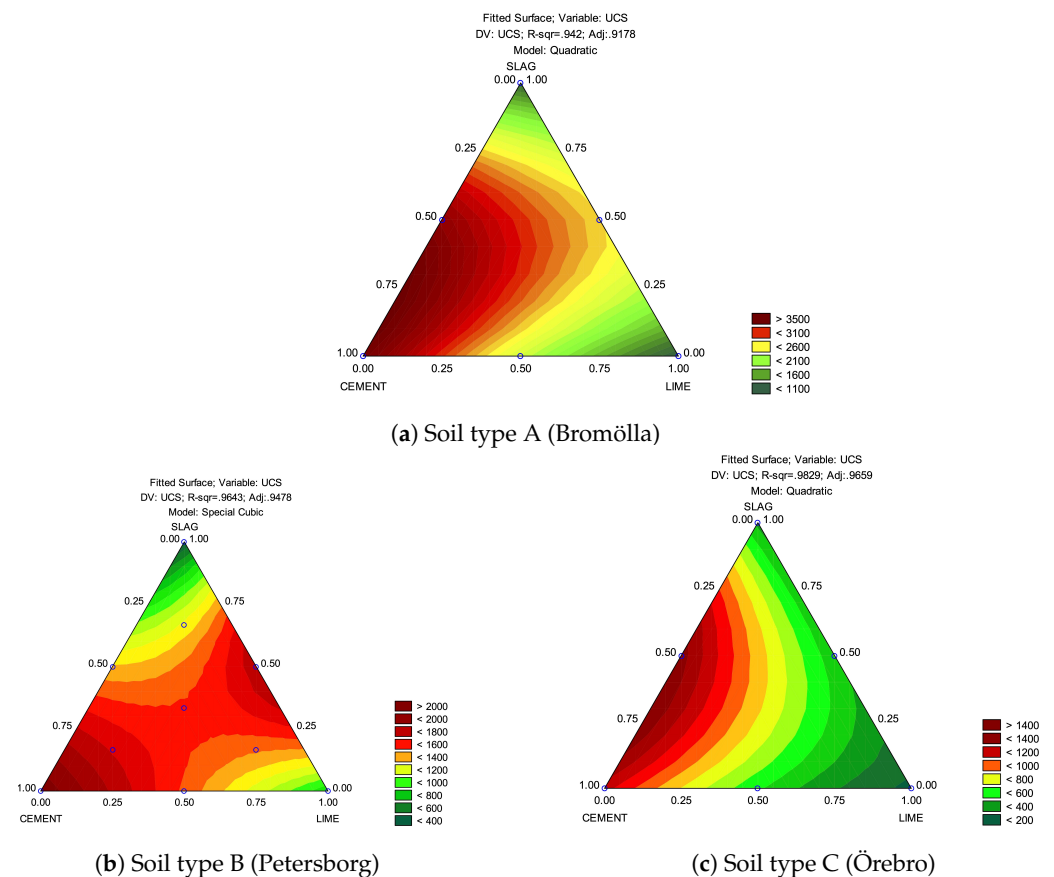


Figure 7. UCS strength for soil–binder mixtures cured for 28 days; soil types: (a) *A*; (b) *B*; (c) *C*.

The OPC–lime blend was not significant and was removed from the regression for type *A*. On day 28 of curing, the OPC remained the dominating element for the UCS of soil. However, GGBFS was larger compared to the lime component (Equation (8)). As for type *B*, samples received significant effects on day 28 (Equation (11)), as in the results on day 7 (Equation (9)). Nevertheless, the effects from the blend “slaked lime/steel slag” were more notable compared to the other blends, which suggests that lime was well suited to soil type *B* as a binder. The additional points were used to check the results in the UCS test on day 28 of curing, which showed an acceptable R^2 value. The effects from lime were not significant for soil type *C*. The effects from lime as a binder were smaller (Equation (12)) compared to types *A* and *B* and could be considered as minor ones. Such minor effect from the slaked lime was due to the low clay content in soil type *C*. Other factors could be the short curing time, as the effects from lime were time-dependent, see Figure 1. Certainly, slaked lime required a longer curing time to result in a reaction similar to that from cement and steel slag.

3.2.3. Measurements of UCS on 90th Day

The results of the UCS values evaluated on day 90 of curing are shown in Figure 8. Equation (13) described the type A with the least effective binder as OPC–GGBFS. This can be compared with Equations (8) and (10) showing significant effects from the OPC–GGBFS blend. The lime–GGBFS mixture showed a notable correlation on day 90 of curing. The effects from the lime–GGBFS mixture with a 50/50% were more significant compared to the single binder of slaked lime. The effects from the blends of OPC/lime and lime/GGBFS are shown for type B (Equation (14)). The maximum UCS was in the range between the UCS of the OPC/lime and lime/GGBFS mixtures (Figure 8). GGBFS had the highest impact on the UCS of soil type C on day 90 of curing, (Figure 8 and Equation (15)).

$$UCS = +5880C + 2270L + 2960S + 4600LS \quad (13)$$

$$UCS = +2390C + 2140L + 810S + 1390CL + 4290LS \quad (14)$$

$$UCS = +1340C + 371L + 1910S \quad (15)$$

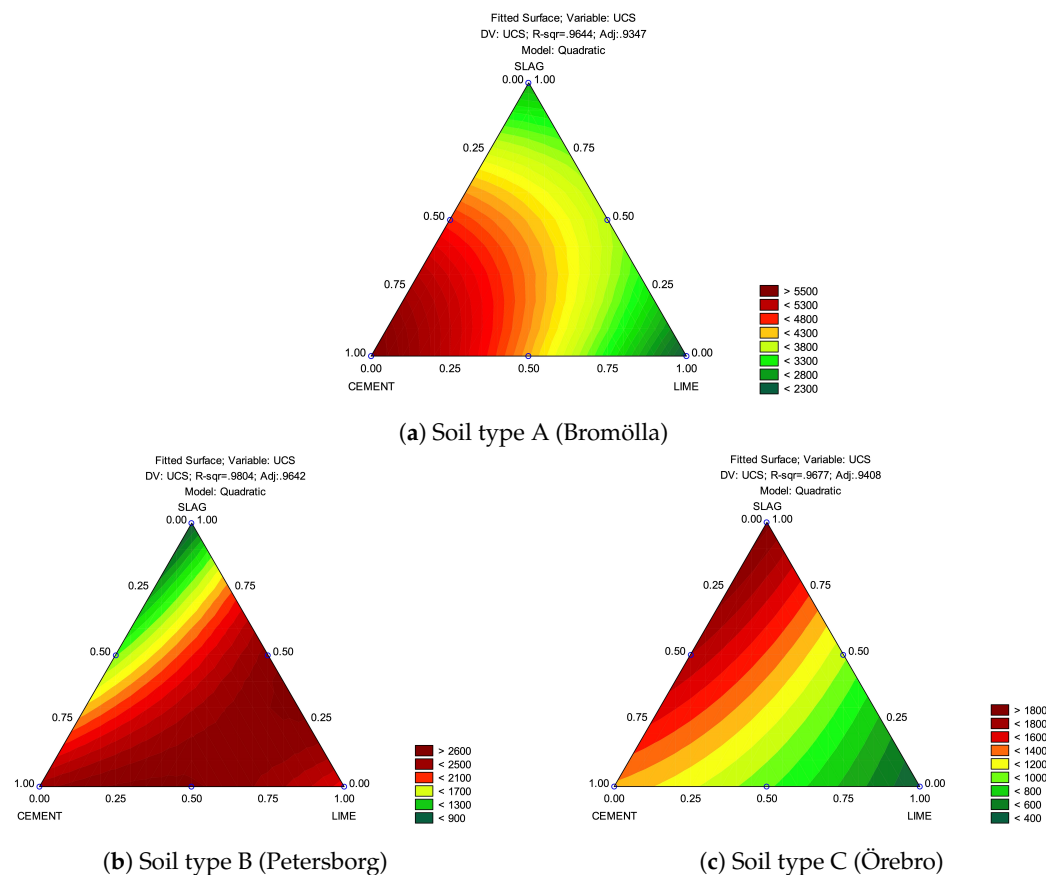


Figure 8. UCS for soil types (a) A, (b) B, (c) C cured for 90 days with various binders.

The clay content was the lowest in soil type C (6%), which suggested that slaked lime had a lesser effect on the UCS of this type of soil (Equation (15)). The minimum 7-day UCS of the cube specimens is specified for cement-bound material 1 and cement bound material 3 in Table 4, which shows that none of the binders reached the limits with 2.5% of the content.

Table 4. Requirements for compressive strength (MPa) for soil stabilised by cement after 7 days of curing.

Shape Form	Category 1	Category 2	Category 3
Cube specimens	4.5	7.5	10.0
Cylindrical specimens	3.6	6.0	8.0

The OPC–GGBFS mixture and GGBFS resulted in soil with a UCS < 2 MPa on day 90 of curing, because the amount of calcium hydroxide in these blends was not sufficient to form a uniform mixture which would produce pozzolanic effects. The GGBFS–lime blend resulted in the highest increase of the UCS values between 7 and 28 days. Table 5 shows that a blend of OPC and lime contributed more to the UCS, compared to the pure OPC or lime. The content of clay in a sandy clay soil was 17% versus that in control clay (55%), which means that the results of soil stabilisation were additionally dependent on the clay content.

Table 5. Effects from binders on strength gain in stabilised clay soil with 55% of clay, on the 7th day of curing. Binders: cement (OPC) and lime (CaO).

Stabilising Agent	10% CaO	10% OPC	10% OPC + 2% CaO
UCS: MPa	1.010	0.790	1.420

4. Discussion

The strength of various types of soil—sandy silty tills and clay till—was evaluated using the selected blended binders taken as pure agents and in mixes. We tested the effects from OPC, GGBFS and slaked lime as single binders and as blended mixtures on soil strength. Specifically, we evaluated the variations of the UCS and MCV in soil. Moreover, we examined the mineral structural and content properties of soil using X-ray diffraction (XRD) and a sieve and assessed the water content in specimens. The tests aimed at improving the parameters of soil prior to road construction. The obtained results led to the following conclusions:

1. The increase in strength was observed in all the tested binders; however, cement demonstrated the best effects, which resulted in quick soil stabilisation.
2. The UCS increase in soil stabilised by the OPC–lime blend was similar to that of GGBFS. However, a binder containing GGBFS gave lower values.
3. The measurements on day 7 of curing showed that the blend of GGBFS and slaked lime worked similarly to the pure slaked lime. However, on day 90 of curing, there was a notable effect on soil strength from the GGBFS–lime blend.
4. The specimens stabilised with GGBFS demonstrated the lowest UCS values on day 7 of curing. However, on the 28th day of curing, they performed similarly to those stabilised by lime.
5. A slow increase in the UCS values for the lime-stabilised specimens was explained by the low clay content in soil classified as type A. The slaked lime performed better as a binder, and had a stronger effect on soil type B.
6. The GGBFS–lime blend demonstrated benefit on the UCS of soil and performed approximately in a similar way as OPC for soil strength after 90 days of curing.
7. The limit for clay content in soil should be 10% for the effects from lime.
8. There were no significant variations in the effects from blends of the three binders with regard to the reduction in soil compaction, as reflected in the MCV values.

This article demonstrated the effects of single binders (cement/lime/steel slag) and their blended mixes on various types of clayey soils collected in three localities of Southern Sweden—Bromölla (Skåne County), Petersborg (Östergötland County) and Örebro (Örebro County). Although the traditional methods of soil stabilisation widely apply OPC or slaked

lime as stabilising agents, using blended binders has become a trend in the construction industry. This is caused by the improved properties of blended mixtures. As a result, blending OPC with GGBFS or OPC with pozzolanic materials, such as fly ash, has gained recent attention in civil engineering.

We noted positive effects from the blends GGBFS/lime on UCS gain in soils of *A* and *B* classes. Moreover, the GGBFS/lime blend had stronger effects on soil strength compared to GGBFS or lime. In soil of class *B*, the mixture of GGBFS and slaked lime performed better than OPC, because the blend of GGBFS/lime did not affect the compatibility of soil as an OPC binder, inasmuch as all the specimens were produced with an identical compaction approach. Second, the amount of clay in specimens of class *B* was enough for effective soil stabilisation, while in soil of class *A*, it was too low for a reaction when adding OPC. The vibratory compaction method demonstrated similar results in the dry density values of soil to the specimens compacted by the MCA method. Therefore, it is possible to achieve these values in situ, as the maximum MCV was lower than 14.

The technical goal of blending stabilising agents was to contribute to the economic efficiency of the workflow, followed by environmental goals for the utilisation of waste material, and to experimentally produce a new binder with better properties for technical reasons. Nonetheless, blending binders does not mechanically lead to the improved properties of the stabilising agent. Instead, the opposite reaction may occur as the result depends on various factors, including soil grain size or temperature, among others. Therefore, mixed binders were tested in this study, to ensure that they performed better than single binders for a particular soil from Southern Sweden.

5. Conclusions

In this paper, we proposed a mixed-binder-based soil stabilisation method which works for various kinds of soil types. The technical implementation of soil stabilisation and compaction is very expensive. At the same time, such works are a necessary requirement prior to all construction projects, including the construction of buildings, foundations, infrastructure, tunnels, roads, railways and highways, as well as the associated transport infrastructure. Indeed, soil quality is one of the crucial factors in civil engineering which ensures safety and workability of the constructed objects. Therefore, the use of advanced, robust and reliable methods for soil compaction and stabilisation are essential for industrial works, since compaction and the UCS of soil are effective indicators of soil quality.

At first, we presented advanced statistical techniques to optimise the ratio of stabilising agents aimed at determining the effects of their blended mixtures. We presented a series of simplex tests used to visualise the effects from binders on clayey soil. Our detailed discussion and experimental results showed that a simplex lattice approach was beneficial for estimating the necessary quantity of binders required for effective soil stabilisation. For the more complex cases, it is recommended to perform several trials for the estimation of various quantities of binders, as independent statistical variables. However, in this case, the total number of trial runs required is much greater, which results in a more complicated assessment of soil strength stabilised by various combinations of binders. Correctly selected binders adjusted to the specific type of soil result in a better stabilisation.

Second, we demonstrated that well-adjusted techniques could significantly improve the time-consuming workflow in civil engineering works and reduce the total economic costs of project implementation. For example, in this study, we showed that using pure OPC for the stabilisation of soil types *A* and *B* resulted in the best effects on the MCV, because soil stabilised by OPC had a higher compaction energy due to a much higher stiffness.

The limitations of the presented work might include the regional aspect related to Swedish soils, which is controlled by the values obtained in the laboratory. Therefore, we cannot directly compare the results of the tested Swedish soil samples with the results obtained on soil tested in other regions. At the same time, real conditions may affect soil response due to regional and local properties and environmental climate setting. As a result, this may lead to variations in the physiochemical parameters of soil and mixing

conditions. As a recommendation for future similar works, testing different various types of blends (proportions of binders within the blends) and different quantities of binders (in absolute mass) would be beneficial. The improvement of soil compaction in situ may include the responses from compacted soil and the soil underneath, upon compaction.

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Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of variance
GGBS	Ground granulated blast furnace slag
MCA	Moisture condition apparatus
MCV	Moisture condition value
OMC	Optimum moisture content
OPC	Ordinary Portland cement
SIG	Swedish Geotechnical Institute
SIS	Swedish Institute for Standards
UCS	Uniaxial compressive strength
USCS	Unified Soil Classification System
WL	Liquid limit
WN	Natural water content
XRD	X-ray diffraction

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