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IMPACT OF STRENGTH-ENHANCING ADMIXTURES ON STABILIZATION OF EXPANSIVE SOIL BY ADDITION OF ALTERNATIVE BINDERS

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Abstract

In this study, the stabilization process is introduced to a clayey expansive soil collected in southern Sweden. The tests examined strength parameters of expansive soil stabilized by different binders using combination of both traditional binders (cement and lime) and alternative materials (slag Merit 5000, fly ash from SCA Lilla Edet and fly ash from coal combustion, ISO certified). The practical goal was to find a binder mixture that is optimized for soil stabilization with respect to technical properties of stabilizing agent as an inert ballast material. The strength of soil stabilized by various binders was examined by velocity of the *P*-waves propagating through specimens. The results show that introducing slag Merit 5000 as an admixture to cement and lime is an effective approach in enhancing strength properties in weak soil, which increases bearing capacity of soil for planned construction works. The results also shown that a mixture of lime and bio ash yields a better effect in the stabilization of a clay. Soil stabilized with cement, cement/slag and lime/slag becomes resistant to freeze-thaw cycles, which is crucial for construction of roads and building foundations.

Keywords:

Compressive strength;
Cement;
Slag;
Fly ash;
Lime.

1 Introduction

Safety, stability and geotechnical performance of civil constructions (roads, building foundations or railways) are highly dependent on properties of soil, such as strength, permeability, compactness, porosity and resistance to traffic load and climate effects (e.g., freeze-thaw cycles, temperature extremes). Therefore, improving the physiochemical and mechanical parameters of soil is aimed to increase its bearing capacity, which has a crucial importance in industrial engineering. Improving mechanical and geotechnical properties of soils is possible by stabilization methods, which are used to increase the Uniaxial Compressive Strength (UCS), bearing capacity, stability and resistance to deformation from traffic. Stabilization of soil is possible by adding binders into the mixture of soil prepared in a mortar mixer as a thick paste. Different binders can be used for soil stabilization with advantages and drawbacks, caused by their physiochemical and mechanical properties.

Cement and lime as materials for soil stabilization are the oldest binders, which have been widely used in geotechnical works owing to their simplicity, availability and cost-effectiveness. The principle of soil stabilization with cement is a chemical reaction of calcium silicate Ca_2SiO_4 with water during hydration and particles of alumina Al_2O_3 and silica SiO with those of soil, which increases soil strength and durability [1–2]. Besides cement, alternative binders can be used as chemical additives for soil stabilization as improved technique: lime [3–5], cement kiln dust (CKD) [6–8], fly ashes [9] or slag [10–12]. Soil reinforcement using such novel binders has been developed recently as an alternative method for stabilization. The choice and ratio of binders depends on soil type and real in-situ conditions.

Lime is one of the oldest binders used to improve engineering properties of soils. Known at least since Romans times, it was used, for instance, to fabricate concrete by mixing with volcanic ash to create a pozzolanic reaction. The positive effects of lime during soil stabilization is caused by its calcium-containing material compound CaO and $Ca(OH)_2$, which improves the key properties of soil: cohesion, adhesion and strength. Besides, mixing lime with ash generates a pozzolanic reaction which is increases workability of the materials constructed atop the stabilized soil. Adding lime to soil reduces its plasticity index, which facilitates higher workability of soil and thus optimizes the construction works. Besides, chemical bonding between soil particles and lime results in a reduced water content in soil and decreased maximum dry density of soil.

Fly ash is the coal combustion product which consist of silicon dioxide SiO_2, aluminium oxide Al_2O_3 and calcium oxide CaO, as major chemical-mineral compounds in coal-bearing rocks. In the technique of soil stabilization, fly ash is used as a catalyst added as a replacement or additive to Portland cement owing its properties as a pozzolanic ingredient. The presence of slag as a soil binder markedly expedites the stabilization process as a chemical agents. The particles of slag fill part of the pore space creating bonding in soil, which improves strength development, durability and technical parameters of the materials. The traditional binders, such as cement and lime, can be diluted with slag and / or fly ash added in various concentrations, with aim to enhance soil strength and workability.

Slag in the construction industry was used since the beginning of XIX century, primarily for building roads, and later, in the middle of XIX century, as a railroad ballast [13]. Due to its latent hydraulic properties, the addition of Ground Granulated Blast Furnace Slag (GGBFS) significantly reduces the swelling, increases compressive strength and decreases plasticity index in soils, which enables its use as a cement additive. Nowadays, slag is used in mixture with cement, where pozzolanic reaction produces cementitious properties during cement hydration, which leads to the strength gain in materials. Applications of slag are diverse and include the use as a cement additive [14], in high-performance concrete or mortar, as an independent binder, in various engineering tasks, such as road or bridges constructions, or for soil stabilization. Slag has the highest carbonation potential among the industrial binders, due their high CaO and MgO content [15].

In this work, we consider the problem of improving clayey soil properties stabilized with various binder combinations (cement, lime, slag and two types of ashes) during 3 months (90 days). To evaluate soil strength we use sonic tests of *P*-waves velocity measurements passing through the soil specimens. The suitability of this method is owing to the geophysical properties of the elastic waves which speed correlates with the strength of the material [16–18]. Thus, in existing studies seismic waves are applied to detect cracks and damages to assess structural safety of the materials [19–20]. Additional techniques of measuring soil and materials properties by using ultrasound waves can be found within these references.

2 Methodology

2.1 Materials

The soil was subjected to tests in accordance with Swedish Standards [21], for the natural soil and cement-based stabilization for the treated soil specimens [22]. The study includes two traditional binders (cement and lime) and three alternative materials. The alternative materials are slag (Merit 5000), fly ash from Svenska Cellulosa AB (SCA) Lilla Edet and fly ash from coal combustion (ISO certified). A base layer gravel 0 - 18 is used as the ballast material, which was selected according to the sample size 10 cm, with a maximum permissible particle size of 20 mm. Another goal was to use soil material with the least deviations in properties to obtain the objectivity in the statistical results. The selected ballast material was inert and did not contribute to the strength growth in combination with binders. Soil samples passed through the Swedish Standards for processing materials in real projects.

2.2 Fabrication of specimens

The ballast material as a support layer was weighed in three batches of 1.7 kg each. Water was measured as 102 g per batch using measuring glasses so that it gave a ratio of 6 % before the addition of binders and 5.8 % when the binders were included. Binders were weighed and added to the soil. The specimens were stabilized with different binders: cement, slag, lime, energy fly slag and bio fly slag. The total binder content was 51 g per batch, which corresponds to a binder content of 3 %

based on the dry weight of the base layer. The batches of sample mixes were compacted in the standard steel mixing cylinders for laboratory testing, which consisted of a steel whisk driven by a heavy-duty drill. The three batches were mixed, then kept for an hour untouched, then combined and mixed. Based on this mixture, three new batches of 1.5 kg each were weighed. The remaining material was used for water ratio determination. After the curing periods 90 days, the specimens were subjected to UCS and sonic tests. On the 90th day of curing period, the samples were cut to a ratio of two, after which the plastic tube was removed.

2.3 Stabilization

The specimens were stabilized with different five binder recipes (cement, lime, slag, energy fly ash and bio fly ash). To ensure the significance level of the results, these recipes were based on previous experience in the Swedish Geotechnical Institute (SGI) in combination with the statistical trial simplex tests. The experimental design of the trial simplex tests was planned with aim at decreasing the total number of experiments and in such a way at optimising the procedure of soil sampling. Second aim was at achieving the effective results of soil stabilization. The statistical experiments minimized the number of trials that need to be performed with the desired level of significance. We used the first-order design, which is the two-level full simplex factorial test. Initially, it was designed to identify the significance of factors, as well as their interactions as variables in a dataset. In this study, we apply it as an optimizer for the workflow. Using simplex test approach, we tested five different binders, which means that about 100 test specimens were fabricated. The specimens were stored for at least 3 months (90 days) to achieve a final strength, even for the slow-curing components, such as slag.

2.4 Sonic tests

The sonic tests, which included measured *P*-wave velocity and shear wave velocity on the stabilized specimens, enabled to perform a quantitative assessment of the soil improvement obtained through the addition of binders in terms of strength development. Sonic testing using applied geophysical methods has become one of the most commonly used approaches for determining laboratory soil stiffness, shear strength and compressive strength. Therefore, we have accepted the sonic test during the evaluation of soil UCS using the accelerometer and technical guidance. The *P*-wave velocity in soil using different types of blended binders was evaluated and measured using bender elements as transmitter from the accelerometer. The schematic workflow of the test setup is as follows. The soil was prepared as a sample in mounded cylindrical form. It was placed on the base pedestal on the foam to exclude the external effects on the proper vibrations of the specimen.

The base pedestal comprises of a cylindrical insert with connected accelerometer element (*P*-wave transmitter). The connection of signal from excited soil specimen was performed using the PC and cable for data capture. After and the receiver of the accelerometer was installed, the signals were induced to the soil specimen and the responses were measured. The receiver of the ICP Accelerometer was connected on the one end of the soil specimen. Afterwards, we induced an impulse force by a small hammer in another end of the cylindrical specimen. The arrival time of the *P*-wave was then measured and recorded in the computer to evaluate the travel time of the compression wave. In such a way, the velocity of *P*-wave was computed from the travel time of the pulse of wave travelling through the soil samples. The data on *P*-wave velocities were stored and documented in the PC. Thus, the *P*-wave velocity values correlated with UCS for the soil specimens stabilized with various binders. The plots indicating the UCS are given in Figs. 1 to 3. Seismic velocities were measured as a function of curing time (up to 90 days) to evaluate the strength development as a function of time and content of various binders used as stabilizing agents.

The seismic velocities of the *P*-waves propagating the samples of the stabilized soil specimens were obtained using the ICP Accelerometer (Model No. 352B10), a lightweight ceramic shear response device developed by PCB Piezotronics. Here the PCB is abbreviated from the PicoCoulomB which is a registered trademark of the company and a technical phrasing which characterises an electrical charge of the type generated by the piezoelectric sensors and measuring the piezoelectricity accumulated in the ceramic materials in response to applied stress. Thus, the Piezotronics integrates the piezoelectricity and electronics for developed technical devices. The stabilized soil was evaluated based on the theory of waves and geophysical properties of soils as a porous media. The speed of the compression *P*-waves and shear waves were measured in the specimens on day 90th. The procedure was as follows. An impulse force was excited in a soil sample, and the *P*-wave speed was recorded and stored in the computer. The arrival time was used to estimate the compression *P*-wave travel time. Phase differences were used for measuring shear wave travel times. The velocity of the *P*-waves was calculated from the travel time of the pulse through the specimens.

3 Results

Figs. 1, 2 and 3 show correlation of binders tested in various proportions on the development of strength in soil, stabilized on day 90th.

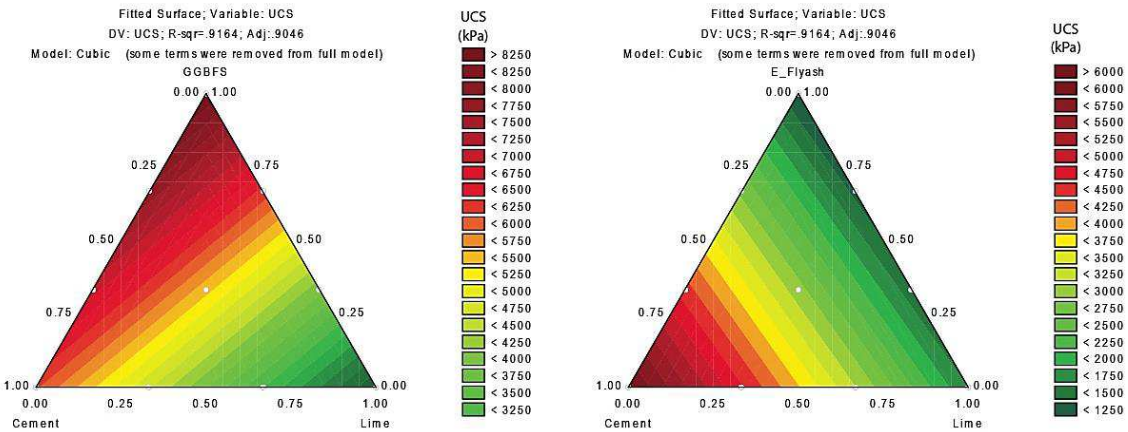

Fig. 1: The UCS in stabilized soil specimens on day 90th of curing period: a) binders - cement, lime, slag (GGBFS); b) binders - cement, lime, energy fly ash.

The stabilization process considerably improved the strength parameters of the tested soil samples. The *P*-wave velocities, correlating with UCS, were obtained by sonic tests, which proved the effectiveness of the soil stabilization by the mix of alternative and traditional binders in improvement of soil strength. Figs. 1 to 3 show slag is the binder that contributes the most to the gain of the compressive strength in soil specimens. Cement comes second in terms of strength. The combination of slag and energy fly ash has the least impact on compressive strength. The response surface in Fig. 1 (left) shows completely linear effects between cement, lime and slag. A marked interplay between the lime and slag that could be seen in seismic measurements on days 7, 14 and 28 cannot be confirmed for the day 90th of the strength values.

Moreover, the combination of lime and slag seems to have a significant effect on hardening process but no effect on the final strength. These observations confirm previous studies on fine-grained moraines [9] where the study included three different types of fine-grained moraines for evaluation of strength after stabilization. The two with the highest clay content showed a significant interaction between lime and slag, while the third fine-grained moraine with the lowest clay content demonstrated the same pattern as shown in Fig. 1. This indicates that the bedrock gravel used in the study is inert and therefore well suited to be used to evaluate the effects from different binders and their interactions with soil during stabilization.

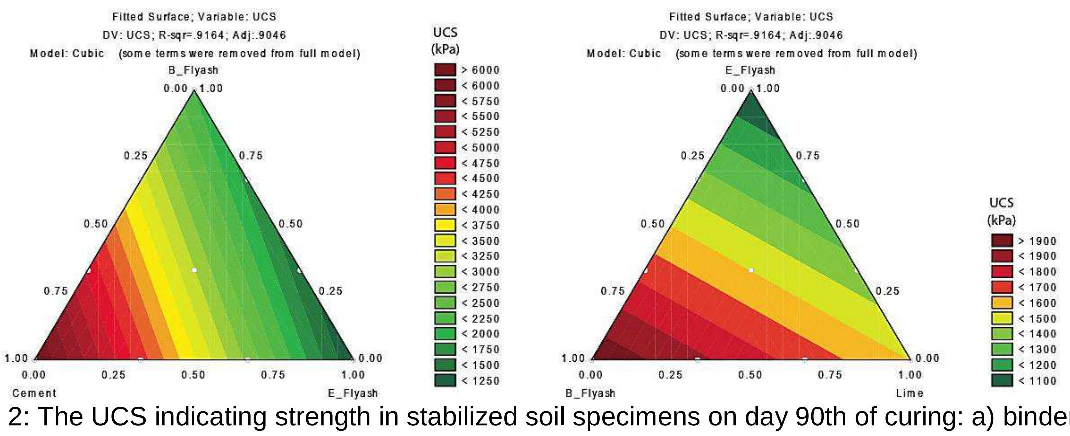

Fig. 2: The UCS indicating strength in stabilized soil specimens on day 90th of curing: a) binders - cement, energy fly ash, bio fly ash; b) binders - bio fly ash, lime, energy fly ash.

The ternary diagrams in Fig. 2 show the results of the effects from binders cement/fly ash and energy fly ash (left) and bio fly ash/lime and energy fly ash (right). As a result of the cementitious mixture by added binders in equal proportions (cement, fly ash and bio fly ash 33 % each), resulted in strength at 3250 kPa, lime colour in Fig. 2, left. In total, this combination resulted in increase of strength from 1250 to above 6000 kPa, Fig. 2, left. Here one can note that added cement generally contributed to the gain of strength (bright red colours by cement added from 50 % up to 100 %). Adding binders as a ratio bio fly ash/lime and energy fly ash showed the increase in strength from 1100 > 1900 kPa, Fig. 2, right.

The analysis of Fig. 3 (left) shows that the addition of GGBFS (slag) as a binder results in clear increase of strength (bright red colours). By added GGBFS with combinations of lime and energy fly ash strength increases from below 3250 up to 8250 kPa and higher. Fig. 3 (right) shows that the combination of cement and slag GGBFS contributes to the significant gain in strength: red colours on the ternary plot showing high values of UCS from 550 to > 8250 kPa. Equal proportions between cement, energy fly ash and slag resulted in strength at 5500 kPa (dark orange in the centre of diagram), while ratio of 75 % of cement, 25 % of energy fly ash resulted in strength at 6350 kPa. Energy fly ash did not significantly contribute to the gain of strength 3250 - 4250 kPa. In contrast, strength notably increased by added slag from 25 % to 50 % in a cement-soil mix.

Fig. 1 to 3 demonstrated strength potential the stabilised soil which improves by added cement/slag/bio fly ash/energy fly ash. The best performance was noted by added cement and slag. It should be also noted that apart from the effects from various binders, soil strength also depends on water/binder ratio, on soil type and its mineralogical properties, as well as on the effects from the compaction process. The relationship between the compressive strength and *P*-wave seismic velocity differs for each stabilized soil type. For example, sand, silt, clay, or other types of soil may show various performance by stabilization and compression, which results in individual strength development. This requires that laboratory testing consider different soil types for each experiment.

The five types of tested binders demonstrated to have strengthened high plastic clay soil with the best performance showed by slag GGBFS and Portland cement, Fig. 4. These binders contain active components Al_20_3, CaO and active SiO_2, which resulted in the increase of the binding properties and strength of a binder-soil mix. The most effective mixture for clay stabilization is a mixture of slag GGBFS, cement and energy fly ash, Fig. 3, right, with achieved strength above 8250 kPa, followed by the combination of slag, lime and energy fly ash with the dominant values from 450 to 7750 kPa. The other two types of tested combinations shown less effective strength: adding cement and the two types of fly ash increase strength slightly above 6000 kPa and the combination of lime and two types of fly ash shown gain in strength slightly above 1900 kPa.

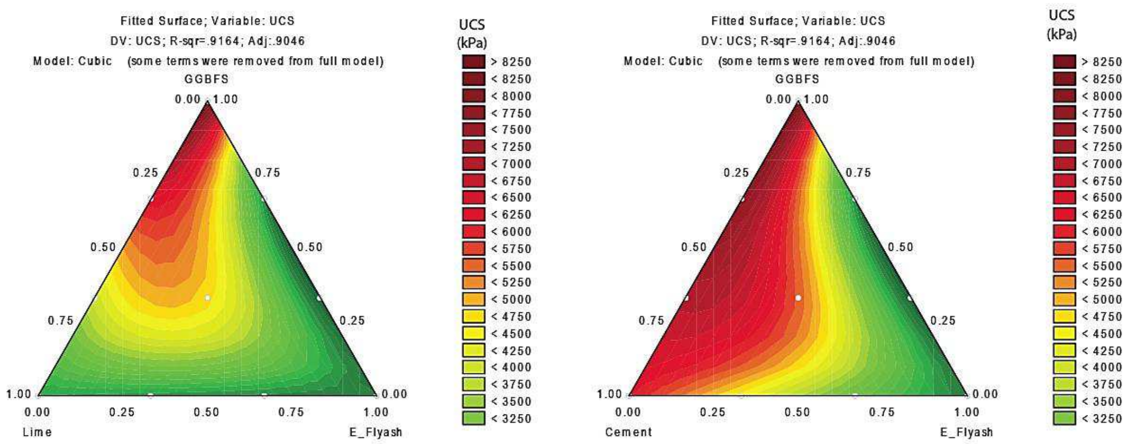

Fig. 3: The UCS indicating strength in stabilized soil specimens on day 90th of curing period: a) binders - lime, energy fly ash, slag (GGBFS); b) binders - cement, energy fly ash, slag.

The properties of stabilised soil were compared based on the basic statistical plotting using MATLAB as ternary diagrams and Pareto charts. The Pareto graph, Fig. 4, represents a sorted histogram of the frequency of the standardized effects estimated as factors at $P = 0.05$. Fig. 4 shows the Pareto chart for standardized effects with the following technical parameters: variable = UCS, tested design: 5-Factor mixture. Mixture total = 1, with performed 82 runs of the experiment. The left subplot shows the MS residual = 232257.1, the right subplot shows the MS residual = 399436.4 with

DV: UCS in both cases. We evaluated our algorithms with a Pareto chart, which is a graph which includes bars and a line graph, where individual parameters of real data variables of binders mixtures are shown in descending order by bars. They represent the standardised effect estimates in absolute values for types of tested mixtures which are annotated using the abbreviations. The abbreviations for the combinations are as follows: (A) – cement; (B) – lime; (C) – slag; (D) – energy fly ash; (E) – bio fly ash. Respectively, their combinations has been abbreviated correspondingly: (AB) – cement + lime; (AC) – cement + slag; (AD) – cement + energy fly ash; (CE) – slag + bio fly ash; (BC) – lime + slag; (BD) – lime + energy fly ash; BCE – lime + slag + bio fly ash; (BE) – lime + bio fly ash, (ABD) – cement + lime + energy fly ash, etc. Respectively, the *p* values are represented by the vertical red dashed line (p = 0.05).

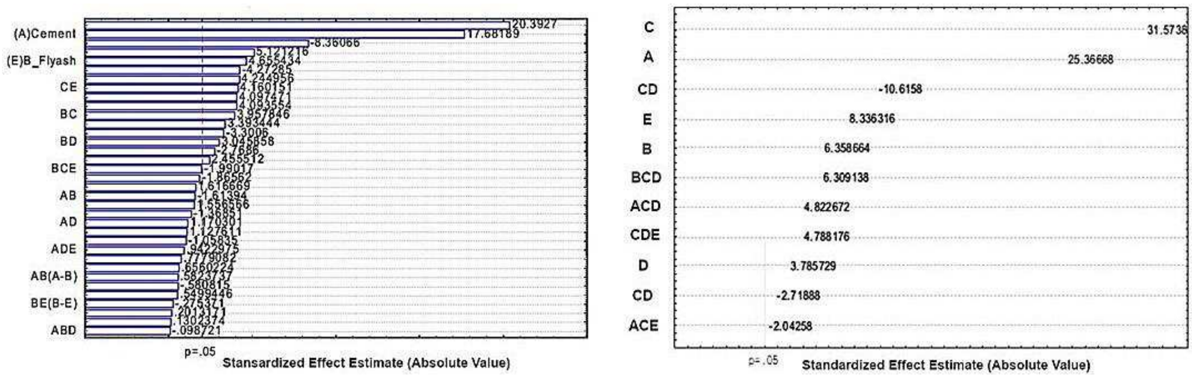

Fig. 4: a) Pareto chart for all the standardized effects from UCS and ratio of binders on day 90th; b) Pareto chart for remaining significant effects from UCS and various combinations of binders.

Every mixture of blended stabilizers is demonstrated by the Pareto bar box. Thus, the Pareto plotted performance of blended binders is introduced in this study to enhance the comparison between the blends and find a proper solution in soil stabilization. The results show that the proposed binders of types C, A, CD and E (that is, slag, cement, mixture slag-energy fly ash and bio fly ash) outperforms the other binders and has large advantages in stabilization of soil with an acceptable solution performance and soil hardening speed, especially for instances of weak expansive soil. The lengths of the bars correspond to the influence of binders on hardening, highlighting the most important agents as the key factors in stabilization. Here GGBFS and Portland cement are the most important binders with absolute values as 20.39 and 17.68, respectively. The *p*-value is shown as a vertical red line, which defines the 95 % confidence interval, Fig, 4. Several factors control the strength of the stabilised soil samples, among which the most important ones are the following:

1) activity of binders (slag and cement were the best for stabilization in terms of chemical bounding),
2) amount and quality of the binders soil composition (fresh binders added in effective proportions),
3) grain size of slag,
4) quality and time of mixing,
5) water/binder ratio,
6) soil/binder proportions,
7) curing period (90 days shown to be a favourable and reliable time for stabilization).

The presented method of soil stabilization by various binders demonstrated a high geotechnical efficiency and convenience of this method, as its realization does not require a complex equipment and soil stabilization can be performed all year round using binders. Our method therefore seems an effective choice for soil stabilization for the case of Sweden with dominating weak expansive soils prone to freeze-thaw cycle. Besides, an empirical correlation was developed between the UCS and velocities of the elastic *P*-wave from the laboratory tests conducted on the soil treated by various binders (cement, lime, slag, and two types of fly ash). In general, *P*-wave velocity increased with curing time up to day 90th and with a ratio of binders added to soil, especially slag and cement. The main aim of this correlation was to evaluate the strength gain from compressive velocity and shear velocity values in tested soil specimens. Such assessment is practical for an effective quality assessment in the soil solidification and stabilization.

4 Discussion

Although many studies have been reported on soil stabilization with traditional binders, such as cement or slag, the literature is not sufficiently includes reports on use of blended binders. The existing studies report, the use of polypropylene and silica fume blended combination for improving strength characteristics of black cotton soil [23], the mixtures of natural lime and volcanic ash for black cotton soil stabilization [24] and or the use of coal bottom ash for stabilization of expansive soils using stabilizing agent CBA [25].

While the traditional binders are capable of soil treatment, they are often more sensitive to the soil types and instabilities of sampling with effects of unique properties of soil samples. This requires optimization of workflow and the use of novel methods. In this study we presented the use of blended mixtures used for stabilization of expansive clayey soils collected in southern Sweden.

The study investigated the effects from alternative binders, such as energy fly ash, bio fly ash, lime combined with slag and cement on physiochemical and geotechnical properties of clayey soil. Other factors included water content, and curing time (we tested soil during 90 days). The combination of alternative and traditional binders as blends for soil reinforcement is profitable for engineering purposes. Novel stabilizing blends can be implemented in diverse civil engineering projects. Reinforced soil can be used as a roadbed or as a foundation unit in buildings or auxiliary infrastructure. From this research work, the following closing remarks can be summarized:

1) Comparing of the effects from different binders, it can be seen that it is the slag from Merox that clearly worked best. The addition of slag inclusions significantly increased the strength properties of soil samples which was detected by measured *P*-wave velocities.

2) The simplex diagram images of reinforced soil specimens demonstrate comparative effects from various binders: cement, lime, slag and two types of fly ash.

3) The effects from added energy and bio fly ashes demonstrated poor response in soil stabilization context. Although energy fly ash is used to improve soil properties, our results shown that energy fly ash did not act well as a binder for expansive soil. A reason for that could be the low amount of binder below a threshold value in a water/binder ratio.

4) Regarding the amount of binder: a higher quantity of binder would make the process of soil stabilization more expensive and is currently not applicable from an economic perspective.

5) Bio fly ash from SCA Lilla Edet demonstrated poor results in soil stabilization, which may be attributed to the carbonation of binder, i.e., lime in the ash reacted with carbon dioxide in the air and inert calcium carbonate has been formed.

6) A better effect of a mixture of lime and bio ash in connection with the stabilization of a clay soil, that is, ash used as lime addition, even in small percent, can improve soil strength.

7) Soil stabilization is a physical interaction between binder and soil, which has a significant effect on the soil structure and properties. Therefore, binders used in larger projects should be used in ‘fresh’ conditions to minimize variations in a stabilized road body.

8) The benefits from combinations of different agents on development of soil strength depend on the percentage of slag, cement and lime as the most effective binders in blends. In this context, cement and lime are used as traditional binders, where lime needs clay mineral and air (carbon dioxide) to initiate hardening. Slag shown effects on strength of the clayey soil.

9) The effects of lime as pure binder have been limited in this study since we had only included inert ballast and storage of samples without access to air. At the same time, pure lime (burnt or quenched) is best suited for the fine-grained expansive soils containing clay minerals.

10) In this study we used a very finely ground slag (sieve size of 0.150 to 0.075 mm) which has high hydraulic properties without activation, i.e., sets and hardens in the presence of water. The addition of such slag as a binder component was highly beneficial for stabilization, due to its properties of adhesion with soil particles. Thus, adding slag Merit 5000 significantly increased soil strength. Such effects are beneficial on geotechnical properties of soil, e.g. prevention of crack propagation.

11) However, stabilization with slag is time-consuming due to a too slow curing process. Therefore, in real projects using slag as a pure binder can be disadvantageous.

12) Finally, we found that the combination of slag/lime or slag/cement accelerates hardening of soil and results in a good and durable product. Soil specimens stabilized with pure cement, cement/slag and lime/slag are resistant to freeze-thaw cycles, provided that there is no continuous water penetration. This is especially beneficial to northern countries with harsh environmental and climate setting, such as Sweden.

Besides, the study extended the applied geophysical methods of sonic tests to the domain of civil engineering for the computation of strength values through measured *P*-wave velocities as well correlating with properties of the materials. In order to improve the effects of stabilization on soil strength, different binders were used, including both traditional agents (cement and lime) and alternative ones (lime and two types of ash: bio fly ash and energy fly ash).

Since pure binders may have limitations on soil stabilization (slow setting of slag), which can be viewed as a disadvantage for real-time projects, blended combination of several binders is proposed to take the advantages from various components. Such combinations are proven to satisfy Swedish requirements of civil engineering in soil stabilization and ensure that positive results in soil stabilization are achieved. Generally, improvement in physiochemical and mechanical properties of soil and its performance due to the treatment with blended binders is higher than treatment with single binders. Extensive numerical experiments were supported by the statistical test and visualized using simplex diagrams and Pareto chart for comparative analysis of the effects from both traditional and alternative binders on soil stabilization.

5 Conclusion

Low strength and deformation of the weak soil can cause one of the serious problems in geotechnical projects, such as constructions of roads, highways, mass building constructions and other engineering-related works. Soil stabilization is a conventional method to improve geotechnical characteristics of soil intended for constructions. One of the challenging problems in civil engineering is how to effectively stabilize large amounts (many tons) of weak soil in a robust and quick way in real-time geotechnical projects. As a response to such need, novel techniques of soil improvement are constantly developing with the aim at testing new materials for effective soil treatment. Given the high cost of reparation of infrastructure damaged in case of weak ground, the use of effective binders is the current goal for research on soil stabilisation. Adding binders for soil hardening and cementation results in significant increase of its UCS. The remaining question is the amount and ratio of binders that are needed for soil stabilization.

The main contribution of this paper is to demonstrate the effects from the two types of additive for the soil, i.e., energy fly ash and bio fly ash, to the traditional binders (slag/lime/cement) with aim at improving geotechnical and engineering properties of soil. These include the important parameters that reflect the resistance of soil to the external loads: compressive strength, cohesion related to shear strength, permeability and elasticity related to hydraulic parameters and changes of soil volume. We show that the optimum binder consists of cement and slag as major stabilizing agents with small addition of novel alternative binders, such as energy fly ash and bio fly ash. Such mixture results in increase of the UCS of the stabilized soil. We proposed a simplex design method for optimising the workflow of binder selection and demonstrated the results as a comparative series of ternary diagrams. Using simplex method we show that adding binders affects the development of strength, however, slag and cement remain the most influencing binders for soil stabilization, which is presented on the graphs. Thus, expansive clayey soil can effectively be treated with alternative additions (fly ash and lime) to the traditional binders (slag or cement) for improving the stabilization method.

Our results on testing soil samples for stabilization demonstrate that using blended binders is a promising technique that can significantly improve the strength properties of soil. We indicated that strength development is positively affected by the addition of cement and slag as major binders, as well as lime, and two types of fly ash added in minor proportions, which can also contribute to the gain of strength. The processing of the experimental results by simplex diagrams, presented as ternary plots, has shown that our method of stabilization is not only robust to the weak type of soils, but also computationally more efficient and stable comparing to the others, since simplex-designed method enabled to decrease the number of tests and optimise the workflow. It is especially useful for real case projects when several tons of soil should be stabilized effectively and quickly. Thus, in this report, a novel methods of testing alternative binders (energy fly ash, bio fly ash and lime) combined with traditional binders (cement and slag) was introduced for the stabilization of soil. The benefits of the demonstrated blended binders, compared to other materials as soil stabilizers, include the increased strength, ease of use in industry, low cost of the materials, high robustness and reliability, as shown on the statistical plots, reasonable time of soil treatment and less consumption of pure cement, which is beneficiary for the environment. The encouraging results of the simplex factorial design create opportunities for further research on engineering methods which perform optimisation of the binders in geotechnical workflow.

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