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LABORATORY EXPERIMENTS ON SOIL STABILIZATION TO ENHANCE STRENGTH PARAMETERS FOR ROAD PAVEMENT

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Clay soils can cause significant distress in road construction due to their low strength. Stabilizing such soil improve with binder agents prior to the geotechnical works can significantly its performance and ensure safety and stability of roads while exploitation. This research envisaged the use of five different binders (lime, energy fly ash, bio fly ash, slag, cement) as an additive stabilizing agents to improve the strength parameters of soil as required in engineering industry standards. The variations of strength was assessed using measurements of P-wave velocity of the elastic waves propagating through soil specimens stabilized by different combination of binders. Measurements were performed on 28th day of soil treatment. The best effects of added binders were noted in the following combinations: cement / energy fly ash / bio fly ash (P-waves >3100 m/s), followed by combination lime / energy fly ash / GGBFS (P-waves >2800 m/s) and cement / lime / energy fly ash (P-waves >2700 m/s). Adding lime is effective due to its fixation and chemical bond with particles. The study contributes to the industrial tests on soil strength for constructing roadbed.

Keywords: road base, driveway, cement, slag, fly ash, lime, stabilization

1. Introduction

Transport network plays a key role in many various aspects of the modern society: sustainability and safety, well-being and tourism, freight, haulage and logistics, connections and communication, economic stability and growth. These aspects have been discussed in many relevant publications pointing at the importance of transport functionality for societal development (Combes and Leurent, 2013; Jacobs-Crisioni *et al.*, 2016; Coppola *et al.*, 2020; Lowe, 2006; Banister and Berechman, 2001; Meijers). In the transport system roads have a dominant role due to the availability, convenience and flexibility of use (Ye *et al.*, 2014; Carboni and Dalla Chiara, 2018). At the same time, safety of transportation arises the question of effective methods of road construction and maintenance of road infrastructures with associated high costs (Janic, 2007; Guan *et al.*, 2022; Moreno-Quintero *et al.*, 2013; Moretti *et al.*, 2016; Hanssen *et al.*, 2012). A crucial factor for transport safety is the quality of road pavement which largely depends on bearing capacity and strength of soil used as a road base.

A performance of road pavements during intense exploitation largely relies on the stability of soils and subgrades. Therefore, the minimization of possible road cracks and the increase of resistance of road base towards stress from traffic requires the updated methods aimed on the improvement of soil quality (Arnold *et al.*, 2005). Stabilization of soil which serve as a road base is a conventional technology widely used in civil engineering (Preteville and Lenoir, 2016; Zhao *et al.*, 2017; Mohamedzein *et al.*, 2022; Zhang and Kevern, 2021; Ye *et al.*, 2021). Soils stabilized by binders are better suitable for the construction of road pavement and as a support layer for basement foundations of associated road infrastructure (Chen, 1988; Etim *et al.*, 2022; Noolu *et al.*, 2022). There are many examples on soil stabilization with various stabilizing agents: cement (Peng and He, 2009; Lindh and Lemenkova, 2022a, 2021b;), lime (Chitrakar *et al.*, 2021; Obuzor *et al.*, 2012), fly ash (Mishra, 2012; Chethan and Shankar, 2021), CKD (Sharo *et al.*, 2021; Lindh and Lemenkova, 2021a; Jimoh *et al.*, 2018), slag (Wang *et al.*, 2020; Lindh and Lemenkova, 2022c; Pai *et al.*, 2020). Binders improve physical and mechanical properties of soil: strength, stiffness, porosity, permeability and compactness, which is crucial for road construction.

As a result of stabilization, weak soils obtain improved geotechnical characteristics (Lindh, 2004; Lekha *et al.*, 2013). Stabilized soil with improved bearing capacity can be applied as a base layer during road construction, providing a strong basis for asphalt surfaces. Thus, the optimized technologies of soil stabilization and solidification result in compacting of soil for road construction (Kamon *et al.*, 1999). Stabilization of soil minimizes the cost of road maintenance throughout the improved lifecycle of road and the associated infrastructure due to the improved compaction, increased strength and bearing capacity of soil. In a societal and economic context, reinforcement of soil with binders increases traffic safety.

Diverse methods of soil stabilization have been used recently and reported in relevant papers. Specifically for road constructions, soil stabilization and solidification can be performed using two major approaches: mechanical (compaction) and chemical. The compaction is a more simple method which aims to densify soil by force through intensive pressure which removes air from soil pores. However, the drawback of this method is that it does not affect the water content in a soil sample, which is not suitable for the cohesive soils prone to moisture fluctuations. Moreover, the application of compactness is also limited by the threshold of the soil grain size, which is caused by the cohesion processes, interconnections and rearrangement of particles (Gerrard, 2000; Spagnoli and, Shimobe, 2020; Blotz *et al.*, 1998).

Chemical stabilization of soil using binders presents a more efficient method, which is specifically useful for the fine-grained weak soils, such as clays. Various binders have different effects on soil and in particular on various types of soil: fine-grained and coarse-grained soil require different stabilizers. Coarse-grained non-cohesive soils are best stabilized by Portland cement, cementitious blends, fly ash, and lime, while fine-grained soils are better stabilized by lime (quick lime, hydrated lime) or combination of lime and cement (Lindh, 2001). Other binders may also be used in various proportions and effects on soil, such as fly ash, bitumen, insoluble polymers, slag. Non-traditional binders may used as local products, e.g., eggshell lime (Oluwatuyi *et al.*, 2018; Beck Saldanha *et al.*, 2021), rice husk ash (Yadav *et al.*, 2017; Owino *et al.*, 2022), coir fiber (Boobalan and Devi, 2022). Thus, major factor for selecting a proper binder for a better soil stabilization is the soil grain size, that is, a contact area between the particles. Besides the traditional binders, several stabilizing agents may be used as blended mixes.

This paper focused on the improvement of soil properties through chemical stabilization using binders as blended mixtures. Soil a road-building material was collected from the selected region in Sweden and is presented by weak type (clay). We analyzed the interaction between the 5 binders used as stabilizing agents for soil: 1) cement, 2) lime, 3) slag, 4) energy fly ash, 5) bio fly ash. The focus of this paper is on the analysis of the effects from various binders and changed proportions between the binders in interaction with soil samples. The goal was to define the best ratio of binders that best affects the quality of samples and results in the stabilized soil, acceptable for road construction according to technical standards.

2. Methods

The soil specimens used in this study included industrially supplied clay collected in the selected regions of Sweden. Soil processing has been performed at the Swedish Geotechnical Institute (SGI). Specifically, the stabilization of soil was carried out as stipulated in Swedish Institute for Standards for lime (SIS, 2018a). The compression tests were performed using SIS standard SS-EN ISO 17892-7:2018 (SIS, 2018b). The measurements seismic P-wave velocity in soil samples were performed using technical standards (SIS, 2018c, 2019) and using existing reports (Rydén *et al.*, 2006).

2.1. Manufacturing soil samples

The soil specimens were manufactured in a special packing equipment that is designed to pack stabilized fine-grained moraine (Lindh, 2004). The samples were packed in a plastic pipe with a surface-mounted steel cylinder. In the packing equipment, the horizontal stress generated by packing is maintained in the way that the samples were not demolded until the storage is completed. The production is carried out in three layers of 1500 g each of a stabilized support layer. Between the different layers, the surface is scratched to ensure good adhesion. After packing, the specimens were taken out of the equipment, measured, weighed and paraffined. The paraffining was done so that no drying of the specimens would take place during the storage process. The paraffin used has a low melting point, 44°C, to minimize the effect on the soil specimen.

The ballast material as a carrier layer was weighed in the three batches of 1700 g each. Water was measured in measuring glasses, so that the corresponding 102 g per batch fold gives a water ratio of 6% before the binder addition, and 5.8% when the amount of binder was included, respectively. The binders were weighed according to the design scheme and standards. According to our experimental design, the specimens were stabilized with any one to five different binders: cement, lime, slag, energy fly ash and bio

fly ash. However, the total binder content was 51 g per batch in each case. In this way we could evaluate the effects of each binder on soil performance. This corresponds to a binder content of 3% based on the dry weight of the carrier layer. The batches were mixed in a steel mixing cylinder. The mixing tool consisted of a steel whisk driven by a powerful drill. After the three batches were mixed, they were kept rest for one hour. The three batches were then combined and mixed. Based on this mixture, three new batches of 1500 g each were weighed. The remaining soil material was used for water ratio determination.

2.2. Material structure

The structure of soil material was evaluated with regard to variability of samples, because soil is a highly variable material, formed and affected by complex geological and environmental processes, which should be considered for road constructions. External factors create variability in the physical and mechanical properties of soil samples, which largely depends on local environmental setting. In turn, spatial variability of soil specimens can impact the performance of infrastructure and roads built above this soil layer. To this end, we examined the homogeneity of specimens by creating two additional samples. Similar to the others, these samples were manufactured in three layers. Between each layer the underlying layer was carefully scratched so that no completely even horizontal layer would arise.

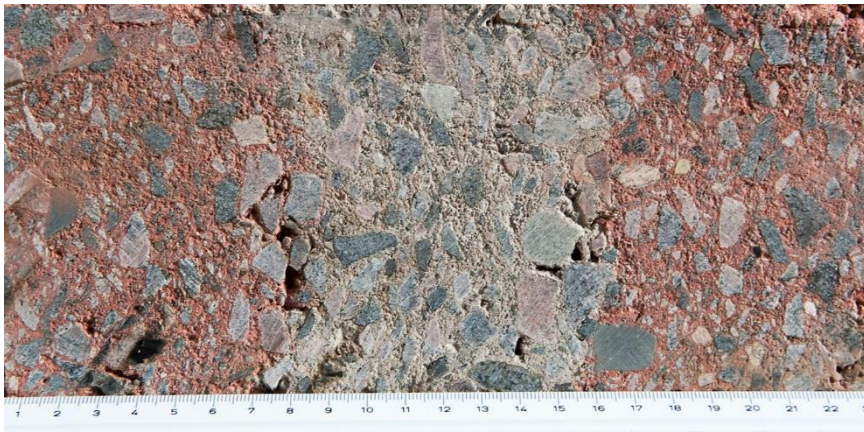


Figure 1. Split specimen with inner closed pore structures at the layer boundaries. Photo: Per Lindh



Figure 2. Internal pore structures arising in connection with manufacturing. Photo: Per Lindh

These two specimens were made with two and one layer dyed with iron oxide (FeO), respectively. In this case, only cement was used as a binder to treat the samples. In one specimen, the middle layer was uncoloured, while in the other two layers there was a red colour additive. For an extra specimen Nr. 2, only

the middle layer was stained. When the specimens had hardened for 28 days. Afterwards, the specimens were split so that there was a sawn cut surface through the axial centre of the specimen, see Figure 1. Figure 1 shows the two inner pore structures in the boundary layer between the layers of a soil specimen. These pore structures can be considered to depend on the manufacturing process as the other areas of the specimen are very homogeneous and compact with a pore structure not visible to a human eye. Figure 2 shows a detail of a saw cut on soil specimen. The photo shows that there was not enough fine material to fill in the entire pore volume during the specimen stamping process.

2.3. Tests on Uniaxial Compressive Strength (UCS)

In this test, samples were compacted at optimum water moisture contents for the various percentage content of five binders. The compacted samples treated by stabilisers (cement, lime, slag, bio fly ash and energy fly ash added to soil) were processed using Swedish standards. The specimens were then carefully paraffined and stored for 7, 14 and 28 days before conducting the UCS. The key approach of this process is to allow the soil structure and the binder mixtures to reach certain level of reaction, acceptable for geotechnical standards. The UCS tests were performed using the 10-ton compression press. The experiments were run by deformation-controlled test according to the SS-EN 13286-41 (SIS, 2021). According to this standard, the breaking load must be reached between 30 and 60 seconds. This time was achieved at a deformation rate of 3 to 4 mm/s. No visible correlations between the bearing boundaries and the fracture surfaces were found on any of the tested specimens. The specimens showed the hourglass-shaped fracture surfaces that were completely independent of the layer boundaries of soil samples.

2.4. Seismic measurements on day 28th

In order to analyse the strength development of the soft clay stabilized by 5 different binders we applied the seismic tests which well indicate the relationship between the velocities of the elastic P-wave and the UCS in soil samples. The velocity of the P-waves was measured on day 28th of the storage of soil samples. Seismic measurements were performed according to the technical standards of SGI using the existing methods reported earlier (Lindh and Lemenkova, 2022b).

3. Results

The content of cement remained the dominant factor in terms of compression wave velocity according to the results of the measurements on 28th day of processing. The effects from the bio ash demonstrate the values are comparable with the effects from the lime / slag mixture, followed by the pure lime, Figure 4 (Pareto diagram).

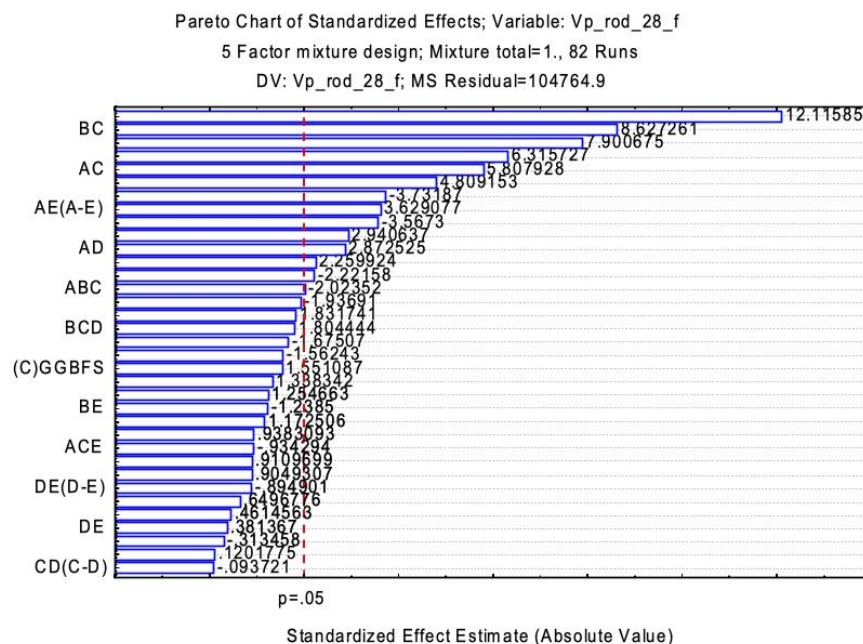


Figure 3. Pareto diagram of all effects included in the cubic model for the soil strength measurements on day 28th

The Pareto diagram in Figure 4 shows small visible effects of added energy fly ash and slag on soil mixture. Other response surfaces also show the same pattern in terms of positive and negative interactions between soil and binders. Note that in Figure 7 (right) there are only linear effects. Figures 5, 6 and 7 give the relationship between UCS and the elastic wave velocity for stabilized samples of soft clay based on the addition of 5 various binders and estimated UCS results. Figures show that adding binders well improves the growth trend of the UCS in soil specimens, as visualized in ternary simplex diagrams.

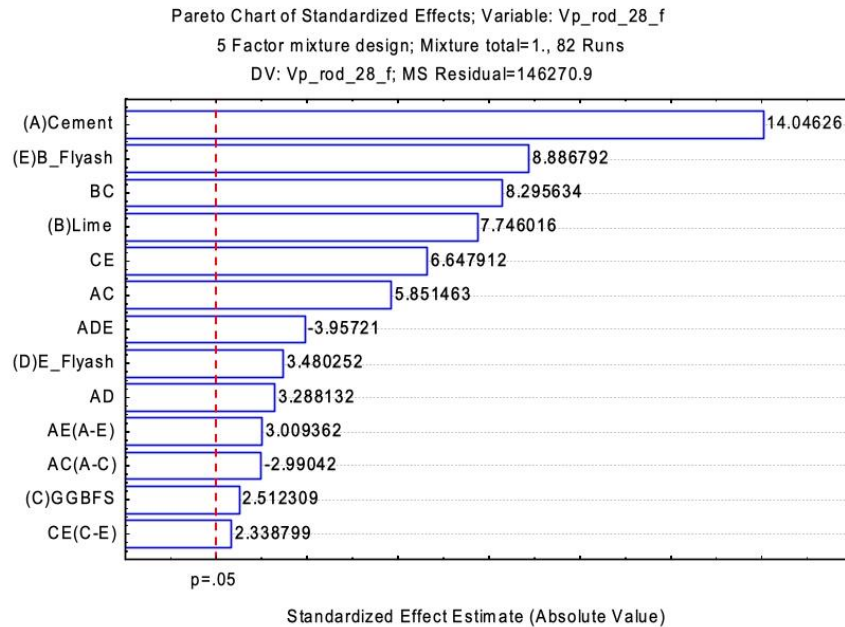


Figure 4. Right: Pareto diagram of the significant effects from binders on stabilized soil included in the cubic model for the measurements on day 28th

The laboratory tests on the stabilised soil with adding various types of binders (cement, lime, lime, and the two types of fly ash), estimation of the soil strength by UCS by measurements of the P-wave velocity were conducted to ascertain what ratio of binders affect the soil properties in the most effective way, and improves its geotechnical characteristics, such as compaction, strength, swelling and cohesion properties of the expansive clay samples.

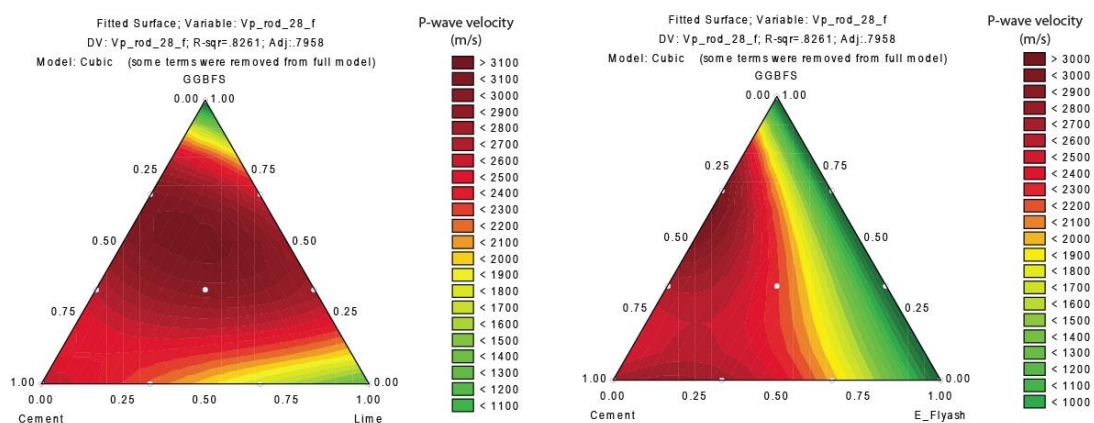


Figure 5. The P-wave velocity indicating the development of strength in soil samples on day 28th in stabilization. Left: interactions from binders cement, lime and slag (GGBFS). Right: interactions from binders: cement, energy fly ash and slag (GGBFS)

The results showing the comparison of the effects from binders are summarized in Figures 3 and 4 (Pareto charts), and the detailed visualization of each combination of binders is shown in ternary diagrams (Figures 5, 6 and 7) showing the response of speed propagation of seismic waves on soil samples, stabilized

using various combination of three binders. As a result of the cementitious mixture by proportions of lime 50% / slag 50%, the percentage of water which fills the pores in between the layers is reduced along with the increases in values of the soil strength (Figure 5, left), as recorded by the P-wave velocities (>3100 m/s). Hence, the magnitude of strength potential of cement/slag/energy fly ash treated expansive clay soil becomes better than that of the raw soil material. Further, the analysis of Figure 5 (right) shows that the addition of GGBFS (slag) as a binder in different proportions between 25% to 50% to the cement ratio of 25% to 50% and variations of energy fly ash from 50% up to 75% to the tested specimen may increase the strength of the expansive clay (bright red area in the diagram).

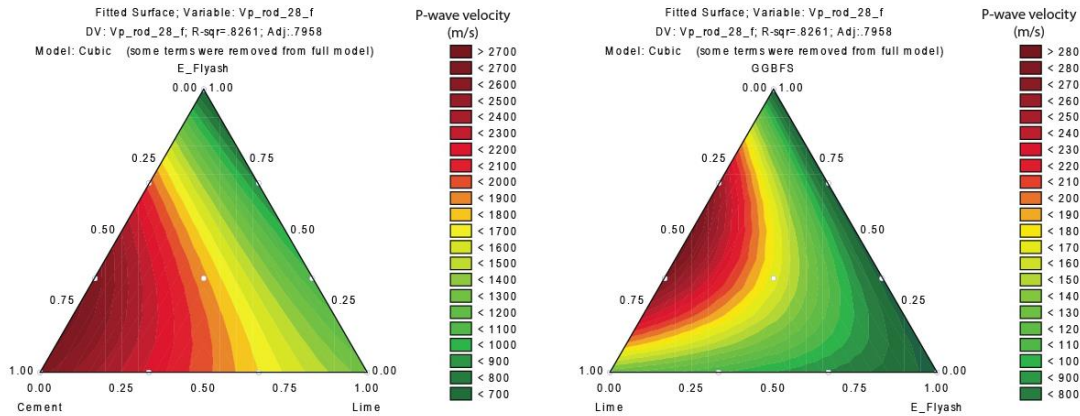


Figure 6. The P-wave velocity indicating the development of strength in soil samples on day 28th in stabilization. Left: interactions from binders cement, lime and energy fly ash). Right: interactions from binders: lime, energy fly as and slag (GGBFS)

It is further observed from the analysis of Figure 6 (left) that the adding energy fly ash increases the strength of the expansive clay (bright red colour corresponds to the highest values of the P-wave speed), as corresponds to the P-wave velocities above 2700 m/s. The combination of GGBFS (slag) added to 50% to lime (50%) will also increase the interaction between the clay particles and lead to soil strength in the stabilized specimen increased, as recorded in P-wave speed above 2800 m/s (Figure 6, right).

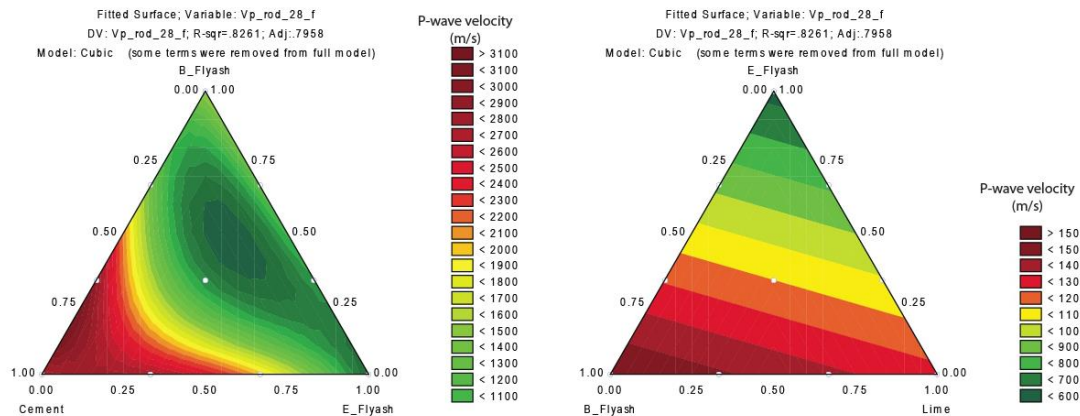


Figure 7. The P-wave velocity indicating the development of strength in soil samples on day 28th in stabilization. Left: interactions from binders cement, energy fly as and bio fly ash. Right: interactions from binders: bio fly ash, lime and energy fly ash

The influence of bio fly ash on strength characteristics of expansive clay shows maximal velocity of P-waves (> 3100 m/s) which corresponds to the highest strength of soil samples as shown by bright red areas (Figure 7, left). In turn, it is ascertained that, the increase in strength is also depends on addition of bio fly ash (Figure 7, right) with added energy fly ash to the mass of clayey soil, as recorded by increase in P-wave velocity to above 1500 m/s. The performance evaluation of the strength as reflected in P-wave velocities of seismic waves propagating soil specimens was carried out using Simplex design method (ternary diagrams) illustrating the changes in binder ratio in each case on the strength of soil samples.

4. Discussion

The effects from various binders on increase of strength of clayey soil were evaluated using five binders taken in different ratios: cement, lime, slag, energy fly ash and bio fly ash. The applied geophysical methods were used to measure the velocities of seismic P-waves propagating the stabilized specimens and represented the development of strength. Large increase in soil strength was obtained by adding energy and bio fly ash into lime, and in a mixture of cement (25% to 50%) to energy fly ash (50% up to 75%). Moreover, large increase in soil strength were also noted in samples containing 50% of lime and 50% slag where P-waves oversteps the speed of 2700 m/s. when lime is utilized up to 50% to cement and slag mixture under testing conditions, this mix also notably improves strength of soil in which is beneficial for pavement and road stability. The UCS test as determined by the laboratory equipment of SGI and standard SIS method (SIS, 2018b) was applied to the specimens with the lowest moisture content at which the bonds between soil particles or aggregations with binders which changed depending on the binder ratio (cement, fly ash, lime and slag), as shown in P-wave velocity.

The P-waves velocities changes corresponding to the different proportions of binders as follows: ranges from <1100 m/s to >3100 m/s for mixtures cement / lime / GGBFS; P-waves ranges from <1000 m/s to >3000 m/s for mixtures cement / energy fly ash / GGBFS (Figure 5). P-waves ranges from <700 to >2700 m/s for mixtures of cement / lime / energy fly ash; P-waves ranges from <800 m/s to >2800 m/s for mixtures lime / energy fly ash / GGBFS (Figure 6). P-waves ranges from <1100 to >3100 m/s for mixtures cement / energy fly ash / bio fly ash; P-waves ranges from <600 m/s to >1500 m/s for mixtures bio fly ash / energy fly ash and lime (Figure 7). Thus, the strength of the soil specimens increases up to the addition of 50% lime and decreases with any further addition of energy fly ash to the additive. The optimum proportion of traditional binders used for stabilizing clayey soil is lime/ cement / slag as one third of the treated soil mixture. From the performance analysis on the Pareto chart, the total standardized effects on stabilization and the performance of strength in absolute values are most noted from cement (14.0), followed by the bio fly ash (8.9), lime, energy fly ash (7.7) and GGBFS (2.5).

The possibility of combination of 5 binders in different proportions as stabilizers for increase of strength of clayey soil intended for road construction is investigated. Tested stabilizing agents included cement, lime, slag, energy fly ash and bio fly ash selected in various ratios in binder. The results suggest that using blended binders for soil stabilization provides an effective way to stabilize clayey soft soils intended to be used as a basis layer for roadbed. Unlike single binders, the use of mixes for improving soil strength results in better and optimized process which his demonstrated in the results, as visually compared in various simplex (ternary) diagrams. The advantages of the applied geophysical methods consists in the correlation between the speed of the seismic wave propagation in the soil mass and its strength. Measured velocities of the elastic P-wave accurately visualized the development of strength in the samples of the soil clay stabilized by the mixes of binders under compressive loading (UCS).

5. Conclusions

In this paper, the strength development of soft clay stabilized by blended binders selected in various proportions for cement, lime, slag, bio fly ash and energy fly ash were evaluated upon the compression of the soil samples using a 10-ton compression device under compressive loading. The results from the investigation show that clayey weak soil with soft content and fine grain structure can be effectively treated by binders combination of lime, cement and fly ash before the geotechnical works. The increase of soil strength is achieved by the chemical reaction of soil particles within the structure with elements of lime and other binders, which produces a cementitious mixture that has greater strength characteristics in the material structure. After the increase of strength properties through stabilization, soil can be used as a road construction material, due to the increase geotechnical characteristics.

The applications of this study include technical engineering works on road construction, specifically improving soil properties used as a base layer for roadbeds. Other use including building of the associated infrastructure related to the road maintenance and general functionality. Possible limitations of the performed study may include the characteristics of the fine soil grain size of clay, which should be considered by the selection of proper binder with lime as the most effective type of binder, as discussed above. In turn, clayey soils are affected lesser by pure cement with lesser cohesion limits compared to the effects from lime. Both energy fly ash and bio fly ash are not as effective reagents as lime, but can contribute to the strength when mixed with more ratio of lime. Both energy and bio fly ash could be used as reagents when mixed with cement or lime. The fixation of lime in clay corresponds to the optimum additive relative to other ratio of binders, which contributes to the increase of strength.

The soil specimens were treated with various ratio of binders. The maximum soil strength increased with a corresponding increase in lime, fly ash and cement contents in soil. The P-wave velocity increased along with the increased strength (UCS). The percentage amount of binders added into the soil can be fixed with notable effects from lime due to its fixation capacity in weak soil (clay, moraines). As demonstrated in this study, lime contributes to the improvement of soil workability and strength to its chemical effects in the course of stabilization as assessed during 28 days.

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