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# Geotechnical Properties of Soil Stabilized with Blended Binders for Sustainable Road Base Applications

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**Abstract:** This study aimed at evaluating the effect of blended binders on the stabilization of clayey soils intended for use as road and pavement materials in selected regions of Sweden. The stabilization potential of blended binders containing five stabilizers (cement, bio fly ash, energy fly ash, slag and lime) was investigated using laboratory tests and statistical analysis. Soil samples were compacted using Swedish Standards on UCS. The specimens were stabilized with blended mixtures containing various ratios of five binders. The effects of changed ratio of binders on soil strength was analyzed using velocities of seismic P-waves penetrating the tested soil samples on the day 14 of the experiment. The difference in the soil surface response indicated variations in strength in the evaluated specimens. We tested combination of blended binders to improve the stabilization of clayey soil. The mix of slag/lime or slag/cement accelerated soil hardening process and gave durable soil product. We noted that pure lime (burnt or quenched) is best suited for the fine-grained soils containing clay minerals. Slag used in this study had a very finely ground structure and had hydraulic properties (hardens under water) without activation. Therefore, slag has a too slow curing process for it to be practical to use in real projects on stabilization of roads. The best performance on soil stabilization was demonstrated by blended binders consisted of lime/fly ash/cement which considerably improved the geotechnical properties and workability of soil and increased its strength. We conclude that bearing capacities of soil intended for road construction can be significantly improved by stabilization using mixed binders, compared to pure binders (cement).

**Keywords:** soil strength; binders; road pavements; soil strength; recycling technologies; materials science; engineering; civil engineering; construction; compressive strength; soil stabilization

**PACS:** 81.40.Cd; 81.40.Ef; 62.20.Qp; 83.50.Xa; 45.70.Mg; 92.40.Lg; 81.40.Lm; 62.20.M–

**MSC:** 76A99; 74E30; 74Fxx

**JEL Classification:** Q00; Q01; Q24; Q55; Q56

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**Citation:** Lindh, P.; Lemenkova, P. Geotechnical Properties of Soil Stabilized with Blended Binders for Sustainable Road Base Applications. *Constr. Mater.* **2023**, 3, 110–126. https://doi.org/10.3390/constrmater3010008

Received: 19 January 2023
Revised: 5 March 2023
Accepted: 7 March 2023
Published: 12 March 2023



## 1. Introduction

Selecting binders for soil stabilization is a widely recognized problem in civil engineering where one tries to find a proper type and percentage of stabilizing agents to improve soil properties [1–3]. For instance, using binders to improve the properties of soil is necessary for road construction. As a result of stabilization by additives, such as cement, lime, fly ash and slag, soil obtains improved workability and better engineering characteristics and geotechnical properties. These are crucial for road construction due to the increased compressive strength, flexion strength, porosity, density and dynamic modulus [4]. Many existing methods, such as [5,6], deal with various binders and evaluate their effects on stabilization of various types of soil. Specifically, for Sweden with its northern environmental and climate conditions stabilisation of expansive soil is crucial due to the strong effects on urban infrastructure [7,8]. For instance, stabilized soil should be more resistant to freeze–thaw cycles and fatigue cracking, which is important for transport network safety in cold regions.

Previous studies have indicated that the addition of various stabilizing agents improved the workability of soils [9–13]. For instance, adding cement improves the strength and bearing capacities of soils [14], while adding lime contributes to gain in strength in tested soil specimens [15]. This suggests the possibility that the experimental addition of various stabilising agents can even more improve soil characteristics. Contrary to these methods, it was proposed recently to use mixtures of diverse combinations of blended binders. Thus, in existing studies [16–21] experimented with the addition of blended binders to soil which caused a significant gain in strength.

Much has been written on the improved properties of soil after adding various binders as stabilizers. For example, ref. [22] reports that the addition of cement to the soft soils fastens acquiring strength results; ref. [23] mentioned stabilizing effect of fly ash and lime additives on strength and durability of soil through neutralizing acidity; ref. [24] tested wearing course asphalt mixtures made with various percentages of fly ash and reported satisfactory volumetric composition which can be achieved by adding fly ash into soil mixture, improved bulk density and filled voids of the composed mineral and asphalt mixture; ref. [25] improved the mechanical behavior of an asphalt mixture using the alternative aggregate boiler coke ash, an element that originates in nickel processing. Further; ref. [26] evaluated the feasibility of using mud and fly ash residues to produce asphalt mixtures.

Long-term practical development of soil stabilization in Sweden resulted in improved technical equipment used for field and laboratory soil investigations, and new design methods [27]. Various binders of were tested and applied for a more effective soil stabilization. For instance, previous studies report [28,29] that the Ground Granulated Blast Furnace Slag (GGBFS) can be effectively used as a replacement of Portland cement in civil engineering and construction engineering works due to its high geotechnical quality and environmental sustainability. Further, the long-term trend of the improvement of properties of the subgrade soils stabilized by fly ash was analyzed for several decades and reported in recent studies [30]. Soil chemically stabilized with blends of cement and fly ash demonstrated improved characteristics in the Unconfined Compressive Strength (UCS) and split tensile strength tests, as demonstrated in previous studies that also mentioned the increased shrinkage limit and crack reduction in soil samples [31].

However, while the results presented in existing studies on blended binders and their applications in various regions with diverse soil types [32–34], are consistent with those obtained by other works on effective methods of soil stabilization [35], it is still unclear how these methods behave when used in specific conditions of Sweden with low winter temperatures and high technical requirements for soil and road specifications. For instance, maintenance of roads during non-favourable conditions of winter-spring period in Sweden is based on using soil resisting to intense rainfalls and freeze–thaw cycles. Therefore, selecting effective binder combinations is especially important for stabilization of soil collected in southern Sweden. As a response to such needs, the goal of this study is to test how different components in binders in binder blends interact during clayey soil stabilization and increase the stability and safety of roads depending on proportions and ratio with regard to water content in clayey soil, which is essential for the climate setting of southern Sweden. The target improvements of soil specimens include gain in strength, resistivity and durability of the stabilized soil in roads, as basic requirements for transport safety.

For instance, while the existing practices of soil stabilization focused on the design of road constructions and transport engineering [36–42], our study contributes to these investigations with a special aim at evaluating the effects of blended binders. The use of blended binders such as slag, cement, lime, energy fly ash and bio fly ash enables to increase the quality of soil and thus to improve the road drainage measures in Swedish climate setting. Because the combination of blended mixtures has better effects on soil properties, such experiments ensure more effective and stable road construction, operation and maintenance. In this way, effective soil stabilization increases safety and durability of roads. Further, in this paper we concentrate on presenting the mixed binders and evaluate their effects on the increase of soil properties intended as a sustainable road base. Suggested improvements concerning using blended binders instead of single binders for soil stabilization included the statistical computing of the optimized ratio of the mixed binders. Mixed binder lead to a better and more durable soil stabilized for road pavement. On the other hand, we showed that blended binders have different properties in terms of the reaction period with soil and curing time, which requires a special evaluation through a series of tests. In this setting we demonstrated that hardening of soil by an optimal combination of blended binders is an important problem in civil engineering and construction industry.

This aim of the present paper is to present current practice in stabilization of clayey soil used for building road surface in Sweden by blended binders. To illustrate the practical importance of the blended binders for Swedish soils, we apply it to real tested clayey soil types collected from the sample area in southern Sweden. Clay is a fine-grained weak soil that tends to change in volume due to the fluctuations in water content under diverse weather conditions [43]. Therefore, such type of soil should be stabilized prior to road construction to increase the strength and stability of road and transportation safety. There are many binder types used for stabilization of weak soil and reported for road construction cases [44,45]. Portland cement and lime are the traditional binders in stabilization contexts where the lime needs clay mineral or air ($CO_2$) for a hardening process to take place [46–49].

Previous paper on stabilization of clays exploited the importance and diverse effects of binders on clays [50–52]. To continue this research, we extended the experiments on combinations of binders for clays collected in southern Sweden and detect the effects from the percentage of various binders on hardening of clayey soil while trying to statistically balance the ratio of binders in a mixture. Experimental trials with different binders used for soil stabilization in Swedish climate aimed at improving the hydraulic performance of soil such as long-term infiltration capacity and porosity.

Based on an experimental combination of various proportions of binders used for soil stabilization, the study sought to identify the following aspects of road construction: (1) problems experienced concerning soil strength used for road construction, focusing on the current Swedish climate; (2) effective soil stabilization enables to avoid possible issues regarding climate impacts such as flash floods and heavy showers; and (3) adaptation measures regarding road stability taking environmental setting of Sweden into account, and improved road functioning by increased strength parameters of clayey soil as a construction material and increased bearing capacity in roads.

Aimed at the developing of the unified framework of clayey soil stabilization by blended binders, our study continues the research on improvement its geotechnical properties which has been observed in multiple previous publications [53–59]. These and other works result from the need of the improved soil properties with the addition of binders in transport infrastructure, which can be achieved by the treatment of soils with stabilising agents. Positive results of increasing gain in strength upon stabilization with the addition of various binders are demonstrated in these papers. The goal of this survey is to provide a series of tests aimed at improving the geotechnical properties of soil. The objective is to ensure high engineering characteristics and safety of roads and sustainability of pavements in local settings of southern Sweden. Thus, the overview of the location and condition of soil used for construction of road facilities was carried out to better select binders.

Binders that work best for clayey soils of southern Sweden ensure stability and strength of roads during future exploitation. Suggestions concerning selecting binder blends, research designed based on simplex lattice experiments and seismic measurements used to evaluate P-wave velocity indicating soil strength aimed at the quality of the stabilized soil for improved road bearing capacity. The economic effects from the stabilized soil has direct economic advantages in road construction industry such as higher material stability, decreased erosion, reduced road maintenance and construction costs, ensured safety in transport network to mention a few of them. All these factors together significantly contribute to the societal development and a well-being of the society.

## 2. Materials and Methods

### *2.1. Implementation of the Experiment*

The following experiments were implemented to evaluate the performance of clayey soil after stabilization with five various binders. We compared the effects from cement, bio fly ash, energy fly ash, slag and lime on the gain in strength of soil specimens evaluated using P-wave velocities. In the first step, soil specimens were fabricated using different binder recipes. To ensure the significance level of the results, the recipes are based on the previous experiments in combination with the statistical trial assessment. The statistical planning minimizes the number of the experiments that need to be performed in order to reach the desired level of significance. For five different binders, 100 test soil specimens were manufactured. These specimens were stored for 90 days to achieve a final strength even for the slow-curing components. During the storage period, the speed of the compression wave and shear wave have been measured in the material samples at different times to quantitatively measure the strength of soil specimens.

To investigate how five different binders work individually and in combination with each other, we used different approaches. A common method is to keep all the parameters constant except for the target one that is varied. In our case, the target parameter was the amount of each tested binder: cement, bio fly ash, energy fly ash, slag and lime, respectively. This is repeated with the next parameter iteratively. Although this method is conventionally used, it includes certain drawbacks as follows. First, the interaction effects and the second-order effects between the different components are missed in the final evaluation of the soil strength. These interactions can be both positive and negative, i.e., missed interaction and interpretation of the results regarding safety issues. Therefore, the methodology of our study considered more effective approaches, such as simplex-lattice design, while evaluating the results (Figure 1).

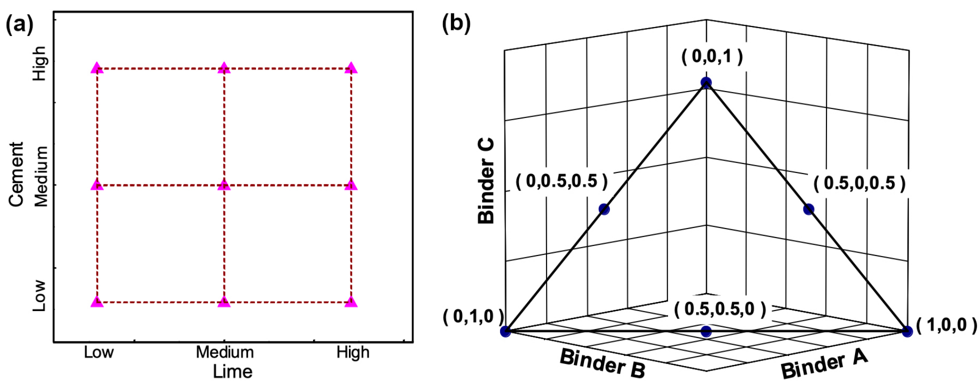


**Figure 1.** Experimental design scheme. (**a**): 3 × 2 factor experiment for evaluation of the effects of binders on soil strength. (**b**): Schematic image of a "mixture design" with three factors; A, B and C. The experimental setup is called simplex-lattice (3 × 2).

As an alternative to the above, there is a response surface method. The approach of the response surface method is based on the assumption that all the variables that affect the soil strength are varied according to a special scheme. In a factorial trial, the amount of binder is varied either according to the low and high admixture, or triple admixture consisting of low, medium and high values depending on whether the second order effects are to be taken into account. Due to such an algorithm, this method is very effective for testing large amounts of soil (e.g., hundreds of tons of the materials), because even few attempts provide enough data for decision making. Another advantage of the response surface method is that it enables to evaluate different binder levels. The disadvantage is that in the specimens with high levels of several binders, the content becomes very high which may affect the results. A simple illustration with only two binders is indicated in Figure 1.

### 2.2. General Workflow

The design experiment of this study followed the existing guidance [60] and includes the following points in problem formulation and solving:

- Identifying the factors affecting soil strength;
- Defining the amounts and the ratio of binders optimal for effective stabilization of clayey soil;
- Identifying the environmental limits affecting the geotechnical properties of soil;
- Selecting the response variables: cement, fly ash and lime in various ratios;
- Experimental modelling and statistical approaches for the data analysis;
- Performing the experiments using the UCS and P-wave seismic tests;
- Quality control aimed at identifying the advantages and drawbacks of the methods.

Parts of the above steps in the methodology take place iteratively, while others were performed in parallel. We considered the statistical approaches in data analysis for the experimental testing aimed at evaluating the optimal binder amount that should be added for the best results in soil stabilization [61]. To increase the efficiency of the experiment, statistical data processing was applied and the outputs were visualized as ternary diagrams and Pareto charts. Moreover, we applied the additional points while performing the statistical data processing [60]:

1. Considering the non-statistical knowledge to the geotechnical problems related to road construction;
2. Keeping the design and analysis as simple and clear as possible;
3. Identifying and recognition of the difference between the empirical practical and theoretical statistical significance;
4. Performing the iterative series of the experiments on soil specimens.

The methodology consists in the optimization of the process of soil stabilization the the main goal to evaluate the soil strength as a crucial criterion of safety for sustainable road construction.

### 2.3. Manufacturing Soil Specimens

The specimens were manufactured in a special compaction equipment of compaction apparatus that is designed to pack the stabilized fine-grained moraine [62], Figure 2. When compacting the specimens, separation was observed in raw soil material. During the fabrication of samples, all the possible precautionary measures were taken in order to minimize separation of soil granula. However, a certain separation occurred with the effect varied depend on different binders. The energy and bio ashes demonstrated more separation compared to the others. The separation of the specimen can be seen in Figure 2 which illustrates the bottom surface of a packed specimen on the left. It indicates an underfilled material with few fine material between the coarser particles. The right part of Figure 2 presents the upper surface of the wrapped specimen. This figure illustrated the overfilled soil specimen, which means that it includes the excessive amount of the fine material. This results in that fact that coarser particles have no direct contact with each other which significantly affects the cohesion properties of soil.

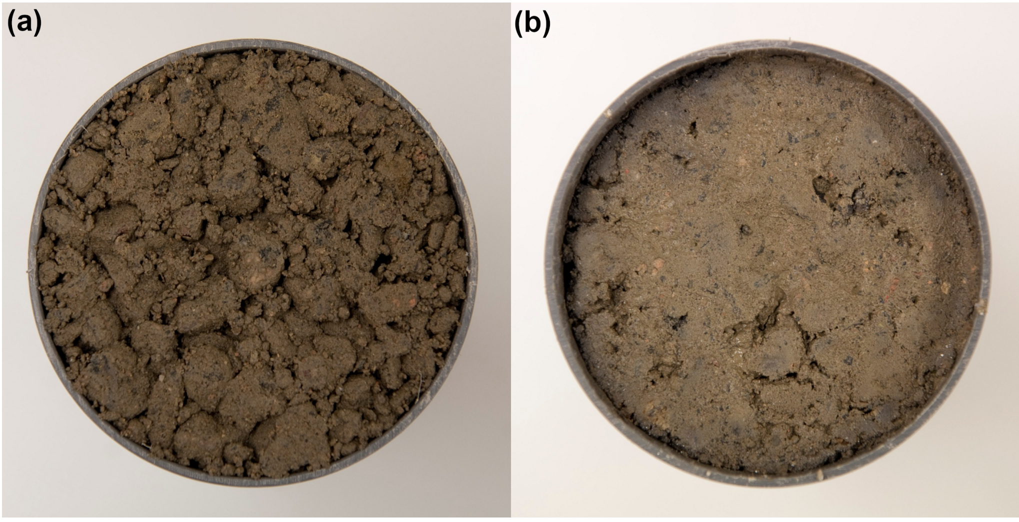


**Figure 2.** Specimen soil samples. (**a**): the lower surface of a stabilized specimen. (**b**): the upper surface of a stabilized specimen.

### *2.4. Soil Stabilization by Binders*

The practical goal was that stabilized soil specimens reach the compressive strength of 4 MPa, since it is a common and acceptable value in road construction context. The compressive testing of soil specimens stabilized by various binder combinations was used to evaluate how the clay material will react when it is being compressed due to the external loads during exploitation of the roads. The choice of binders was limited to five different variants: cement, cement and slag, lime and slag binders. Two binder types include the traditional binders (cement and lime) while the other three binders are the alternative novel types: slag GGBFS, energy ash and bio ash.

Cement was used as a main reference binder, because it is a well documented binder widely used for stabilization of soil used as a material for construction of road pavement. The ashes were regarded as the binders from the category of residual products. The total amount of binder was chosen in such a way that they would be representative for road stabilization. The selected binder recipes used for soil stabilization were based on the previous experience to ensure the quality of soil and the lifetime of roads through improved its bearing capacity. Thus, the improved quality of soil used for road construction improves the lifetime of a road, decreases expensive maintenance activities to repair roads and road condition. The significance level of the results was ensured with statistical trial planning.

The general aim was to increase the resistance of soil towards the freeze–thaw cycles, provided that there is no continuous water penetration on the road. To this end, no extra water was added in the freeze–thaw experiments. The second aim is to evaluate the behavior of soil and its response under crushing loads, as well as plastic flow behavior and ductile fracture limits. The equipment used in this test was originally developed to compress the fine-grained stabilized moraines, and it worked well for road base applications. For compression of the stabilized base course gravel, the equipment works satisfactorily, but the pore structures affected its performance for the fine-grained soils. During the compaction, the separation was reduced to obtain a gap between the two soil layers forming the specimens.

### 2.5. Seismic Measurements

After collecting and refining the soil samples, the specimens were stored for 90 days. During this curing period, the resonant frequency measurements were performed on the soil specimens using existing methods described earlier as free–free resonate column tests [63–67]. The seismic measurements in this study were performed as evaluation of P-wave velocity after the curing of the soil specimens on day 14. The paraffin on the end faces was removed during the actual measurements after which the end faces were resealed. According to this method, the experiments were repeated with measured both axial values (compression wave) and radial values (shear wave). The radial measurements gave a large scattering in values caused by the low strength of specimens and performance outside of the plastic tube.

### 2.6. Statistical Analysis

After the completion of the previous steps, the statistical analysis was performed for objective data quality control, as data might be a subject to errors in course of the experiment. The scope of the statistical testing was to estimate the best combination of binders in blended mixtures through selecting optimal combination and ratios of binders. The ultimate goal is to increase the quality of roads and lifetimes of pavements due to the improved soil characteristics. To this end, a series of trial tests was performed before the final experiment using the statistical hypothesis. The null hypothesis ($H_0$) in this case is that all the binders give the same strength, while the alternative hypothesis is that they do not give the same strength. Two different assumptions can be made when testing these hypotheses represented by Equations (1) and (2):

$$\alpha = P(typeIwrong) = P(rejectH_0|H_0istrue) \tag{1}$$

$$\beta = P(typeIIwrong) = P(failstorejectH_0|H_0isfalse) \tag{2}$$

where $\alpha$ is usually called the significance level of the test. In this case, $\alpha = 0.05$ was used. This means 5% probability that $H_0$ will be rejected even though the $H_0$ is true.

### 2.7. Simplex-Lattice Design

A mixture design based on the simplex-lattice approach was selected for the experimental setup. A simplex-lattice design can be adjusted according to either a square model or a special cubic model. For a simplex-lattice design with three factors, the square model is described by the following Equation (3):

$$y = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{1,2} x_1 x_2 + \beta_{1,3} x_1 x_3 + \beta_{2,3} x_2 x_3 + \epsilon \tag{3}$$

where $\beta$ is the coefficient of regression; $\epsilon$ is the residual error; $x_1$ is the value of binders which indicate factors; $y$ is the dependent variable. The cubic model can be described as follows in the Equation (4):

$$y = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{1,2} x_1 x_2 + \beta_{1,3} x_1 x_3 + \beta_{2,3} x_2 x_3 + \beta_{1,2,3} x_1 x_2 x_3 + \epsilon \tag{4}$$

where $x_1$ is the value of binders, $\beta$ is the coefficient of regression; $y$ is the response area and $\epsilon$ describes the error term. The difference between the square and cubic model is that in the cubic model, the cubic term $x_1 x_2 x_3$ is also determined. However, the increased resolution in the cubic model involves a larger number of experiments which should be performed. In this study, we defined the following parameters: five different factors corresponding the types of five binders; a cubic design which enables to include an increased number of internal points and an increased proportion of points on the stripes and double trials; the total number of specimens is 82 soil samples.

### 2.8. Freeze-Thaw Tests

Fine-grained clayey soils are not suitable as subbase layers in roads and constructions because of their compressibility and frost susceptibility. Therefore, to improve the engineering properties of fine-grained clayey soils and to increase its shear strength, binders were added and the freeze–thaw experiments were performed to evaluate the effects of stabilization and assess the resistance of soil to reduced temperature below zero. The freeze–thaw tests were performed according to the exiting standard of SS-EN 137244. During the freeze–thaw experiments, soil specimens were frozen for a total of 56 cycles with no extra water added. The measurements were performed on days 7, 14, 28, 42 and 56 with varied temperature, as shown in Figure 3. The freeze–thaw cycles during spring–winter period are typical for northern climate conditions of Sweden. The freeze–thaw cycles influence the curing of soil and negatively affect the strength of the stabilized soil. Moreover, the reaction of different soil types varies as a response to freeze–thaw cycles depending to the parameters of stabilization such as curing period, binder content and proportions. Therefore, testing the behavior of stabilized soil during changed temperature is essential for evaluating its future performance prior to road construction.

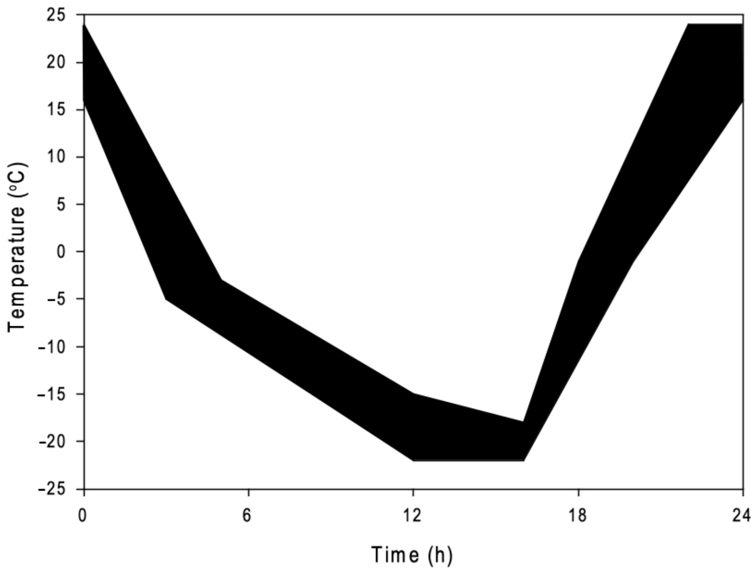


**Figure 3.** Temperature cycle for the freeze–thaw experiments.

## 3. Results

The impact of the blended binders used for soil stabilization on the engineering properties of clayey soils was investigated with focus on the increase of strength. We have tested the effects of various binders in diverse combination and proportions on soil stabilization. In this section, we show the results of the improved strength of the stabilized soil estimated by P-wave velocities and visualized in ternary diagrams. Upon soil stabilisation, the obtained values in strength were evaluated statistically and visualized as Pareto charts in Figure 4. The results show that the strength increases with curing time and added binders.

Diverse combination of various binders provides different effects on soil strength which prove the effects from various binders. In this chart (Figure 4), the abbreviations for the five binders are denoted by letters: A–cement, B–lime, C–slag GGBFS, D–energy fly ash, E–bio fly ash. Accordingly, the combinations of binders are given as follows, Figure 4: BC–lime+slag, CE–slag+bio fly ash, AC–cement+slag GGBFS, ABC–cement+lime+slag (a triple combination), AE–cement+ bio fly ash, BCE–lime+slag GGBFS BE+bio fly ash, BDE–lime+energy fly ash+bio fly ash, BCD–lime+slag GGBFS+energy fly ash, ACE–cement+slag+bio fly ash, DE–energy fly ash+bio fly ash, and BD–lime+energy fly ash.

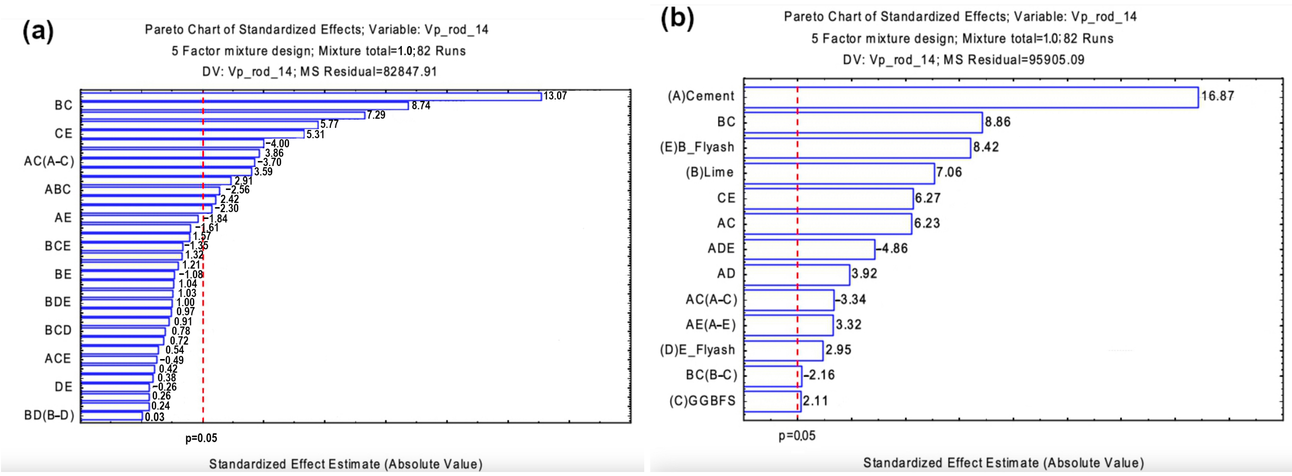


**Figure 4.** (**a**): Pareto diagram of all the effects included in the cubic model for estimated gain in strength of soil on day 14. (**b**): Pareto diagram of the significant effects from binders on stabilized soil included in the cubic model for the measurements on day 14.

In general, the proposed method tends to find the optimal combination of binders with regard to the stabilization of clayey soil where specimens are selected without external and internal undesired pore structure. The controlling parameters are the strength development of the soil material, final gain in strength and improved resistance of soil to freeze–thaw cycles. Both the destructive testing (uniaxial compressive strength) and non-destructive (seismic) are used as the test methods. Figure 4 presents the significant effects after the 14 days of curing period of the stabilized soil samples. A visual comparison of the results indicates that the proportions of cement in a blended mixture of binders is still a clearly dominant factor for the compression wave velocity. We next compare the interaction between lime and slag (a mixture of BC, as explained above) and evaluate their effects on soil strength. Thus, the combination BC has increased in size and overpassed the bio ash.

The P-wave velocity indicating the stabilization effects on soil is demonstrated in ternary diagrams in Figures 5–7. In the evaluation of the experimental results, gradual elimination of non-significant effects has been applied, i.e., the first analysis contains all the effects. Then the non-significant effects are removed until the model consists only of significant effects. The method is called 'backward elimination' and described by [68]. Figure 5 illustrates the variations of P-wave velocity measured on day 14 during soil stabilization, indicating soil strength in the stabilized specimens by added various types of binders. Further, Figure 5 demonstrates the effects of added cement, energy ash and lime on changed soil strength. Here the left graph displays the increased interaction between lime and slag, while the right graph shows a lesser interaction between cement and energy ash and a larger interaction between cement and slag when stabilising soil specimens.

To evaluate the results both qualitatively and quantitatively, the P-wave velocities were calculated for soil samples stabilized by various percentage of the three binders. Figure 6a compared our results with case of cement, lime and slag binders to those of the energy fly ash and slag binders, Figure 6b. The results containing cement are consistently better with P-wave velocity exceeding 2700 m/s, except for the blend with high combination of the GGBFS and lime where P-wave velocity exceed 2400 m/s. In both cases the areas of the highest gain in strength are shown in red colour. The interaction between cement and energy ash is also illustrated in Figure 6a.

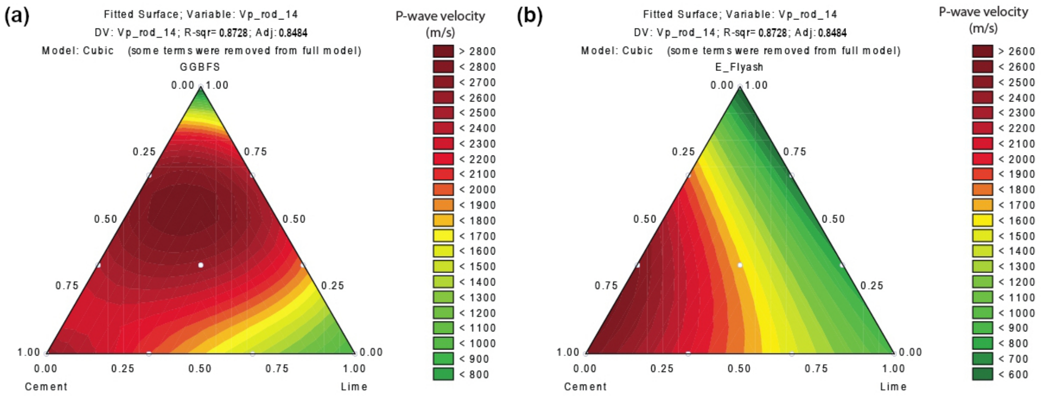


**Figure 5.** The P-wave velocity on day 14 during soil stabilization. (**a**): increased interaction between lime and slag. (**b**): larger interaction between cement and slag.

Of the three different residual products, the slag Merox clearly works best. The ashes work poorly in this stabilization context. Energy ash has a well-documented effect and can harden on its own [49]. However, this study disclosed that the energy fly ash does not act well as a binder in a stabilization context of clayey soil. One reason for the poor response from the ashes may be low amount of binders which could be below a threshold value. However, a higher amount of binders would make the use of the product more expensive which is currently is not relevant from an economic perspective. In some cases, other reasons may be the control factors and cause which combination and types of ashes to be selected as components for blended binders. However, the issue of the permanence should also be taken into account when fabricating blended mixtures. Finally, Figure 6b also indicates that the interaction effects between cement and energy ash are amplified.

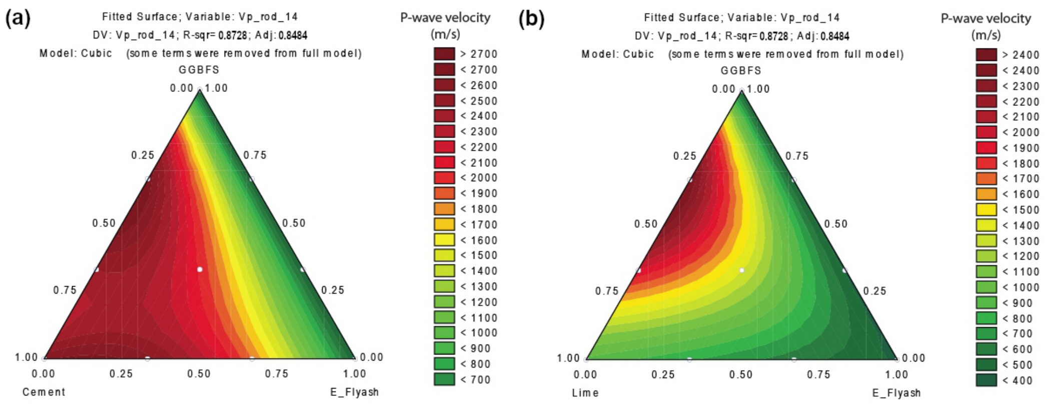


**Figure 6.** The response of the soil strength after compression indicated by the P-wave velocity measured on day 14 upon stabilization. (**a**): interaction between cement, lime and slag. (**b**): large interaction between energy fly ash and slag.

Figure 7 provides another comparison, completing an assessment of the soil strength after stabilization by blended mixture of cement, energy fly ash and bio fly ash binders (left) and the two types of fly ash and lime (right). Thus, Figure 7b reveals the interaction effects between the fly ash and lime. Figure 7a presents the same pattern of the effects from binders on soil stabilization: a negative contribution from the combination ADE (cement/energy ash/bio ash). Both completions indicate the low effects from the energy fly ash on soil stabilization (shown in figures in dark green colour). the strength in using ternary types of diagrams is in its ability to integrate information from triple combination of binders using for soil stabilization, as illustrated in the presented Figures 5–7.

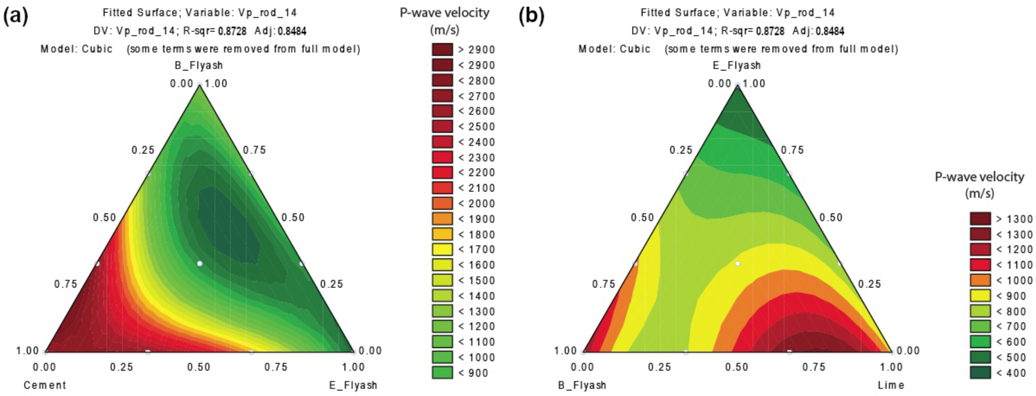


**Figure 7.** The response of the soil strength after compression indicated by the P-wave velocity measured on day 14 upon stabilization. (**a**): increased interactions between cement and fly ash. (**b**): increased interaction effects between fly ash and lime.

As the bio fly ash from the SCA Lilla Edet shows poorer results. This may be due to the carbonation of the binder, i.e., the presence of lime in ash has reacted with the $CO_2$ in the air and inert $CaCO_3$ (cf. limestone) has been formed. Previous studies arrived with a better effect from the mixture of lime and fly ash in connection with the stabilization of clayey soil [69–71]. There is no clear answer to the question why the energy fly ash only functions as an inert filler. One reason could be that there is a threshold value of the water binder number. If ash is to be used in larger projects, the availability of the 'fresh' ash (i.e., recently made product) should be ensured to minimize possible variations in the stabilized road base.

## 4. Discussion

This study verified the feasibility of application of blended binders (cement, lime, slag, energy fly ash and bio fly ash) on clayey soil stabilization, specifically for road construction in southern Sweden. The tests included the UCS of soil specimens treated with binder mixtures and measurement of P-wave velocities for evaluation of strength properties. The results are of importance for road construction and increase the durability and life cycle of roads through the improved construction materials. We tested five different binders and their effects on stabilization of soil planned for road construction. This is a common factor test meaning that samples have to be evaluated in a large strength diapason. Furthermore, the question arises as to how one should handle the amount of water in binder mixture. For the soil collected in southern Sweden, the optimal water ratio is 6%. With a varied amount of binder, water binder number will also vary and affect the strength of the specimens. In contrast, if water binder number remains constant, water ratio should vary within the soil-binder mixture, which in turn will vary the degree of compaction of the specimens. The degree of compaction of soil enables to evaluate the effect of binders on soil strength.

The evaluation of soil strength was performed using the applied geophysical methods. Thus, we measured the frequency of the seismic P-waves which notably varied along with changed soil properties: strength, density, stiffness and composition of soil specimens. The results have been demonstrated on a series of ternary diagrams and two Pareto charts for the comparative analysis. The quality of the tests was controlled by the standard handbooks and guidances used for the implementation of the soil tests in the Swedish Geotechnical Institute (SGI). In this study, five different binders were mixed in various proportions with clayey soils with the goal of improving their strength and durability of roads during construction works. Four steps of the laboratory processing of soil samples were performed on unstabilized and stabilized soils, including: (1) soil compaction, (2) soil stabilization by blended binders and UCS test, (3) freeze–thaw durability experiments with varied temperature, and (4) analysis of soil strength by seismic measurements using measured velocity of P-waves.

While this study uses slag, lime, energy fly ash, bio fly ash and cement for clay stabilisation, this approach can be extended to other alternative binders by adding polymers [72] calcium carbide residue (CCR) [73], or various lime dosage levels [74]. In addition, gypsum can be used for stabilization of clays to improve the microstructure for the contaminated soils [75]. Further, the plasticity properties of the fine-grained clayey soils can be improved by adding traditional binders such as lime and cement added with various content of stabilizers in a mixture [76,77] or the combinations of cement and GGBFS [78].

The use of blended binders has been limited in modern soil stabilization practices, although mixtures of various binders can be regarded as an effective alternative binders for improving the engineering properties of clayey soil. In our experiments, the highest strengths in soil specimens were achieved for the mixtures of slag, lime and cement, while bio fly ash from the SCA Lilla Edet demonstrated poorer results, which may be due to the carbonation of the binder. The comparable gain in strength is yielded when used in energy fly ash which does not act sufficiently well as a binder in a stabilization context. In contrast, slag and lime outperformed the soil strength values in terms of the effects from the blended binders on soil. The results demonstrated that a higher dosage of slag Merox and cement was required to improve the strength of clayey soil. Thus, a notable increase in strength of clayey soils was obtained by adding slag, lime and cement with some addition of fly ash. Following the experimental testing, the study presented a data analysis based on the statistical processing using ternary simplex diagrams for each binder combination and Pareto chart for the comparative analysis.

A possible disadvantage of the presented 'mixture design' method is that the binder content is not an independent variable, i.e., we tested the total amount of binder for each specimen, which is the same but consists of different mixtures: a ratio of single binder components in a binder blend. This means that only a total binder content is tested, compared to the ordinary factorial experiment where two or three levels of binder contents were tested. In order to treat several different levels of binder content, two or three 'mixture tests' must then be performed. As the study primarily focuses on examining the effects of the akin mixture in an ordinary binder, it was chosen to perform the experiments at the only one level (that is, 3% mixture). Despite this limitation, 82 different specimens were included in the experiment and tested positively, as reported above.

To address the above drawbacks, we performed the experiments with the constrained design which included the increased amount of the preliminary tests and a more complex evaluation of the results. We applied the third alternative, i.e., a mixture experiment, which is a special form of the response surface methodology where factors are the components of the mixture and the response is a function of the proportion of each ingredient. We compared the effects from lime, slag and fly ash binders on clay stabilization. Since this study has only included the inert soil mass and storage without the access to air, the effects of the lime binder were limited. Pure lime (burnt or quenched) is best suited for the fine-grained soils containing clay minerals. Slag is usually referred to as a binder component that requires activation (high pH) to react [79,80].

The specific contribution of this paper consist in using blended binders. Thus, whilst a large number of projects and reported studies utilize pure binders (e.g., cement, lime or CKD), there is a lack of knowledge regarding the use of mixed combinations of binders for stabilization of weak soils, which experimentally include novel types of binders, such as energy fly ash or bio fly ash. Therefore, we demonstrated that blended binders are particularly effective for stabilising clayey soil in the soft composition. We used these binders in combination with cement, lime and slag for soil stabilization where slag was used with a very finely ground structure and hydraulic properties (hardens under water) without activation. Such properties have also been observed in previous studies [81,82].

Slag demonstrated to have a slow curing effects on clayey soil. Therefore, the use of pure slag is not practical in real projects that require quick stabilization of dozens of tons of soil materials. Therefore, we tested the combination of the blended binders to improve the stabilization of soil. Specifically, the combination of slag and lime or slag and cement accelerates the process of soil hardening and gives a good and durable product, as also noted in previous studies [83]. Hence, this study contributed to existing research gaps on evaluation of the effects from blended binders on stabilization of clayey soil used for road construction. Moreover, we demonstrated that using the alternative binders as a partial replacements of cement presents an environmentally friendly method of soil improvement where binders are mixed with clayey soil specimens. Compared to the use of pure cement for soil stabilization, the use of blended mixtures presents better perspectives for the environmental sustainability and city infrastructure.

## 5. Conclusions

We have addressed the problem of using blended binders which are gaining interest in road engineering industry for soil stabilization as efficient materials and environmentally effective replacements to pure cement. This problem is formulated in this paper as optimising the selection of binders using statistical approach and a series of experiments on clay samples. The research was undertaken to determine and demonstrate how blended binders produce a better effect on clayey soil stabilization, and to illustrate graphically the performance of soil treated by mixtures of five binders in various combinations: cement, lime, slag, bio fly ash and energy fly ash. The results were visualized on the ternary simplex diagrams. The soil strength increased with added blended binders in various ratios, detected using seismic measurements of P-wave frequency.

Below we propose a list of further approaches to continue this study to better analyze soil performance stabilized with various binders:

- Fatigue tests on stabilized material, e.g., compare with asphalt.
- Examination of the nonlinearity of soil material (e.g., elongation stiffness)
- Testing relationship between seismic, E-modulus and strength of the stabilized soil
- Improvement of specimen production

Our empirical evaluation of using blended binders demonstrates superior performance of soil and hardening results relative to the state of the art use of single binders. Nevertheless, the use of blended binders for soil stabilization, specifically novel types, such as energy fly ash or bio fly ash, in a challenge in the context of road improvement. The analysis of the experiments determining the effects from various binders on soil behavior performed included simplex lattice design and visualized as ternary plots. The proposed framework aimed at describing the relations between adding the specific binders on improving soil properties and hardening. Three logical relationships between the ratio of the corresponding five binders were categorized: cement, lime, slag and two types of fly ash.

This study revealed that the stabilization of clayey soils with blended binders consisted of lime, fly ash and cement considerably improves the geotechnical properties and workability of soil and contributes to gain in strength. The significance of this paper is that it also presented a theoretical analysis of the relation between additives and soil properties as estimated by P-wave velocities indicating the stabilization effects on soil. Further, we performed the freeze–thaw experiments for soil collected in Swedish environment and included the statistical analysis aimed at optimization of mixture design. Specifically, we have derived the results from the gain in soil strength after UCS tests for several cases of binders and compared the results in ternary plots. The results demonstrated the encouraging and positive effects from the use of blended binders, since all the stabilized soil specimens improved the UCS, as recorded by the P-wave seismic testing. To conclude, the bearing capacity of soil was significantly improved by the stabilization using blended binders, which presents the effective solution for the improvement of the engineering materials used for road constructions.

The key idea of our proposed technique is to use various combinations of binder components in the triplets of mixture blends composed by various stabilizing agents. By restricting the sum of stabilizing agents always to 100%, their single components varied in proportions, thus showing the effects of adding more of less of each type of binder on the gain in soil strength. We show that our technique, supported by statistical combinatorics, is able to assist in selecting optimal binder combinations when stabilizing large amount of materials: up to several dozens of tons of soil in the industrial scale during construction works. Our simplex-lattice design is much more efficient than the *in-situ* soil stabilizing due to the computed models showing the effects of binders on soil strength. It can be easily incorporated into diverse similar construction works where large amount of expansive soil should be stabilized by binder blends. Thus, it can be used as a valuable modelling tool for used for solutions of clay stabilization and evaluation of the degree of gain in soil strength in civil engineering.

**Author Contributions:** Supervision, conceptualization, writing—original draft preparation, data curation, methodology, software, visualization, funding acquisition, and project administration, P.L. (Per Lindh); writing—original draft preparation, methodology, software, formal analysis, resources, validation, writing—review and editing, and investigation, P.L. (Polina Lemenkova). All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was supported by the SBUF (Development Fund of the Swedish Construction Industry), Nordkalk AB, SSAB Merox AB and Svenska Cellulosa AB (SCA) Lilla Edet Pappersbruk.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors thank the anonymous reviewers for reading, suggestions and comments that improved an earlier version of this manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| GGBFS | Ground Granulated Blast Furnace Slag |
| SGI | Swedish Geotechnical Institute |
| UCS | Uniaxial Compressive Strength |

## References

1. Consoli, N.C.; Marin, E.J.B.; Samaniego, R.A.Q.; Heineck, K.S.; Johann, A.D.R. Use of Sustainable Binders in Soil Stabilization. *J. Mater. Civ. Eng.* **2019**, *31*, 06018023. [CrossRef]
2. da Rocha, C.G.; Marin, E.J.B.; Samaniego, R.A.Q.; Consoli, N.C. Decision-Making Model for Soil Stabilization: Minimizing Cost and Environmental Impacts. *J. Mater. Civ. Eng.* **2021**, *33*, 06020024. [CrossRef]
3. Freitag, P.; Maurer, H.; Reichenauer, T.G. Selection of Optimized Binders for Dechlorination of Trichloroethylene-Contaminated Sites by Jet Grouting and Deep Soil Mixing. *J. Environ. Eng.* **2021**, *147*, 04021052. [CrossRef]
4. Caraşca, O. Soil Improvement by Mixing: Techniques and Performances. *Energy Procedia* **2016**, *85*, 85–92. [CrossRef]
5. Mypati, V.N.K.; Saride, S. Feasibility of Alkali-Activated Low-Calcium Fly Ash as a Binder for Deep Soil Mixing. *J. Mater. Civ. Eng.* **2022**, *34*, 04021410. [CrossRef]
6. Sargent, P.; Hughes, P.N.; Rouainia, M.; Glendinning, S. Soil Stabilisation Using Sustainable Industrial By-Product Binders and Alkali Activation. In *GeoCongress 2012*; Chapter GeoCongress 2012: State of the Art and Practice in Geotechnical Engineering; American Society of Civil Engineers: Reston, VA, USA, 2012; pp. 948–957. [CrossRef]
7. Amorim, J.; Segersson, D.; Körnich, H.; Asker, C.; Olsson, E.; Gidhagen, L. High resolution simulation of Stockholm's air temperature and its interactions with urban development. *Urban Clim.* **2020**, *32*, 100632. [CrossRef]
8. Gustavsson, T.; Bogren, J.; Green, C. Road climate in cities: A study of the Stockholm area, south-East Sweden. *Meteorol. Appl.* **2001**, *8*, 481–489. [CrossRef]
9. Etim, R.; Attah, I.; Yohanna, P. Experimental study on potential of oyster shell ash in structural strength improvement of lateritic soil for road construction. *Int. J. Pavement Res. Technol.* **2020**, *13*, 341–351. [CrossRef]
10. Fasihnikoutalab, M.H.; Pourakbar, S.; Ball, R.J.; Unluer, C.; Cristelo, N. Sustainable soil stabilization with ground granulated blast-furnace slag activated by olivine and sodium hydroxide. *Acta Geotech.* **2020**, *15*, 1981–1991. [CrossRef]

11. Kogbara, R.; Yi, Y.; Al-Tabbaa, A. Process envelopes for stabilization/solidification of contaminated soil using lime–Slag blend. *Environ. Sci. Pollut. Res.* **2011**, *18*, 1286–1296. [CrossRef] [PubMed]
12. Lindh, P.; Lemenkova, P. Seismic velocity of P-waves to evaluate strength of stabilized soil for Svenska Cellulosa Aktiebolaget Biorefinery Östrand AB, Timrå. *Bull. Pol. Acad. Sci. Tech. Sci.* **2022**, *70*, 1–9. [CrossRef]
13. Mavroulidou, M.; Gray, C.; Gunn, M.; Pantoja-Muñoz, L. A Study of Innovative Alkali-Activated Binders for Soil stabilization in the Context of Engineering Sustainability and Circular Economy. *Circ. Econ. Sustain.* **2021**, *2*, 1627–1651. [CrossRef]
14. Ekpo, D.; Fajobi, A.; Ayodele, A. Response of two lateritic soils to cement kiln dust-periwinkle shell ash blends as road sub-base materials. *Int. J. Pavement Res. Technol.* **2021**, *14*, 550–559. [CrossRef]
15. Frempong, E.M. A comparative assessment of sand and lime stabilization of residual micaceous compressible soils for road construction. *Geotech. Geol. Eng.* **1995**, *13*, 181–198. [CrossRef]
16. Abbey, S.J.; Eyo, E.U.; Okeke, C.; Ngambi, S. Experimental study on the use of RoadCem blended with by-product cementitious materials for stabilization of clay soils. *Constr. Build. Mater.* **2021**, *280*, 122476. [CrossRef]
17. Al-Hdabi, A.; Al Nageim, H.; Seton, L. Superior cold rolled asphalt mixtures using supplementary cementations materials. *Constr. Build. Mater.* **2014**, *64*, 95–102. [CrossRef]
18. Lindh, P.; Lemenkova, P. Dynamics of Strength Gain in Sandy Soil Stabilised with Mixed Binders Evaluated by Elastic P-Waves during Compressive Loading. *Materials* **2022**, *15*, 7798. [CrossRef]
19. Jafer, H.M.; Atherton, W.; Sadique, M.; Ruddock, F.; Loffill, E. Development of a new ternary blended cementitious binder produced from waste materials for use in soft soil stabilization. *J. Clean. Prod.* **2018**, *172*, 516–528. [CrossRef]
20. Li, J.S.; Chen, L.; Zhan, B.; Wang, L.; Poon, C.; Tsang, D. Sustainable stabilization/solidification of arsenic-containing soil by blast slag and cement blends. *Chemosphere* **2021**, *271*, 129868. [CrossRef] [PubMed]
21. Wang, F.; Wang, H.; Jin, F.; Al-Tabbaa, A. The performance of blended conventional and novel binders in the in-situ stabilization/solidification of a contaminated site soil. *J. Hazard. Mater.* **2015**, *285*, 46–52. [CrossRef]
22. Consoli, N.; Winter, D.; Rilho, A.S.; Festugato, L.; dos Santos Teixeira, B. A testing procedure for predicting strength in artificially cemented soft soils. *Eng. Geol.* **2015**, *195*, 327–334. [CrossRef]
23. Meskini, S.; Samdi, A.; Ejjaouani, H.; Remmal, T. Valorization of phosphogypsum as a road material: Stabilizing effect of fly ash and lime additives on strength and durability. *J. Clean. Prod.* **2021**, *323*, 129161. [CrossRef]
24. Mirković, K.; Tošić, N.; Mladenović, G. Effect of different types of fly ash on properties of asphalt mixtures. *Adv. Civ. Eng.* **2019**, *2019*, 1–11. [CrossRef]
25. Navarrete, C.; Guimarães, A.C.R.; Marques, M.E.S.; Castro, C.D.; Toulkeridis, T. Resistance to Fatigue in Asphalts Used in Military Airports of the Brazilian Amazon through the Use of Nickel-Holding Ash. *Appl. Sci.* **2022**, *12*, 9134. [CrossRef]
26. Lima, M.S.S.; Hajibabaei, M.; Thives, L.P.; Haritonovs, V.; Buttgereit, A.; Queiroz, C.; Gschösser, F. Environmental potentials of asphalt mixtures fabricated with red mud and fly ash. *Road Mater. Pavement Des.* **2021**, *22*, S690–S701. [CrossRef]
27. Bjerrum, L.; Flodin, N. The Development of Soil Mechanics in Sweden, 1900–1925. *Géotechnique* **1960**, *10*, 1–18. [CrossRef]
28. Higgins, D. Briefing: GGBS and sustainability. *Proc. Inst. Civ. Eng.–Constr. Mater.* **2007**, *160*, 99–101. [CrossRef]
29. Lindh, P.; Lemenkova, P. 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. *Electronics* **2022**, *11*, 3726. [CrossRef]
30. Parsons, R.; Kneebone, E. Field performance of fly ash stabilized subgrades. *Ground Improv.* **2005**, *9*, 33–38. [CrossRef]
31. Olgun, M. Effects of polypropylene fiber inclusion on the strength and volume change characteristics of cement-fly ash stabilized clay soil. *Geosynth. Int.* **2013**, *20*, 263–275. [CrossRef]
32. Jie, Y.X.; Li, G.X.; Tang, F.; Jin, Y.; Hua, J.X. Soil Stabilization in the Fill Project of the Olympic Rowing-Canoeing Park in Beijing. *J. Mater. Civ. Eng.* **2013**, *25*, 462–471. [CrossRef]
33. Holz, B.; Batchelor, O. Stabilization of Abandoned Coal Mines for a Motorway Upgrade, Queensland, Australia. In *Grouting and Deep Mixing 2012*; American Society of Civil Engineers: Reston, VA, USA, 2012; pp. 1912–1923. [CrossRef]
34. Jamnongpipatkul, P.; Dechasakulsom, M.; Sukolrat, J. Application of Air Foam Stabilized Soil for Bridge-Embankment Transition Zone in Thailand. In *Asphalt Material Characterization, Accelerated Testing, and Highway Management*; American Society of Civil Engineers: Reston, VA, USA, 2009; pp. 181–193. [CrossRef]
35. Moh, Z.C. Soil Stabilization with Cement and Sodium Additives. *J. Soil Mech. Found. Div.* **1962**, *88*, 81–105. [CrossRef]
36. Celauro, B.; Bevilacqua, A.; Lo Bosco, D.; Celauro, C. Design Procedures for Soil-Lime Stabilization for Road and Railway Embankments. Part 2-Experimental Validation. *Procedia–Soc. Behav. Sci.* **2012**, *53*, 568–579. [CrossRef]
37. Glossop, R.; Wilson, G.C. Soil stability problems in road engineering. *Proc. Inst. Civ. Eng.* **1953**, *2*, 219–253. [CrossRef]
38. Markwick, A.H.D.; Keep, H.S. The use of low-grade aggregates and soils in the construction of bases for roads and aerodromes. *Road Eng. Division. Inst. Civ. Eng. Eng. Div. Pap.* **1942**, *1*, 1–30. [CrossRef]
39. Nelson, J.D.; Miller, D.J. *Expansive Soils: Problems and Practice in Foundation and Pavement Engineering*; John Wiley & Sons Inc.: Hoboken, NJ, USA, 1992.
40. Olsen, T.; Kasper, T.; de Wit, J. Immersed tunnels in soft soil conditions experience from the last 20 years. *Tunn. Undergr. Space Technol.* **2022**, *121*, 104315. [CrossRef]
41. Lindh, P.; Lemenkova, P. Laboratory Experiments on Soil Stabilization to Enhance Strength Parameters for Road Pavement. *Transp. Telecommun. J.* **2023**, *24*, 73–82. [CrossRef]

42. Sear, L.K.A. Properties and use of coal fly ash. In *Use of Fly Ash for Road Construction, Runways and Similar Projects*; Thomas Telford Ltd.: London, UK, 2001; Chapter 5, pp. 136–168.
43. Sudhakar, S.; Duraisekaran, E.; Dilli Vignesh, G.; Kanna, G.D. Performance Evaluation of Quarry Dust Treated Expansive Clay for Road Foundations. *Iran. J. Sci. Technology. Trans. Civ. Eng.* **2021**, *45*, 2637–2649. [CrossRef]
44. Antunes, V.; Simão, N.; Freire, A. A Soil-Cement Formulation for Road Pavement Base and Sub Base Layers: A Case Study. *Transp. Infrastruct. Geotechnol.* **2017**, *4*, 126–141. [CrossRef]
45. Park, H.K.; Lee, H.; Vimonsatit, V. Investigation of Pindan soil modified with polymer stablisers for road pavement. *J. Infrastruct. Preserv. Resil.* **2020**, *1*, 9. [CrossRef]
46. Bell, F.G. Lime stabilization of clay soils. *Bull. Int. Assoc. Eng. Geol.* **1989**, *39*, 67–74. [CrossRef]
47. Hilt, G.; Davidson, D. Lime fixation of clayey soils. *Highw. Res. Board Bull.* **1960**, *262*, 20–32.
48. Lindh, P.; Lemenkova, P. Impact of Strength-Enhancing Admixtures on Stabilization of Expansive Soil by Addition of Alternative Binders. *Civ. Environ. Eng.* **2022**, *18*, 726–735. [CrossRef]
49. Taylor, H.F.W. *Cement Chemistry*, 2nd ed.; Thomas Telford Publishing: London, UK, 1997; 361p. [CrossRef]
50. Okagbue, C.O. Stabilization of Clay Using Woodash. *J. Mater. Civ. Eng.* **2007**, *19*, 14–18. [CrossRef]
51. Estabragh, A.R.; Kholoosi, M.M.; Ghaziani, F.; Javadi, A.A. Stabilization and Solidification of a Clay Soil Contaminated with MTBE. *J. Environ. Eng.* **2017**, *143*, 04017054. [CrossRef]
52. Xu, B.; Yi, Y. Soft Clay Stabilization Using Three Industry Byproducts. *J. Mater. Civ. Eng.* **2021**, *33*, 06021002. [CrossRef]
53. Sörengård, M.; Gago-Ferrero, P.; Kleja, D.B.; Ahrens, L. Laboratory-scale and pilot-scale stabilization and solidification (S/S) remediation of soil contaminated with per- and polyfluoroalkyl substances (PFASs). *J. Hazard. Mater.* **2021**, *402*, 123453. [CrossRef]
54. Al-Swaidani, A.; Hammoud, I.; Meziab, A. Effect of adding natural pozzolana on geotechnical properties of lime-stabilized clayey soil. *J. Rock Mech. Geotech. Eng.* **2016**, *8*, 714–725. [CrossRef]
55. Feng, Y.S.; Du, Y.J.; Zhou, A.; Zhang, M.; Li, J.S.; Zhou, S.J.; Xia, W.Y. Geoenvironmental properties of industrially contaminated site soil solidified/stabilized with a sustainable by-product-based binder. *Sci. Total Environ.* **2021**, *765*, 142778. [CrossRef]
56. Lindh, P.; Lemenkova, P. Leaching of Heavy Metals from Contaminated Soil Stabilised by Portland Cement and Slag Bremen. *Ecol. Chem. Eng. S* **2022**, *29*, 537–552. [CrossRef]
57. Maheepala, M.; Nasvi, M.; Robert, D.; Gunasekara, C.; Kurukulasuriya, L. A comprehensive review on geotechnical properties of alkali activated binder treated expansive soil. *J. Clean. Prod.* **2022**, *363*, 132488. [CrossRef]
58. Lindh, P.; Lemenkova, P. Shear bond and compressive strength of clay stabilised with lime/cement jet grouting and deep mixing: A case of Norvik, Nynäshamn. *Nonlinear Eng.* **2022**, *11*, 693–710. [CrossRef]
59. Nordmark, D.; Vestin, J.; Hansson, L.; Kumpiene, J. Long-term evaluation of geotechnical and environmental properties of ash-stabilized road. *J. Environ. Manag.* **2022**, *318*, 115504. [CrossRef]
60. Montgomery, D.C. *Design and Analysis of Experiments*; Wiley & Sons, Inc.: Hoboken, NJ, USA, 1997.
61. Box, G.E.P.; Hunter, W.G.; Hunter, J.S. *Statistics for Experimenters*, 2nd ed.; Wiley-Interscience: New York, NY, USA, 2005; 655p.
62. Lindh, P. Compaction- and Strength Properties of Stabilized and Unstabilized Fine-Grained Tills. Ph.D. Thesis, Lund University, Lund, Sweden, 2004. [CrossRef]
63. Aldaood, A.; Khalil, A.; Bouasker, M.; Al-Mukhtar, M. Experimental Study on the Mechanical Behavior of Cemented Soil Reinforced with Straw Fiber. *Geotech. Geol. Eng.* **2021**, *39*, 2985–3001. [CrossRef]
64. Lindh, P.; Lemenkova, P. Resonant Frequency Ultrasonic P-Waves for Evaluating Uniaxial Compressive Strength of the Stabilized Slag–Cement Sediments. *Nord. Concr. Res.* **2021**, *65*, 39–62. [CrossRef]
65. Lindh, P.; Lemenkova, P. Soil contamination from heavy metals and persistent organic pollutants (PAH, PCB and HCB) in the coastal area of Västernorrland, Sweden. *Gospod. Surowcami Miner.–Miner. Resour. Manag.* **2022**, *38*, 147–168. [CrossRef]
66. Thomas, G.; Rangaswamy, K. Small strain stiffness and site-specific Seismic response of nano-silica stabilized soft clay in Kochi, India: A case study. *Arab. J. Geosci.* **2022**, *15*, 106. [CrossRef]
67. Ryden, N.; Ekdahl, U.; Lindh, P. Quality Control of Cement stabilized Soil Using Non-destructive Seismic Tests. *Adv. Test. Fresh Cem. Mater. Lect.* **2006**, *34*, 3–4.
68. Myers, R.H.; Montgomery, D.C. *Response Surface Methodology. Process and Product Optimization Using Designed Experiments*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 1995.
69. Andavan, S.; Pagadala, V.K. A study on soil stabilization by addition of fly ash and lime. *Mater. Today Proc.* **2020**, *22*, 1125–1129.
70. Toksöz Hozatlıoğlu, D.; Yılmaz, I. Shallow mixing and column performances of lime, fly ash and gypsum on the stabilization of swelling soils. *Eng. Geol.* **2021**, *280*, 105931. [CrossRef]
71. Khadka, S.D.; Jayawickrama, P.W.; Senadheera, S.; Segvic, B. Stabilization of highly expansive soils containing sulfate using metakaolin and fly ash based geopolymer modified with lime and gypsum. *Transp. Geotech.* **2020**, *23*, 100327. [CrossRef]
72. Rezaeimalek, S.; Nasouri, R.; Huang, J.; Bin-Shafique, S. Curing Method and Mix Design Evaluation of a Styrene-Acrylic Based Liquid Polymer for Sand and Clay Stabilization. *J. Mater. Civ. Eng.* **2018**, *30*, 04018200. [CrossRef]
73. Horpibulsuk, S.; Phetchuay, C.; Chinkulkijniwat, A. Soil Stabilization by Calcium Carbide Residue and Fly Ash. *J. Mater. Civ. Eng.* **2012**, *24*, 184–193. [CrossRef]
74. Pedarla, A.; Chittoori, S.; Puppala, A.J.; Hoyos, L.R.; Saride, S. Influence of Lime Dosage on Stabilization Effectiveness of Montmorillonite Dominant Clays. In *GeoFlorida 2010*; American Society of Civil Engineers: Reston, VA, USA, 2010; pp. 767–776. [CrossRef]

75. Latifi, N.; Vahedifard, F.; Siddiqua, S.; Horpibulsuk, S. Solidification–Stabilization of Heavy Metal–Contaminated Clays Using Gypsum: Multiscale Assessment. *Int. J. Geomech.* **2018**, *18*, 04018150. [CrossRef]
76. Mutaz, E.; Dafalla, M.A.; Shamrani, M.A. Stabilization of Al-Ghatt Clay Shale by Using a Mixture of Lime and Cement. In *Road Materials and New Innovations in Pavement Engineering*; American Society of Civil Engineers: Reston, VA, USA, 2011; pp. 81–88. [CrossRef]
77. Rogers, C.D.; Boardman, D.I.; Papadimitriou, G. Stress Path Testing of Realistically Cured Lime and Lime/Cement Stabilized Clay. *J. Mater. Civ. Eng.* **2006**, *18*, 259–266. [CrossRef]
78. Andersson, R.; Carlsson, T.; Leppänen, M. Hydraulic Cement Based Binders for Mass Stabilization of Organic Soils. In *Soft Ground Technology*; American Society of Civil Engineers: Reston, VA, USA, 2001; pp. 158–169. [CrossRef]
79. Sherwood, P. *Soil Stabilization with Cement and Lime*; TRL, HMSO: Richmond, UK, 1993.
80. Lindh, P.; Lemenkova, P. Geochemical tests to study the effects of cement ratio on potassium and TBT leaching and the pH of the marine sediments from the Kattegat Strait, Port of Gothenburg, Sweden. *Baltica* **2022**, *35*, 47–59. [CrossRef]
81. Lindh, P. *Soil Stabilization of Fine-Grained Till Soils*; Technical Report 1008; Lund University: Lund, Sweden, 2000; Report TVGT.
82. Lindh, P. Optimizing binder blends for shallow stabilization of fine-grained soils. *Ground Improv.* **2001**, *5*, 23–34. [CrossRef]
83. Lindh, P.; Lemenkova, P. Evaluation of Different Binder Combinations of Cement, Slag and CKD for S/S Treatment of TBT Contaminated Sediments. *Acta Mech. Autom.* **2021**, *15*, 236–248. [CrossRef]