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CIVIL ENGINEERING

Seismic velocity of P-waves to evaluate strength of stabilized soil for Svenska Cellulosa Aktiebolaget Biorefinery Östrand AB, Timrå

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Abstract. Evaluating soil strength by geophysical methods using P-waves was undertaken in this study to assess the effects of changed binder ratios on stabilization and compression characteristics. The materials included dredged sediments collected in the seabed of Timrå region, north Sweden. The Portland cement (Basement CEM II/A-V, SS EN 197-1) and ground granulated blast furnace slag (GGBFS) were used as stabilizers. The experiments were performed on behalf of the Svenska Cellulosa Aktiebolaget (SCA) Biorefinery Östrand AB pulp mill. Quantity of binder included 150, 120 and 100 kg. The properties of soil were evaluated after 28, 42, 43, 70, 71 and 85 days of curing using applied geophysical methods of measuring the travel time of primary wave propagation. The P-waves were determined to evaluate the strength of stabilized soils. The results demonstrated variation of P-waves velocity depending on stabilizing agent and curing time in various ratios: Low water/High binder ($L_W H_B$), High water/Low binder ($H_W L_B$) and percentage of agents (CEM II/A-V/GGBFS) as 30%/70%, 50%/50% and 70%/30%. The compression characteristics of soils were assessed using uniaxial compressive strength (UCS). The P-wave velocities were higher for samples stabilized with $L_W H_B$ compared to those with $H_W L_B$. The primary wave propagation increased over curing time for all stabilized mixes along with the increased UCS, which proves a tight correlation with the increased strength of soil solidified by the agents. Increased water ratio gives a lower strength by maintained amount of binder and vice versa.

Key words: unconfined compressive strength; P-wave velocity; stabilized soil; cement; slag.

1. INTRODUCTION

Bearing capacity of soil plays a key role in construction industry. High strength of soil ensures ground stability, safety and sustainability of structures [1]. Increasing soil strength can be achieved by stabilizing the soil with binders. Selecting optimal ratio of binders (*e.g.*, cement, slag) is important for increase of soil strength [2–4], but requires a practical evaluation of cement-slag-water ratio for stabilizing soil, as a series of tests. The strength of the stabilized soil can be assessed by measuring velocities of P-wave propagation through soil assessed after a curing period.

Various methods of evaluating soil properties, including computer-based modelling, have been employed in existing studies. These include estimating the porosity [5, 6], density [7, 8], comparison of binder combinations [9], admixtures as cement replacement [10], economic and environmental assessment of S/S [11], suction behaviour of soil to assess bearing capacity [12]. The S/S techniques improve the silty clay structure by increasing cementation bonding and reducing the pore space in soil microstructure [13]. Selecting optimal binder components (cement, cement kiln dust and slag) affects the results of S/S of the sediments [14].

Stabilization of soil by the cementitious binder increases its strength, as large pores in soil become filled with binder [15]. As a result, total pore volume in a soil mass decreases, which makes it suitable for the industrial constructions: roads or buildings. Experimental changing of ratio of binders (lime, cement, and lime-cement) improves soil strength and resistance. For example, adding lime to the soil mass before S/S by cement improves its physical and mechanical properties [16]. The S/S can apply various proportions of Portland cement for treating soil contaminated with phenol choosing and carbon [17]. Thus, soil could be effectively treated by the cement/activated-carbon S/S. Evaluation of the uniaxial compressive strength (UCS), [18] enables to highlight correlations among the physical, dynamic and mechanical properties of the materials.

Soil stabilization is commonly used in civil engineering. Evaluation of soil is generally based on the empirical assessment of its geotechnical parameters [19–21]. It forms the fundamental basis for estimating the foundation capacity of soil and assessment of its suitability for building structures. Soil may be processed from the *in-situ* collected samples using laboratory-based tests to measure responses to stress. Recent approaches tend to apply the non-destructive approaches in soil testing. Ultrasonic testing by P-wave velocities is a rapidly growing appli-

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cation in evaluation of the stabilized soils. The geophysical approaches in civil engineering, such as measuring P-waves, become an effective alternative to the traditional methods, as more robust and non-destructive methods. Many studies applied geophysical methods in geotechnical measurements to improve the evaluation of the soil properties by measuring P-waves propagation velocity in samples [22–26].

Estimating the wave velocity for assessing soil mechanical property can be advantageously used in the field and laboratory under real and controlled conditions [27]. For instance, measuring shear wave velocity is a fast means for the determination of small-strain shear modulus in materials [28]. Estimating wave velocity is based on measuring speed and amplitude of sound waves that pass through soil. Detecting signals of waves provides a basis for analysis of soil conductivity and petrophysical properties: bulk density, porosity, clay content, strength. This is because the velocity of seismic waves depends on the material properties and generally increases with higher density and rigidity of material [29]. However, since stiffness increases at faster rate compared to density, seismic velocity is faster in a denser soil [30]. Moreover, the velocity strongly depends on the porosity of the material and significantly increases even with a small decrease in porosity [31].

Measuring shear wave velocity for estimation of stiffness and strength of the soft and silty clayey soil is a reported practice [32, 33]. Void ratio in soil and effective mean normal stress can be estimated for analysis of the large-strain response and relationship between soil strength and wave propagation [34]. Strength of soil can also be assessed through the analysis of cohesive behaviour [35]. More examples of the evaluation of the compressive strength include the analysis of biomodification of the recycled concrete aggregate [36], or optimized methods for fabrication of composites through modified mechanical and tribological properties for increasing their compressive strength and hardness [37].

In this paper, the stabilization and solidification (S/S) of soils were performed as a part of the reinforcement work in the selected coastal area of the Baltic Sea, northern Sweden. The Svenska Cellulosa Aktiebolaget (SCA) Biorefinery Östrand AB plans to build a new biorefinery for the production of fuel in form of petrol and diesel using biological raw materials. This construction is planned to extend the existing infrastructure of the pulp mill in the industrial area located in Timrå municipality, Fig. 1. Planned works require extra area to be prepared through soil stabilization and more space gained for the construction area.

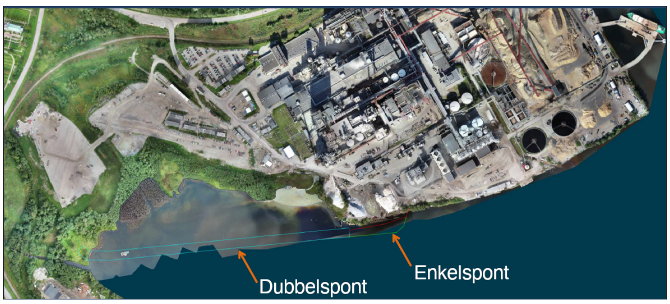

Fig. 1. Reinforcement barrier for water and land area. Source: SCA Biorefinery Östrand AB

The aim of this work was to stabilize the sediments dredged from the seabed using binders to increase the compressive strength of soil. The properties of soil were evaluated using applied geophysical methods of measuring velocities of the propagating P-wave that pass through the samples.

2. METHODS

The purpose of this study is to investigate the properties of soil after S/S treatment, to define the best combination of binders that can improve its geotechnical properties. The workflow consisted of the by measuring velocity of ultrasonic primary waves using geophysical methods [38, 39].

Measuring P-wave velocity is a fast, robust and straightforward technique for analysing physical and mechanical properties of soils. Its non-destructive nature enables the same specimen to be measured unlimited number of times without being damaged. The specimens were measured using the Free-Free Resonant (FFR) testing, aimed to measure natural frequencies of free vibration of the tested soil specimens.

The P-wave velocity was measured in a longitudinal direction. Practically, using the values of frequencies received from the FFR tests one can estimate the compression strength of soil using correlations between the wave velocity and the undrained shear strength [40]. Besides, geotechnical soil parameters can be determined using FFR, such as shear wave, seismic moduli, stiffness moduli and Poisson's ratio [41].

2.1. Materials

The tests were conducted in a geotechnical laboratory of the Swedish Geotechnical Institute (SGI) using sediment samples originally sampled by SCA stabilized by a combination of cement (Basement CEM II / A-V, SS EN 197-1) and Ground Granulated Blast Furnace Slag (GGBFS), trade name Bremen slag SS EN 15167-1. The UCS of the stabilized soil was measured by the P-wave travel time through soil samples. The major geotechnical parameters of soil include shear strength, permeability, compaction and particle size. In this study we obtained shear strength parameters changed from 48 to 1093 kPa for 3 ratios of stabilizers (Table 1). The soil compaction shown maximal dry density at 1.12 g/cm^3 by 38.75% of water in a binder. The clay content in the tested soil was 7.6%.

Mixtures were prepared in the SGI by mixing soil samples with specific types of stabilizers (CEM II/A-V, SS EN 197-1 and GGBFS). The amounts and ratios of stabilizers were varied between batches which were treated with a combination of stabilizers in the following ratios: 30/70, 50/50 and 70/30. The workflow included three levels of binder quantity in kg per m^3 of the dredged material. Various levels of binder quantity per m^3 of the dredged material were tested: 150 kg, 120 kg and 100 kg. The quality requirements included the following conditions: UCS of at least 140 kPa (ca $\geq$ 70 kPa) after 90 days; replacements in the stabilized material < 5 cm two years after the S/S. The quality objective regarding soil permeability constituted geotechnical quality requirements.

Table 1
Results of the tests on the uniaxial compressive strength

Sample	Compressive strength (kPa)	Shear strength (kPa)
$H_W L_B$_c/s_70/30_01	96	48
$H_W L_B$_c/s_50/50_01	294	147
$H_W L_B$_c/s_30/70_01	1046	523
$H_W L_B$_c/s_70/30_02	96	48
$H_W L_B$_c/s_50/50_02	294	147
$H_W L_B$_c/s_30/70_02	1090	545
$L_W H_B$_c/s_70/30_01	246	123
$L_W H_B$_c/s_50/50_01	718	359
$L_W H_B$_c/s_30/70_01	2262	1131
$L_W H_B$_c/s_70/30_02	264	132
$L_W H_B$_c/s_50/50_02	710	355
$L_W H_B$_c/s_30/70_02	2186	1093

The binders CEM II/A-V, SS EN 197-1 and GGBFS were selected as the stabilizing agents due to their quality and availability. Both binders are available on the commercial market and have been used in previous projects of the SGI, including the Arendal, port of Gothenburg [14]. The GGBS is one of the by-products of iron and steel, and economic as a binder for large quantities of soil [42] and beneficial to the environment as a replacement for Portland cement. The GGBS added to soil as an admixture significantly enhances its mechanical strength during the S/S [43]. The Basecement Slite produced by the Cementa (Heidelberg Cement Group) (https://www.cementa.se/en/bascement-eng) replaces the previous Byggcementen CEM II/A-L, due to better technical characteristics. The compaction characteristics of measured soil are summarised in Table 1.

2.2. Techniques

Joint analysis of the UCS and seismic velocity data was used to detect the strength of soil specimens. The UCS aimed to determine the strength of a cohesive clayey soil by measuring the maximum axial compressive stress that a cohesive soil specimen can withstand under zero confining stress.

The sediments were dredged using a 1 m^3 bucket, filled into the separate containers and sent to the SGI for testing. The soil in each container was homogenised: sediments were placed in a mixer and mixed with added binders and water. Following ratios were used for stabilization: Low Water/High Binder ($L_W H_B$), High Water/Low Binder ($H_W L_B$), Low Water/Extra Low Binder ($L_W EL_B$). The ratio of binder varied as cement/slag as 50/50 and cement/slag proportion as 30/70 and 70/30. The material was stored in climate rooms at constant moisture and T 7°C). The aggregate sample B6b was divided into two barrels with tight-fitting lids. Afterwards, one of the barrels was mixed with more added water to simulate a higher water ratio of the dredged material.

The workflow followed the technical specifications of the Swedish Institute for Standards (SIS) [44]. The tests were performed on the day of sample processing and subsequent on days 28, 43 and 70 of curing for the case of $H_W L_B$ mix; days 28, 42 and 71 for $L_W H_B$; 28 and 85 for $L_W EL_B$, respectively, Fig. 2. Mixing and thinning process lasted about 5 min by means of mechanical stirring to achieve a homogeneous structure. The stabilized sediments were then filled into the plastic barrels. For each mix of stabilized soil, the specimens were cast into 15 pistons with sampling sleeves and with covers.

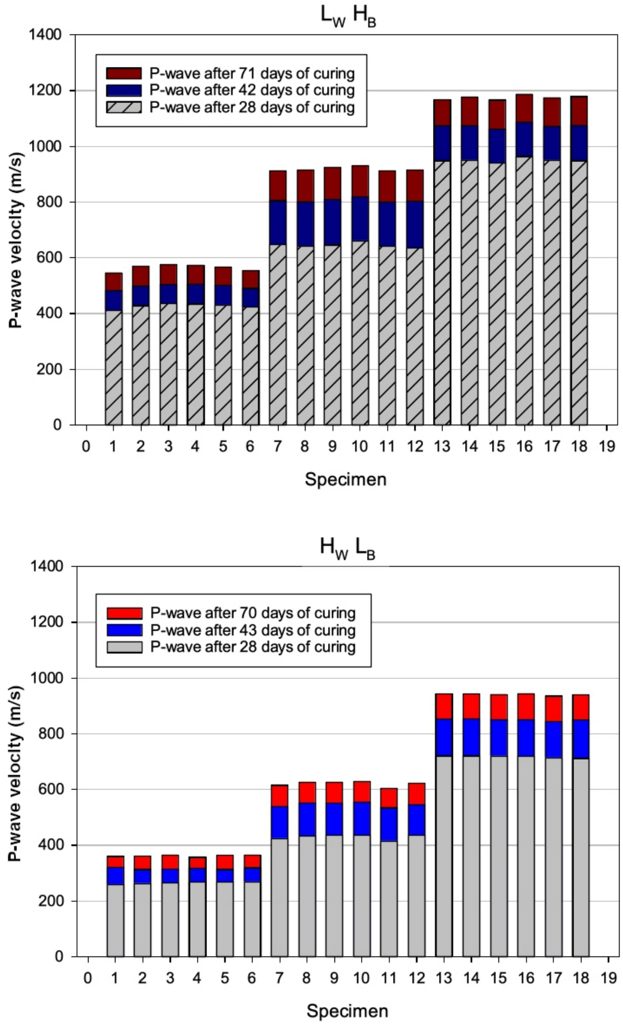

Fig. 2. P-wave velocity after mixing of soil with binders in ratios $L_W H_B$ (above) and $H_W L_B$ (below). The three recipes show 1–6 as cement/slag 70/30, 7–12 as cement/slag 50/50 and 13–18 as cement/slag 30/70

The P-wave measuring equipment included the lightweight ceramic shear response ICP Accelerometer (Model Nr. 352B10) by PCB Piezotronics with available technical documentation [45–47]. The sample configuration of the P-wave velocity was evaluated using the setting of the device which has a frequency range of (±5%) 2 to 10000 Hz. The samples were placed freely on a foam rubber substrate, and then set in oscillation using a hammer. When the sample is on a foam rubber pad, it can vibrate freely. These vibrations were measured using the accelerometer attached to the samples, adapted to the size and mass of the specimens (in our case, the cylindrical form of specimens).

The P-wave velocity has been measured in three cases for all collected samples in connection with tests on the uniaxial compressive strength (UCS) for relevant soil samples. The workflow applied the existing methodology of seismic velocity testing in geotechnical works, originally elaborated by SIS [48,49]. The experiments with $L_W H_B$ proportions of binder were performed following the compression on the 28, 42 and 71 days after mixing soil samples with binder (Fig. 2).

Likewise, the experiments with $H_W L_B$ ratio of binder were performed on samples on days 28, 43 and 70 after mixing sediments with binder (Fig. 2). The P-wave velocity was measured on the three days of curing for both cases of ratio ($H_W L_B$ and $L_W H_B$). The measurements were recorded, statistically processed as graphs and visualised in the plots, presented in Section 3.

The compression characteristics of soils were determined using the UCS testing. The comparative analysis of the compressive strength for samples with different mixes ($L_W H_B$ versus $H_W L_B$) and proportions of cement/slag as 70/30, 50/50 and 30/70 were recorded, evaluated and visualized in Fig. 3 where

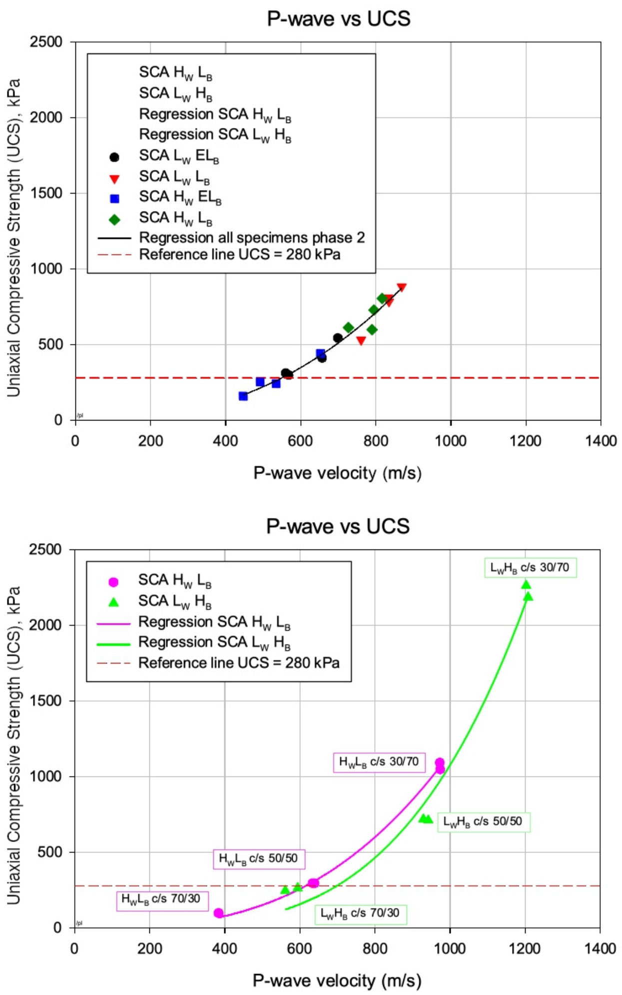

Fig. 3. P-wave velocity as a function of the UCS. *Above*: after 85 days of storage. *Below*: after 90 days of storage at 20°C

the regression lines are shown for the two cases: ratio $L_W H_B$ (green line) and ratio $H_W L_B$ (magenta line). The compressive strength has been measured on day 90th of storage at a temperature of 20°C as a function of the P-wave velocity. The P-wave velocity was measured for the days 28 and 85 after mixing specimens for the combinations $L_W L_B$, $L_W EL_B$, $H_W L_B$ and $H_W EL_B$ (Fig. 4).

The data were recorded and statistically processed as graphs. The UCS tests were measured on the 85th day of storage and analysed for a correlation between the UCS and P-wave velocity. The compaction of soil stabilized by binders in various ratios was evaluated upon the performed tests on the UCS. The mixes were prepared with various content of water/binder (cement and slag) which is representative of the evaluation of each case for the stabilized samples. The tests were conducted using the available equipment of SGI according to existing workflow of SIS for geotechnical works [50]. The requirement for testing UCS was set as 140 kPa with a safety factor of 2, *i.e.*, 280 kPa, (Fig. 3, red dotted reference line). The testing method of shear strength was based on the existing SIS standards and technical guidance [51].

A correlation between the binder content and water content in a soil mix was assessed and visualised as a factor experiment (Fig. 5) showing linear effect between water ratio and the amount of binder in the processed soil. Thus, it shows that the increased water ratio results in lower compressive strength of soil, while the amount of binder is kept maintained. The seismic tests included the determination of the velocity of P-waves in soil stabilized by binders in various ratios: $L_W L_B$, $L_W EL_B$, $H_W L_B$ and $H_W EL_B$ (Fig. 4).

3. RESULTS

The experiment included testing of the two levels of binder quantity per m^3 of the dredged material: 150 kg and 120 kg. The evolution of P wave propagation in soil-cement samples was tested after 28, 42, 70 and 85 days ± one-day derogations. Compressive strength was evaluated at 90 days and correlated with P-wave propagation. The results of the P-wave velocity measurements are reported in Fig. 2. These show small mutual differences within each recipe but a significant difference between the different recipes. For example, for samples in the $L_W H_B$ series, the UCS varied between the 246 and 2262 kPa. In the $H_W L_B$ series, the UCS varied between 96 and 1090 kPa, Fig. 3.

High confirmation of the performed tests was achieved during the experiment sets when determining the UCS. The results are summarised in Table 1. The velocity of P-wave propagation with curing time for all the S/S soil mixes is summarised in Fig. 2. To evaluate the effects of various ratios of stabilizers on UCS, different soil-binder batches were prepared. A minimum compressive strength of 280 kPa was obtained with the amounts of binder with CEM II-GGBS in ratios 50/50, 30/70 but below 280 kPa for 70/30, Table 1. The UCS was relatively lesser for CEM II-GGBS 70/30 stabilization compared to 50/50 and 30/70 due to the low Ca content of slag. For stabilizing high-plasticity clayey soil, slag is preferred because of its low CaO

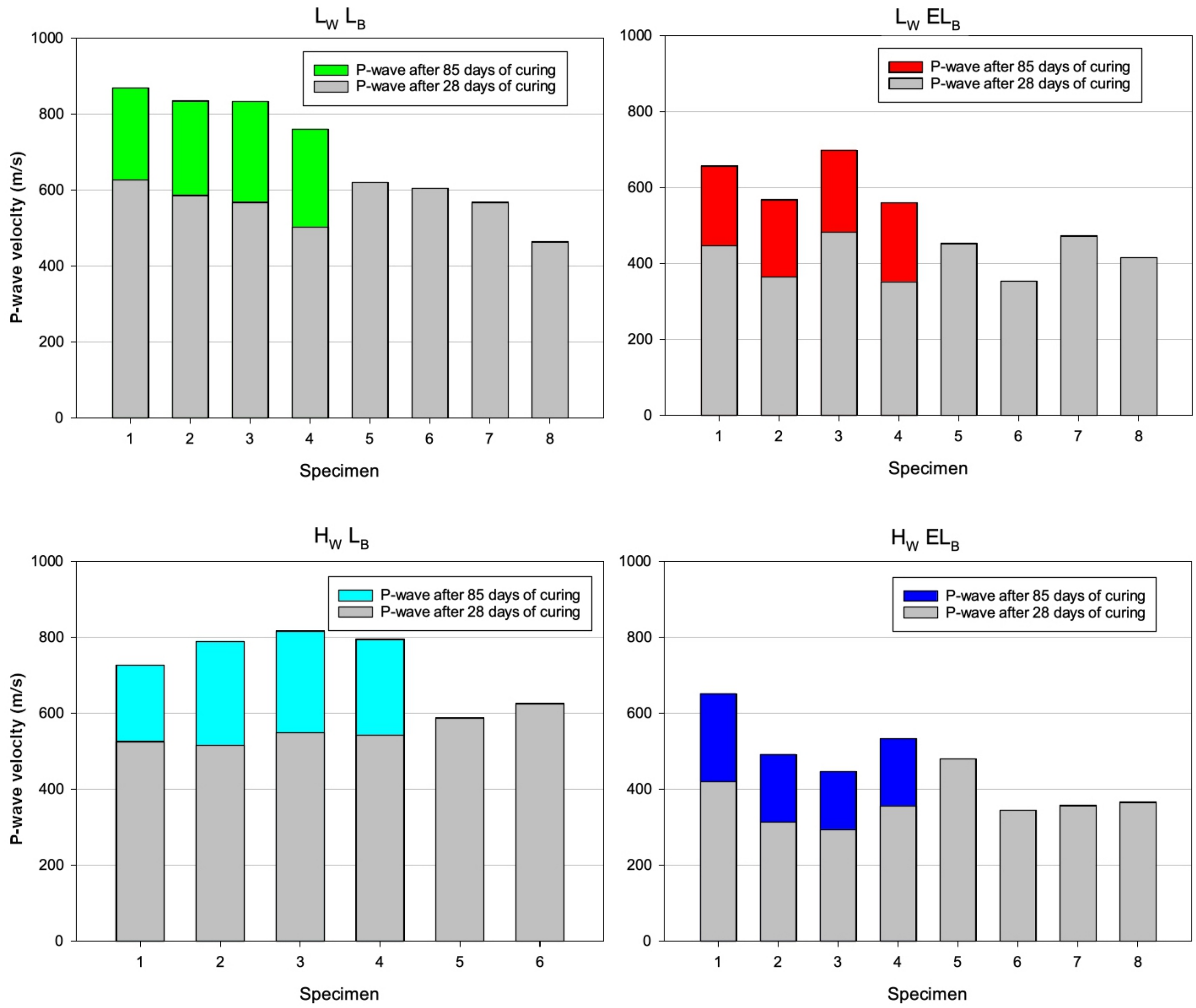

Fig. 4. P-wave velocity propagation for various binder combinations measured on day 28th and 85th after mixing

content, whereas lime-based stabilizers such as cement exacerbate the case through undue swelling of soil. The P-wave velocity of all tested samples (30/70; 50/50 and 70/30) is shown in Fig. 2.

The experiment also included testing the third level of binder quantity per m^3 of the dredged material: 100 kg. For the test series part two, a total of 30 test specimens were processed, according to Table 2. The test specimens in the following stage contained 30% CEM-II and 70% GGBS, as the optimum water/binder content for the S/S soils.

Figure 4 shows the results of the P-wave measurements for specimens processed during the experiment. For ratio $H_W L_B$, only 6 specimens were prepared to avoid repeatability, as this combination was included in a previous stage of the experiment.

Table 2
Amount and ratio of binders used for stabilizing specimens

Binder/water ratio	L_W (139%)	H_W (190%)
L_B (120 kg/m^3)	8	6
EL_B (100 kg/m^3)	8	8

The specimens showed a slightly greater mutual variation in relationships. The P-wave velocity on 28 and 85 days of curing in various combinations of binders are shown in Fig. 5. Testing P-wave propagation was done on samples with changed binder/water ratio and at different times. The results of four approaches were used to analyze the correlation between the P-waves and properties of stabilized soil.

The P-wave velocity increased along with curing time, see colour bars on day 85 against grey bars on day 28, Fig. 4. The increase from the day of compaction during 57 days between the two control days is notable for all cases. The samples were processed on the 85th day of storage using UCS tests after evaluating the P-wave velocity of each specimen.

The choice of the 85th day was selected due to the technical factors which did not affect physical properties of soil, neither caused significant difference in the UCS of the materials. The results are reported in Fig. 3, above. Finally, the results of the tests and those were performed as a complete 2*2-factor experiment was used for estimating the analysis of variance (ANOVA) which showed that there is a linear relationship between the amount of binder and water ratio, Fig. 5.

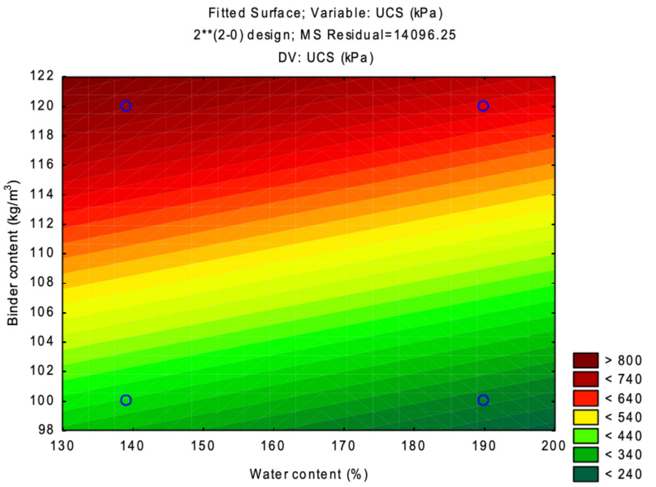

Fig. 5. Factor experiment showing linear effects between the water ratio and the amount of binder. The increased water ratio results in a lower UCS despite constant amount of binder maintained in a soil mix

4. DISCUSSION

The assessment of the material properties is one of the most important problems in geotechnical studies and construction industry. One of the main challenges is finding a correct method for the optimum design mixtures of binders used for effective S/S of soils. Various methods of estimating soil parameters were used successfully in civil engineering [33, 52–54]. In seismic methods, including ultrasonic tests, P-wave velocity increases along with the increased rigidity of medium, which is an expected phenomenon in cementation process. The correlations for different mixtures and the proportions of binders may vary for different case studies. Thus, besides the existing theoretical guidelines such tests should always be supported by the practical assessment of soil strength and stability.

This study demonstrated the results of variations of the P-wave velocity and compression characteristics of soil stabilized by various binder ratios over time in Timrå locality, Sweden. The novelty of the paper consists in the documented application of geophysical methods to study strength of soil samples collected at the sites of planned industrial construction on behalf of the SCA Biorefinery Östrand AB. The advanced approach was presented to evaluate the UCS in soil stabilized with various binder ratios using P-wave velocity. We performed these seismic tests using data on P-wave propagation to study properties of soils measured by the UCS tested to evaluate the bearing capacity of soil prepared as a ground area. The ultrasonic P-wave velocity was measured on soil stabilized by cement and slag in various ratios. The correlation between P-wave propagation, UCS of soil stabilized by various type of stabilizers, their ratio and curing time was investigated.

The analysis of the UCS of soil mixes depending on the percentage of binders and curing period is presented. The UCS of soils grew with an increase in stabilizer content ($H_B L_W$) and curing time which is proved by the geophysical tests on P-wave velocity. Specifically in this study we evaluated local specificity for Sweden sediment soil. This study considered regional specifics of soils from northern Sweden, to ensure safety of constructions in the coastal areas of the Bothnian Bay where soft clayey soils are dominating. To address this problem, a series of tests have been performed in the SGI to evaluate the optimum binder-water ratio for soil collected from Östrand area.

5. CONCLUSIONS AND RECOMMENDATIONS

This study assessed the feasibility of geophysical methods of ultrasonic P-wave testing to evaluate soil strength. Because soil was stabilized with various binder ratios, we evaluated the effects of different amounts of cement, slag and water on stabilization. The UCSs of stabilized soil treated with three combinations of stabilizers (CEM II-GGBS in ratios 30/70, 50/50 and 70/30) are shown in Table 1. As can be seen, soil treated with ratio 30/70 of CEM II-GGBS has higher strength which is caused by the high amounts of Ca responsible for the higher strength of stabilizers.

Along with curing progress, the reactions occurred between the soil samples and the stabilizing agents in various proportions that were tested and evaluated. We noted that these reactions resulted in the increased stiffness and rigidity of soil. It is explained by the increase of the P-wave velocity of wave propagation along with the increased stiffness of soil which shows a tight correlation. The P-wave velocity depends not only on the dynamic modulus of elasticity (stiffness) and Poisson ratio, but mainly on apparent density. This is one of the key parameters that should be evaluated for all tested soil-cement materials. Apparent density is the essential material property that correlates with the speed of elastic wave propagation in the material. This property gives more precise information on soil porosity reduction due to the addition of mineral binder.

Moreover, it was observed that the P-wave velocities of soil stabilized with $L_W L_B$ and $H_W L_B$ were higher compared to those of $L_W E L_B$ and $H_W E L_B$ (Fig. 4). The P-wave velocities of soil stabilized with binders of ratio $L_W L_B$ were the highest compared to those obtained for other mixtures (Fig. 3, red triangles). The GGBFS was used along with CEM II/A-V, because the low calcium content of slag improved stabilizing of clayey soil. Admixtures of GGBFS contributed to increase the compressive strength of soil-cement mixes.

As a recommendation for future studies, a series of tests can be added to model the elastic behaviour of soil aimed to determine small-strain shear modulus and the response to the dynamic loading. As mixes are incorporated into the subsoil, a complement to the given analysis would include testing responses of specimens to the triaxial stresses using triaxial apparatus. An example is the bender elements test aimed to measure the propagation of the S and P waves on mixtures built into the subsoil. A comparison of strength by uniaxial and triaxial tests would be beneficial practically for engineering reasons and to assess the applicability of the simplified method.

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