Hardening Accelerators (X-Seed 100 BASF, PCC, LKD and SALT) as Strength-Enhancing Admixture Solutions for Soil Stabilization

Per Lindh, Polina Lemenkova

▶ To cite this version:

Per Lindh, Polina Lemenkova. Hardening Accelerators (X-Seed 100 BASF, PCC, LKD and SALT) as Strength-Enhancing Admixture Solutions for Soil Stabilization. Slovak Journal of Civil Engineering, 2023, 31 (1), pp.10-21. 10.2478/sjce-2023-0002 . hal-04055510

HAL Id: hal-04055510
https://hal.science/hal-04055510

Submitted on 2 Apr 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

sciendo Slovak Journal of Civil Engineering

Vol. 31, 2023, No. 1, 10 – 21
DOI: 10.2478/sjce-2023-0002

HARDENING ACCELERATORS (X-SEED 100 BASF, PCC, LKD AND SALT) AS STRENGTH-ENHANCING ADMIXTURE SOLUTIONS FOR SOIL STABILIZATION

Per LINDH[1,2*], Polina LEMENKOVA[3**]

Abstract

This study is aimed at evaluating the strength of stabilised soil collected from the Port of Norvik, Stockholm, Sweden, where 350,000 m³ of clay had to be stabilized. The tests were performed in the laboratory of the Swedish Geotechnical Institute (SGI). The soil was stabilised by binder mixtures using Portland cement clinker (PCC) and lime and lime kiln dust (LKD). Accelerators (X-seed 100 BASF, PCC, LKD and salt) were added to the soil samples for quicker stabilization. The strength of the stabilised soil was assessed using resonance frequency measurements of seismic P-waves by an ICP accelerometer in order to estimate the shear strength of the soil and to evaluate the effects from the accelerators, binder ratios, and the curing temperature on the gains in stabilization and strength. Various proportions of the binders were tested, i.e.: 50/50 cement/lime and 50/50 PCC/lime. The temperature was measured using a calorimeter in double experiments. The results showed that the accelerators improve the strength in the stabilized specimens and enhance the soil performance for engineering construction work.

Address

[1] Department of Investments, Technology & Environment, Swedish Transport Administration, Box 366/ Neptunigatan 52, SE-201 23 Malmö, Sweden. e-mail: per.lindh@trafikverket.se ORCiD ID: https://orcid.org/0000-0002-0577-9936

[2] Division of Building Materials, Lunds Tekniska Hogskola (Faculty of Engineering), Lund University, Box 118, SE-221-00, Lund, Sweden. email: per.lindh@byggtek.lth.se

[3] Laboratory of Image Synthesis and Analysis, École polytechnique de Bruxelles (Brussels Faculty of Engineering), Université Libre de Bruxelles, Building L, Campus du Solbosch, ULB—LISA CP165/57, Avenue Franklin D. Roosevelt 50, B-1050, Brussels, Belgium. ORCiD ID: https://orcid.org/0000-0002-5759-1089

* ***Corresponding author:*** *per.lindh@byggtek.lth.se
**polina.lemenkova@ulb.be

Key words

- Accelerator,
- X-seed 100,
- Lime kiln dust,
- Construction materials,
- Geotechnical engineering,
- Resonance frequency,
- P-waves,
- Structural mechanics,
- Engineering geology.

1 INTRODUCTION

Fine-grained cohesive soil should be stabilised before its use in construction work (Dahlin et al., 1999; She et al., 2019; Lindh, 2004; Zhou et al., 2017; Lemenkov and Lemenkova, 2021a). Stabilisation improves the engineering properties of fine-grained soil by increasing its compressive strength (Brencich et al., 2021; Lemenkov and Lemenkova, 2021b; Wu et al., 2021), reducing its plasticity (Kasprzhitskii et al., 2016) and shrink-swell potential (Chen et al., 2002; Saride et al., 2013), and improving its mineralogical, morphological and structural characteristics (James, 2020; Wang et al., 2021). These improvements result in a higher bearing capacity, reduced settlement, and more predictable behavior of the problematic soil.

Various methods are employed to achieve more stable soil. They include mechanical and chemical approaches, as reported in previous studies (Koukouzas et al., 2022; Lindh et al., 2000; Källén et al., 2014, 2016; Lindh and Lemenkova, 2021a). The chemical stabilization of clayey soils is usually a complex hydration process involving reactions between the

© 2023 The Author(s). This is an open access article licensed under the Creative Commons Attribution 4 .0 License (https://creativecommons.org/licenses/by/4.0/)

additive and clay-water systems within the soil structure (Patel, 2019). The success of soil stabilization strongly depends on a variety of factors, i.e., the physiochemical properties of the soil (Zhang et al., 2022); the water-binder ratio (Wang et al., 2022a); the mixing efforts; the curing conditions; the temperature and the duration of the solidification (Lindh and Winter, 2003); the hydration mechanism of the binders (Scrivener et al., 2015); the effect of the accelerators added to the binder; and the organic and foreign inclusions or contaminants in the original soil structure; e.g., clay, silt and fine-grained or coarse-grained types of soil (Lindh, 2003; Akomah et al., 2021). Therefore, the final effect on the setting of the soil mixture may vary during the stabilization process.

Binders can either include traditional or novel materials. Cement is the oldest and most recognized soil binder (Buritatum et al., 2021) due to its effectiveness; it is the primary hydraulic binder for soil (Young, 2001). However, to improve its speed and effectiveness, other binders may be included as well. For instance, lime, polymer-based binders, industrial by-products or cementitious materials, such as fly ash or cement kiln dust, may be combined with cement. Various combinations of the binders are then tested in a laboratory to determine the most effective and economic solution (Khabiri and Ebrahimialavijeh, 2021; Lindh 2001).

The search for effective methods of rapid soil stabilization is one of the fundamental tasks in the construction industry and particularly in civil engineering. The question of rapid soil stabilization arises with larger treatment quantities (hundreds of tons). Adding accelerators to traditional binders for soil stabilization has recently attracted much attention in civil engineering and the construction industry (Meng et al., 2017; Luo et al., 2021; Kantesaria et al., 2021; Zhang et al., 2021; Zhao and Khoshnazar, 2021; Wang et al., 2022b). Combinations of admixtures significantly improve the physical and mechanical properties of clayey soil. Accelerators can be used as catalysts to reduce reaction times, which lead to higher early strengths, rapid hydration, and the improved microstructure of cement as a binder for soil stabilization. Adding catalysts as admixtures may also increase the compressive strength of the materials (Yang et al., 2021).

Quantifying the degree of soil improvement requires field and laboratory testing. Measuring the soil's strength (undrained or drained), stiffness (modulus), and density are typical approaches. A more recent method measures the vibratory resonance frequency of a laboratory specimen to evaluate the stiffness and strength of the stabilised soil (Mamoon and Ahmad, 1990; Coe and Brandenberg, 2010; Verástegui-Flores et al., 2015; Lindh and Lemenkova, 2021b). A seismic testing procedure has been developed by the Swedish Institute of Standards (SIS, 2019) and applied for practical use in the Swedish Geotechnical Institute (SGI).

In this paper we have evaluated the effects of adding accelerators to soil stabilised with binder mixtures of Portland cement clinker (PCC), lime, and lime kiln dust (LKD). Various accelerators (X-seed 100 BASF, PCC, LKD and salt) were added, and their effect on the soil stabilization was assessed using the P-wave resonance (stiffness) of the laboratory specimens. The measurements were then correlated with laboratory strength tests.

2 FORMULATION OF THE PROBLEM

Traditionally, specimens of stabilized soil have been compacted in piston sampling sleeves with a diameter of 50 mm and a length of 170 mm (i.e., 5×17 cm). In an external assignment at the Port of Norvik, Stockholm, where 350,000 m^3 of clay was to be stabilized, we were given the opportunity to conduct statistical experiments in an empirical study in order to evaluate the effectiveness of new and untested binders. A traditional approach could be to test only a single combination of binders, while varying the percentage of the binder added to the soil. However, by altering the composition of the binder itself as well as varying the percentage added to the soil, we were able to evaluate a broader variety of possible design solutions. Of course, this required a much larger number of tests to establish a meaningful data set for the statistical tests.

The main approach of this study was to use our laboratory's geophysical equipment and the resonant frequency method to quantify the improvement of the soil due to various additives. In the traditional packaging of the test sleeves, they are filled to about an 80 % volume with the stabilized soil and leaving a portion of the sleeve empty. However, during the experiments with the resonance frequency measurements (P-wave), it was found that the empty part of the sleeve gave a resonance frequency that hides the resonance frequency of the specimen itself. This could bias the experimental results. Furthermore, there was a problem with the packed surface not being flat, which also disturbed the measurements. Therefore, the solution to these problems was to fill the test specimens completely with the material, which is similar to the procedure for surface stabilization. There are two options to achieve this goal: 1) fill in the standard sleeves completely; 2) make shorter sleeves that are trimmed (smoothed) immediately after packing and before the curing soil. We selected the latter technique.

Resonance frequency measurements were demonstrated to be a useful geophysical technique that provides a high degree of repeatability due to its non-destructive nature. It enables comparing samples stored at different temperatures and obtaining a correct K-factor for calculating maturity numbers (Åhnberg and Holm, 1987). Introducing the maturity number with regard to the development of P-wave velocity enabled the calculation of the maturity and strength of the soil specimens. In combination with the experimental results of the P-waves, the maturity number enables evaluating and assessing the shear strength and UCS development of the stabilized soil. It can be effectively used when measuring P-waves to integrate field measurements with laboratory experiments. However, more research is needed to understand the effect of the stress level on curing the soil. A simple calorimeter measurement has been shown to be a fast and cheap method to check the reactivity of different binders and their combinations with accelerators by evaluating the temperature developments in the binder mixture. This method has a very high degree of repeatability using the existing description and approach.

In connection with this method, questions have arisen as to how such binding agents as accelerators could affect the increase in the strength of the stabilized soil. Due to the fact that alternative binders are not as reactive as lime and cement, they produce a slower increase in soil strength. Slower increases of soil strength are likely to have a negative impact on civil engineering projects, especially those connected with construction works, e.g., roads or buildings. Furthermore, there have been considerations as to whether the accelerators would reduce leaching from any contaminated sediments. This is important since early gel formation and curing is desirable to prevent the early leaching of stabilized sediments. The focus of the study is to improve the techniques for testing soil specimens stabilised with binders to improve the bearing capacity of soil. The soil specimens included samples of marine sediments dredged from the Port of Norvik in Stockholm.

The study investigated whether it is possible to fabricate a test specimen in a new, more time-efficient way that could be stored in a sleeve and used for strength estimates by resonance frequency measurements during the storage period. The objective of the study is to improve and adapt packaging equipment for a non-destructive testing of soil strength using geophysical methods of P-waves in such a way that testing can take place during the entire curing process of the samples. The aims of the study were: a) to determine the effects of accelerators on the speed of soil stabilization; b) to test how the storage temperature affects the increase in soil strength; c) to verify that the intended method performs well and can be applied as an effective production method for soil sampling and the measuring of the strength of the stabilized specimens; and d) to estimate the effects of using accelerators and different curing temperatures.

3 METHODOLOGY

Three different tasks have been evaluated in the project: i) adding binders with the subsequent packaging of soil samples; ii) resonance frequency measurements of the soil using P-waves aimed at measuring the natural frequencies of the vibrations in the tested specimen to indicate the soil strength; iii) a simplified calorimeter measurement of the reactivity of the binders used for soil stabilization.

3.1 Mixing and packing of soil samples

The mixing experiments involved an initial homogenization of the soil aimed at building a uniform cylindrical soil column with a sample. The specimens used in this study included fine-grained ML-silt types according to ASTM. These include inorganic silts, very fine sand, rock flour, silty or clayey fine sands, and clayey silts with a slight degree of plasticity (index <4). Such soil types exhibit little or no strength when air dried, according to the ASTM D2487-06, Unified Soil Classification System (Howard, 1986). The particle size distribution (grading) of the soil samples was determined according to the Swedish standard SS-EN ISO 17892-4:2016 (SIS, 2016) with a maximum <20 mm diameter of the larger element particles. Most of the grain size particles were less than 0.06 mm, i.e., the mechanical behavior of the soil was affected by its fine fractions. The mineralogical identification of the specimens shown in addition to the silt (grain size <0.063 mm) also included the occasional occurrence of well-graded sands and gravelly sands (SW), poorly graded sands (SP), and silty sands (SM) (grain size 0.063-2 mm). Sometimes, silty gravels as well as gravel-sand-silt mixtures were found (GM) and clayey gravels with gravel-sand clays (GC). The specimens also very rarely had inclusions of well-graded gravels, gravel-sand mixtures (GW), and poorly-graded gravels and gravel-sand (GP) (2-8 mm grain size diameters).

The dry specimens were thoroughly mixed with distilled water in a mixing bowl by a large mixer for 5 minutes. Water was added during the mixing process, and the samples were further mixed continuously until the consistency limits and linear

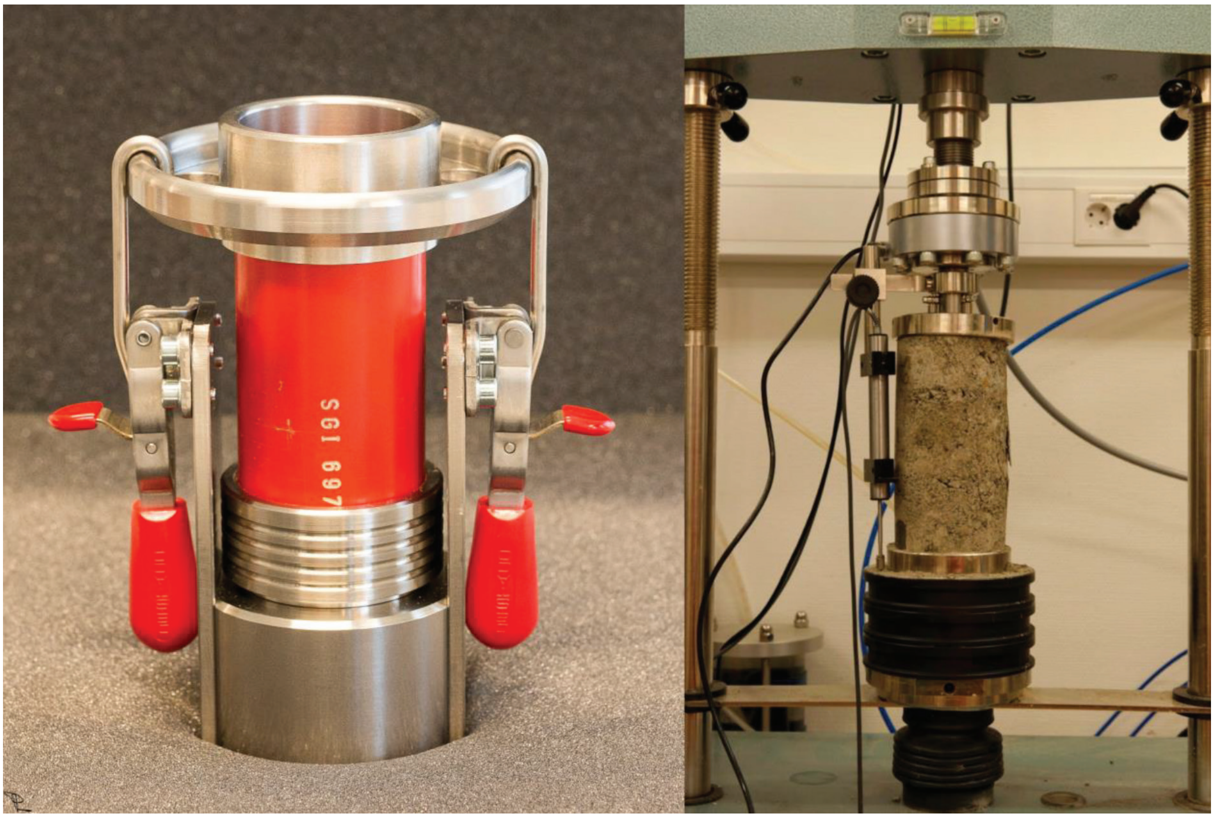

Fig. 1 *Left: Photo showing packaging equipment for packing specimens with a height of 100 mm. Right: UCS testing apparatus showing a specimen after the UCS test. Photo source: Per Lindh*

shrinkage were achieved. Afterwards, the binder blends and accelerators were added to these samples in different proportions (cement, lime, LKD, X-seed 100 and salt) and mixed with the soil for 5 minutes for homogenization. Immediately after mixing, the soil was packed into sampling sleeves, i.e., into plastic containers, which had a diameter/height of 5×17 cm. The specimens were packed in long sleeves and short sleeves with similar densities of the samples. The trimming of the sleeves after packing and before curing demonstrated their effectiveness. During the placement of the specimens, the sleeve was shaken on the table to loosen the air pores and ensure the even distribution of the soil. The optimal water ratio was determined based on the dry density of the soil using the SIS standard (SIS, 2003) as a volume fraction on the basis of the ratio of the measured water content mass to the known dry bulk density material. The amount and combination of the binder were determined before mixing based on the various percentages by weight.

Ordinary sampling sleeves with a height of 170 mm were used where the sleeve was manually packed in layers up to ca. 150 mm. The soil samples were trimmed to 100 mm to produce an L/D ratio of the specimen as 1/2, so that the end effects did not dominate the compressive behavior. In the traditional methods, the samples are usually packed directly into the sleeves without any holders. In this study, we applied the modified variants with 100 mm long sleeves. Fig. 1 (left) shows the equipment used for the study, which included a cylindrical mould with a bracket to hold it down to the base. The UCS tests were carried out in a 10-ton testing apparatus, Fig. 1 (right). The tests were run for the deformation control of the soil samples according to the SS-EN 13286-41 standard with a breaking load reached within one minute and a deformation rate of 3 to 4 mm/s.

3.2 Resonance frequency measurements by P-waves

The strength of the stabilized soil was evaluated using the non-destructive method of measuring the P-wave velocities, based on the theory of waves and the geophysical properties of soil as a porous media. The advantages of using P-waves for testing the physical properties of soil is that they are sensitive to the material's structure and travel through all kinds of media, including porous and solid structures, liquids and gases. Moreover, among the other elastic seismic waves, i.e., Rayleigh, Love, shear (S), and compression (P), P-waves have the greatest velocity, which is convenient for measuring material properties. Seismic P-waves transmit energy by the vibration of the soil particles, which vibrate in the direction of the wave propagation.

The seismic tests included measurements of the velocity of the P-waves propagating through the soil. A comparison of the different specimens enabled assessing the gains in soil strength obtained through the addition of binders. The core idea is that the values of the P-wave velocity correlate with the strength of the soil. Seismic measurements were performed using the proprietary software of the Swedish Geotechnical Institute (SGI). The equipment for the P-wave measurements included the lightweight ceramic shear response (ICP) Accelerometer (PCB Piezotronics Group Inc. (2013). The resonance frequency measurement was performed using a vibration source and vibration receiver in the ICP Accelerometer. The receiver was connected to a computer for data collection (Figs. 2 and 3). The P-wave velocity was measured

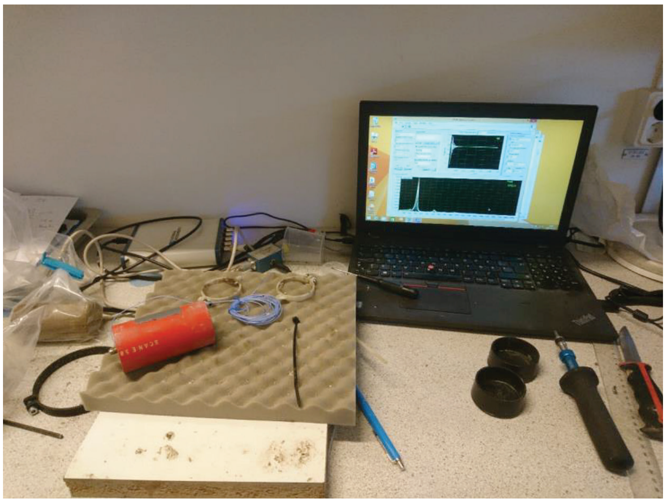

Fig. 2 *Setup of seismic experiments for measuring P-wave velocity. Photo: Per Lindh*

using a standard device setting with a frequency range of 2 to 10000 Hz (±5%).

The procedure included the following workflow: The soil specimens tested in the cylindrical form were placed on a foam rubber pad substrate in order to vibrate freely. An impulse force was excited in the specimens with a transient impulse source (Impact Resonance Testing) through oscillation by a hammer force. The vibrations in the samples were detected by the ICP Accelerometer attached to the specimens. The vibrations were measured as a function of the time of the P-wave velocity propagation through the specimens. The data were recorded and transformed to the resonance frequency (Hz) via a software program (see Fig. 3, which illustrates the process).

The receiver was adjusted on one end of the sample. An impulse force was excited by the hammer at the other end of the sample. The arrival time was used to estimate the P-wave travel time. The velocity of the P-wave was calculated from the travel time of the pulse of the wave propagating through the specimens. The data on the P-wave velocities were recorded in the computer. The post-processing of the data on the P-wave velocity measured on the specimens was based on a methodology developed by SIS using 'Free-free resonance column' software developed at SGI by Martin Holmen, Fig. 3.

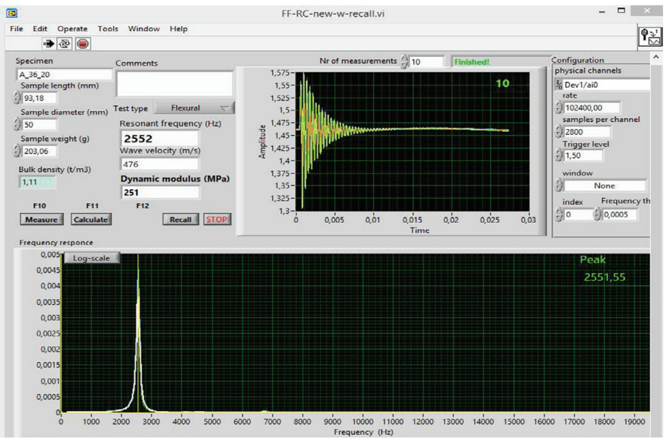

Fig. 3 *Seismic program testing the bend mode on a stabilized soil specimen*

The P-wave velocity was estimated as V = L/t, where V = velocity (m/s), L = sample length (m) and T = travel time (s) which was adapted from previous works (Ismail and Ryden, 2014). The P-wave velocity of the indicated strength of the soil specimens was stabilised by different binders. The P-wave velocities (Vp-value) increased with the curing time and with the percentage of the cementitious binder. The speed of the compression P-waves was measured in the specimens for the whole period on days 28 (Fig. 7), 50 (Fig. 8), 41 (Fig. 9 and 10) and 100 (Fig. 11). There are three fundamental oscillation modes for the cylindrical test body. These included: 1) the axial 2) bending and 3) torsional modes. The axial oscillation mode generates a compression wave (primary wave, P-wave). The torsion mode generates secondary waves and S-waves. P and S-waves are those waves that are primarily used in surface wave seismic tests, as well as in crosshole and downhole seismic tests. These were used to measure the shear and P-wave velocity profiles of the soil according to the standards (SIS, 2019).

Fig. 4 *Photo showing a simplified calorimeter consisting of a thermos and a temperature logger. Photo source: Per Lindh*

The S-wave has an advantage in that it is not significantly affected by the degree of the water saturation of the material. The P-wave, on the other hand, is greatly affected by the degree of water saturation. In an unsaturated sample body, the P-wave measurement gives the P-wave velocity of the material, while in a water-saturated sample body, water contributes to an increase of the speed of the P-wave evaluated. This is caused by the geophysical properties of P-waves: the P-wave velocity of water is usually greater than the P-wave velocity of a solid soil body. This phenomenon can be used to determine whether a specimen is saturated with water or not.

The bend mode generates a wave, which can be described simply as a combination of S and P-waves. This wave is very easy to excite and usually gives the best signal, see Fig. 2, which results in its wide application in seismic experiments. Similar approaches have been applied in earlier works, e.g., longitudinal resonance tests (Drnevich and Ashlock, 2017), torsional resonance tests (Lo Presti et al., 1997, 2007; Drnevich et al., 1987; Isenhower et al., 1987), resonance column tests (Vrettos and Banzibaganye, 2022); and bender element tests. Besides, some cases report the incorrect calculation of the shear wave from the bending wave measurements (Verástegui-Flores, 2015). Therefore, the use of the bending mode to calculate the shear wave velocity gives an overestimation of its value. The plots showing the results and demonstrating the P-wave velocity developed over the curing time are given in Figs. 7–11. The seismic velocities were measured as a function of the curing time to evaluate the strength development in the stabilized soil.

3.3 Simplified calorimeter

The simplified calorimeter consisted of a steel thermos equipped with a thermometer, Fig. 4. The variations in the temperature of the binder slurry (water, binder and accelerants) were measured in the thermos. Here, the ratio between the weight of the water and the weight of the binder was 1.0. A WBR of 1.0 means an equal weight of water and binder, i.e., the water/binder ratio is 1:1. The water used in the experiments was at room temperature. The experiment compared the exothermic properties of the different mixtures. The difference in the heat capacity between the binders could be calculated. However, the method has been developed for a direct comparison of the temperatures.

4 RESULTS

4.1 Mixing and packing of soil in short sleeves

The increased P-wave velocity of the soil samples is associated with the increased strength of soil stabilized with binders. In this experiment we employed three different binders, i.e., as cement, lime, LKD, and X-seed 100 accelerators to test the effect of the stabilizer contents on the improved properties of the soil tested by seismic tests. Three different types of binder mixtures were tested as shown in Tab. 1. One can see that Case No. 1 was based on a mixture of the soil with a cement/lime/LKD blend; Case No. 2 – with cement/lime binders and the accelerator X-seed 100, and Case No. 3 with cement/lime and salt.

Tab. 1. *Stabilizing agents (binders and accelerators) included as the components to the soil mixture in Cases Nos. 1, 2 and 3.*

Case	Cement	Lime	LKD	X-seed 100	Salt
1	x	x	x	–	–
2	x	x	–	x	–
3	x	x	–	–	x

The first binder mixture used cement, lime and lime kiln dust (LKD). LKD is not a standardized product, which is why the chemical composition has greater variations compared to the traditional binders. The second binder mixture consisted of cement, lime, and accelerator X-seed 100, BASF. The X-Seed 100 was developed by BASF Technology Center in Trostberg/Germany (TBA Trimmiser Baustoffe AG, 2010). This technology is based on an injection of the pore solution of the cement with synthetically manufactured calcium-silicate-hydrate crystallites as liquid admixtures (TBA Trimmiser Baustoffe AG 2010). The X-Seed 100 accelerator is an effective strength-enhancing admixture solution, which notably improves the development of strength in the Portland cement used in the construction industry and for soil stabilization. The third binder mixture contained cement, lime and salt.

The percentage of the admixture of X-seed 100 for each of the three cases was 2.5%, 5% and 7.5%, respectively, which was defined based on the amount of the binder. Adding the X-Seed 100 as an accelerator enabled the promotion of better soil hardening at room temperature, which contributed to the stabilization of the soil. In the third mixture, cement, lime and salt were used as accelerators and demonstrated the development of strength in the soil samples stabilized by the binders in proportions of 40/60%, 50/50% and 25/75% of the cement/lime and 40/40/20% of the cement/lime/salt combination. For the samples stabilized with salt, 20,10 and 55% weight percentages (%) of salt were used for Case No. 3, based on the amount of the binder. The combination of binders and accelerators totals 100%, see Table 2. However, the results show no significant difference between the samples stabilized with or without salt, see Figs. 9 and 10 for a comparison. The mean and standard deviations of the packed samples were calculated to verify the quality of the packaging, Fig. 5. The components of the binders and accelerators were mixed together with different ratios in mixtures, Tab. 2.

Tab. 2. *Mixtures of the proportions of stabilizing agents (binders and accelerators) in Cases Nos. 1, 2 and 3 and the samples a, b and c tested.*

Case	Binders		Accelerators		
	Cement	Lime	LKD	X-seed 100	Salt
1a,b,c	60,40,40	40,40,30	0,20,30	–	–
2a,b,c	60,50,40	37.5,45,52,5	–	2.5,5.0,7.5	–
3a,b,c	40,50,25	40,40,20	–	–	20,10,55

To compare the present results with those from the experiments on the packaging traditionally used, a compilation was made from a previous study (Norvik), where the specimens were packed in a 170 mm sleeve and then trimmed down to a 100 mm sleeve in connection with the routine testing. The soil density was estimated according to the existing methods of the Swedish Institute of Standards (SIS, 2017a) using the trimmed specimens.

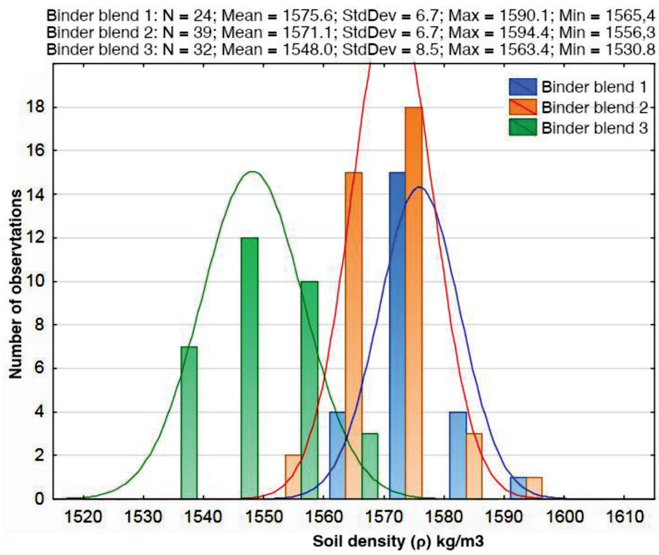

Fig. 5 *Density of the soil specimens packed in short sleeves.*

A statistical summary is presented in Fig. 6 with the standard deviation varying between 10.8 and 12.9. The colours on the graph in Fig. 6 correspond to the amounts of the binder blends (binder and soil) in kg, as follows: the blue is for Blend No. 1, which has 80 kg, the orange stands for 100 kg of Blend No. 2 and the green stands for Blend No. 3 (120 kg of materials). The results indicate the slightly higher values of the mean and smaller standard deviations, according to the new method. However, future studies should include a t-test designed with the zero hypothesis that there is no difference between the methods.

The most probable explanation for the differences between the two methods is that there is less friction in a cylindrical soil column when packing according to the new method, which gives a higher degree of packing, fewer deformities, and thus a higher density of the soil samples.

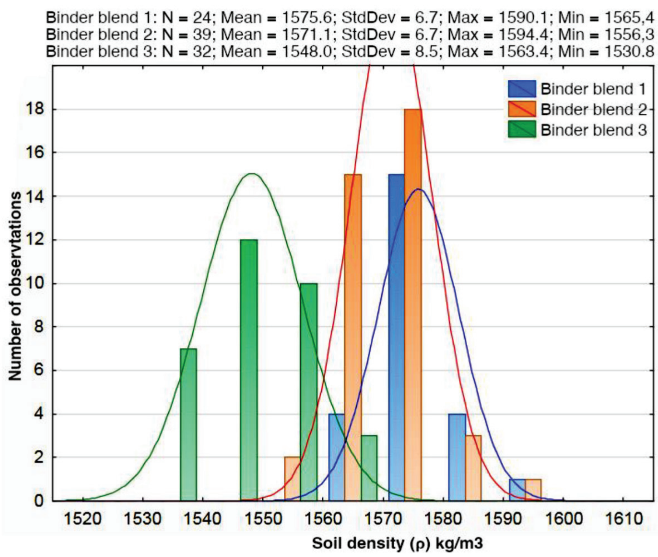

Fig. 6 *Density of the specimens packed in long-sleeves (standard procedure).*

4.2 Results of the resonance frequency measurements

In the experiment, UCS testing was performed on all the soil specimens using Swedish standard SS-17892-7:2017 (SIS, 2017b). Each specimen was loaded until the peak stress was obtained. The tests included the addition of various percentages of binders (cement/lime/LKD, and X-seed 100 and salt accelerators) to the specimens. The specimens were treated for different curing periods, i.e., a total of over 3 months (28, 41, 50 and 100 days); they were then extracted from the sleeves, subjected to UCS testing, and tested by the P-waves.

Fig. 7 shows the results of the P-wave velocities tested on the stabilized specimens by 20 °C from Day 1 to 28. The indices of the curves include the temperature and the number of the sample. Thus, *T20_x* means a storage temperature of 20°C and that it is Sample No. X. Index A indicates that the sample contains an accelerator. From Fig. 7 we can conclude that the P-wave velocity increased from the initial speed of 450 m/s until 750 m/s in 7 days of curing in the five soil-binder mixture specimens tested with the addition of accelerators X-seed and salt, after which the P-wave speed stabilized, increased slightly, and reached a maximum of 900 m/s on Day 28 of the curing period.

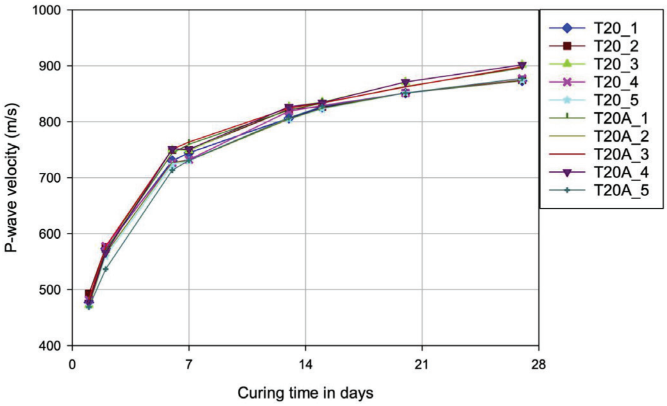

Fig. 7 *P-wave velocity as a function of the storage time at 20 °C.*

The evaluation of the accelerators (X-seed 100 and salt) using the P-wave velocity did not indicate a significant difference in the curing process either at a curing temperature of 7°C or at a temperature of 20°C, see Figs. 7 and 8 for a comparison. From Fig. 8 we can also see that the speed of the P-waves correlates well to the curing time for several of the single specimens stabilized with binders and accelerators. Thus, Fig. 8 displays the speed-ups for the P-wave velocities from Day 7 to Day 50 owing to the increase in strength in the specimens over the time of curing due to the accelerants added into the binder mixtures. Thus, compared to the results of previous studies on the measured strength of the fine-grained soil using traditional methods (Lindh, 2001, 2004), the addition of the accelerators increased the gain in strength in the soil specimens.

The curves in Fig. 8 correspond to the speed of the P-waves, which increased from 500 m/s to 780 m/s starting from Day 7 to 50 of the curing. Adding the accelerators to the cement, lime and LKD caused a maximum increase in the P-wave with the addition of 2.5%, 5% and 7.5% of the X-seed, respectively. It is worth noting that the velocity of the P-waves gained in speed during the initial curing period (days 1 to 7), after which it stabilized. We can further conclude that the speed-ups of the P-waves differed by the various temperatures. Thus, Fig. 7 shows the P-waves measured at a 20°T, while Fig. 8 is at 7°T. Comparing these two figures, one can see that the higher temperature (20°T) resulted in the increased speed of the P-wave. For instance, on day 14, the P-waves increased up to 820 m/s at 20°T (Fig. 7), while Fig. 8 shows that at 7°T, the measured P-wave velocities on the same day (14) did not exceed 620 m/s, which points at the effects from the temperature on the curing.

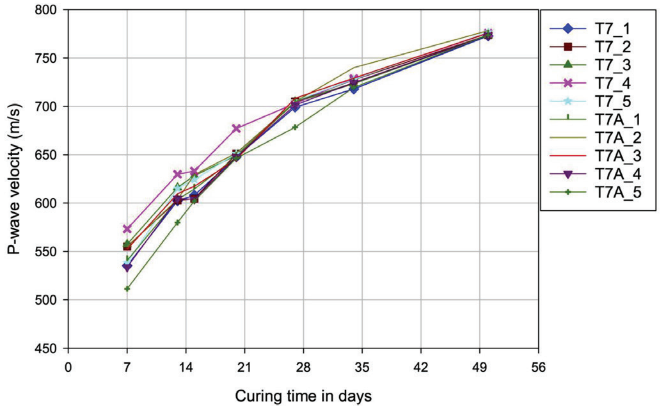

Fig. 8 *P-wave velocity as a function of curing time at 7 C°. T7_x means a storage temperature of 7 C° and Sample No. X. Index A means that sample includes an accelerator.*

Fig. 9 shows the results of the tests at 20°C. The indices of the curves signify the temperature and number of the sample. Thus, *BT_20_Sy_x* means curing T at 20 °C, and *Sy* indicates that the sample contains salt as an accelerator; x means the sample number. Index *y* varies from 1 to 4, where 1 indicates that the sample contains 1 % salt based on the amount of the binder. Fig 9 demonstrates that adding salt as an accelerator (in a content of 1 % with respect to the binder amount) increased the P-wave velocities up to 1050 m/s on day 41 by a curing temperature of 20°C.

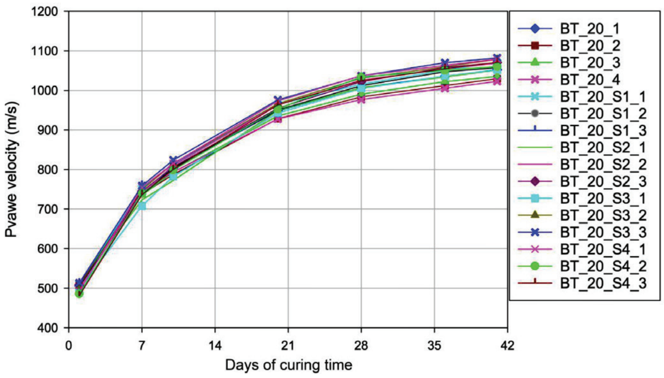

Fig. 9 *P-wave velocity as a function of the curing time at 20 °C.*

It also seems that the increase in speed is slightly more compared to Fig. 7, where the speed of the P-waves stabilized after day 21 at the same curing temperature. This indicates the positive contributions from the salt added as an accelerator on the continued gain in strength in the soil specimens. For the samples stabilized with salt as an accelerator, 1, 2, 3 and 4 %

by weight of the salt were used based on the amount of the binder. The results do not show any significant difference in the P-wave values between the samples with and without salt, see Figs. 9 and 10 for a comparison.

However, the performance of the gain in strength differs by the changed temperatures. Thus, Fig. 9 shows the tests performed at 20°C, while Fig. 10 shows tests performed at 20°C. Comparing these two graphs, we can see that the increase in P-wave speed (i.e., gain in strength) occurs more promptly and then stabilizes at 20°C, while it increases more moderately at 7°C, which indicates the external effects of the ambiance while testing the samples. Fig. 9 shows the increase in P-waves from 450 to 1400 for the samples stabilised with the added salt at T 20°C during the curing period from 1 to 41 days, while Fig. 10 shows the almost linear increase of the P-wave speed from 400 to 800 m/s for the period of Days 2 to 41 at T 7°C, where the lower parameters of the speed correspond to the lower temperature, respectively.

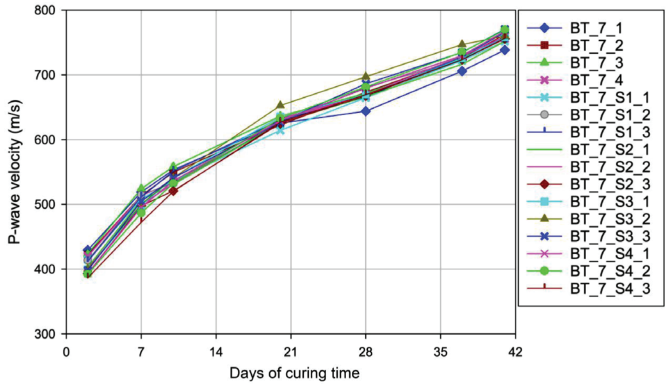

Fig. 10 *P-wave velocity as a function of storage time at 7 °C. BT_7_Sy_x means a storage temperature of 7 °C, and Sy indicates that the sample contains salt, while x means the sample number. Index y varies from 1 to 4, where 1 indicates that the sample contains 1% salt based on the amount of binder.*

However, adding various binders and accelerators contributes only slightly to the gain in strength, for example, in the case of Portland cement clinker (PCC) with a low gypsum content; a faster development of strength is obtained compared with a case of ordinary cement, see Fig. 11.

Fig. 11 shows the curves of the P-wave velocities versus the curing time (Days 1 to 100) for the six different cases of clay stabilized with 50/50 Portland cement type IIA / lime and 50/50 PCC / lime with added Portland cement clinker (PCC) with a low gypsum content. Comparing the cases of the added PCC and normal Portland cement, we can conclude that the final strengths achieved higher values by PCC, see Fig. 11 where the dots correspond to the added PCC, while the triangles denote cement as the binder. For example, the reduction in the curing time in these cases is calculated as follows: on day 21, the values with added Cem IIA/QI show the speed of the P-waves for sample 1 as 850 m/s, for sample 2 as 900 m/s, and for sample 3 as 865 m/s. In contrast, we can see that the added PCC increased the speed of the waves up to 970 and 980 m/s, respectively for the two different samples.

Likewise, on Day 42, the values with added Cem IIA/QI show the speed of the P-waves for sample 1 as 960 m/s, for sample 2 as 985 m/s, and for sample 3 as 940 m/s. In contrast, the added PCC increased the speed of the waves above 1000 m/s with values of 1030, 1040 and 1055 m/s, respectively, for the three different samples. This difference in the speed of 70 m/s continues and can be clearly seen as a distance gap between the batches of curves for the PCC-stabilized and cement-stabilised soil, respectively (Fig. 11). This illustrates certain benefits of the accelerators added to the binders for the soil hardening process.

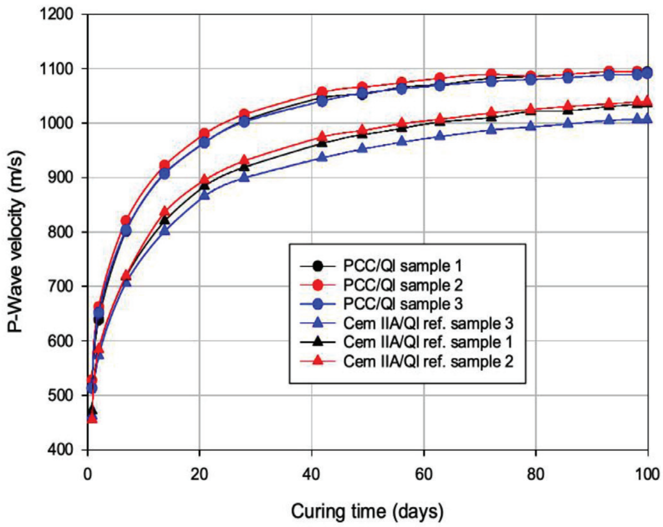

Fig. 11 *P-wave velocity as a function of the curing time for clay stabilized with 50/50 cement / lime and 50/50 PCC / lime. In the experiment, triple samplings were made for the statistical soundness of the test. Note the significant difference between the different groups.*

These effects can be explained by the properties of PCC, which contains a lower amount of gypsum. As a result, this gives a faster reaction compared to traditional cement, which can be clearly seen in Fig. 11. This faster reaction could be used to reduce processing time or to apply it in combination with a slow curing binder in order to obtain a satisfactory curing process.

The application of the resonance frequency measurements on the stabilized soil specimens is a proven technique with high repeatability due to its non-destructive nature (Barnaure et al., 2021; Dimter et al., 2016; Multon et al., 2022; Di Sante et al., 2022). Figs. 7 to 10 show the results from the P-wave measurements. The advantages of this method include the possibility of measuring the same soil specimen for a longer period of time without having affected its initial structure. This method can be used in this way to easily calculate the K-factor in the equation of the maturity number (M_T), using the existing formula, see below (Åhnberg and Holm, 1987).

$$M_T = [20+(T-20)*K]^2 * \sqrt{t}$$

where

T = temperature (°C)
t = time (days)

By storing specimens at different temperatures, e.g., 7 and 20 °C, see Fig. 12, the correct value of the M_T can be calculated, and a correct comparison between the different curing temperatures can be performed. For example, the M_T of soil treated at T 7°C (red line in Fig. 12) at the speed of P-waves of 400

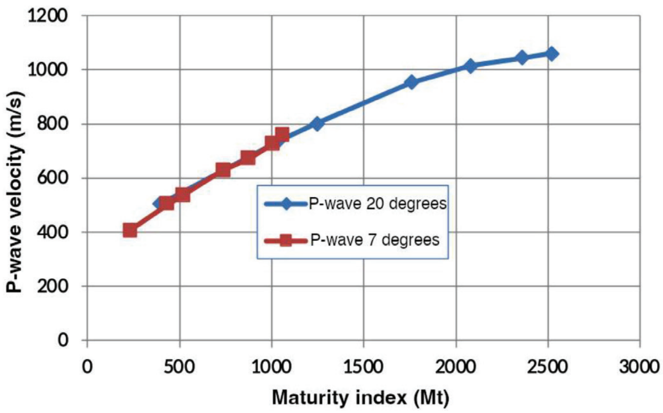

Fig. 12 *P-wave versus the maturity number for soil samples cured at different temperatures.*

m/s shows a value of 350 and then gradually increases in an almost linear way until 1100 by a P-wave velocity of 790 m/s with observations at T 7°C.

The M_T measured at T 20°C started at a P-wave speed of 550 m/s and coincided with those values at T 7°C; afterwards, the measurements continued with a similar correlation (the blue line in Fig. 12), showing, for instance, that the M_T 2000 is achieved by P-waves at 1000 m/s, after which the increase in M_T gradually stabilized and reached the maximal measured value of 2550 by P-waves at 1030 m/s, Fig. 12.

The geotechnical tests included testing the hardening process of the material, i.e., evaluating how much the strength developed after a certain number of days of curing at a certain temperature, which is of importance for both the geotechnical and environmental types of assessment. The testing strength was performed according to the Swedish standards for the uniaxial (unconfined) compressive strength (UCS) of soil (SIS, 2017b). The environmental assessment could also profit from the geophysical applications, which are of great importance in determining at what time leaching tests should be performed based on the curing time and temperature. A summary of how the shear strength relates to the P-wave velocity is presented in Fig. 13.

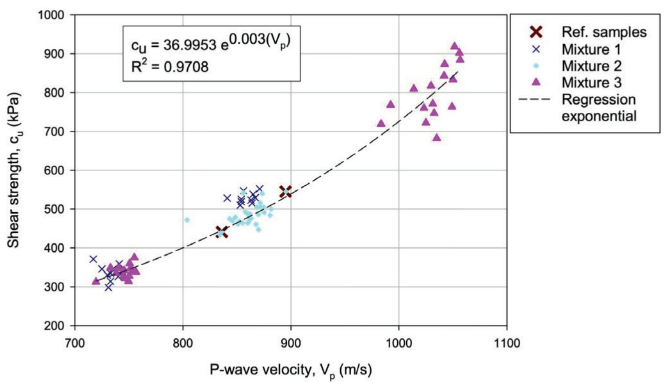

Fig. 13 *Graph showing the P-wave velocity as a function of the shear strength of the tested soil stabilized by various combinations of binders (Portland cement and lime) and accelerators. The accelerators include LKD in Mixture 1, X-seed 100 in Mixture 2 and salt in Mixture 3.*

As shown in Fig. 13, adding accelerators to the stabilized soil has an effect on the increase in shear strength and the corresponding increase in P-wave velocities. The results are generalized as an exponential curve with three major clusters of data that correspond to the groups of soil specimens tested. Here, the shear strength and P-wave velocity are evaluated for the three control groups of soil stabilized by the binders (Portland cement and lime) and accelerator (LKD in Mixture 1, X-seed 100 in Mixture 2, and salt in Mixture 3). Thus, Fig. 13 indicates that by adding the accelerators, the shear strength of the soil in the first group of measurements was estimated to be in a range between 300 to 380 kPa, with P-waves from 720 to 760 m/s. The speed of the P-waves increased slightly after the gain in strength, which corresponds to the P-waves at the interval between 830 and 890 m/s and the shear strength at 420–560 kPa (the second cluster in Fig. 13). The maximal P-waves are due to the strength developed during the curing time, which corresponds to the P-waves of 970–1060 m/s and the shear strength at the interval of 685-910 kPa (the third cluster in Fig. 13). In such a way, the maximal increase in strength will slightly increase by adding the X-seed and salt accelerators as the stabilizers to the soil (lime, LKD and cement), which is reflected in the P-wave speed.

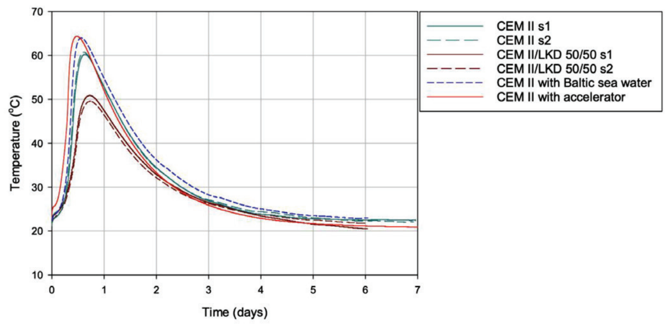

Fig. 14 *Temperature measurements for various binders and binder combinations*

4.3 Results of simple calorimeter measurements

The method of measuring the development of the temperature in a binder slurry using a simple calorimeter results in a high repeatability in double experiments, see Fig. 14. Note that slightly higher temperatures are recorded when using salt water and X-seed 100 accelerators. A further increase in temperature can be obtained with a cement paste with a low gypsum content. This can be partly used to achieve higher temperatures in the stabilized soil samples but also to start the reactions of binders with a lower degree of reactivity.

5 CONCLUSIONS

By adding accelerators to the binders, we evaluated the shear strength, UCS, and the stiffness of soil using laboratory experiments and statistical analysis. We performed a soil stabilization of soft and expansive fine-grained clays collected in southern Sweden. We evaluated alternative accelerators (X-seed, PCC, LKD and salt) as strength-enhancing admixtures used for stabilization of the soil. Although the major effects came from the binder themselves, a certain contribution to the gain of strength was also noted from the accelerators. Besides, we analysed the effects of varying the curing temperature on the properties of the specimens stabilized. To this end, we evaluated the properties of soil at two temperatures (7°C and 20°C) using a simplified calorimeter and thermos. Moreover, we experimented with fabricating the samples and determined that specimens with an initial height of 100 mm worked well. Our method resulted in a lower standard deviation, compared to the traditional approaches. However, this should be verified by supplementary experiments in future studies. The total time required for the fabrication, trimming, and handling of the specimens was slightly longer compared to the traditional procedures.

Adding accelerators as additional materials along with the use of traditional binders for improving stabilization is worthwhile, even to a minor degree. In addition to the technical benefits, some of the residual products, such as fly ash, have a lower reactivity and are usually less exothermic. The results indicated that the accelerators tested do not work in conjunction with the dry method, which is the most common method of testing soil in Sweden, where the binder is mixed dry. The reason for this is assumed to be due to the lack of free water in the matrix. However, adding PCC with a low gypsum content to the soil mixture worked satisfactorily with regard to the dry method. In this study we evaluated the effects from the accelerators using the wet method, which means that the binder is initially mixed with water and then with soil. Furthermore, this technique has potential in connection with the stabilization of dredged soil to accelerate the curing and to reduce or prevent early leaching. The study included specimens cured under different temperatures and stabilized by different binder mixtures with and without accelerators, which were tested by UCS and measured by the seismic velocities of P-waves. Increasing the curing temperature of the stabilized specimens resulted in a notably faster gain in strength and higher shear strength values, which were detected by P-wave sonic tests and plotted on graphs.

This study evaluated the effects from adding accelerators to other binders, which, to a certain extent, contribute to the gain in strength in soil. In turn, the increased strength of soil stabilized by cement and cementitious materials allows for its higher suitability in such geotechnical engineering works as road or highway construction. Besides, the use of accelerators can lead to a reduced amount of binder used, which reduces negative environmental effects, e.g., from cement, which are caused by the CO_2 emissions associated with cementitious products. The stabilization of soil enhances its performance characteristics, improves its bearing capacity and durability, and ensures safe and stable constructions in geotechnical works. Finally, other advantages of using accelerators consist in their economic effects (reduced costs of the soil stabilization process). These results can be considered when selecting soil stabilization methods in the construction industry.

Acknowledgements

The authors gratefully acknowledge the technical contributions of Martin Holmén and Fredrik Burman, staff personnel from the Swedish Geotechnical Institute (SGI).

REFERENCES

Akomah, U. – Nwaogazie, I. L. – Akaranta, O. – David, A. O. (2021) *Comparative Analysis of Activated Corn Cob and Bentonite Clay for the Removal of Lead and Nickel from Raw Water*. Slovak Journal of Civil Engineering, 29(2), 30–38. https://doi.org/10.2478/sjce-2021-0011

Åhnberg, H. – Holm, G. (1987) *Om inverkan av härdningstemperaturen på skjuvhållfastheten hos kalk- och cementstabiliserad jord*. Statens geotekniska institut, Rapport 30. [On the effect of the curing temperature on the shear strength of lime and cement stabilized soil. Swedish Geotechnical Institute, Report 30.

Barnaure, M. – Bonnet, S. – Poullain, P. (2021) Earth buildings with local materials: Assessing the variability of properties measured using non-destructive methods. Construction and Building Materials, 281, 122613. https://doi.org/10.1016/j.conbuildmat.2021.122613

Brencich, A. – Łątka, D. – Matysek, P. – Orban, Z. – Sterpi, E. (2021) *Compressive strength of solid clay brickwork of masonry bridges: Estimate through Schmidt Hammer tests*. Construction and Building Materials, 306, 124494. https://doi.org/10.1016/j.conbuildmat.2021.124494

Buritatum, A. – Horpibulsuk, S. – Udomchai, A. – Suddeepong, A. – Takaikaew, T. – Vichitcholchai, N. – Horpibulsuk, J. – Arulrajah, A. (2021) *Durability improvement of cement stabilized pavement base using natural rubber latex*. Transportation Geotechnics, 28, 100518. https://doi.org/10.1016/j.trgeo.2021.100518

Chen, C. – Roseberg, R. J. – Selker, J. S. (2002) *Using microsprinkler irrigation to reduce leaching in a shrink/swell clay soil.* Agricultural Water Management, 54, 2, 159-171. https://doi.org/10.1016/S0378-3774(01)00150-0

Coe, J. – Brandenberg, S. J. (2010) *p-Wave Reflection Imaging of Submerged Soil Models Using Ultrasound*. Journal of Geotechnical and Geoenvironmental Engineering, 136, 10, 1358–1367. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000346

Dahlin, T. – Svensson, M. – Lindh, P. (1999) *DC Resistivity and SASW for Validation of Efficiency in So il St abilisation Prior to Road Construction*. In: Proceedings EEGS' 99, Budapest, Hungary, 6-9 Sept. 1999, 1–3. https://doi.org/10.3997/2214-4609.201406466

Di Sante, M., Bernardo, D., Bellezza, I., Fratalocchi, E., Mazzieri, F. (2022) *Linking small-strain stiffness to development of chemical reactions in lime-treated soils*. Transportation Geotechnics, 34, 100742. https://doi.org/10.1016/j.trgeo.2022.100742

Dimter, S. – Rukavina, T. – Minažek, K. (2016) *Estimation of elastic properties of fly ash–stabilized mixes using nondestructive evaluation methods*. Construction and Building Materials 102, 505–514. http://dx.doi.org/10.1016/j.conbuildmat.2015.10.175

Drnevich, V. P. – Isenhower, W. M. – Stokoe, K. H. – Allen, J. C. (1987) *Instrumentation for Torsional Shear/Resonant Column Measurements Under Anisotropic Stresses*. Geotechnical Testing Journal 10(4). https://doi.org/10.1520/GTJ10544J

Drnevich, V. P. – Ashlock, J. C. (2017) *Measurement of Damping in Soils by the Resonant Column Test.* In: Proceedings Geotechnical Frontiers 2017: Seismic Performance and Liquefaction. GSP 281, March 12–15, 2017, Orlando, FL, USA. https://doi.org/10.1061/9780784480489.009

Howard, A. K. (1986) *Soil classification handbook: unified soil classification system*. Denver, CO, USA: Geotechnical Branch, Division of Research and Laboratory Services, Engineering and Research Center, Bureau of Reclamation.

Isenhower, W. M. – Stokoe, K. H., II – Allen, J. C. (1987) *Instrumentation for Torsional Shear/ Resonant Column Measurements Under Anisotropic Stresses.* Geotechnical Testing Journal, GTJODJ, 10(4), 183–191.

Ismail, A. I. M. – Ryden, N. (2014) *The Quality Control of Engineering Properties for Stabilizing Silty Nile Delta Clay Soil, Egypt*. Geotechnical and Geological Engineering, 32, 773–781. https://doi.org/10.1007/s10706-014-9756-5

James, J. (2020) *Sugarcane press mud modification of expansive soil stabilized at optimum lime content: Strength, mineralogy and microstructural investigation*. Journal of Rock Mechanics and Geotechnical Engineering, 12, 2, 395-402. https://doi.org/10.1016/j.jrmge.2019.10.005

Källén, H. – Heyden, A. – Lindh, P. (2014) *Estimation of grain size in asphalt samples using digital image analysis*. In Andrew G. Tescher, editor, Applications of Digital Image Processing XXXVII, 9217, 292–300. International Society for Optics and Photonics, SPIE. https://doi.org/10.1117/12.2061730

Källén, H. – Heyden, A. – Åström, K. – Lindh, P. (2016) *Measuring and evaluating bitumen coverage of stones using two different digital image analysis methods*. Measurement, 84, 56–67, 2016. https://doi.org/10.1016/j.measurement.2016.02.007

Kantesaria, N. – Chandra, P. – Sachan, A. (2021) *Stabilization of Expansive Soil Using Agar Biopolymer*. In: International Foundations Congress and Equipment Expo 2021 (IFCEE), May 10–14, 2021, Dallas, TX, U.S.A, pp. 272-281. https://doi.org/10.1061/9780784483411.026

Kasprzhitskii, A. – Lazorenko, G. – Yavna, V. – Daniel, Ph. (2016) *DFT theoretical and FT-IR spectroscopic investigations of the plasticity of clay minerals dispersions*. Journal of Molecular Structure 1109, 97–105. https://doi.org/10.1016/j.mol-struc.2015.12.064

Khabiri, M. M. – Ebrahimialavijeh, B. (2021) *Effect of Modifying Aggregates by Rap and the Simultaneous Use of Adhesives for the Stabilization of a Sandy Pavement Subgrade*. Slovak Journal of Civil Engineering, 29, 2, 1–8. https://doi.org/10.2478/sjce-2021-0008

Koukouzas, N. – Tyrologou, P. – Koutsovitis, P. – Karapanos, D. – Karkalis, C. (2022) *15 – Soil stabilization. Handbook of Fly Ash*, pp. 475–500. Butterworth-Heinemann. ISBN: 978-0-12-817686-3. https://doi.org/10.1016/B978-0-12-817686-3.00004-9

Lemenkov, V. – Lemenkova, P. (2021a) *Testing Deformation and Compressive Strength of the Frozen Fine-Grained Soils With Changed Porosity and Density*. Journal of Applied Engineering Sciences, 11, 113–120. https://doi.org/10.2478/jaes-2021-0015

Lemenkov, V. – Lemenkova, P. (2021b) *Measuring Equivalent Cohesion Ceq of the Frozen Soils by Compression Strength Using Kriolab Equipment*. Civil and Environmental Engineering Reports, 31, 63–84. https://doi.org/10.2478/ceer-2021-0020.

Lindh, P. – Dahlin, T. – Svensson, M. (2000) *Comparisons between different test methods for soil stabilisation*. In: Proceedings of the ISRM International Symposium, Melbourne; Australia, 19-24 Nov. 2000, 1–5.

Lindh P. (2001) *Optimizing binder blends for shallow stabilisation of fine-grained soils*. Ground Improvement, 5(1), 23–34. https://doi.org/10.1680/grim.2001.5.1.23

Lindh, P. (2003) *Mcv and shear strength of compacted fine-grained tills*. In: Proceedings of 12th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, 4–8 Aug. 2003, Singapore, 493–496.

Lindh, P. (2004) *Compaction- and strength properties of stabilised and unstabilised fine-grained tills.* PhD thesis, Lund University, Lund, Sweden. ISRN: LUTVDG/TVGT-1013–SE. https://doi.org/10.13140/RG.2.1.1313.6481

Lindh, P. – Winter, M. G. (2003) *Sample preparation effects on the compaction properties of Swedish fine-grained tills.* Quarterly Journal of Engineering Geology and Hydrogeology 36(4), pp. 321–330. https://doi.org/10.1144/1470-9236/03-018

Lindh, P. – Lemenkova, P. (2021a) *Evaluation of Different Binder Combinations of Cement, Slag and CKD for S/S Treatment of TBT Contaminated Sediments*. Acta Mechanica et Automatica 15(4), pp. 236–248. https://doi.org/10.2478/ama-2021-0030

Lindh, P. – Lemenkova, P. (2021b) *Resonant Frequency Ultrasonic P-Waves for Evaluating Uniaxial Compressive Strength of the Stabilized Slag–Cement Sediments*. Nordic Concrete Research 65(2), pp. 39–62. https://doi.org/10.2478/ncr-2021-0012

Lo Presti, D. C. F. – Jamiolkowski, M. – Pallara, O. – Cavallaro, A. – Pedroni, S. (1997) *Shear modulus and damping of soils*. Géotechnique, 47(3), 603–617. https://doi.org/10.1680/geot.1997.47.3.603

Lo Presti, D. – Pallara, O. – Mensi, E. (2007) *Characterization of Soil Deposits for Seismic Response Analysis*. In: Ling, H.I., Callisto, L., Leshchinsky, D., Koseki, J. (eds) Soil Stress-Strain Behavior: Measurement, Modeling and Analysis. Solid Mechanics and Its Applications, 146. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6146-2_2

Luo, B. – Luo, Z. – Wang, D. – Shen, C. – Xia, M. (2021) *Influence of alkaline and alkali-free accelerators on strength, hydration and microstructure characteristics of ultra-high performance concrete*. Journal of Materials Research and Technology, 15, 3283–3295. https://doi.org/10.1016/j.jmrt.2021.09.133

Mamoon, S. M. – Ahmad, S. (1990) *Seismic Response of Piles to Obliquely Incident SH, SV, and P Waves*. Journal of Geotechnical Engineering, 116, 2, 186–204. https://doi.org/10.1061/(ASCE)0733-9410(1990)116:2(186)

Meng, T. – Qiang, Y. – Hu, A. – Xu, C. – Lin, L. (2017) *Effect of compound nano-CaCO3 addition on strength development and microstructure of cement-stabilized soil in the marine environment.* Construction and Building Materials, 151, 775-781. https://doi.org/10.1016/j.conbuildmat.2017.06.016

Multon, S. – Verdier, J. – Villain, G. – Sogbossi, H. – Dérobert, X. – Cagnon H. – Balayssac, J.-P. (2022) *Non-destructive measurements for the evaluation of the air permeability of concrete structures.* Measurement, 196 111204. https://doi.org/10.1016/j.measurement.2022.111204

Patel, A. (2019) *3 – Soil stabilization. In: Geotechnical Investigations and Improvement of Ground Conditions*. Woodhead Publishing Series in Civil and Structural Engineering. Woodhead Publishing, pp. 19-27. ISBN: 978-0-12-817048-9. https://doi.org/10.1016/B978-0-12-817048-9.00003-2

PCB Piezotronics Group Inc. (2013) Model 352B10. Miniature, lightweight (0.7 gm), ceramic shear ICP® accel., 10 mV/g, 2 to Installation and Operating Manual. https://www.pcb.com/contentstore/docs/pcb_corporate/vibration/products/manuals/352b10.pdf

Saride, S. – Puppala, A. J. – Chikyala, S. R. (2013) *Swell-shrink and strength behaviors of lime and cement stabilized expansive organic clays.* Applied Clay Science, 85, 39-45. https://doi.org/10.1016/j.clay.2013.09.008

Scrivener, K. L. - Juillan, P. - Monteiro, P. J. M. (2015) *Advances in understanding cement hydration mechanisms*. Cement and Concrete Research, 78, Part A, 38–56. https://doi.org/10.1016/j.cemconres.2015.05.025

She, W. – Wei, L. – Zhao, G. – Yang, G. – Jiang, J. – Hong, J. (2019) *New insights into the frost heave behavior of coarse grained soils for high-speed railway roadbed: Clustering effect of fines*. Cold Regions Science and Technology, 167, 102863. https://doi.org/10.1016/j.coldre-gions.2019.102863

SIS (2003) Soil quality – Determination of soil water content as a volume fraction on the basis of known dry bulk density – Gravimetric method. https://www.sis.se/en/produkter/environment-health-protection-safety/soil-qual-ity-pedology/hydrological-properties-of-soils/ssiso16586/

SIS (2016) Geotechnical investigation and testing – Laboratory testing of soil – Part 4: Determination of par-ticle size distribution (ISO 17892-4:2016). https://www. sis.se/en/produkter/environment-health-protection-safety/soil-quality-pedology/physical-properties-of-soils/sseni-so1789242016/

SIS (2017a) Soil quality – Determination of particle density (ISO 11508:2017). *SS-EN ISO 11508:2017.* https://www. sis.se/en/produkter/environment-health-protection-safety/soil-quality-pedology/physical-properties-of-soils/ss-en-iso-115082017/

SIS (2017b) Geotechnical investigation and testing – Laboratory testing of soil – Part 7: Unconfined compression test (ISO 17892-7:2017). https://www.sis.se/en/produkter/environment-health-protection-safety/soil-quality-pedolo-gy/physical-properties-of-soils/ss-en-iso-17892-72018/

SIS (2019) Standard Test Methods for Downhole Seismic Testing. ASTM standard D7400/D7400M-19. STD-80010978. https://www.sis.se/en/produkter/external-cate-gories/construction-astm-vol-04/soil-and-rock-ii-d5877--latest-astm-vol-0409/astm-d7400d7400m-19/

TBA Trimmiser Baustoffe AG (2010) Report from practice on the X-Seed 100® accelerator from BASF [Online ac-cess: 07.04.2022]. URL: https://www.bft-international. com/en/artikel/artikel_en_965624.html

Verástegui-Flores, R. D. – Di Emidio, G. – Bezuijen, A. – Vanwalleghem, J. – Kersemans, M. (2015) *Evaluation of the free-free resonant frequency method to determine stiffness moduli of cement-treated soil*. Soils and Foundation, 55(5), 930–950. https://doi.org/10.1016/j.sandf.2015.09.001

Vrettos, C. – Banzibaganye, G. (2022) *Effects of specimen size and inertia on resonant column tests applied to sands.* Soil Dynamics and Earthquake Engineering 155, 107136. https://doi.org/10.1016/j.soildyn.2021.107136

Wang, C. – Feng, G. – Zhang, Z. – Huang, M. – Qi, W. – Ma, L. (2021) *Geometrical and statistical analysis of dynamic crack morphology in shrink-swell soils with addition of maize roots or salinity (NaCl).* Soil and Tillage Research, 212, 105057. https://doi.org/10.1016/j.still.2021.105057

Wang, F. - Li, K. - Liu, Y. (2022a) *Optimal water-cement ratio of cement-stabilized soil.* Construction and Building Materials, 320, 126211. https://doi.org/10.1016/j.conbuild-mat.2021.126211

Wang, Y. - Shi, C. - Lei, L. - Ma, Y. - Liu, J. - Hu, X. (2022b) *Formulation of an alkali-free accelerator and its effects on hydration and mechanical properties of Portland cement.* Cement and Concrete Composites, 129, 104485. https://doi.org/10.1016/j.cemconcomp.2022.104485

Wu, J. – Min, Y. – Li, B. – Zheng, X. (2021) *Stiffness and strength development of the soft clay stabilized by the one-part geopolymer under one-dimensional compressive loading.* Soils and Foundations, 61, 4, 974–988. https://doi.org/10.1016/j.sandf.2021.06.001

Yang, J. - Yang, M. - He, X. - Ma, M. - Fan, M. - Su, Y. - Tan, H. (2021) *Green reaction-type nucleation seed accelerator prepared from coal fly ash ground in water environment.* Construction and Building Materials, 306, 124840. https://doi.org/10.1016/j.conbuildmat.2021.124840

Young, J. F. (2001) *Portland Cements*. In: Jürgen Buschow et al. (eds.). Encyclopedia of Materials: Science and Tech-nology (2nd Ed.). Elsevier, Oxford, UK. pp. 7768–7773. ISBN: 978-0-08-043 152-9. https://doi.org/10.1016/B0-08- 043152-6/01398-X

Zhang, J. – Tan, H. – He, X. – Zhao, R. – Yang, J. – Su, Y. (2021) *Nano particles prepared from hardened cement paste by wet grinding and its utilization as an accelerator in Portland cement*. Journal of Cleaner Production, 283, 124632. https://doi.org/10.1016/j.jclepro.2020.124632

Zhang, Y. – Wang, F. – Tian, Q. —Shen, Z. (2022) Chapter 3 – Natural or engineered clays for stabilization/solidifica-tion. Low Carbon Stabilization and Solidification of Haz-ardous Wastes, 31-47. https://doi.org/10.1016/B978-0-12- 824004-5.00024-4

Zhao, D. - Khoshnazar, R. (2021) *Hydration and microstructural development of calcined clay cement paste in the presence of calcium-silicate-hydrate (C–S–H) seed.* Ce-ment and Concrete Composites, 122, 104162. https://doi. org/10.1016/j.cemconcomp.2021.104162

Zhou, M. – Du, Y.-J. – Wang, F. – Arulrajah, A. – Horpibulsuk, S. (2017) *Earth pressures on the trenched HDPE pipes in fine-grained soils during construction phase: Full-scale field trial and finite element modeling*. Transportation Geotechnics, 12, 56-69. https://doi.org/10.1016/j.tr-geo.2017.08.002