

METHODOLOGY FOR SAMPLE PREPARATION FOR QUALITY CONTROL OF STABILIZED DREDGED SEDIMENT

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ABSTRACT

Periodic dredging of harbors and other waterways is carried out to ensure sufficient depth for navigation. The Stabilization/Solidification method (S/S) is the global approach for improving the geotechnical characteristics and stabilizing pollutions in the low-compressive-strength dredged sediment (DS) for land reclamation. For this, different binders, such as cement, fly ash, and slag, are mixed with DS. The quality of mixing influences treated DS directly; therefore, this study investigated the effect of mixing time on the physical properties of treated DS, such as the unconfined compressive strength (UCS). Moreover, the potential for using electrical resistivity (ER) measurements and isothermal calorimetry (IC) tests to evaluate the mixing quality at the early stage were examined. Dredged sediments from the harbor of Stavanger, and Oslo in Norway, were mixed with binders using different water-binder ratios (w/b), and free-free-resonant (FFR) and UCS tests were performed to evaluate mixing time effects on the treated sediments. The results indicate that the higher the water content is, the higher the mixing time to reach the maximum compressive strength needs to be. The potential of ER and IC for quality control of treated DS at early stages was tested on one DS. It was found that these techniques have the potential to evaluate early-stage DS quality. The correlation between ER, CL, and UCS tests will be investigated in the future.

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1. INTRODUCTION

Dredging is performed periodically in channels, ports, and rivers worldwide to maintain adequate depth for navigation, and consequently, large masses of sediments need to be taken care of annually. These sediments have high moisture content, low strength, high compressibility, and contain toxic compounds. Stabilization/Solidification (S/S) has been widely established as an effective procedure to manage contaminated dredged sediment.

In stabilization/solidification (S/S) projects, the procedure for mixing binders in the laboratory varies between different countries. In Japan and some other countries, it is recommended to mix for 10 min to have a homogenized mixture, while in Portugal, it is 3 min. In Sweden, 5 min of mixing is recommended to homogenize a mixture [1]. Yang et al. show that the unconfined compressive strength (UCS) of cement paste backfill (CPB) increases from 1 min up to 4 min of mixing time and then decreases for longer mixing times than 4 min [2]. Yaghoubi et al. showed that by increasing mixing from 5 min to 15 min, the UCS of stabilized soil was enhanced [3].

Although several studies have shown the effects of mixing time on mechanical properties and homogeneity of stabilized soil, there is still a need to standardize and harmonize mixing methods for stabilized soil applications.

The quality of treated DS is evaluated by both destructive and non-destructive tests that can be used both for laboratory and field samples. The 28-day unconfined compressive strength (UCS) is one of the destructive tests that can be performed on samples prepared at the laboratory or on the core samples that are taken from the site. During the 28-day waiting time before the results from the laboratory large amounts of stabilized soil may have been produced on-site. If the compressive strength of the 28-day samples fails to meet project specifications, the subsequent costs of re-stabilization or removal of the affected layers can become very high. Seismic-based testing methods such as the free-free resonance test, that categorized as a non-destructive method, have been employed for evaluating the quality of treated DS during the curing period [4], [5], [6]. However, a drawback of this approach is the time required for the treated soil to become sufficiently hardened to obtain the initial quality assessment results. Therefore, there is a need to develop more rapid and non-destructive methods to evaluate the quality of treated DS when it is still fresh.

Electrical resistivity (ER) and isothermal calorimetry (IC) measurements are two alternative non-destructive tests. The former measurement can be employed both in the field and laboratory to measure the electrical resistance of the treated DS, and the latter method measures the heat generated by the binder reactions. Some studies have shown that ER and IC could be correlated with compressive strength for cement mortar [7], [8].

This study focused on examining the influence of mixing time on the unconfined compressive strength of stabilized soil. The primary objective was to determine the optimal mixing time for laboratory procedures and examining two non-

destructive tests (ER and IC) as alternative QC/QA control at early stage of stabilizing DS.

2. MATERIAL AND TEST METHOD

2.1. Materials

Two batches of dredged sediment with different water content were sampled in two harbors. Before the determination of water content and density, an electric paddle mortar mixer was used to homogenize each batch. Then, 8 samples were taken from each batch. The results are presented in table 1.

Table 1. Dredged sediment water content and density

Batch number	Dredged sediment collection site	Water content		Density	
		Mean%	COV%	Mean (kg/m ³)	COV%
1	Stavanger harbor, Norway	349	1.98	1130	0.79
2	Oslo Harbor, Norway	88	0.9	1510	0.73

The binders used for the mixing process were CEM III B for batch 1, a combination of 40% Portland limestone cement (PLC) and 60% ground granulated blast-furnace slag (GGBS) for batch 2.

2.2. Sample preparation and testing method

Mixing of DS and binder was by an electrical hand mixer for batch 1, and a KitchenAid Aristan stand mixer with a flat beater for batch 2. For each mix, 1 kg of the DS was weighed and mixed with the binders at different durations. To ensure thorough mixing with the KitchenAid mixer, the mixing was paused after 1 min, when material adhering to the flat beater and the inside of the bowl was scraped off, similarly to what is prescribed in EN 196-1 and ASTM C305. Batch 2 was sieved to eliminate grains with a diameter exceeding 4 mm to ensure that the particle size of the DS would be less than 1/10 of the inner diameter of the mold to provide more homogeneous raw material. Batch 1 was not sieved. The quantity of binders used to strengthen a DS can differ significantly based on the soil's condition and the project's needs. Typically, the required amount of binder falls between 80 and 200 kg/m³ for treated DS. Therefore, tests are needed to find the best binder dosage for stabilization with the target compressive strength. For batch 1, the calculated binder dosage was 100 kg per m³ of sediment, and for batch 2 we used 107 kg per m³ of sediment. Mixing times were 4, 9, and 14 minutes. Samples were prepared by pouring the treated dredged sediments into plastic tubes measuring 50 mm in diameter and 170 mm in height. The plastic tubes were filled in three layers, with each layer being tapped against the floor to ensure all entrapped air came out. All specimens were placed in a water bath at 20 °C for one week. Following this, to conduct the 7-day FFR test, all specimens were removed and trimmed to achieve the height-to-diameter ratio of 2. Each

specimen was placed in an individual plastic bag along with a moist tissue to prevent drying. The FFR test was conducted after 7, 14, and 28 days of curing, while the UCS test was performed after 28 days.

Electrical resistivity measurement was conducted to monitor the hydration process and assess the quality of samples during the curing phase of treated DS from batch 2. Accordingly, three water-to-binder ratios (w/b) were used: 4, 6, and 8. For each w/b ratio, two cylindrical samples, each with a diameter of 50 mm and a length of 170 mm, were prepared. These samples were subjected to electrical resistivity measurements using an instrumentation system developed by Dahlin et al., wherein the resistance of each sample to the flow of electric current was determined [9]. *Isothermal calorimetry* is a method used to quantify the thermal power generated by the hydration reactions of cementitious materials [10]. After the mixing of DS from batch 2 with binders, the samples were transferred into 20 mL plastic vials and sealed with plastic lids. Then, the vials were charged into the calorimetric equipment (TAM Air, Thermometric AB) to measure the heat production rate (thermal power) of the samples, from which the produced heat can be calculated for example 2 days or 1 week of curing to assess the quality of the treated DS.

3. RESULTS AND DISCUSSION

3.1. Effects of mixing time on compressive strength

Tables 2 and 3 show the P -wave velocity and compressive strength in relation to the mixing time for each batch. The finding indicates that by increasing dredged sediments' water content, to obtain higher compressive strength, it is needed to mix longer than in the situation where the dredged sediment has low water content. In batch 1, the water-binder ratio is 8; therefore, regarding the existing lower binder content in admixture, mixing less than 9 minutes decreased the compressive strength. In previous literature, the study showed that in the case of lower binder content, mixing time shorter than 10 min decreases the unconfined compressive strength [1]. As the mixing time increases, the mixing torque increases [11]; furthermore, the effectiveness of the mixing force transmitted by the blade depends on the viscosity of the material being mixed [12], and the viscosity of the material depends on water content. Thus, in materials with higher viscosity and low water content, less force is required from the blade to disperse the material because the DS can transmit most of the forces. Conversely, in DS with high water content and low viscosity, a portion of the force from the blade compensates due to the less stiffness of the mixture. Therefore, a higher force from the blade is needed to disperse the material effectively.

Mixing beyond 9 min decreases the compressive strength. One possible description for this phenomenon is that segregation between materials occurs by mixing for more than 9 minutes. In the case of batch 2, with low water content, 4 min mixing is enough to achieve the highest compressive strength.

The results in tables 2 and 3 also show that the coefficient of variance for UCS reduces when sieving raw material and mixing with a Kitchen Aid mixer with a

flat blade and has a more homogeneous mixture compared to a kitchen hand mixer.

Table 2. Batch 1 FFR and UCS test results

Mixing time (minutes)	<i>P</i> wave velocity			Unconfined compressive strength		
	Days after treatment	Mean value of FFR (m/s)	Coefficient of variance (%)	Days after treatment	Mean value of UCS (kPa)	Coefficient of variance (%)
4	7	156	4	28	206	14
	14	239	2.3			
	28	329	4.9			
9	7	171	3.2	28	277	11.6
	14	264	3.5			
	28	346	3.5			
14	7	169	1.6	28	260	8.9
	14	263	2.2			
	28	338	2.1			

Table 3. Batch 2 FFR and UCS test results

Mixing time (minutes)	<i>P</i> wave velocity			Unconfined compressive strength		
	Days after treatment	Mean value of FFR (m/s)	Coefficient of variance (%)	Days after treatment	Mean value of UCS (kPa)	Coefficient of variance (%)
4	7	321	6.3	28	453	0.8
	14	500	3			
	28	721	1.6			
9	7	318	6.9	28	450	0.2
	14	485	1.3			
	28	709	0.4			
14	7	295	2.1	28	435	0.5
	14	461	2			
	28	684	1.2			

3.2. Potential of using calorimetry and electrical resistivity for early-stage quality control

Figure 1 shows V_p and 28-day compressive strength, respectively, with different water-binder ratios; as was expected, with an increase in the water-binder ratio, both the *P*-wave velocity and UCS decrease. Furthermore, the differences in compressive strength between a water-binder ratio of 4 and 6 are greater than the differences between a water-binder ratio of 6 and 8. The IC and ER measurements showed the same trend (fig. 3) as the UCS and FFR tests.

Figure 2 shows the Pearson's correlation heat-maps between FFR, UCS, ER, and heat release to examine the correlation coefficient through linear regression between these measurements. The correlation coefficient, ranging from -1 to +1, indicates the strength and direction of the relationship between two variables. A value of +1 suggests a perfect positive correlation, -1 signifies a perfect negative correlation, while 0 indicates no correlation between the variables. For calorimetry, it is recommended to perform a correlation between measurements taken after 48 hours of curing or more. On the other hand, the coefficients suggest that it might be possible to correlate 48 or 72-hour measurement data from ER with UCS. The correlation between FFR tests at 7, 14, and 28 days and UCS tests is clearly strong. Consequently, there is a strong and positive correlation between V_p , ER, and heat release.

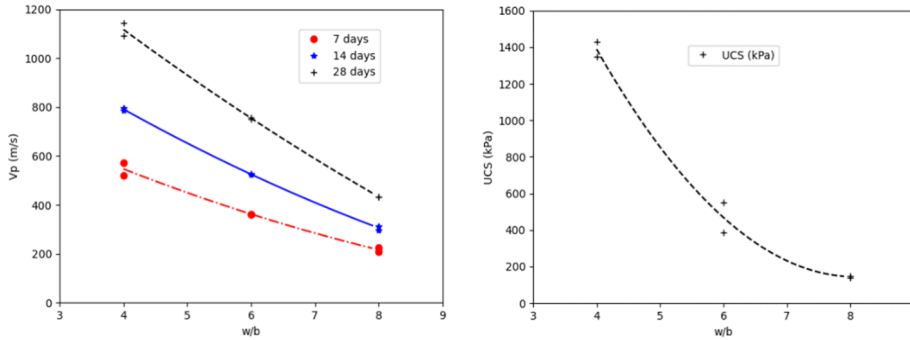


Figure 1 Left: V_p (m/s) against w/b , right: UCS (kPa) against w/b

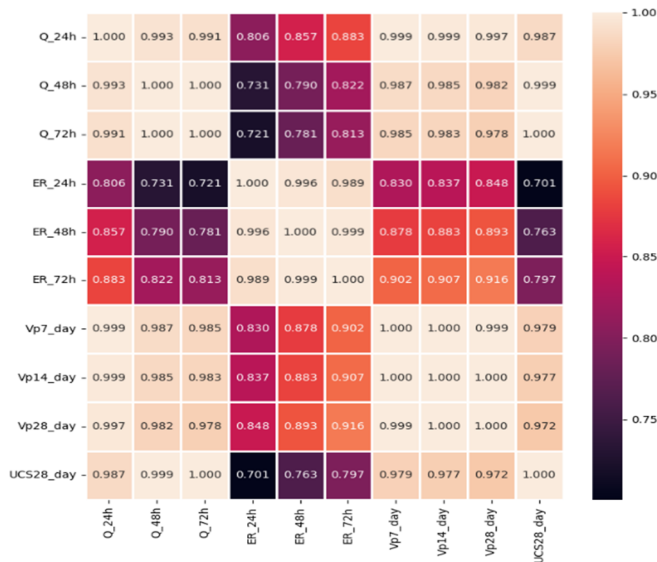


Figure 2 Pearson correlation coefficient

Figure 3 illustrates that with increasing curing time, both ER and heat release exhibit an upward trend. Conversely, as the water-to-binder (w/b) ratio increases, both ER and heat-release measurements decrease. This is attributed to the lower amount of binder, resulting in reduced reaction and consequently less heat release. Conversely, samples with a higher w/b ratio have more water content and less tortuous pathways, leading to a more conductive behavior.

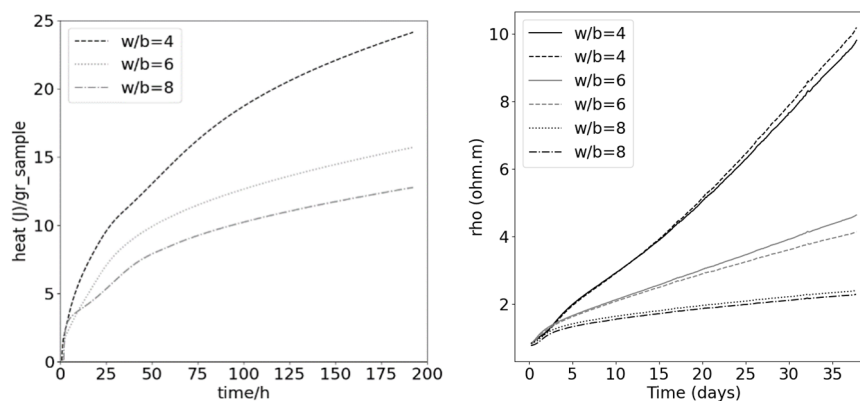


Figure 3 Left: Cumulative heat release per weight of sample versus time, right: measured electrical resistivity as a function of time.

4. CONCLUSIONS

In this study the effects of mixing time on the 28-days compressive strength of stabilized dredged sediment were examined, moreover two methods for quality controls of stabilized dredged sediment in early-stage were. The following conclusions were drawn from the analysis.

Mixture with high water content needs more mixing time to reach maximum compressive strength.

The use of a laboratory mixer with a flat beater blade results in less variability compared to a kitchen hand mixer with a smaller blade, resulting in reduced result variability.

To obtain less scattered results, it is recommended to sieve the dredged sediment (DS) using a sieve size that is 1/10th the diameter of the sampler. In this study, the sampler diameter was 50 mm, and the DS was sieved using a 4 mm sieve prior to mixing.

The results obtained from calorimetry and electrical resistivity tests demonstrate that these two methods can be employed on-site during the early stages of material production to evaluate the quality of the treated material before it hardens, thereby enabling timely interventions and preventing costly repairs.

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REFERENCES

- [1] W. Al-Jabban, J. Laue, S. Knutsson, and N. Al-Ansari, “Briefing: Common laboratory procedures to prepare and cure stabilised soil specimens: a short review,” *Geotechnical Research*, vol. 7, no. 1, pp. 3–10, Mar. 2020.
- [2] P. Chindapasirt, P. De Silva, and S. Hanjitsuwan, “Effect of High-Speed Mixing on Properties of High Calcium Fly Ash Geopolymer Paste,” *Arab J Sci Eng*, vol. 39, no. 8, pp. 6001–6007, Aug. 2014.
- [3] M. Yaghoubi, A. Arulrajah, M. M. Disfani, S. Horpibulsuk, S. Darmawan, and J. Wang, “Impact of field conditions on the strength development of a geopolymer stabilized marine clay,” *Applied Clay Science*, vol. 167, pp. 33–42, Jan. 2019.
- [4] E. N. Landis and S. P. Shah, “Frequency-Dependent Stress Wave Attenuation in Cement-Based Materials,” *Journal of Engineering Mechanics*, vol. 121, no. 6, pp. 737–743, Jun. 1995.
- [5] N. Rydén, U. Ekdahl, and P. Lindh, “Quality Control of Cement Stabilised Soil using Non-Destructive Seismic Tests,” 2006.
- [6] A. Guimond-Barrett, E. Nauleau, A. Le Kouby, A. Pantet, P. Reiffsteck, and F. Martineau, “Free–Free Resonance Testing of In Situ Deep Mixed Soils,” *Geotech. Test. J.*, vol. 36, no. 2, p. 20120058, Mar. 2013.
- [7] N. A. Vincent, R. Shivashankar, K. N. Lokesh, and J. M. Jacob, “Laboratory Electrical Resistivity Studies on Cement Stabilized Soil,” *International Scholarly Research Notices*, vol. 2017, pp. 1–15, Apr. 2017.
- [8] L. Frølich, L. Wadsö, and P. Sandberg, “Using isothermal calorimetry to predict one day mortar strengths,” *Cement and Concrete Research*, vol. 88, pp. 108–113, Oct. 2016.
- [9] T. Dahlin, M. Lumetzberger, P. Hedblom, S. Rejkjær, and P. Olsson, “Novel Electrode Design for Non-Destructive Resistivity Measurement on Material in Geotechnical Standard Sample Cylinders,” in *NSG2023 29th European Meeting of Environmental and Engineering Geophysics*, Edinburgh, United Kingdom, : European Association of Geoscientists & Engineers, 2023, pp. 1–5.
- [10] L. Wadsö, “Applications of an eight-channel isothermal conduction calorimeter for cement hydration studies,” *Cement International*, vol. Jg. 3, no. Nr 5, Art. no. Nr 5, 2005.
- [11] B. Silva, A. P. Ferreira Pinto, A. Gomes, and A. Candeias, “Influence of Water Content and Mixing Conditions on the Properties of Lime-Based Materials,” *Buildings*, vol. 13, p. 1530, Jun. 2023.
- [12] M. Yang and H. M. Jennings, “Influences of mixing methods on the microstructure and rheological behavior of cement paste,” *Advanced Cement Based Materials*, vol. 2, no. 2, Art. no. 2, Mar. 1995.