Methods to Investigate the Quality of Stabilized Dredged Sediments Mohammadhossein Gholampoor

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Abstract: Dredging operations in ports, rivers, and waterways are essential for maintaining navigable depths, but they result in large volumes of dredged sediments (DS) that are often unsuitable for immediate reuse due to their high moisture content, low strength, and contamination. Stabilization and solidification (S/S) techniques are widely employed to improve the geotechnical properties of DS, making the material more stable and less prone to environmental hazards. However, ensuring the quality of stabilized DS is crucial for both environmental safety and the success of construction projects. Traditionally, quality control has relied on destructive methods, such as the 28-day unconfined compressive strength (UCS) test, which delays feedback and increases project costs and risks. Thus, the development of efficient, real-time quality control methods is necessary to optimize the stabilization process. This thesis introduces two innovative, non-destructive methods for early-stage quality control of stabilized DS: isothermal calorimetry (IC) and electrical resistivity (ER). Both methods offer significant advantages over conventional destructive tests by providing early predictions of the strength and stability of treated sediments. Both IC and ER methods have shown to be effective in providing early, real-time feedback on the stabilization process, significantly reducing the risks associated with delayed quality control. This approach not only improves efficiency but also minimizes the financial and environmental costs associated with re-stabilization or material disposal if quality issues are identified too late. In addition to exploring novel quality control methods, this thesis also investigates the role of the mixing procedure in influencing the mechanical properties of stabilized DS. The study reveals that					
mixing time is a critical factor in achieving optimal strength and homogeneity in the treated material. Specifically, the results show that sediments with higher moisture content require longer mixing times to fully incorporate the binders and develop sufficient strength. However, excessive mixing can lead to reductions in strength, indicating that there is an optimal window for mixing that varies depending on the specific characteristics of the DS, such as water content and binder composition.					
The findings of this thesis highlight the importance of both real-time quality control and optimized mixing procedures in the stabilization of dredged sediments. By combining isothermal calorimetry and electrical resistivity for early predictions of strength with carefully controlled mixing procedures, this research provides a comprehensive approach to improving the effectiveness and efficiency of stabilization projects. The insights gained from this study can be applied to large-scale dredging operations, reducing the time and cost associated with quality control while minimizing environmental risks. These advancements offer a significant contribution to the field of soil stabilization, particularly in addressing the challenges posed by large volumes of dredged sediments that require treatment.					
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List of Papers

Paper I

Gholampoor M.H., Johansson P., Lindh P., and Wadsö L., (2024), Early quality control of stabilized dredged material by correlating heat production with strength, submitted to Ground Improvement and is accepted to publish.

Paper II

Gholampoor M.H., Dahlin T., Lumetzberger M., and Hedblom P., (2024), Correlation between electrical resistivity and compressive strength of stabilized dredged sediment for early quality control, published in Transportation Engineering.

Paper III

Gholampoor M.H., Johansson P., Lindh P., Dahlin T., and Wadsö L., (2024), Methodology for sample preparation for quality control of stabilized dredged sediment, Nordic Geotechnical Meeting, 2024, Göteborg.

Papers not included in thesis

Paper I

Tamadonyazdian E., Gholampoor M.H., Farsäter K. and Bayat pour M., (2024), Evaluation of solidification/stabilization technology performance by combining economic and environmental impacts assessments for a port in Sweden, Nordic Geotechnical Meeting, 2024, Göteborg.

Abbreviations

Stabilization/Solidification
Unconfined compressive strength
Free-free resonance test
Dredged sediment
Isothermal calorimetry
Electrical resistivity
Quality control
Quality assurance
Water-binder ratio

1.Introduction

1.1 Background

Soil stabilization is the modification of the properties of a soil to improve its performance and engineering characteristics. This process involves various techniques, broadly categorized into two types: mechanical stabilization and chemical stabilization. Mechanical stabilization uses pre-loading, static, and dynamic compaction to modify soil properties. On the other hand, chemical stabilization involves the addition of chemical binders to the natural soil [1–4]. Chemical stabilization can be executed in two ways: in situ or ex-situ. In-situ stabilization is conducted directly in the field without excavation, where binders are mixed with the soil. Examples of in-situ stabilization include lime-cement columns and jet-grouting. Ex-situ stabilization, on the other hand, involves excavating the soil, mixing it with binders, and then placing back the mixture. This method is particularly effective for treating highly contaminated soils.

Dredging is carried out in channels, ports, and rivers to maintain the proper depth for navigation. It involves removing sediment, which can be a significant volume of material. In Europe, dredging generates around 300 million tons of sediment each year [5]. This sediment has high moisture content, low strength, significant compressibility, and is often contaminated [6–12]. Traditional methods for managing dredged sediment were landfilling or disposal into the sea. Several countries ban ocean discharging due to environmental concerns raised by this. Furthermore, landfilling produces polluted by-products (like biogas and leachate), and there is limited space to landfill excavated dredged sediment [13]. Consequently, strategies for environmentally safe management of dredging sediments have become a significant global concern.

Stabilization/Solidification (S/S) is a well-established technique for handling contaminated dredged sediment. During this process, the sediment is mixed with binders that react to form a solid matrix. This results in improved geotechnical properties of sediment and that the contaminants are encapsulated within the paste matrix [14–16]. The Stabilization and Solidification (S/S) technology combines two distinct processes: *Stabilization* involves a chemical reaction that reduces the leachability of contaminants by encapsulating them, and *solidification* enhances the physical properties of waste material by reacting binders with water, effectively binding together the dredged sediment (DS) material. [17].

In Stabilization/Solidification (S/S) projects, it is necessary to conduct laboratory experiments before starting the project. This phase involves selecting the right binder amount to ensure the treated sediment meets the desired targets [18,19]. The mixing procedure for binders varies across different countries. Although many studies have explored the effects of mixing on the mechanical properties and uniformity of stabilized soil, there is still a need to establish standardized mixing methods for applications involving stabilized soil [20–24]. Standardizing mixing techniques would offer several benefits. First, it would enhance the reproducibility of experiments, allowing researchers to validate and verify results more effectively. Second, harmonizing mixing methods would promote international collaboration, facilitating knowledge exchange and advancements in the field.

In addition to the laboratory mixing procedure, another important aspect of S/S projects is implementing quality control (QC) and quality assurance (QA) measures. These measures are essential as they evaluate the effectiveness of the treatment process before, during, and after production, focusing on two key factors: leachability and mechanical behavior of the treated dredged sediment (DS) [25]. The QC/QA encompasses a range of assessments conducted through *destructive* and non-destructive means, further categorized into in-situ and laboratory tests. In-situ tests include methods such as *cone penetration testing* (CPT), *standard penetration* testing (SPT), pressure meter testing, plate load testing, Swedish weight sounding (used in Sweden and Finland since the 1970s and in Japan) and modified total sounding. These tests primarily control the mechanical properties of the treated DS. Conversely, destructive laboratory tests, such as the *uniaxial compressive strength* test (UCS) and the laboratory vane test, are widely employed to assess mechanical properties. However, it is crucial to recognize that in-situ tests offer limited insights, providing information only at specific discrete points within the stabilization area. This limitation underscores the necessity for a substantial number of tests to obtain statistically significant results, emphasizing the importance of developing a comprehensive real-time and non-destructive OC/OA methodology to address this challenge effectively. Non-destructive techniques, particularly seismic-based methods, are commonly utilized in situ and laboratory settings. Examples include ultrasonic testing and free-free resonance testing (FFR) [26–30].

1.2. Aims and research questions

This study aims to introduce two novel non-destructive methods for quality control of treated dredged sediment in laboratory settings. In addition, the understanding of laboratory mixing procedures for stabilizing dredged sediments, specifically exploring mixing time effects on mechanical properties of stabilized dredged sediments, was investigated. To accomplish these aims, the following research questions have been formulated:

- i. How can heat of hydration measurements be utilized as a non-destructive quality control method for stabilizing dredged sediment?
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- ii. Can electrical resistivity monitoring also be used for evaluating the quality of treated DS?
- iii. How can binder content be determined by ER and IC tests during the execution of projects in the field?
- iv. How does the mixing procedure affect the quality of stabilized dredged sediment?

1.3. Structure of this thesis

The present thesis comprises the following chapters: chapter 2 is about the theoretical background, chapter 3 shows the materials and methods used in this study, chapter 4 is an overview of the results and discussion, and chapter 5 summarizes the attached papers. After this follows the three papers. These papers collectively address the stated objectives of the thesis in the following manner:

Paper I: (i) and (iii)
Paper II: (ii) and (iii)

Paper III: (iv)

Paper I shows a correlation between heat-release and 28-day compressive strength of stabilized DS, which can be used for checking the quality of stabilized DS at the early stage. *Paper II* focused on implementing electrical resistivity as a non-destructive method for predicting the compressive strength of the stabilized/solidified DS while the product is still fresh. In *paper III*, the effects of mixing time on compressive strength regarding different initial water content were investigated.

2. Theoretical background

This chapter begins by outlining the weight-volume relationships of soil. Next, the hydration process is presented, highlighting the theoretical aspects of heat of hydration and changes in electrical resistivity. The mechanical properties of stabilized soil, such as compressive strength and elastic modulus, are then described. Finally, the chapter presents the theory of mixing.

2.1. Weight-volume relationships in soil

The soil mass is typically divided into three distinct phases: solid, water, and air. Figure 1 illustrates this division within the soil mass, depicting its volume (V) and weight (W), delineating each phase separately.



Figure 1: Weigh-volume relationships for soil aggregate

In accordance with figure 1, the following relationships can be outlined:

Void ratio e is defined as the ratio of the volume of voids to the volume of solids:

$$e = \frac{V_V}{V_S} \tag{1}$$

Porosity n is defined as the ratio of the volume of voids to the total volume:

$$n = \frac{V_V}{V} \tag{2}$$

Based on equations (1) and (2), the relationship between void ratio and porosity can be expressed as:

$$n = \frac{e}{1+e} \tag{3}$$

Water content w represents the ratio of the weight of water to the weight of dry soil solids, typically expressed as a percentage:

$$w(\%) = \frac{W_w}{W_s} \times 100 \tag{4}$$

Unit weight (density) γ is defined as the ratio of total weight to the total volume:

$$\gamma = \frac{W}{V} \tag{5}$$

Equation (5) yields different results depending on the type of weight utilized. If saturated weight is employed, it provides the unit weight of saturated soil; conversely, when the dry weight of the soil is used, it defines the dry unit weight of soil.

2.2. Bulk density of stabilized soil

Regarding stabilized soil, the theoretical bulk density after mixing can be expressed using equation 6:

$$\rho_{SDS} = \frac{M_w + M_s + M_b}{\frac{M_w}{G_w} + \frac{M_s}{G_s} + \frac{M_b}{G_b}} \tag{6}$$

Here, $M_{\rm S}$ represents the weight of dry DS in grams, $M_{\rm w}$ signifies the water in grams, and $M_{\rm b}$ is weight of binder (g), while $G_{\rm w}$, $G_{\rm s}$ and $G_{\rm b}$ are the specific gravity of water, soil and binders, respectively in (g/cm³).

2.3. Hydration process

2.3.1. From the heat-release point of view

When water interacts with Portland cement – which is here used to illustrate a hydration process even if it is not the only binder used in the stabilisation of DS - a sequence of chemical reactions starts, collectively called hydration. This process is complex due to the composition of Portland cement, which comprises various clinker minerals. Each of these minerals reacts at a certain rate, leading to the formation of different hydrates. The primary clinker minerals include tricalcium silicate (C₃S), dicalcium silicate (C₂S), tricalcium aluminate (C₃A), and calcium aluminoferrite (C₄AF) [31]. The principal product of hydration is calcium silicate hydrates C-S-H (equations 7 and 8). The following equations schematically show the hydration mechanisms:

$$C_3S+H_2O \longrightarrow C-S-H+Ca(OH)_2$$
(7)

$$C_2S+H_2O \longrightarrow C-S-H+Ca(OH)_2$$
(8)

$$C_3A+H_2O \longrightarrow C_3AH_6 \tag{9}$$

$$C_4AF + H_2O \longrightarrow C_3AH_6 + CF_4 \tag{10}$$

The process of hydration generates heat, referred to as hydration heat, which can be quantified using a calorimeter. By measuring this heat, the entirety of the hydration process is monitored.

Figure 2 illustrates the typical shape of cement paste's rate heat production, as measured by calorimetry. This process is segmented into four phases. *Phase 1* initiates immediately after mixing when water first contacts the cement. A peak thermal power is observed due to the initial processes. During *phase 2*, known as the induction stage or dormant period, heat release rate decreases due to slower reactions process. *Phase 3*, termed the acceleration stage, witnesses an increase in heat release rate as calcium silicates (C₃S) react to form calcium silicate hydrates (C-S-H), initiating the strength development. *Phase 4*, the deceleration stage, marks the attainment of peak thermal power, accompanied by a decrease in the availability of free ions in the solution, thus slowing down the reaction and reducing the thermal power. This phase typically culminates in achieving the desired strength [32,33].



Figure 2: Typical thermal power (rate of heat of hydration) of a Portland cement as a function of time.

2.3.2. From the electrical resistivity point of view

In recent years, electrical resistivity (ER) has become an essential tool for studying the hydration process in stabilized soil [34,35]. As described in the previous section, Calorimetry measures this process by the heat released from chemical reactions, while the ER method assesses it through resistivity, which is a function of several physical and chemical aspects. This includes the pore solution characteristics, changes in mobility and concentration, and the development of pore structure. The primary focus is on understanding the microstructural changes during hydration. Some researchers argue that resistivity reflects the hydration process, as shown by hydration heat [36]. Several factors can affect the resistivity of stabilized soil, including specimen geometry, temperature, saturation level, and porosity [37,38]. Figure 3 shows a typical ER measurement profile during the curing period.



Figure 3: Schematic result of electrical resistivity measurement on stabilized soil material

As shown in Figure 3, the electrical resistivity decreases at the beginning of the hydration (phase 1, phase 2) and increases in phase 3. When the cement comes into contact with water, the dissolution of ions like Ca²⁺, K⁺, Na⁺, OH⁻, and SO4²⁻ starts, and these ions are conductive; therefore, the resistivity decreases. By forming C-S-H, the ions content decreases, and by the growth of the C-S-H structure, the conductivity path becomes more tortuous, consequently increasing the resistivity.

2.4. Mechanical properties of stabilized soil

The conventional method used in laboratories to evaluate the quality of stabilized soil is the unconfined compression strength (UCS) test. Specimens utilized in this test can feature either circular or square cross-sections, with a minimum diameter of 34 mm or a minimum area of 1000 mm². Cylindrical specimens are recommended to have a height-to-diameter ratio falling within the range of 1.8 to 2.5. In contrast, specimens with a square cross-section should maintain a height-to-side length ratio ranging from 2.0 to 2.8. Throughout the compression test, the specimen undergoes a strain rate equivalent to 1-2% of its height per minute, adhering to the specifications outlined in EN ISO 17892-7:2017 [39]. Compressive strength (q_u , Pa) is the maximum load endured per unit original area and can be computed using Equation 11.

$$q_u = \frac{F_{max}}{A} \tag{11}$$

 F_{max} (N) is the maximum force, and A (m²) is the cross-sectional area of the sample at the start of the measurement.

The stress-strain diagram can be derived from the collected data. An elastic modulus can either be calculated from the slope of the linear segment of the measured curve (*E*) or from the the ratio of stress and strain at 50% of maximum stress (E_{50}). Figure 4 shows a typical result of compressive strength testing.



Figure 4: Schematic stress-strain results from UCS test and elastic modulus calculations (see the test).

Numerous variables, including the water-to-binder ratio and binder type, influence the compressive strength of stabilized soil. Extensive research has been conducted to establish equations predicting compressive strength based on the water-to-binder ratio. One possible relationship is Abrams' law, which was developed as a correlation between concrete strength and the water-to-binder ratio (equation 12). In Japan, the prevalent equation for estimating the strength of cement-treated clay also draws from principles in concrete engineering (equation 13) [40–42].

$$q_u = \frac{A}{\frac{W}{Bb}} \tag{12}$$

$$q_u = \frac{A}{\left(\frac{W_c}{b}\right)^x} + B \tag{13}$$

In equation 12, the variables w/b represent the water-to-binder ratio, while A and B are constants that rely on factors such as soil type, binder composition, sample

preparation methods, curing conditions, and testing methodology. Additionally, in equation 13, w_c/b represents the ratio of clay-water mass to binder mass, with A, B, and x serving as experimental constants.

Moreover, a correlation exists between elastic modulus and compressive strength. According to the Swedish Transport Administration guideline, the relationship between elastic modulus E_{50} and compressive strength for samples with strengths up to 280 kPa is described by equation 14. Researchers have tested various binder compositions and soils, revealing remarkably similar relationships [43]. For organic and inorganic stabilized clay the elastic modulus for all curing times (7, 21-31 days), varied between $50 \times q_u$ to $180 \times q_u$ according to reference [43].

$$E_{50} = 30 \times q_u^{1.22} \tag{14}$$

2.5. Mixing theory

Two critical aspects of mixing are often discussed: the mixing energy and the maximum force required to disperse agglomerates within a fluid. These models are vital in predicting the efficiency of mixing processes and optimizing the necessary parameters for achieving homogeneity.

A foundational theory on mixing energy was proposed by Orban in 1986, which has since been expanded upon in numerous studies. This theory introduced a key equation for calculating the mixing energy, expressed as [44]:

$$\frac{E}{M} = \frac{k\omega^2 t}{V} \tag{15}$$

Where k is an experimentally constant (Nm/kgm⁻³/rpm), ω is the rotational speed (rad/s), t is mixing time (s), and V is the volume of slurry (m³).

In another relevant equation for mixing energy, that was developed by Padgett (1996), the mixing energy is directly related to shear rate [45]:

$$\frac{E}{M} = \mu t D \tag{16}$$

Where μ (Ns/m²) is the viscosity of the fluid, *t* is mixing time, and *D* is the shear rate (s⁻¹).

Equation 17 shows how the maximum dispersive force between two particles transmitted through a fluid relates to viscosity [46]. The equation shows that higher viscosity needs a lower force to disperse the agglomerate on the mix.

$$F_{max} = 3\pi\mu R_1 R_2 D \tag{17}$$

Here, F_{max} (N) is the maximum force needed to disperse the agglomerate, μ (N.s/m2) is the fluid's viscosity, R_1 and R_2 (m) are the radii of the two particles, and D (s⁻¹) is the shear rate.

Equations 15 and 16 can be applied both in laboratory settings and on a larger scale in the field. In the laboratory, these equations help calculate the mixing energy needed to achieve a homogeneous mix. Once the appropriate energy input has been determined, these findings can be directly used to field conditions by adjusting the mixing parameters, such as time and impeller speed, to replicate the same energy input in larger volumes. This approach ensures the consistency and scalability of mixing processes from controlled environments to real-world applications, optimizing performance while maintaining the desired material properties.

3. Materials and methods

This study comprises two distinct phases. *Phase I* investigates two non-destructive methods for assessing the quality of treated DS at an early stage. *Phase II* pertains to laboratory sample preparation, specifically examining the influence of mixing time on the compressive strength of treated DS. This section describes the materials and methods employed for each phase.

3.1. Phase I: QC/QA of treated DS at early stage

3.1.1. Introduction

As mentioned in *Section 1*, evaluating the quality of mixing in stabilized soil is typically achieved through the 28-day compressive strength test in the laboratory and/or conducting in-situ tests. However, performing these tests requires a waiting period for the stabilized products to attain the necessary strength. Large quantities of stabilized soil may already be produced during this waiting period. If the stabilized dredged sediment (DS) quality fails to meet project specifications, the subsequent costs of re-stabilization or removal of the affected layers can be substantial. Generally, besides the unconfined compressive test, seismic-based testing methods (FFR) have been utilized at the laboratory to measure the compressive wave velocity (V_p) or the shear wave velocity (V_s) over time to assess strength development; results from such tests correlate with the 28-day UCS test, which makes it possible to perform seismic-based tests in-situ and compare with laboratory measurement to predict the 28-days strength in the field before 28days. However, the FFR test needs some waiting period before measurements ca be made and it would be hard to utilize this method when the treated DS is fresh. Therefore, it is necessary to explore alternative methods that can evaluate the quality of freshly treated DS at an early stage. In phase I of this study, two alternative methods are introduced that can be used to assess the quality of stabilized DS while it is still fresh.

An alternative method for evaluating the effectiveness of stabilized soil is to measure the heat generated during the binder reactions using an *isothermal calorimeter*. *Isothermal calorimetry* is a technique that assesses the thermal power (rate of heat production) resulting from the hydration reactions of cementitious materials [47]. This approach enables the continuous monitoring of the overall reaction rate of the cementitious binder, providing insights into its behaviour that conventional compressive strength tests with fixed setting times may not capture. Moreover, results can be obtained from about one hour after mixing. Researchers have effectively utilized isothermal calorimetry to forecast strength by establishing correlations between the heat of hydration and the compressive strength of mortar and concrete [33,48–51].

A second alternative method to monitor the hydration process in stabilized soil is electrical resistivity (ER) measurement, which has been popular in geotechnical and geo-environmental studies in recent years due to time effectiveness and cost. The ER method is cheaper and faster than other conventional laboratory and field tests when it is needed to deal with a large number of soil samples, due to the nondestructive nature of the test and speed of testing.

The electrical characteristics of cementitious materials have been a subject of research for close to a century [52–54]. Berry and Saad performed laboratory electrical resistivity tests to develop empirical correlations between electrical resistivity and key soil parameters such as liquid limit, plastic limit, plasticity index, moisture content, and effective cohesion. These models provide a valuable framework for predicting the geotechnical properties of medium-grained clayey sandy soils, including strength characteristics like internal friction angle and cohesion, based on their electrical resistivity measurements [55]. Wei et al. established a linear relationship between 28-day compressive strength and resistivity of cement paste after 24 hours [56].

3.1.2. Dredged sediment

In phase I of this study, a dredged sediment from Gothenburg harbor was used as a raw material. The raw material was stored in a 120 L plastic container with a tight lid that prevents evaporation and changes in the moisture content of the stored material over time. The container was kept still at the laboratory for a while to let the fine material settle to the bottom of the container. The water that gathered on the top was decanted and stored in a 50 L plastic container. Then, the DS was sieved through a 4 mm mesh to reach a uniform material with a maximum size less than 1/10 diameter of the standard sampling form that has a 50 mm diameter. The sieved material was called batch A. Subsequently, a 2100 W electric paddle mortar mixer was employed to homogenize the raw material. Eight samples were extracted for property assessment such as density and water content of this batch (A). Figure 5

shows the electrical paddle mortar mixer that used to homogenizing the raw DS materials.



Figure 5: Left: Electrical paddle mortar mixer, right: Dredged sediment (Photo by author).

Moreover, a grading test was done on 1.5 kg of DS, and according to the test, the raw material consisted of 31% clay and was, therefore, categorized as clayey silt. It has a liquid limit of 83% and an average organic content of around 6% according to standard SS27105 [57]. The mean water content and density of batch A were 138% and 1345 kg/m³, respectively, with standard deviations of 0.3% and 22 based on sample size n=8.

After finding the base properties of batch A, two more batches with higher water contents were made by adding the decanted water to samples taken from batch A. These batches were named batch B and batch C. Batch B had a water content of 185%, and for batch C, the water content was set to 291%. The measured densities for batches B and C were 1241 and 1163 kg/m³, respectively.

3.1.3. Binder

Binders used in this phase were made from 40% Portland limestone cement classified as CEM II/A-LL 42.5 R according to EN-197 [58] and 60% of a ground granulated blast furnace slag (GGBFS). The properties of binders are shown in table 1.

Table 1. Binder composition

Binders	Sio₂ %	Al ₂ O ₃ %	CaO %	MgO %	SO₃ %	Na₂O %	K₂O %	TiO₂ %	Fe₂O₃ %
CEM IIA	19.31	4.31	61.08	2.38	2.96	0.29	0.86	0.14	2.28
GGBFS	30- 35	10-13	30- 34	12-15	N.D.	N.D.	N.D.	1.5- 2.5	N.D.

3.1.4. Mixing procedure and sample preparation

At this phase of the study, to evaluate the quality of the stabilized dredged sediments, two non-destructive methods, *isothermal calorimetry* (IC) and *electrical resistivity* (ER), were used for each batch described above by taking 1.5 kg of DS and the binder (60% slag and 40% cement) at water-binder ratios 4, 5, 6, 7, and 8. The mixing was performed with a KitchenAid Artisan stand mixer with a flat blade. The mixing time set to 5 min with a speed of 75 rpm. The mixing was paused after 1 minute to scrape off any material adhering to the flat beater and the inner surface of the bowl, as is described in EN 196-1 and ASTM C305. Mixing was then resumed for the specified duration [76,77].

After blending the dredged sediment (DS) with binders, sampling was carried out using standard cylindrical forms commonly utilized in Sweden [78], with a diameter of 50 mm and a height of 170 mm. Each tube was filled in three stages and after each stage the tube was tapped against the floor to release any trapped air from the mixing process. Subsequently, all samples were placed in a water bath at 20 °C for one week. To conduct the 7-day free-free resonance (FFR) test, all specimens were removed from the water bath and trimmed to achieve a height-to-diameter ratio of 2. Finally, after completing the FFR test, each sample was placed in a plastic bag with wet tissue to maintain moisture content during the remainder of the curing period. Figures 6 to 10 show the Kitchen Aid mixer, prepared samples, water bath

with samples, trimming samples procedure, and trimmed samples that were placed in plastic bags.



Figure 6: The Kitchen Aids mixer used in this study (photo by author)



Figure 7: Prepared samples in standard tube (photo by author)



Figure 8: Submerged samples in water bath (photo by author)



Figure 9: Trimming samples to reach dimensions (50mm diameter and 100 mm height) for FFR, and UCS test (photo by Torleif Dahlin)



Figure 10: Trimmed samples that kept in plastic bag with wet tissue (photo by author)

To measure the heat release in IC for each mix with different w/b, one sample was taken by pouring treated DS stepwise into 120 ml plastic vessels containing cylindrical plastic meshes 25.5 mm in diameter and 51 mm in length (Figure 11). After pouring treated DS into the vessels, to ensure that the entrapped air went out, the vessels were tapped against the table, capped with a sealed lid, and placed into the calorimeter, described in the next section, at 20 °C. The measurement started directly and continued for one week.

The plastic mesh in the vessel allows small samples with a diameter of 25.5 mm and a length of 50 mm to be taken out for the FFR tests after 7, 14, and 28 days of curing. One sample from raw material without adding a binder was used as a reference for heat release measurements.

To measure the electrical resistivity of treated DS during the curing period, one sample was taken for each mix by pouring the mixture into a cylindrical form with the same dimensions as a standard form used for the UCS test (50 mm diameter and 170 mm height). It was impossible to use the tapping method to take out the entrapped air from samples; therefore, the rodding method was used to take out the air and compact the samples. The test method is described in the next section. After sampling, the whole instrument was placed in a climate room with a controlled temperature of 20 °C; the measurement continued for up to 28 days of continuous

curing. After 28 days, the samples were used for UCS and FFR tests. Figure 12 shows the sampling for ER tests.



Figure 11: Plastic vessel for calorimetry test with cylindrical plastic mesh that simplified the extraction of a cylindrical sample for FFR testing after hardening; in the right hand image, the mesh is only half inserted into the sample (photos by Lars Wadsö)



Figure 12: Sampling for ER tests (photo by Torleif Dahlin)

3.1.5. Testing method

The Unconfined Compressive Strength (UCS) test was utilized to assess the compressive strength of samples following a 28-day curing period. The free-free resonance (FFR) test was conducted after 7, 14, and 28 days of curing. Furthermore, two non-destructive tests, isothermal calorimetry and electrical resistivity, were employed to monitor the quality of the treated DS at its initial stages. These methodologies are elaborated upon in the subsequent sections.

3.1.5.1. Unconfined compressive strength

The UCS test was done on samples that were 50 mm in diameter and 100 mm in height after a curing period of 28 days. The strain rate was 1 mm/min until the samples failed or reached a 15% axial strain threshold. We used an MTS 810 material test system machine to conduct the UCS test. Figure 13 shows the machine during testing.



Figure 13: MTS810 machine during testing (photo by author)

3.1.5.2. Non-destructive Free-Free resonance test

The stiffness of stabilized soil materials under small strains can be measured using non-destructive Free-Free Resonant (FFR) tests. This method is based on the onedimensional wave-spread theory of elastic rods and measures the shear and elastic modulus. The frequency range obtained from the test can be correlated with stiffness.

To obtain free boundary conditions, cylindrical specimens are placed horizontally on a layer of soft foam. Vibrations are initiated by impacting the specimens with a small hammer, and a compact-size accelerometer (model 352C33 from PCB) is used to record the specimen's vibrational response. The orientation for measuring vibration frequency is determined by the accelerometer's placement and the origin of the vibration source. Two orientations are possible: longitudinal (axial), which is used to determine the compressive wave velocity (V_p), and transverse, which provides the frequency for calculating the shear wave velocity (V_s). Figure 14 illustrates the assessment of longitudinal frequency and figure 15 shows a schematic representation of the frequency and applying equation 18, the values for V_p of the specimen can be calculated [59–62]. In this study only the longitudinal frequency was measured.



Figure 14: Longitudinal FFR test (photo by author)


Figure 15: Sample frequency measurement in FFR test (photo by author)

$$V_p = 2f_p L \tag{18}$$

Here, V_p (m/s) is compressive wave velocity,

 $f_{\rm p}$ (Hz) is axial frequency of vibration, and L (m) is the sample length. The dynamic elastic modulus calculated with equation 19:

$$E_{dynamic} = \rho V_p^2 \tag{19}$$

where ρ (kg/m³) is the bulk density of treated DS.

3.1.5.3. Isothermal calorimetry (IC)

Two I-Cal Betong (Calmetrix Inc.), each with eight isothermal heat conduction calorimeters, were used in this study phase to measure the thermal power of stabilized dredged sediment during the first week of the curing period. Figure 16 shows a schematic heat conduction calorimeter. The heat flow sensors measure the heat transfer rate, Φ (W), from the specimen to the heat sink. The output of this heat flow sensor is a voltage, U (V), which is multiplied by a calibration coefficient, to give the heat flow. Another essential factor that should be measured to calculate the heat flow is the baseline output voltage, U_0 (V), which is the voltage output from

the calorimeter when there is no heat production at the sample position. Equation 20 shows the heat transfer calculation using the calibration coefficient ε and baseline voltage U_0 .

$$\Phi = \varepsilon (U - U_0) \tag{20}$$

Another relevant factor to consider is the time constant τ (s), which quantifies the thermal inertia of both the sample and the calorimeter. By utilizing the time constant, one can use the Tian correction to remove (or at least decrease) the impact of thermal inertia (also known as time lag) on measurements, particularly in scenarios involving rapid fluctuations in thermal power. Equation 21 is the mathematical formula for the Tian correction.

$$P = \Phi + \tau \frac{d\Phi}{dt} \tag{21}$$

Here, P(W) is the thermal power. Ideally, the Tian equation converts heat flow into the actual thermal power generated within a sample.

Another aspect to consider is the thermal disturbance that occurs when a sample is introduced into the calorimeter, causing a temperature difference between the sample and the calorimeter. In the calorimeters used in the present study, this disturbance typically persists for at least one hour, but with the application of the Tian equation, this duration may be reduced to around 30 minutes. The initial disturbance poses challenges when integrating the results to determine the heat, as we aim to exclude the initial disturbance from the integral. To address this, integration begins after a specified period following the sample's introduction; in our study, we opted for a one-hour delay. Consequently, heat produced within the first hour is not incorporated into the heat integral.



Figure 16: Isothermal calorimetry measurement concept

3.1.5.4. Electrical resistivity (ER) measurement

There are two main methods for measuring resistivity: surface resistivity and bulk resistivity. The Wenner method uses surface resistivity and involves placing electrodes in a straight line on the soil surface, with equal distances between them [63]. Bulk resistivity can be divided into different categories depending on the frequency of current and electrode configuration [64].

The present measurements were conducted using a tool designed by Dahlin et al. It falls under the bulk resistivity method, which involves assessing the resistance of each sample to electric current flow [65]. The instrument comprises a cylinder lid with electrodes shaped like pieces of a pie, made from a 5 mm thick stainless-steel plate, as illustrated in Figure 17.



Figure 17: Electrical resistivity sample holders with electrode lids (Photo by Torleif Dahlin)

The electrical resistivity of a material is defined as its electrical resistance per unit area of cross-section and unit length, as depicted in equation 22.

$$R = \frac{\rho L}{A} \tag{22}$$

Where *R* is resistance (Ω), *L* is the length of the sample (m), *A* is the cross-section area (m²), and ρ is the electrical resistivity (Ω m).

Ohm's law defines the relation between current *I* (A), differential voltage ΔV (V), and resistance *R* (Ω), as equation 23.

$$R = \frac{\Delta V}{I} \tag{23}$$

3.2. Phase II: mixing time effects on treated DS strength

3.2.1. Introduction

Regarding soil stabilization, at the preliminary stage, it is necessary to prepare specimens at the laboratory to find the best recipe that achieves the desired compressive strength. Previous studies have shown that the mixing process affects rheological behavior and the quality of the mixture in stabilized soil, and consequently affects the final mechanical properties of treated soil. Inadequate mixing could result from short mixing time leading to low mechanical strength of stabilized soil [22,66–72].

The mixing durations employed in soil stabilization processes vary across different regions. For example, in Japan and several other countries, a recommended mixing time of 10 minutes is suggested to achieve a homogeneous mixture, while Portugal advises a shorter duration of 3 minutes. In Sweden, the recommended mixing time for homogenizing a mixture is 5 minutes [20,73,74]. Yang et al. observed that the unconfined Compressive Strength (UCS) of cement paste backfill (CPB) experiences an increase from 1 minute up to 4 minutes of mixing time, followed by a decline for durations exceeding 4 minutes [75]. Yaghoubi et al. noted that augmenting the mixing time from 5 minutes to 15 minutes the UCS of stabilized soil [16]. Various investigations have demonstrated that the properties of stabilized soil are significantly influenced by the mixing time after adding the cementitious binder. Furthermore, this mixing duration can be affected by factors such as water content, soil type, gradation, and organic content [20]. This section introduces the sample preparation for determining the effects of mixing time on the compressive strength of stabilized DS.

3.2.2. Dredged sediment

To assess the impact of mixing duration on the mechanical characteristics of stabilized dredged sediment (DS), samples were collected from four batches numbered 1-4 of dredged sediments, each with a different water content, obtained from three harbors. Before determining the water content and density of the DSs, batches 3 and 4 underwent sieving to remove grains with a diameter exceeding 4 mm, ensuring that the particle size of the DS remained less than 1/10th of the inner diameter of the mould. Batches 1 and 2 remained unsieved. Basic properties of the DS are given in Table 2. It should be noted that the contents of the sediments, such as organic content and clay content, were not measured.

Table 2. Dredged sediment water content and density

Batch number	Dredged	Water of	content		Density		
	collection site	Mean (%)	Coefficient of variation (%)	Mean (kg/m³)	Coefficient of variation (%)		
1	Stavanger harbor, Norway	349	1.98	1130	0.79		
2	Stavanger harbor, Norway	270	1.88	1190	0.70		
3	Oslo harbor, Norway	88	0.9	1510	0.73		
4	Gothenburg harbor, Sweden	172	0.39	1300	0.59		

3.2.3. Binders

In the mixing procedure, binders were utilized, with batches 1 and 2 incorporating CEM IIIB, while batches 3 and 4 were mixed with a blend of Portland cement (CEM IIA) and ground granulated blast-furnace slag (GGBFS).

3.2.4. Mixing procedure and sample preparation

The amount of binder required for soil strengthening can vary considerably depending on the soil's condition and the project's specific requirements. Generally, the necessary quantity of binding material ranges from 80 to 200 kg/m³ for treated soil. Consequently, trial-and-error testing is necessary to determine the optimal binder dosage for stabilization and achieve the desired compressive strength [76,77]. Table 3 details the type of binder, quantity of binders, type of mixer used, and the mixing speed and duration for each batch considered in this investigation [78,79].

Table 3. Binders type and quantity, mixer type, mixing speed and duration for phase II of study

Batch number	Binder type	Weight of binder (kg/m³)	Mixer type	Mixing speed (rpm)	Mixing duration (min)
1	CEM IIIB	100	Electrical hand mixer	-	4, 9, and 14
2	CEM IIIB	195	Kitchen Aid	75	5, 10, and 15
3	CEM IIA/ GGBFS	43/ 64	Kitchen Aid	75	4, 9, and 14
4	CEM IIA/ GGBFS	76/ 114	Kitchen Aid	75	4, 9, and 14

For each mixture, 1 kg of dredged sediment (DS) was weighed and mixed with the binders for varying durations. The procedure of mixing with the KitchenAid mixer was described before for phase I of this study.

3.2.5. Testing methods

In Phase II, the Unconfined Compressive Strength (UCS) test was utilized to assess the compressive strength of samples following a 28-day curing period. The free-free resonance (FFR) test was conducted after 7, 14, and 28 days of curing. The testing methods were described in phase I of this study.

4.Experimental Results and Discussion

This chapter presents the results of the two phases of the experimental study. It is divided into two subsections: *Phase I* shows Isothermal calorimetry and electrical resistivity correlation with compressive strength as two non-destructive methods for quality controls of stabilized soil in the early stage, and *phase II* shows results for mixing time effects on compressive strength.

4.1. Phase I

In this phase of the study, the geotechnical properties of stabilized dredged sediment, like porosity, water content, and density, were evaluated after treatment, and two non-destructive methods, isothermal calorimetry measurements and electrical resistivity test, were introduced as alternative methods for evaluating the quality of treated DS at the early stage of stabilization.

4.1.1. Bulk density and water content of treated DS

Figure 18 shows the theoretical bulk density and measured bulk density of treated DS for samples from UCS and ER measurements. Figure 19 shows the measured water content and theoretical water content after treating DS. Theoretically, while the binders are added to the DS due to the increase in the weight of solids, the density should increase in comparison with raw material. According to equation 6, mentioned in section 2 of this study, the theoretical bulk density of the mixture was calculated and compared with the measured density that was done after 7 days of stabilization. As it is seen and described in papers I and II, the theoretical bulk density is higher than the measured density. This difference comes due to voids that exist in samples during preparation. Moreover, in samples that are prepared for ER measurement, as described before, the rodding method is used for compacting samples during the moulding procedure; therefore, there is more variation in measured bulk density. Generally, the differences between theoretical and measured density are higher, when the water content and w/b are lower. For water content of

138%, the viscosity of the mixture is higher than the mixture with water content of 291%; therefore, the differences between measured and theoretical density in the former mixture is higher than the latter.



Figure 18: Theoretical and measured bulk density against water-binder ratio, left: samples from UCS test, right: samples from ER test

Figure 19 shows measured water content one week after stabilization and theoretical water content at the start as a function of w/b. Adding a binder should decrease the water content of products compared to raw DS water content because the binder consumes water and forms solid during the hydration process. Moreover, as discussed in paper I, decreasing the binder content (increasing w/b) does not significantly change the differences between theoretical and measured WC. To calculate the theoretical water content as outlined in Equation 4 of this thesis, the weight of the binder is added to the weight of the dry solids (DS). This addition increases the denominator of the equation, thereby resulting in a decrease in the calculated value of the function.



Figure 19: Theoretical and measured water content against the water-binder ratio of treated DS

4.1.2. FFR measurement

As described before, FFR measurement is one of the non-destructive test methods for evaluating the quality of stabilized soil. The advantage of this test is that it allows the repetition of the test on the same samples at different times (for example, at 7, 14, and 28 days). With this test, it is possible to monitor strength improvement over time on samples. Papers I and II showed FFR measurements on samples from the UCS test, ER measurements, and small samples from IC measurements against the w/b ratio. By increasing w/b, the measured V_p decreases, as shown in Figure 20. The results show that for samples with water content of 138% and 185%, the rate of V_p decrease increasing w/b is linear and with a highly negative slope. In contrast, for samples with water content 291% seems non-linear, and V_p for w/b=4, 5, and 6 are approximately constant, for samples with w/b higher than 6, the V_p has the same slope as other samples with lower water content.



Figure 20: P-wave measurement in different curing times (7, 14, and 28 days) against water-binder ratio for samples from UCS test

The samples from the IC measurement and ER test have the same trend for the FFR test as shown in papers I and II, and by comparing the V_p that was measured on samples from IC and ER with samples from UCS test show a linear positive correlation that means that instead of taking different samples for UCS test there is a possibility to use ER samples for UCS. One can also use V_p measurement on IC and ER samples to get a good estimation of the p-wave velocity, and thus the elastic modulus (Paper I, and II).

4.1.3. Compressive strength and elastic modulus of treated DS

The compressive strength is measured by utilizing an unconfined compressive strength test method that usually is performed 28 days after stabilization. Typical stress-strain curves obtained from such tests are shown in papers I and II. Regarding the results, it is obvious that by increasing the water-binder ratio or the water content, the strength of treated DS decreases, the behaviour of the products then turns from ductile to more cohesive behaviour, and the maximum compressive strength happens at a higher strain value. From the figures shown in papers I and II, the stress-strain curves that belong to the samples with higher water content and w/b have smoother shapes and are shifted to the right compared to other samples with low water content and w/b.

There are some empirical equations can be used to predict how the compressive strength of concrete and cement soil mixtures changes if the water/binder ratio

changes. The most well-known is Abrams' law, equation 12. There are also relations for predicting the strength from porosity and cement content ratio, equation 24 [80,81].

$$qu = A \times \left(\frac{n}{C_{iv}}\right)^B \tag{24}$$

Here, A and B are constants that depend on soil type, binder composition, sample preparation method, curing conditions, and testing methodology; *n* is porosity; C_{iv} is the volumetric cement ratio. Abrams' law, initially used in concrete technology, shows that the key parameter to achieve strength is the water-binder ratio. At the same time, in the soil-cement system, the porosity and cement content also play key roles in achieving the desired strength (equation 24). As demonstrated in Paper I, Abrams' law can be used to predict the compressive strength of treated DS with high water content. Additionally, Paper II confirms that Equation 24 is valid for treated DS as well.

In section 2 of this thesis, a robust correlation between elastic modulus and compressive strength was established, a finding that has been consistently observed by numerous researchers. Our study, which involved calculating the elastic modulus from stress-strain curves and correlating it with 28-day compressive strength, further solidifies this correlation. In our results for dredged sediment with different water content and w/b, the elastic modulus (E_{50}) varies between 100×qu to 200×qu (figure. 21), providing a reliable basis for future research and practical applications.



Figure 21: Correlation between elastic modulus (E₅₀) and compressive strength

4.1.4. Calorimetry and electrical resistivity measurement of treated DS

This part presents the calorimetry measurement of treated DS during the first week of curing after stabilizing. Paper I shows cumulative heat-release and thermal-power measurements, and as it is shown, by increasing w/b, the heat-release per gram sample decreases. Moreover, as discussed in paper I, IC measurement can be used as a non-destructive method to predict the 28-day compressive strength and binder content at the mixture in the early stage of the curing period while the treated DS is still fresh. It should be noted that, in this context, the IC method is categorized as non-destructive because the sample is not destroyed during testing, and there is the possibility to continue the measurements for long periods of time, and also to use the sample for other tests after the calorimetric measurement. However, this method does not measure the strength like the Schmidt hammer or other non-destructive tests. Figure 22 shows the correlation between heat-release and binder weight per weight of the sample, and Figure 23 shows the correlation between heat-release and 28-day compressive strength.

In Figure 22, the results are normalized by the sample's weight, which effectively eliminates the influence of water content. As a result, the graph reflects heat release solely without the interference of water. It can be observed that with an increase in binder content and curing time, the amount of heat released also increases. Furthermore, examining the correlation coefficients for each curve reveals that after 48 hours of curing, the correlation coefficient is approximately 0.9. This suggests that after two days of curing, binder content can be reliably estimated using heat release measurements. This method could serve as a useful tool in the field for controlling binder content without needing to account for water content or the water-to-binder ratio.



Figure 22: Correlations between binder content and heat-release, both normalized with weight of samples



Figure 23: Correlations between heat release after 24 h, 48 h, and 72 h of curing normalized with weight of samples against 28-day compressive strength.

Figure 23 shows that there is a linear correlation between heat release normalized with sample weight and compressive strength. After two days of stabilizing and measuring heat release, the final compressive strength can be predicted by considering the water content. The result is valid only for the DS used in this study, which means that new correlation graphs are needed for each treated DS. Therefore, the following steps should be performed on a laboratory scale before each practical project is executed.

Step 1: Make IC tests, for example during 48 h, and 28-day compressive strength measurements using the binder and DS that will be used in a project. Make measurements with different w/b and water contents.

Step 2: Produce correlation diagrams, like Figure 23, between heat release at a specific time (e.g., 48 h) and UCS for all water content and w/b mixture.

Step 3: In the field, take a fresh sample of DS and obtain the water content of raw DS; then, after stabilizing (mixing with binder), take samples for IC measurement.

Step 4: After, for example, 48 h of calorimetric measurement, integrate the thermal power during this period to get the heat release and find the corresponding UCS by considering the water content of DS with the help of graphs made in step 2. Figure 23, the middle graph, shows an example of predicting the UCS from heat and water content.

It is important to note that the purpose of normalizing the results by the sample's weight is to develop a method that can be easily applied in the field. On a large scale, measuring the weight of a sample is both quicker and more practical in field conditions, making this approach more efficient for real-world applications.

Another alternative technique introduced in phase I of this thesis for quality control at the early stage of stabilizing DS is monitoring electrical resistivity during the curing period. This is also categorized as a non-destructive method. As shown in paper II, the ER has an inverse relation to w/b, while the water content is 138% and 185%, and it is directly related to curing time. On the other hand, while the water content reaches 291%, the relationship between w/b and ER becomes different.

Figure 24 shows the relation between binder content and ER, and the results illustrate that after 24 h of the curing period, it is possible to predict binder content by measuring electrical resistivity. It has been known that electrical resistivity is not only dependent on the porosity of the treated DS but also that the homogeneity, size, and shape of cementitious particles can affect the tortuosity of the conduction path, and as the sample becomes more homogenous, with smaller and angular cementitious particles, the ER increases. These factors are affected by the binder/solid ratio, and according to figure 24, with a water content of 291%, the solid content is lower than samples with a water content of 138%; therefore, the

effects of binder/solid ratio is lowered, and the correlation line (black lines) is linear compared to the other samples with water content 185%, and 138%.



Figure 24: Electrical resistivity against binder content for different curing time periods.

Figure 25, shows the correlation between 28-day compressive strength and ER measurement during 72 h of curing time.



Figure 25: Electrical resistivity against compressive strength for different curing time periods.

Figure 25 illustrates that there is a linear correlation between ER and 28-day UCS for each w/b, and the lower bound shows samples with WC=291%, while the upper bound is for samples with an initial water content of 138%. As mentioned in paper II, many researchers have shown the linear correlation between ER and strength in concrete or cement paste with low w/b, which is similar to this study's results. To be able to use this correlation to predict the compressive strength of products in an S/S project, laboratory testing on the DS that will be used in the field is needed to measure the ER and UCS. By this means, before conducting the large-scale project, the correlation between ER and UCS produces and during the project; by measuring the ER at an early stage of stabilizing and comparing with results obtained at the laboratory, it would be possible to predict the range of final UCS of the stabilized DS. At this short time, the treated DS still has low strength and can be removed easily.

4.2. Phase II

This part presents the results from the second part of the study about the laboratory mixing procedure of stabilized DS.

Tables 4 to 7 show compressive strength and P-wave velocity against mixing time for batches 1 to 4. Results indicate that for batches 1 and 2 with high water content, by increasing mixing time from 4 and 5 minutes to 9 and 10 minutes, the 28-day compressive strength increased, and by continuing mixing time up to 14 and 15 minutes, the strength decreased.

For batches 3 and 4, the strengths do not change significantly by increasing the mixing time from 4 to 9 minutes, and by increasing the mixing time to 14 minutes, the compressive strength decreases slightly.

According to equation 17, the maximum dispersive force transmitted through a mixture is related to its viscosity, which in turn depends on water content. As water content increases, viscosity decreases. Consequently, a lower viscosity requires more force to separate agglomerated particles compared to a higher viscosity mixture. In this study, viscosity measurements were not performed, and since the viscosity for each batch remained constant, the only factor influencing mixing was the mixing time. Additionally, based on Equations 15 and 16, for Batches 1 and 2, the 9- and 10-minute mixing durations produce more energy compared to Batches 3 and 4, which only required 4 minutes of mixing. This confirms that when the water content in the DS is high, greater mixing energy is needed to disperse agglomerates and achieve a more homogeneous mixture, in contrast to lower water content DS.

Table 4. P_wave velocity and compressive strength results against mixing time for batch 1 mixing

Mixing time (minutes)		P_Wave velo	city	Unconfined compressive strength			
	Days after stabilization	Mean value of FFR (m/s)	Coefficient of variance (%)	Days after stabilization	Mean value of strength (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 5. P_wave velocity and compressive strength results against mixing time for batch 2 mixing

Mixing		P_Wave velo	city	Unconfined compressive strength			
time (minutes)	Days after stabilization	Mean value of FFR (m/s)	Coefficient of variance (%)	Days after stabilization	Mean value of strength (kPa)	Coefficient of variance (%)	
5	7	201	2.50	28	936	4.71	
	14	448	3.86				
	28	743	5.30				
10	7	196	1.17	28	953	2.26	
	14	445	1.14				
	28	748	3.50				
15	7	186	1.36	28	877	5.6	
	14	430	2.77				
	28	756	5.77				

Table 6. P_wave velocity and compressive strength results against mixing time for batch 3 mixing

Mixing		P_Wave velo	city	Unconfined compressive strength			
time (minutes)	Days after stabilization	Mean value of FFR (m/s)	Coefficient of variance (%)	Days after stabilization	Mean value of strength (kPa)	Coefficient of variance (%)	
4	7	321	6.34	28	453	0.78	
	14	500	2.99				
	28	721	1.62				
9	7	318	6.88	28	450	0.15	
	14	485	1.34				
	28	709	0.37				
14	7	295	2.1	28	435	0.48	
	14	462	1.99				
	28	684	1.25				

Mixing		P_Wave velo	city	Unconfined compressive strength			
time (minutes)	Days after stabilization	Mean value of FFR (m/s)	Coefficient of variance (%)	Days after stabilization	Mean value of strength (kPa)	Coefficient of variance (%)	
4	7	536	0.59	28	1146	0.48	
	14	806	0.56				
	28	1075	0.57				
9	7	522	3.98	28	1138	0.46	
	14	805	0.29				
	28	1075	0.27				
14	7	526	0.28	28	1137	0.65	
	14	804	0.45				
	28	1073	0.25				

Table 7. P_wave velocity and compressive strength results against mixing time for batch 4 mixing

Calculating the mixing energy in the laboratory relative to the mixing time makes it feasible to determine the required mixing time for a large-scale operation using a different mixer. This allows for achieving the same mixing energy and, consequently, replicating the laboratory results at a larger scale.

The coefficient of variance for UCS testing in batches 3 and 4 is lower than the results for batches 1 and 2, which indicates that sieving the raw material before mixing with a 4 mm sieve improves the homogeneity of mixing so that the variation in the results decreases.

5.Conclusion

The presented study consists of two phases. In Phase I, the study evaluates the mechanical properties of treated DS and uses electrical resistivity measurement and isothermal calorimetry as two non-destructive methods to predict the mechanical properties and quality of treated DS at an early stage, and in Phase II, the effects of the mixing method, with a focus on the mixing time, is studied. The following conclusions can be made from the study:

- By measuring heat release with isothermal calorimetry in the laboratory and correlating it with UCS before starting a project, the quality of treated DS can be checked at an early stage during the execution of large-scale projects.

- Monitoring the electrical resistivity could be used as a non-destructive method to predict the compressive strength and quality of stabilized soil.

- There is a possibility to evaluate binder content by using both methods (IC and ER).

- For stabilized sediment used in this study E_{50} varies in a range between $100 \times q_u$ to $200 \times q_u$.

- DS with higher water content requires a longer mixing time compared to DS with lower water content to reach maximum compressive strength. According to our experimental study results, there is an optimum mixing time to achieve this maximum compressive strength.

- It is recommended to sieve the sedminets to homogenize them for laboratory measurements and thus reduce variation in the experimental results.

6. Summary of papers

This chapter gives a short summary of the three papers found in appendices I, II and III in this thesis.

6.1. Summary of paper I

Title: Early quality control of stabilized dredged material by correlating heat production with strength

Authors: Mohammadhossein Gholampoor, Lars Wadsö, Peter Johansson and Per Lindh

Manuscript: Accepted to published in Ground Improvement journal.

This paper presents isothermal calorimetry as an alternative method for assessing the quality of stabilized dredged sediment within 48 h after treatment by predicting the 28-day compressive strength. Dredged sediment from Göta älv, Gothenburg, Sweden was collected and mixed with 40% PLC and 60% GGBFS with water binder ratios 4, 5, 6, 7 and 8. Compressive strength were measured after 28-day of curing to assess the strength of treated DS. The free-free resonance test (FFR) performed at 7, 14 and 28 days after curing was used to evaluate the improvement of mechanical properties during curing period up to 28 days. Isothermal calorimetry measurement was used to monitor the heat of hydration during the first week of the curing after stabilizing. The heat release correlated with compressive strength, and we could recommend a method for predicting the 28-days strength of stabilized soil at the early stage of stabilizing, while the samples are fresh.

The results show that increasing binder content and decreasing water content cause the behaviour of treated DS to become more brittle. Moreover, there is a correlation between compressive wave velocity measured for standard samples with 50 mm diameter and for small sample with 25 mm diameter; the latter were obtained from the calorimetry test. Furthermore, isothermal calorimetry measurement 48 h after stabilization can be used to evaluate the binder content and long-term compressive strength of treated DS at an early stage.

6.2. Summary of paper II

Title: Correlation between electrical resistivity and compressive strength of stabilized dredged sediment for early quality control

Authors: Mohammadhossein Gholampoor, Torleif Dahlin, Mikael Lumetzberger, Per Hedblom.

Published in Transportation Engineering

In this paper, we introduced the electrical resistivity measurement to monitor the hydration process and used it as a method for predicting the compressive strength and binder content of stabilized DS. The sample preparation is the same as in paper I and in this paper, we showed that the bulk density for samples that were prepared by the tapping method and samples that were compacted by the rodding method have a good correlation. Moreover, the results showed that the compressive strength for treated DS could be estimated by ratio of porosity/cement content which follows the same trend as previous research that has been done by other researchers on stabilized soil.

Monitoring the electrical resistivity gives the possibility to evaluate the binder content and predict the compressive strength by having the w/b ratio and water content.

6.3. Summary of paper III

Title: Methodology for sample preparation for quality control of stabilized dredged sediment

Author: Mohammadhossein Gholampoor, Per Lindh, Peter Johansson, Torleif Dahlin and Lars Wadsö

19th Nordic Geotechnical meeting- Göteborg 2024

In this paper, the effects of mixing time on 28-days compressive strength of stabilized dredged sediment was examined and two methods for quality controls of stabilized DS in early stage of stabilizing were introduced. To evaluate the mixing time effects, dredged sediments from Stavanger with initial water content 349% and Oslo harbour with initial water content 88% in Norway were sampled. The DS from Stavanger mixed with CEMIIIB while DS from Oslo harbour stabilized with 40%

Portland limestone cement and 60% ground granulated blast-furnace slag. The mixing time set to 4, 9 and 14 minutes. Moreover, to examine the usefulness of isothermal calorimetry and electrical resistivity measurements as two alternative methods for quality control of stabilized DS, we prepared samples from Oslo harbour with three water-binder ratios: 4, 6 and 8. The treated samples were used for measuring heat-release and electrical resistivity during the curing period.

The results showed that samples with higher water content need more mixing time compared to samples with lower water content to reach the maximum compressive strength. Moreover, to have less scattered results in laboratory measurements, it was recommended to sieve raw materials using for example a 4 mm sieve (the size depending on diameter of samples to be made). The isothermal calorimetry and ER measurements showed a good correlation with 28-days compressive strength.

7. Future research

In this chapter, suggestions and motivation for future research are presented.

7.1. Experimental research

According to the results of this thesis, when the water content of the raw material is around 291%, the resistivity measurement shows a different pattern from that of the other batches. Therefore, it would be interesting to check the ER measurement for stabilized DS when the initial water content varies between 185% and 300% to find the threshold of water content.

7.2. Probabilistic and AI model

With the help of the probabilistic method and due to DS's initial properties, such as bulk density and water content that were measured at the lab, it is possible to draw the probabilistic density function of these properties. Then, by performing some laboratory tests with different water-binder ratios and checking the 28-day compressive strength, it would be possible to use an AI model such as random-forest regression. We could find a method to predict the receipt to reach the expected USC in 28 days, which could reduce laboratory work in the future. This research needs a big data set, but it is possible to use previous data sets that other researchers have made.

7.3. Large scale test

Recent research was done on a laboratory scale with a constant temperature. In reality, the temperature would be varied. It is recommended that some tests be performed in the field and that a method to measure electrical resistivity and calorimetry on a large scale without using a sampler be found.

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Attachments
Paper I

Date: 2024-10-24

Title: Early quality control of stabilized dredged material by correlating heat production with strength

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Keywords: Soil stabilisation, Dredged sediment, Non-destructive test, High water content, Quality control, Isothermal calorimetry

Abstract:

This study explores the use of isothermal calorimetry to assess heat release during the initial phases of dredged sediment stabilization with the primary goal of predicting the 28 days unconfined compressive strength (UCS) and enhancing the stabilization process' quality control (QC). The study was performed on dredged sediment (DS) samples collected from Göta river, Gothenburg, Sweden. The water content of the raw DS was set to 138%, 185%, and 291%, and mixing was performed with water-binder ratios 4, 5, 6, 7, and 8 using a binder consisting of 40% Portland limestone cement and 60% slag. The heat release measurements were conducted during the first seven days of hydration, non-destructive free-free resonance tests (FFR) were performed at 7, 14, and 28 days of hydration, and the 28 days UCS was done to assess the compressive strength of stabilized DS. For each water content, a statistical analysis was performed to determine the strength of the relationship, specifically using linear regression to assess how well early calorimetric data could predict the UCS and a correlation was found between the 28 days compressive strength and heat release of stabilized DS after a 48 h of hydration. By measuring water content and heat release in the early stages of stabilization, it is thus possible to assess the binder content and predict the ultimate compressive strength of a treated dredged sediment.

Notation:

DS	Dredged Sediment
S/S	Stabilization/Solidification
QC	Quality Control
QA	Quality Assurance
WC	Water Content
w/b	Water-binder ratio
PC	Portland Cement
GGBFS	Ground Granulated Blast Furnace
FA	Fly Ash
UCS	Unconfined Compressive Strength
CPT	Cone Penetration Test
SPT	Standard Penetration Test
Vp	Compressive Wave Velocity
Vs	Shear Wave Velocity
IC	Iso-thermal Calorimetry
E ₅₀	Elastic Modulus
E _{dynamic}	Elastic Modulus in small starin
ρ	Bulk density of treated DS
P SDS	Bulk density of treated DS
Ms	Mass of dry DS
Mw	Mass of water
M _b	Mass of binder
Gs	Specific gravity of DS
Gw	Specific gravity of water
G _b	Specific gravity of binder
Φ(W)	Heat transfer rate
U(V)	Voltage that is transformed into heat flow
E(W/V)	Calibration coefficient
$\tau(s)$	Time constant

P(W) Thermal power

1. Introduction

Dredging plays a vital role in managing waterways, rivers, lakes, and harbor basins, ensuring the necessary depth for navigation and supporting the construction of port and harbor infrastructure (Mink FR, Dirks WO, Van Raalte GE, De Vlieger HU, Russell MA.,). The dredged sediments (DS) removed are typically soft marine soils characterized by high initial water content and low shear strength, and are therefore unsuitable for use in the construction sector without prior treatment (Burt, 1996; Ross and Mehta, 1989; Xu et al., 2020). Chemical stabilization is an effective method to improve the mechanical properties of DS. Within this approach, binding agents such as Portland cement (PC) and pozzolanic materials, including ground granulated blast furnace slag (GGBFS), a by-product of the steel industry, and fly ash (FA) (Abd-EI.Aziz et al., 2012; Dermatas and Meng, 2003; Fernández Pereira et al., 2009; Yaghoubi et al., 2019; Zhang et al., 2020) are mixed with the sediments, leading to a reaction that generates a solid matrix. This process improves the geotechnical properties, thus making it possible to use sediments as construction materials (Barjoveanu et al., 2018).

A stabilization project has different phases that are driven by specific criteria for the desired quality of the final stabilized in-situ products. Initially, a laboratory trial mix test is conducted to determine the optimal type and quantity of binder. Secondly, a field test is carried out to validate the practicality of the mixing recipe. Finally, the project is executed based on the established mix design (Kitazume, 2021)-(Maher et al., 2013). To confirm that the desired quality of the stabilized soil is reached, quality assurance (QA) and quality control (QC) measures need to be applied before, during, and after production (Castellano et al., 2016; Chen et al., 2021; Liu and Zhang, 2021; Zhang et al., 2020; Zuo et al., 2023).

Numerous methods have been devised for appraising the mechanical properties of stabilized soil (Forsman et al., 2017). Typically, a combination of in-situ and laboratory tests are employed. Standard tests such as the cone penetration test (CPT), standard penetration test (SPT), and plate load test are performed in the field, while the unconfined compressive strength (UCS) test is conducted in the laboratory to assess the quality of soil stabilization. As the strength development in stabilized dredged sediment is slow, these quality control tests must be conducted at quite long

times after mixing to ensure that the product has a high enough strength level for the tests to be successful (Forsman et al., 2017; Larsson, 2005). Therefore, large volumes of treated DS can be produced before the quality of the treated DS is known, and it is very costly to re-stabilize or remove the treated DS if it does not fulfill the project's requirement. Moreover, it is essential to acknowledge that the outcomes of in-situ tests are limited to specific discrete points within the stabilization area, potentially failing to provide a comprehensive assessment of the overall quality of the stabilization process. Because of this limitation, a substantial number of tests are needed to obtain statistically significant results, emphasizing the need to develop a comprehensive real-time and non-destructive QA/QC methodology to address this challenge effectively (Afrin, 2017; Ding et al., 2020; Makusa, 2013; Porbaha, 2002; Puppala et al., 2005; Puppala and Porbaha, 2004; Xu and Chang, 2016).

Seismic-based testing methods, such as ultrasonic pulse velocity (UPV) (",ASTM C597-97. Standard Test Method for Pulse Velocity Through Concrete.,"), are non-destructive techniques that can be used to follow the development of stiffness in hydrating specimens. Landis et al. (Landis and Shah, 1995), used such methods to convincingly illustrate that the wave propagation characteristics of cement-based materials, ranging from fine cement paste to concrete, can be quantified, establishing a clear correlation with the level of non-uniformity within the material Furthermore, many researchers have performed free-free resonance (FFR) tests on cement-based specimens. They correlated compressive and shear wave velocity (*V*_p and *V*_s) with compressive strength and found that these velocities increased non-linearly with increasing compressive strength (Chaiprakaikeow et al., 2017; Guimond-Barrett et al., 2013; Hov et al., 2023; Jamsawang et al., 2022; Rydén et al., 2006; TRAITES, 2013). However, for this test to be feasible, specimens must attain a minimum level of strength. The time it takes to achieve the minimum strength is affected by initial water content and water-binder ratio.

An alternative approach for assessing the quality of stabilized soil involves measuring the heat generated during the binder reactions using an isothermal calorimeter. Isothermal calorimetry is a technique that quantifies the thermal power (heat production rate) produced by the hydration reactions of small samples of cementitious materials (Wadsö, 2005). This method allows for monitoring the cementitious binder's overall reaction rate. It provides insights into binder behavior not captured by a conventional compressive strength test, and it can give results from about 1 h after mixing. Researchers have successfully employed isothermal calorimetry to predict the strength

of both mortars and concrete by establishing correlations between the heat of hydration and the compressive strength (Bentz et al., 2012; Frølich et al., 2016; Koenders et al., 2014; Kuryłowicz-Cudowska, 2022; Li et al., 2020). The primary aim of this study is to extend the application of the isothermal calorimetry method to the assessment of stabilized DS, a material with very high water content and low binder content compared with concrete. The objective is to establish a correlation between the heat release patterns at an early age and the compressive strength of the stabilized dredged sediment at, e.g., 28 days in the laboratory scale. Such a correlation will enable us to estimate the long-term strength of the material at an early stage of development. Additionally, such results can be used to validate that the correct amount of binder is used in stabilized dredged sediments during field production.

2. Materials

2.1 Dredged sediment

The dredged sediment (DS) used was from Göta älv, Gothenburg, Sweden. It was stored in a closed container at the laboratory so that the sediment settled at the bottom. The water on top was decanted and stored in another container. The resulting dredged sediment (DS) was sieved through a 4 mm mesh to obtain a uniform sample (Gholampoor et al., 2024) called batch A. This batch was thoroughly homogenized by mixing for 5 min using an electric paddle mortar mixer and samples were taken for determining water content (by EN-1097-5-2008) and density (by measuring the mass of 1000 ml of DS). The density and water content of batch A were 1340 ± 22 kg/m³ and $138.0\pm0.3\%$, respectively (mean and standard deviation, *n*=8). Density was measured by weighing 1 L of material and the water content was determined by weighing before and after drying at 110 °C. The material classification of the batch A material according to grading analysis (SS 027123 ("Standard - Geotechnical tests - Particle size distribution -Sieving SS 27123 - Swedish Institute for Standards, SIS,")) was clayey silt and the average organic content was 6% (SS 27105,")). The measured liquid limit of batch A was 83%. The test was performed according to ASTM standard (Astm, 2010). No chemical analysis was made.

Two other batches with higher water contents were created from batch A by additions of the decanted water. These batches, B and C, had water contents of 185.0%±0.4 and 291.0%±0.9, and

densities of 1241±20 and 1163±5 kg/m³, respectively. Water content levels of 138%, 185%, and 291% were selected to reflect the typical range of moisture found in dredged sediment in situ.

2.2 Binder

The binder was made from 40% Portland limestone cement (CEM II/A-LL 42.5 R, EN-197 [37]) and 60% of a ground granulated blast furnace slag (GGBFS, Merit, Swecem) ("Standard - Ground granulated blast furnace slag for use in concrete, mortar and grout - Part 1,"), a binder combination used for ground stabilization in Sweden. Table 1 shows the composition of these materials.

Table 1 Composition of the materials.

Binder	SiO ₂ %	$AI_2O_3\%$	CaO %	MgO %	TiO ₂ %	SO3 %	Na ₂ O	K ₂ O %	Fe_2O_3
							%		%
CEM	19.31	4.31	61.08	2.38	0.14	2.96	0.29	0.86	2.28
II/A-LL									
GGBFS	30-35	10-13	30-34	12-15	1.5-2.5	N.D.*	N.D.*	N.D.*	N.D.*
"N.D." stands for "Not Detected"									

2.3 Sample preparation

For each batch A, B, and C, mixtures were made with water-binder ratios (w/b) of 4, 5, 6, 7, and 8. This experiment matrix was repeated twice with similar results even if there were some problems with the temperature stability during the first run. The results of the second run is presented here. The mixing was made with a KitchenAid Artisan stand mixer with a flat beater. The mixing time was 5 min, and the mixing speed was 75 rpm. For the mixing process, 1.5 kg of DS was taken, binders were added according to w/b, and mixing was initially made for 1 min. The mixer was then halted to scrape off any material adhering to the blade and the bowl. Following this, the mixing continued for an additional 4 min. Two samples for FFR and UCS were prepared from each mixing by pouring the treated DS into plastic tubes with a bottom plug measuring 50 mm in diameter and 170 mm in height. The plastic tubes were filled in three layers and tapped against the floor around 50 times after filling each layer to remove air. The specimens were placed in a water bath at 20 °C for 7 days. Following this, the specimens were removed from the plastic tubes, trimmed to a height-to-diameter ratio of 2, and FFR tested. Water content was measured on the removed part, and the bulk density of the samples was determined on the FFR specimens. The specimens were stored at 20 °C in plastic bags with moist tissue paper to prevent



Figure 3. Bulk density and water content of treated DS plotted against water-binder ratio. Open markers show initial values calculated as described in the text; solid markers show measured values after 7 days of curing.

According to the results, both calculated and measured density decrease by increasing the water-binder ratio due to less binder. Moreover, there is a difference between calculated and measured bulk density, and by increasing the w/b and decreasing binder content, the differences are reduced. This difference is probably due to entrapped air in samples after preparation, which is not taken into account in the calculations. The right diagram shows that both calculated and measured water content decrease by decreasing w/b. The reduction in soil water content commonly observed after stabilization, results from the incorporation of dry binders into the soil and the binding of water in chemical reaction products during hydration (Alrubaye et al., 2016; Cui and Fall, 2018). Also, water evaporation during mixing may influence the water content, but only to a minor extent in our study. The calculated water content is higher than the measured water content, which was measured 7 days after curing because during the hydration process, water was consumed by binders (Lu et al., 2023), and as is seen in figure 3, by increasing the content of the binder, the water consumption increases, and the differences between calculated and measured water content increases.

4.2. Free-free resonance test

drying. At 7, 14 and 28 days, FFR tests were performed, and at 28 days UCS measurements were made.

For measuring the heat release by isothermal calorimetry (IC), samples were taken by step-wise pouring treated DS into 120 ml plastic vials containing cylindrical plastic meshes (25 mm inner diameter, 50 mm in height), and tapping them against the table to remove air. Then the vessels were capped and placed in calorimeters (I-Cal Betong, Calmetrix Inc) at 20 °C and measured on for 7 days.

The cylindrical plastic meshes was used to easily extract cylindrical samples (50 mm length, 25 mm diameter) of the materials that had been measured on in the calorimeters to make FFR measurements on them at 7, 14, and 28 days. One sample of untreated DS (no binder) with a water content of 185%, was taken as a reference measurement for heat release. It showed essentially zero thermal power.

To investigate the influence of water-binder ratio and the DS on the rate of hydration, calorimetric measurements were also made on pastes made with the same binder as above and with w/b ratios of 0.4, 0.6, 0.8, 1, 2, 4, and 8. The mixing of these sample were made by hand in the 120 ml plastic vials.

3. Test methods

3.1 Unconfined compressive strength

The conventional laboratory method for assessing the quality of treated DS is the unconfined compression strength (UCS) test. The 2:1 cylinder strength was measured in accordance with the specifications outlined in EN ISO 17892-7 ("Standard - Geotechnical investigation and testing - Laboratory testing of soil - Part 7,"). In this study, the UCS test was performed on samples of 50 mm diameter and 100 mm height after 28 days of curing and the strain rate was 1 mm/min until the samples failed or the strain reaches 15%.

3.2 Nondestructive Free-Free resonance test

The free-free resonant frequency measurement (FFR), also called the free-free resonant column (FFRC) in the civil engineering field (Ryden, 2009a), is a non-destructive test suitable for measuring small-strain elastic modulus of cemented-based materials or cohesive soils in the laboratory by applying a one-dimensional wave-spread theory on an elastic rod. The small-strain elastic modulus can be correlated with the frequencies obtained from cylindrical test specimens, if their length is greater or equal to twice their diameter. The cylindrical specimens are positioned horizontally on a layer of soft foam, thus approximating free boundary conditions. A small hammer is used to initiate vibrations in the specimens. The hammer's mass is concentrated at the point of impact with sufficient mass to induce measurable

vibrations without excessively displacing or damaging the specimen. Recording the specimen's vibrational response was achieved using a compact-size accelerometers (PCB Piezoelectronics 352C33 and 352B10).

Depending on the placement of the accelerometer and the origin of the vibration source, FFR can measure the frequency of vibration in two orientations: longitudinal (axial), which can be utilized to determine the compressive wave velocity (V_p), and transversal which provides the frequency for calculating shear wave velocity (V_s). Figure 1 illustrates the longitudinal frequency assessment that was used in the present study and Fig. 2 shows an example of a frequency measurement. By selecting the primary dominant frequency and applying Eq. 1, the values for V_p of the specimen can be calculated (Ahnberg and Holmen, 2008; Åhnberg and Holmén, 2011; Ryden, 2009b; Rydén et al., 2006).







Figure 2. Example of accelerometer data

$$V_p = 2f_p L \tag{1}$$

Here, V_p (m/s) is compressive wave velocity, f_p (Hz) is axial frequency of vibration, and L (m) is the sample length. From the compressive wave velocity, the dynamic elastic modulus in small strain $E_{dynamic}$ (Pa) was calculated by Eq. 2 (Verástegui-Flores et al., 2015).

$$E_{\rm dynamic} = \rho V_{\rm p}^{\ 2} \tag{2}$$

where ρ (kg/m³) is the bulk density of the treated DS.

3.3 Isothermal calorimetry (IC)

Two I-Cal Betong (Calmetrix Inc.) instruments, each with eight isothermal heat conduction calorimeters, were used to measure the heat-release rate (thermal power) on hydrating treated DS samples. These field calorimeters have a sample size of 120 mL and have fixed references. The heat produced by the sample is conducted away to a thermostated environment to maintain a constant temperature. Within an isothermal heat conduction calorimeter, heat flow sensors quantify the heat transfer rate Φ (W) from the specimens to the calorimetric heat sink. The output from these heat flow sensors is a voltage U (V) that is transformed into heat flow by multiplication with a calibration coefficient ε (W/V). The calibration coefficients were measured by applying a known thermal power with electrical heaters; in the present case the heaters were placed in metal disks inside the same type of plastic vials as was used in the measurements. It should be noted that there is a difference between the heat flow that leaves a sample and the thermal power that is produced in a sample; because of the thermal lag of the instrument these are not equal if the thermal power is changing rapidly, as it is in the beginning of a hydration measurement.

A second parameter of interest is the baseline U_0 (V), the voltage when there is no heat production in the sample position. This voltage is usually close to zero, but it is still important to measure it accurately if the calorimetric output is to be integrated, as in the present study, as a baseline error will add up during integration and can produce a significant error in the calculated heat. The application of the calibration coefficient and the baseline is done by Eq. 3.

$$\Phi = \varepsilon (U - U_0) \tag{3}$$

A third parameter that can be of interest is the time constant τ (s), which is a measure of the thermal inertia of the sample and the calorimeter. With the time constant, the so-called Tian correction can be applied to decrease the influence of the thermal inertia (time lag) on a measurement in which rapid changes in thermal power *P* (W) occurs, Eq. 4.

$$P = \Phi + \tau \frac{d\Phi}{dt} \tag{4}$$

In an ideal case the Tian equation converts the measured heat flow to actual thermal power produced in a sample. However, the Tian equation is only approximate, and can thus only produce a partial correction of the time lag, and for the present measurements it is only of interest for the first hours after mixing, when rapid changes in the heat flow occur.

A fourth factor to consider is that when we charge a sample into the calorimeter, the calorimeter will be thermally disturbed (as the sample has a different temperature from the calorimeter). In the present calorimeters, this disturbance will last for about 1 h, but this time is shortened to about 30 min when the Tian equation is applied. The initial disturbance causes problems with the integration of the result to give the heat, as we do not want to include the initial disturbance in the integral. The solution is to start the integration after a certain time after a sample was charged; we have chosen 1 h in the present study; this means that heat produced before 1 h is not included in the heat integral.

4. Results and Discussion

4.1 Water content and bulk density 7 days after stabilization

Figure 3 shows the average measured bulk density and water content of the treated DS after 7 days of curing, compared with the calculated initial bulk density and water content. Equation 5 determines the bulk density ρ_{SDS} , which requires the masses of water, solids, and binders and their volumes (specific gravities). Dry DS, cement, and GGBFS were assumed to have specific gravities of 2.7, 3.15, and 2.9, respectively. The water content was calculated by adding the dry binder mass to the DS, i.e., by assuming that no hydration – that both decreases the amount of water and increases the amount of solid – had taken place.

$$\rho_{SDS} = \frac{\frac{M_w + M_s + M_b}{M_w}}{\frac{M_w}{G_w} + \frac{M_s}{G_s} + \frac{M_b}{G_b}}$$
(5)

Where, M_S is mass of dry DS (g), M_b is mass of binders (g), M_w is mass of water (g), G_w , G_s and G_b are specific gravity of water, dry DS and binders (g/cm³).

Figure 4 presents the compressive wave velocity (V_p) obtained through the free-free resonance test at 7, 14, and 28 days conducted on samples with a diameter of 50 mm and a length of 100 mm. As expected, an increase in water content leads to a decrease in V_p for samples with the same water-tobinder ratio. The FFR test is most effective on samples that possess sufficient strength, and the initial water content influences its performance. In samples with a high water content (WC = 291%), after 7 days of curing, the compressive wave velocity (V_p) remains relatively consistent across different water-



Figure 4. Compressive wave velocity on samples with diameter 50 mm versus w/b: a) 7 days, b) 14 days, c) 28 days.

to-binder ratios (w/b). However, at 14 and 28 days of hydration, an increase in w/b results in a slight decrease in V_p . Conversely, in samples with lower water content (WC = 138%), V_p decreases sharply with increasing w/b. Notably, samples with a w/b ratio of 8 exhibit similar compressive wave velocities regardless of the water content, whereas those with a w/b ratio of 4 show more significant differences. Figure 5 shows the same type of results as figure 4, but on calorimetric samples that are only 50 mm in length (compared to 100 mm for the UCS samples). The results show the same pattern, indicating that the smaller specimens also give useful results.



Figure 5. Compressive wave velocity measured on samples with 25 mm diameter versus w/b: a) 7 days, b) 14 days, c) 28 days

In Figure 6, a comparison is presented between the results from FFR measurements on specimens of the two different sizes. It is seen that there is a good correlation, but that the larger UCS samples tend to give higher values. The 1:1 slope and the linear correlation between the data sets have a difference in slope of about 15%. The findings are consistent with previous research, which indicates that wave velocity is influenced more by a material's homogeneity than by specimen size, provided that the length-to-diameter ratio is maintained at 2.0 (Ersoy et al., 2019; Fener, 2011).



Figure 6. Correlation between compressive wave velocity measured on samples with diameter 25 mm (x-axis) and samples with diameter 50 mm (y-axis) at 7, 14, and 28 days after treatment.

Note that specimen size does not enter the evaluation equation, so the result that smaller samples also can be used only shows that the measurement method reproduces the ideal conditions of the FFR-test (like that the sample does not interact with the surroundings and that the mass of the microphone is negligeable compared to the mass of the sample. The slight deviation of the results in figure 6 from 1:1, may result from that the conditions for the small samples are slightly less ideal than for the larger samples. Nevertheless, our results show that the smaller samples are also useful for following the development of the mechanical properties.

4.3. Compressive strength and elastic modulus

The compressive strength (USC) at 28 days was determined, and stress-strain diagrams were generated for each test; representative diagrams are given in figure 7, while figure 8 illustrates the 28 days compressive strength as a function of the water/binder ratio. The measured UCS exhibits a similar trend as V_p ; by decreasing w/b, the mechanical properties are improved, but the relative improvement is not the same for different water contents. For instance, with a water content of 291%, the average maximum and minimum strengths are 550 and 290 kPa, respectively.

(a ratio of about 2), while at a water content of 138%, the average strengths range between 2040 and 470 kPa (a ratio of about 4).

Adding binders enhances the strength and stiffness of the raw soils and results in a transition from a ductile or cohesive nature to a more brittle state. In figure 7, we can observe that as the maximal strain increases, the compressive strength decreases. The curve shapes that are shown in figure 7 are normal for stabilized DS (Lindh and Lemenkova, 2023)

It has been shown that Abrams' law ((Abrams, 1918), Eq. 6), an empirical correlation between w/b and compressive strength (*UCS*) originally formulated for concrete, also works for stabilized soil, and the values of B = 1.17-1.41 obtained in the present study are similar to findings from prior investigations (Hov et al., 2022; Hov and Larsson, 2023; Miura et al., 2001).

$$UCS = \frac{A}{B^{w/b}} \tag{6}$$



Figure 7. Stress-strain diagrams for selected specimens with different w/b



Figure 8. Compressive strength against w/b for different water content at 28 days

The static elastic modulus (E_{50}) of treated DS is modulus of elasticity at 50% strength derived from the stress-strain diagrams of UCS tests, while the dynamic elastic modulus is calculated with Eq. 3 from measured compressive wave velocity. Figure 9 presents these two elastic moduli for the present samples.



Figure 9. Elastic moduli versus w/b for different water content: a) Static elastic modulus (E_{50}), b) Dynamic elastic modulus

4.4. Isothermal calorimetry

Representative results for thermal power and cumulative heat-release, both per mass of binder, are given in Figure 10. The heat was calculated by integrating the thermal power, starting 1 h after mixing. As all results are given per mass of binder, the diagrams show the hydration kinetics of the binder.

Because of the uncertainty in the baseline, the uncertainty in the heat increases with time of integration. We have therefore only given results up to 70 h, where we estimate that the uncertainty in the heat is $\pm 5 \text{ J/g}_{\text{binder}}$ (based on two standard deviations of the differences between two baseline determination made during the measurement period).

We have also made measurements on binder pastes (no DS) with different w/b; these results are seen in Figure 11. When comparing the results of Figures 10-11, it is seen that:

- The initial kinetics are rather different for pastes and treated DS, but after about 24 h all curves follow similar trajectories, and the heat produced after 48 h is in the same order.
- The induction period followed by the main hydration that is seen for all the paste samples irrespective of their w/b – is not seen in the treated DS.

 For pastes, the 24 h heat production is higher for lower w/b, but for treated DS, for each water content (WC) the heat is higher for higher w/b. However, when the different WC are compared, lower WC gives higher heat.

The differences seen between the neat pastes and the treated DS are caused by soluble substances in the DS. It is well known that many different substances influence the hydration kinetics of binders (Weeks et al., 2008). Although we have not assessed the content of soluble compounds in the DS used in the present study, we can envision that the high organic content (6%) can influence the hydration kinetics. It is common that organic soils and humic acids retard cement hydration (Beddaa et al., 2019) but in the present study there was no clear retardation.



Figure 10. a) Thermal power per mass of binder as a function of time, b) Cumulative heat release per mass of binder versus time .

When a dredged sediment (DS) is combined with a binder, the thermal power and heat-release profiles are unique fingerprints that show the kinetics of the hydration. Calorimetric data from cement paste

measurements or measurements with other types of DS should not be used to predict outcomes for a new project involving a different D. In a worst-case scenario, contaminants in a DS can delay or inhibit (Garci Juenger and Jennings, 2002) the hydration process and render the solidification process without effect on the mechanical properties.



Figure 11. Results for cement paste (no DS). a) Thermal power as a function of time, b) Cumulative heat release per mass of binder versus time for cement paste

In the present laboratory study, the mass of binder in each sample was known and the results was therefore plotted per mass of binder. In the field, calorimetry can instead be used to assess that the correct amount of binder has been used in a treated DS. To show how this can be done, our measured heats at 24, 48 and 72 h have in Figure 12 instead been plotted per mass of sample The relations between heat per mass of the sample and mass of binder per mass of the sample are linear, with an $R^2>0.95$. These results indicate that the binder content can be estimated from heat release, and that isothermal calorimetry thus can be used as a QC tool in the field.



Figure 12. Normalized heat release correlated with normalized binder mass: a) 24 h, b) 48 h, c) 72 h. Note the different scales of the y-axis.

Figure 13 illustrates the relationship between normalized binder content and normalized heat release for all water contents. The data shows that, after 48 h of curing, there is a fair correlation between binder content and heat release for all samples (R²>0.89).



Figure 13. Normalized heat release correlated with normalized binder mass.

4.5. Correlation between UCS and heat release

The primary objective of this study is to establish a correlation between 28 days unconfined compressive strength (UCS) and heat release after 1 or 2 days, providing a method to assess the quality of treated DS in its early state. In figure 14, plots of 28 days UCS against heat release for the three water contents show linear correlations, showing that short term heat together with initial moisture content can be used as an indicator of long term strength. The three graphs represent 24 h, 48 h, and 72 h heat release compared to 28 day UCS. In the 24 h graph two of the regression lines cross, making the use of this data uncertain, but for the 48 h data, the result is good enough to be used to predict 28 d UCS from the heat and the water content.

The correlation between heat release and UCS is linear, with R²≥0.96 for water content less than 200% and R²=0.84 for water content 291%. Note that these results are specific to the DS-binder

combination tested in this study and will not apply to all types of DS and binders. In practical terms, the following procedure can be used to evaluate the quality of treated DS in the field at an early stage:

- 1. Perform isothermal calorimetry tests at up to, e.g., 2 days, and UCS at 28 d (or longer time) with the relevant DS and binder and with different combinations of w/b and water contents.
- 2. Create relations between short term heat release (at for example 48 h) and long term UCS for different water contents.
- In the field, take fresh samples of treated binder and measure water content and heat-release (during for example 48 h).
- 4. To predict the UCS, integrate the thermal power to get the heat and find the UCS corresponding to the measured water content by interpolation in the y-direction. Figure 14 (b) shows an example of this.



Figure 14. Heat release versus UCS correlation: a) 24 h after curing, b) 48 h after curing, c) 72 h after curing

5. Conclusion

We have presented a method to control the quality of stabilized dredged sediment at the early stage, while the treated sediments are still fresh and capable of being re-stabilized or removed if the quality of

treated sediment does not fulfill the project's requirements. Based on mechanical measurements and calorimetric measurements of treated dredged sediments (DS) with different water and binder contents, we found that:

- The modulus of elasticity and compressive wave velocity have the same trend as compressive strength.
- A linear correlation exists between compressive wave velocity measured for standard samples with 50 mm diameter and samples from calorimetric measurements with 25 mm diameter.
- Measurements with isothermal calorimetry for 48 h can be used to assess the content of the binder in the mix. This can then be used together with the water content to predict the 28 d strength and thus to be used as a QC control measure in the field.

6. Research significance

We introduce a novel method for the early quality control of stabilized dredged sediment using 48 h isothermal calorimetry to predict the long term unconfined compressive strength (UCS). The ability to correlate heat production within the first 48 hours of hydration with the 28-day UCS provides a rapid, non-destructive, and reliable approach to assessing stabilization quality early in the process. This method could be used both at the laboratory phase and in the field. The findings have significant practical implications for large-scale construction and dredging projects where treated sediments are reused as construction material. This method allows for the early detection of stabilization issues, reducing the need for costly rework and ensuring that the material meets strength requirements before large volumes are produced. This approach enhances project efficiency and contributes to sustainability by supporting the reuse of dredged sediments in construction, minimizing waste and environmental impact. From a scientific standpoint, this study expands the use of isothermal calorimetry beyond its traditional application in cement and concrete studies, applying it to a new material with high water content and low binder ratios. This contribution adds to the growing body of knowledge on early-stage strength prediction techniques, providing a foundation for future research on various binder-sediment combinations in geotechnical engineering.

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Paper II



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Full Length Article

Correlation between electrical resistivity and compressive strength of stabilized dredged sediment for early quality control

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ABSTRACT

Quality control of stabilized dredged sediment (DS) presents significant challenges due to its high-water content. Nowadays, many in-situ and laboratory tests have been used to evaluate the quality of treated DS, and the dominant method is 28-day unconfined compressive strength that can be done on undisturbed samples from the field and the laboratory. Due to the waiting period to get results from the tests and the destructive nature of tests, it is desirable to use a non-destructive method to control the quality of stabilized DS at an early stage. This study suggests electrical resistivity measurement as a non-destructive and fast method for evaluating the quality of stabilized DS. Dredged sediment samples from Göta älv, Gothenburg, with different water contents, were stabilized with different water-binder ratios at the laboratory. The quality of treated sediments was evaluated by uniaxial compressive strength (UCS) after 28-day of stabilizing, while strength development during the curing period was checked with a free-free resonance test at 7, 14, and 28 days of curing, and the electrical resistivity (ER) measurement monitored on some samples during the curing period. The results indicate that a combination of UCS tests and ER measurements can be utilized early stage evaluation of the quality of stabilized DS already after 24, 48 or 72 h. According to the results, after 24 h of hydration, the electrical resistivity was less than 1 Ω m. After 72 h of hydration, the resistivity was between 1 to 2.5 Ω m, which shows the development of strength. The 28-day strength varied from 0.25 MPa to 2 MPa while the resistivity varied between 3 Ωm to 22 Ωm . The observed variations in resistivity and compressive strength can be attributed to differences in the water-to-binder ratio across the samples.

This approach offers a practical, non-destructive method for detecting early quality issues of stabilized DS, enabling quicker decision-making and potentially reducing project timelines and costs while maintaining the integrity and safety of construction projects involving stabilized dredged sediments.

1. Introduction

The progression of urbanization and industrialization has led to an annual generation of a significant volume of dredged sediment (DS) [1–3], with high water content and a high organic concentration that causes high compressibility and low compressive strength from a geotechnical point of view. Traditional methods of DS management included sea dumping and land disposal, which result in the depletion of land resources and pose risks of secondary pollution and environmental safety hazards. Thus, there is a need to utilize an effective and safer procedure for managing dredged sediment and repurposing it for geotechnical or construction purposes. Stabilization/Solidification (S/S)

technology offers a comprehensive approach to enhance both the mechanical and environmental qualities of DS. This method uses cement, lime, and other supplementary cementitious materials like gypsum, coal ash, recycled bassanite, and ground granulated blast furnace slag (GGBFS) [4]. Consequently, adding binders contribute significantly to transforming dredged soil into valuable civil engineering materials suitable for road embankments and structural backfilling applications. [5–12].

In order to carry out the S/SS S project effectively, it is crucial to conduct laboratory trial tests to determine the best type of binders and their respective quantities needed to achieve the desired specific quality, accounting for both mechanical properties and leachability. This is

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followed by a pilot project to validate the results obtained from the laboratory tests in real-world field conditions [13,14] Once the mix design has been confirmed, the project implementation phase can commence, with rigorous quality assurance (QA) and quality control (QC) measures being applied at every stage, including pre-production, production, and post-production phases of stabilizing the DS [15-19]. There are several techniques available to evaluate the mechanical characteristics of treated DS [20,21]. Typically, a blend of in-situ and laboratory assessments is utilized. Common tests such as the Cone Penetration Test (CPT), Standard Penetration Test (SPT), plate load test, and unconfined compressive strength (UCS) on undisturbed samples are conventionally employed to gauge the efficacy of soil stabilization. It is important to note that due to the slow rate of strength development in stabilized dredged sediment, quality control evaluations must be conducted at specific intervals post-mixing to ensure the material achieves the desired strength level [20,21]. In the field, it is not feasible to stop the project and wait to evaluate the quality of treated DS, so multiple layers of treated DS are executed, and if the stabilized DS does not meet requirements, it may be more cost-effective to restabilize or remove it from the project.

Moreover, it is essential to recognize that in-situ test results are limited to discrete points within the stabilization area. This could hinder a comprehensive evaluation of the overall stabilization quality. Therefore, a significant number of tests are essential to obtain statistically significant findings, emphasizing the need for the development of a comprehensive, real-time, and non-destructive Quality Assurance/Quality Control (QA/QC) methodology to effectively address this challenge [22,23].

Non-destructive testing techniques, such as the ultrasonic test method, are becoming increasingly popular [24] for performing quality control and quality assurance in many aspects of engineering projects. Among these methods, the free-free resonant (FFR) test is used to determine compressive and shear wave velocities (*Vp* and *Vs*) and assess elastic modulus. By correlating these velocities with 28-day unconfined compressive strength (UCS), it is possible to monitor the quality of cement-based materials early on in a wide area [25–30], however, it is essential to keep in mind that the FFR test should be conducted on adequately hardened specimens, separate from the typical 28-day duration for UCS tests. FFR test results obtained from soft samples may not be reliable, leading to inaccurate quality assessments. Therefore, it is crucial to assess treated specimens while still fresh. This will enable cost-effective adjustments or removal, if necessary, and efficient quality control measures.

Soil electrical resistivity (ER) testing stands as a widely adopted method within geotechnical and geoenvironmental studies, owing to its efficiency in terms of time and cost, and its applicability both on-site and in laboratory settings. This method is particularly favored for its nondestructive nature, offering advantages over traditional field and laboratory tests. ER test outcomes are contingent upon several factors, including porosity, ion concentration in fluid, density, saturation degree, and particle morphology [31]. Similarly, in the context of stabilized soil, Liu et al. [32] have demonstrated that ER is influenced by factors such as cement content, whereby an increase in cement content leads to decreased porosity and water content, consequently elevating resistivity. Additionally, the degree of saturation impacts ER, with increased saturation resulting in decreased resistivity. Furthermore, curing duration affects ER by fostering chemical reactions, such as the formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which bind the soil structure more tightly, consequently increasing resistivity.

Prior studies have shown that ER measurements can effectively probe the mechanical and deformation properties of both natural and engineered soils [32–36]. In the field of cementitious materials, ER has been employed to monitor the hydration process of cement paste [37]. Regarding the literature studies that have been done, many scholars showed that ER measurement holds promise in assessing the hydration process and correlating with compressive strength, thereby serving as a potential method for quality control in cement paste and stabilized soil applications [32,38–41], However, limited research has been conducted on utilizing ER to evaluate the quality of stabilized dredged sediment (DS) with high water content exceeding the liquid limit and low cement content.

This study investigated geotechnical properties such as uniaxial compressive strength, modulus of elasticity, and porosity of stabilized dredged sediment with various initial water content (WC) and different water-binder ratios (w/b). Finally, the compressive strength of treated DS was correlated with electrical resistivity. The objective of this study is to utilize ER measurements as a non-destructive method to evaluate the 28-day compressive strength and binder content of treated DS at an early stage of stabilizing, which can be performed in the laboratory and field to control the quality of the product. At the same time, it is still fresh and can reduce the cost of restabilizing or removing treated material, as well as reducing material waste from the project if treated DS quality and strength do not meet the requirements of a project. This innovative approach allows for the assessment of stabilization quality within hours instead of weeks, offering a significant advantage over traditional methods. By providing early insights into the structural development of treated sediments, this method supports more proactive and cost-effective project management. Furthermore, the correlation between ER and UCS values established in this study highlights the potential of this method as an early indicator of stabilization success.

2. Material and methods

2.1. Material

The dredged sediment (DS) utilized in this study originated from Göta älv, Gothenburg in Sweden. Following collection, it was stored in a sealed container within the laboratory to allow for sediment settling, with subsequent separation of the water layer, which was then decanted and stored separately. The resultant DS underwent sieving using a 4 mm mesh to obtain a uniform sample termed batch A. Batch A underwent homogenization through mixing for 5 min using an electric paddle mortar mixer, followed by the extraction of samples for the determination of water content (in accordance with EN-1097-5-2008) and density (measured by the mass of 1000 ml of DS). It is important to note that these procedures are particularly relevant for laboratory preparation on a small scale. In contrast, for large-scale applications, sieving the material is not necessary. Furthermore, the mixer used in large-scale field operations is equipped with larger blades, which generate more energy, enabling a more homogeneous mixture in a shorter amount of time. The water content and density of batch A were determined to be 138±0.3 % and 1345±22 kg/m, respectively, based on eight replicate measurements (mean and standard deviation). Furthermore, the material classification of batch A was conducted through grading analysis as per standard SS 027123 [42], revealing it to be clayey silt with an average organic content of 6 % according to standard SS27105 [43]. The measured liquid limit of batch A was determined to be 83 %. Table 1 shows the properties of DS.

Subsequently, two additional batches, B and C, were created from batch A by incorporating the decanted water. Batch B had a water content of 185 % and a density of 1241 kg/m, while batch C had a water content of 291 % and a density of 1163 kg/m, effectively covering the study's target water content range of 130 % to 300 %.

The binder composition consisted of 40 % Portland limestone cement (PLC) (CEM II/A-LL 42.5 R, [44]) blended with 60 % ground granulated

Table 1
Properties of the dredged sediment.

Clay %	Silt %	Sand %	Organic content %	Classification
31.5	60	10	6	Clayey Silt

Table 2

Properties of the materials.

Binder	SiO_2 %	Al ₂ O ₃ Al _{2O3} %	CaO %	MgO %	SO_3 %	Na ₂ O %
PLC	19.31	4.31	61.08	2.38	2.96	0.29
GGBFS	30–35	10–13	30–34	12–15	N.D.	N.D.

blast furnace slag (GGBFS) [45]. Table 2 shows the properties of these materials.

2.2. Sample preparation

For each batch (A, B, and C), mixtures were prepared using varying water-to-binder ratios (w/b) ranging from 4 to 8, and Table 3 shows the mix design. This experimental setup was replicated twice and the results from both series are consistent, with the exception of one sample in Series 2 for which ER data were lost for a few days due to a contact problem. To ensure the integrity and continuity of the analysis, the results for Series 1 are presented here.

Mixing was conducted using a KitchenAid Artisan stand mixer equipped with a flat beater, operating at a speed of 75 rpm for a duration of 5 min. During mixing, 1.5 kg of DS was utilized, with binders added according to the specified w/b ratio. Initially, mixing was performed for 1 min, followed by a pause to scrape off any adhering material from the blade and bowl edges. Subsequently, mixing resumed for an additional 4 min.

From each mixing batch, two samples were extracted for Free-Free Resonant (FFR) and Unconfined Compressive Strength (UCS) testing. These samples were poured into glass fiber reinforced plastic tubes measuring 50 mm in diameter and 170 mm in height, of the type used in standard geotechnical investigation in Sweden that was introduced by SGF [46], filled in three layers and tapped against the floor to remove air. All specimens were capped and then submerged in a water bath at 20 °C for one week. After this period, specimens that became hard enough were removed from the tubes, trimmed by using a laboratory sample holder with a diameter of 50 mm and a height of 100 mm to achieve a height-to-diameter ratio of 2, and subjected to FFR testing. Water content was measured from the removed portion, and the bulk density of the samples was determined. Subsequently, specimens were stored at 20 $^\circ\mathrm{C}$ in plastic bags containing moist tissue paper to prevent desiccation. FFR tests were conducted at 14 and 28 days, while UCS measurements were taken at the 28-day mark.

To measure electrical resistivity (ER), a sample was extracted for each mixing by filling treated DS into a cylindrical tube of the same type as previously described, layered incrementally in 5–6 rounds. Rather than utilizing the tapping method for compacting the treated DS, the rodding method was employed to expel entrapped air. Previous research has indicated that both methods yield similar results, the rodding

Table	3
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Mix design and test scheme.

method may result in slightly lower compressive strength compared to tapping [47]. Following sampling, all systems were placed in a climate-controlled room set to 20 $^{\circ}$ C, and measurements were initiated and continued for up to 28 days of curing.

2.3. Test methods

2.3.1. Unconfined compressive strength

The standard laboratory approach for evaluating the quality of treated DS involves conducting unconfined compression strength (UCS) tests. These tests utilize specimens with either circular or square crosssections, with prescribed minimum dimensions. Cylindrical specimens must possess a height-to-diameter ratio falling within the range of 1.8 to 2.5, while specimens with a square cross-section should maintain a height-to-side length ratio ranging from 2.0 to 2.8. During the compression test, the specimen undergoes deformation at a strain rate of 1-2% of its height per minute, adhering to the guidelines outlined in EN ISO 17892–7:2017 [48]. In this study, the machine that used for pressing samples was MTS 810 servohydraulic universal testing machine that located at the Civil Engineering laboratory at Lund University, and all tests were conducted on samples with a diameter of 50 mm and a height of 100 mm after 28 days of curing, employing a strain rate of 1 mm/min until failure or until reaching 15 % axial strain. The compressive strength (q_u) is determined using Eq. (1):

$$q_{\rm u} = \frac{F_{\rm max}}{A} \tag{1}$$

where F_{max} (N) is the maximum load and A (m²) is the original area of the sample's cross section. Additionally, the stress-strain relationship was plotted to calculate the elastic modulus (E₅₀). This modulus is defined as the ratio of stress to strain at the point where the stress reaches 50 % of the failure stress [49].

2.3.2. Nondestructive free-free resonance test

The free-free resonant (FFR) testing methodology is a nondestructive technique well-suited for evaluating the small-strain elastic modulus and shear modulus of cemented-based materials or cohesive soils within laboratory settings. This approach employs a onedimensional wave-spread theory of elastic rods. The stiffness characteristics of the material can be directly linked to the frequencies obtained from the test, provided that the specimen adheres to the criterion $L \ge 2D$. During testing, cylindrical specimens are horizontally positioned atop a layer of soft foam, simulating free boundary conditions. Vibrations are induced in the specimens using a small hammer, with its mass concentrated at the point of impact to ensure measurable vibrations without causing excessive displacement or damage to the specimen. The vibrational response of the specimen is recorded using a compact-size accelerometer model (PCB 352C33) [50].

Experiment series	WC %	w/b	Solid/binder	Number of samples for each series	FFR test days	UCS test days	ER test durations
1 and 2	138	4	2.89	3	7, 14, 28	28	28 days
		5	3.61	3	7, 14, 28	28	28 days
		6	4.33	3	7, 14, 28	28	28 days
		7	5.05	3	7, 14, 28	28	28 days
		8	5.7	3	7, 14, 28	28	28 days
	185	4	2.15	3	7, 14, 28	28	28 days
		5	2.69	3	7, 14, 28	28	28 days
		6	3.23	3	7, 14, 28	28	28 days
		7	3.77	3	7, 14, 28	28	28 days
		8	4.31	3	7, 14, 28	28	28 days
	291	4	1.37	3	7, 14, 28	28	28 days
		5	1.71	3	7, 14, 28	28	28 days
		6	2.05	3	7, 14, 28	28	28 days
		7	2.40	3	7, 14, 28	28	28 days
		8	2.74	3	7, 14, 28	28	28 days

Depending on the placement of the accelerometer and the origin of the vibration source, the accelerometer can measure vibration frequency in two orientations: longitudinal (axial), useful for determining compressive wave velocity (V_p), and transverse, which provides the frequency required for calculating shear wave velocity (V_s). In the current study, longitudinal frequency assessment, as depicted in Fig. 1a, was utilized. Fig. 1b illustrates a schematic representation of the frequency measurement procedure during testing. By identifying the primary dominant frequency and applying Eq. (2), the values for the compressive wave velocity (V_p) of the specimen can be calculated [25, 51–53].

$$V_p = 2f_p L \tag{2}$$

In this equation, V_p (m/s) represents the compressive wave velocity, f_p (Hz) is the axial frequency of vibration, and L (m) denotes the sample length. With the help of the compressive wave velocity, we can compute the dynamic elastic modulus in small strain $E_{dynamic}$ (Pa) using the formula presented in Eq [54].

$$E_{\rm dynamic} = \rho V_p^2 \tag{3}$$

where ρ (kg/m) is the bulk density of the treated DS.

2.3.3. Electrical resistivity measurement

Electrical resistivity of the treated DS was measured using lids with built-in electrodes that were designed for the SGF standard sample tubes [55], determining the resistance of material samples of known dimension and geometry [46,56]. The top and bottom lids have four pie-shaped stainless steel electrodes each, one at the top and one at the bottom of the cylinders, which are used as current and potential electrodes for 4-electrode measurements in different permutations (Fig. 2). Thanks to the non-penetrating electrodes the FFR and UCS tests can be performed on the same undisturbed samples, which would not have been possible with standard 4-electrode soil boxes [57]. Measurement technical problems associated with unknown contact resistances in 2-electrode measurements also avoided [58]. The different electrode permutations result in reciprocal data pairs that are used for assessing data quality via calculating measurement errors [55]. A monitoring



Fig. 1. a) Free-free resonance frequency test, longitudinal measurement. b) Example of accelerometer data.

setup based on ABEM Terrameter LS2 controlled by scripts in a PC was used to carry out the automated measurements at 1 hour intervals at the beginning of the curing process and 6 hour intervals after the initial phase. A transmitted current of 1 mA was used for the measurements.

Two sets of 8 sample tubes each were used in parallel, thus the setup was capable of testing 16 samples in parallel (Fig. 2). For the current study, 15 samples were prepared with 3 levels of water content (138 %, 185 %, and 291 %) and 5 distinct w/b ratios (4, 5, 6, 7, 8). The last sample tube was filled with raw dredged sediment with a water content of 185 % to serve as a reference. The measurement of electrical resistivity (ER) was determined using Eq. (4).

$$\rho = \mathrm{RK} = R\frac{A}{L} = \frac{\Delta V}{I}\frac{A}{L} \tag{4}$$

where A is the cross-sectional area of the sample, L is the length of the sample, K = A/L, ΔV is voltage differences, and I is the current that goes through the sample. The length of the samples is measured with a caliper tool, since it can vary depending on the filling level in the sample tube.

The temperature was kept constant at 20 °C \pm 0.5 °C in the laboratory measurements which in combination with small samples makes temperature effects neglectable. Temperature at the ends of the samples was measured with the Pt1000 sensors that are integrated in the electrode lids. For field-scale measurement, on the other hand, the temperature can vary in a wide range during the curing process and would need to be accounted for.

2.3.4. Porosity of treated DS in relation to water-binder ratio

The porosity of treated DS at the mixing point, n, can be calculated by Eq. (5).

$$n = \frac{\frac{W}{b}}{\frac{W}{b} + \frac{1}{G_b} + \frac{1}{a_w \times G_s}}$$
(5)

Where w/b is a water-binder ratio, G_b and G_s refer to the specific gravity of the binder and DS, respectively, and a_w is cement content in relation to the solid weight of DS. The porosity at the mixing time shows the maximum porosity before the hydration process starts. This means that after the starting point, the porosity decreases by increasing the hydration products and filling up the voids [59].

3. Results and discussion

3.1. Bulk density

Fig. 3 displays the measured and theoretical bulk density values for samples prepared for UCS and ER tests. As expected, both the measured and theoretical bulk densities exceed that of the raw material due to the addition of dry cement mass, which effectively increases the total mass per unit volume. Furthermore, the theoretical bulk density, determined using Eq. (5) and applicable to fully saturated specimens, consistently surpasses the measured bulk density in both sample sets. This discrepancy can be attributed to the presence of entrapped air during the sampling process. Moreover, during the hydration process, the C-S-H forming fills voids in samples and causes swelling of treated samples, which increases the volume and decreases the density in comparison to the calculated density.

Our results indicate that as the water-to-binder (w/b) ratio increases, the disparities between theoretical and measured densities diminish. Specifically, at a w/b ratio of 8 and a water content of 291 %, negligible differences were observed. This shows that higher w/b ratios and water contents facilitate easier compaction by the tapping method of the treated DS during sampling. Conversely, at the lowest water content (138 %) with a w/b ratio of 4, the observed discrepancy is most pronounced.



Fig. 2. a) SGF type sample tube with standard lids fitted, plus ASSERT electrode lids with integrated temperature sensors [55]. b) Set of 8 samples prepared for monitoring.



Fig. 3. Bulk density of treated DS a) one week after curing, b) 28 days after curing, plotted against water-binder ratio. Solid markers show measured values while the open markers show values calculated as described in the text.

$$\rho_{sds} = \frac{M_{DS} + M_b}{\frac{M_w}{G_w} + \frac{M_s}{G_s} + \frac{M_b}{G_b}}$$
(6)

 M_{DS} is the weight of dredged sediment (g), M_b is the weight of binders (g), M_w is the weight of water (g), G_w , G_s and G_b are the specific gravity of water, DS and binders (g/cm3).

Fig. 4 illustrates a comparison between the measured bulk density of samples for UCS testing evaluated after one week of curing and the measured bulk density obtained from samples for ER testing measured after 28 days of curing, along with a comparison to the fitted line and the perfect line. The figure demonstrates a notable correlation between the density obtained at one week and that at 28 days for treated DS using two different compaction methods (tapping and rodding) with R^2 =0.96. Notably, the tapping method yields slightly higher bulk density compared to the rodding method. Additionally, a decrease in water content leads to an increase in the scatter of the data, attributed to variations in the workability of the treated DS. Higher water content enhances workability and consequently facilitates easier compaction. Furthermore the results show that after one week of curing, the density will not change significantly.

3.2. Free-free resonance test and compressive strength

The results of compressive wave velocity (V_p) tests conducted on samples with a diameter of 50 mm and a length of 100 mm for compressive strength evaluation are presented in Fig. 5.

The tests were carried out at 7, 14 and 28 days. Fig. 6 compares the 28-day compressive wave velocity obtained from the ER test against the $V_{\rm p}$ measurement depicted in Fig. 5.

As expected, increasing w/b leads to a decrease in V_p , and the general trend shows that the rate of decrease is higher in samples with an initial water content of 138 % compared to samples with a water content of 291 %. By comparison, the V_p of samples with the same w/b but different water content, although the cement content in samples with higher WC is more than samples with lower WC, to keep the ratio of w/b constant, the V_p is much lower in samples with the higher WC. By increasing the water content, the solid content of DS decreased at the constant volume of DS; therefore, the treated DS turned into a softer paste. As an example, in the samples with w/b = 4, the V_p varies between 700 m/s to 1150 m/s; on the other hand, for samples with w/b = 8 the cement content is also low. Fig. 6 shows the correlation between V_p measurement from samples



Fig. 4. Bulk density of treated samples from UCS versus bulk density of samples from ER measurement. The black line shows the 1:1 line that goes through (0,0) and the red line represents the trendline (R-squared=0.9646) for all data.

that were compacted by the tapping method and the rodding method, which is for samples used for the

ER test with R^2 equal to 0.98. Therefore, instead of taking separate samples for UCS and ER, there is a possibility of using just ER samples, which would reduce laboratory work and decrease material consumption.

The compressive strength (UCS) after 28 days was evaluated, and stress-strain diagrams were produced for each test. Stress-strain diagrams for this data are depicted in Fig. 7.

Samples B4-B8 belong to Batch B, while samples C4-C8 belong to Batch C. Batch B has an initial water content of 185 %, whereas Batch C has an initial water content of 291 % as described before. The numbers 4–8 following the labels denote the water-binder ratio. For instance, B4 represents a sample from Batch B with a water-binder ratio of 4.

As expected, the addition of binders significantly enhances the strength and rigidity of the untreated DS. This transformation leads to a shift from their ductility or cohesive characteristics to a more brittle state as is obvious from our results. Fig. 7 further illustrates this, showing that as strain increases, compressive strength decreases. For instance, specimens B4 and B5, characterized by a water content of 185 % and w/b ratios of 4 and 5, respectively, exhibited failure at strains below 1 %. However, as the water-to-binder ratio and water content increased, failure occurred at strains exceeding 1 %. Notably, for specimens C7 and C8, featuring a water content of 291 % and w/b ratios of 7 and 8, respectively, the strain at failure surpassed 2 %. Furthermore, a



Fig. 6. Correlation between 28- day compressive wave velocity that measured on samples that prepared for ER test and samples from UCS test.

800

 V_p (m/s) measured on ER samples

900

1000

1100

700

comparison of the behavior of different samples provides valuable insights. For instance, sample C4, which contained 291 % water and a w/b of 4, exhibited similar characteristics to sample B8, with a water content of 185 % and w/b = 8. Similarly, samples C5, C6, C7, and C8 showed



Fig. 7. Stress-strain diagram for each batch with different w/b.



 V_p (m/s) measured on UCS samples

600

500

500

600

Fig. 5. Compressive wave velocity on samples that prepared for UCS test versus w/b: a) 7 days, b) 14 days, c) 28 days.

approximately the same ductility. In contrast, the differences in samples from batch B were significant and visible. This comparison suggests that when the initial water content is high, the addition of cement might not significantly affect ductility and mechanical behavior, a finding that warrants further investigation.

To determine the static elastic modulus of treated DS, we analyze the linear segments of stress-strain diagrams that we acquired during UCS tests. To compute the dynamic elastic modulus we use Eq. (3) based on the compressive wave velocity that we measure. In Fig. 8, we can see both elastic moduli across various levels of water content and water-tobinders ratios. The results show that as we decrease the water-binder ratio, we observe an increase in the elastic modulus. However, the rate of increase is dependent on the initial water content of the mixture. For instance, when the water content is 138 %, the static elastic modulus (left figure) decreases from 426 MPa to 78 MPa. On the other hand, for samples with a water content of 291 %, the range of elastic modulus varies between 104 and 34 MPa.

In Fig. 9, we can see the relationship between porosity/binder content (a_w) and 28 days of compressive strength. Previous research has shown that the compressive strength of cement-soil is dependent on the ratio of porosity/cement-content [60–62] and can be represented by Eq. (7).

$$UCS = A \times \left(\frac{n}{a_w}\right)^B \tag{7}$$

Where A (kPa) and B (unitless) are constants that depend on the type of binders, type of soil, and curing condition [60,63,64], n is porosity (unitless), and a_w is the cement content (unitless) and UCS is the compressive strength of treated samples in kPa. The treated DS that was used in this study followed the same trend. It is worth noting that our samples have the same binder type, soil type, and curing condition, with the only difference being the water content between batches. We obtained different A and B constants due to water content differences between samples. Fig. 9 also shows that by increasing the ratio of porosity/cement content, the compressive strength decreases. The slope of the decline is shallower in water content of 291 % compared to the water content of 138 %. As previously mentioned, porosity and cement content affect compressive strength, but the water content has a more dominant effect. The line with WC=291 % shows the n/aw less than two other lines with WC=138 % and 185 %, but the UCS is lesser, which shows that the effect of water content is higher than other parameters.



Fig. 9. Relation between porosity/cement content (n/aw) against 28-day compressive strength (UCS) in different water content.

3.3. Electrical resistivity

This study aims to use electrical resistivity as a quality control method in the early stage of stabilized DS while the treated DS is still fresh; therefore, in this section, the electrical resistivity results focus on results for the first 3 days of curing in which the samples are fresh and soft. Data quality was controlled by calculating the standard deviation of measured data from the different electrode permutations, which was less than 1 % for all measurements. Fig. 10 displays the electrical resistivity measurement during the 28-day curing process of samples against the days of curing. The curves comprise all measured values without any smoothing of data where the lack of outliers bear witness of the stable data quality. The x-axis represents the time for curing and the y-axis represents ER (Ωm) on a logarithmic scale. The measurements indicate that the ER of samples increases as the w/b ratio decreases for samples with an initial water content of 138 % and 185 %, while the increment is not the same for samples with a water content of 291 %. After one month, most of the binders reacted with water, and the hydration products filled most of the pores in the samples, which resulted in decreased electrical conductivity. Previous scholars widely acknowledged that enhanced resistivity is associated with cementitious particles that exhibit a greater degree of homogeneity in distribution, along with being smaller and possessing more angular characteristics. [65]. These



Fig. 8. Elastic modulus against w/b for different water content: a) Static elastic modulus, b) Dynamic elastic modulus the solid markers show the average and open markers show the measured data.


Fig. 10. Electrical resistivity measurement against time of curing during 28 days.

factors are related to the binder/solid ratio. However, in samples with high water content, these relations seem more complicated. They might only be described if some extra investigation is performed, such as an X-ray on samples, to observe what happens microscopically.

Fig. 11 shows the ER results against curing days at the early stage which illustrates that the electrical resistivity increases with time for each w/b ratio and water content that have been used in this study. Looking at the first 3 days of curing for samples with WC=138 %, 185 % show a steeper slope for w/b 4, 5, and 6 compared to samples with WC=291 % with the same w/b. On the other hand, for w/b = 7 and 8 the

rate of increment of ER is approximately in the same range and even for samples with WC=138 % (blue line), the slope of increment becomes shallower after 2 days of curing. With continuing curing time for more than3 days, the rate of ER increment decreases, and as it is seen for samples with WC=138 % with w/b = 6.7, and 8, the ER development slope is very gentle, and the line catches up with other samples that had higher water content. According to previous research, water plays a role not only as an ion transporter but also affects the shape and formation of the pore structure in the paste, which both have direct effects on electrical resistivity [56]. The effects of the w/b ratio act differently before



Fig. 11. Electrical resistivity measurement during first 3 days of curing period.

and after the induction period of cement-based material [66–68], and are influenced by how the w/b ratio is changing. The w/b could be changed in three ways; the first method is keeping water content constant and decreasing the binder content, which decreases the dissolution ions, and the solid/binder ratio increases, causing an increase in total ER by increasing w/b. The second method is keeping the binder content constant and changing the water content. In this case, the ER decreases by increasing w/b, and the third one is mixing both methods, in which the changing ER would be irregular because both water content and binder content change, and the ER would change in terms of the competition between both factors.

Fig. 12 shows the correlation between ER and binder content for curing periods 24 h, 48 h, and 72 h, as well as different water-binder ratios and water content. According to the results, by increasing the water content, the electrical resistivity decreases. As an example, if looking at the data for samples with w/b = 4, by decreasing the water content, the ER increases. Moreover, for samples with the same water content, by increasing the w/b ratio, the electrical resistivity increases. Like samples with a water content of 291 %, the ER increases by increasing w/b after 24 h of curing. This trend continuous even after 48 h of curing, but looking at the 72 h of measurement for samples with water content of 138 %, by increasing w/b, the ER decreases while at the same curing time, for samples with 291 % water content still, the ER is enhanced by increasing w/b. As expected both curing time and water content affect ER measurement. When the binder is mixed with dredged sediment, at the time when binders come into contact with water, the hydration starts, and this process is divided into 6 phases called: (I) dissolution phase, (II) induction phase, (III) setting phase, (IV) hardening phase, (V) acceleration phase, and (VI) stable phase [69]. At the dissolution and induction phases that start directly after mixing, the mineral phases of cement like C3A start dissolving and releasing conductive ions, consequently, the electrical resistivity decreases. Therefore, in the sample that has a high binder content, the number of ions that dissolve and transport by water is higher, so the conductivity increases resulting in less electrical resistivity [38]. In other phases, at the beginning of setting time and starting forming C-S-H the conductive ions content decreases and hydration gel products grow up, causing tortuosity of the conductive path that results in increasing ER and compressive strength [66–68]. Fig. 12 can be used to predict the binder content in samples, which helps estimate the quality of treated dry solids (DS) and ensure compliance with design guidelines. Initially, the graph

can be created in a laboratory through trial tests. Then, during field operations, the electrical resistance (ER) of the samples is measured at intervals of 24, 48, and 72 h after curing. By comparing these field measurements with the laboratory-generated graphs, one can estimate the amount of cement used for each batch of mixing in the field. The work steps could be as follows:

- Laboratory trial test: In the laboratory, samples with different w/b and water content should be prepared, and the electrical resistivity measurement during the curing period should be continuous. Then, 28-day compressive strength should be measured for each sample. Graphs like Fig. 12 would be produced after these tests.
- Field test: While performing the project, by sampling from each batch and measuring ER during 24, 48, and 72 h of curing.
- Estimation process: For instance, if a field sample has an ER of 0.8, and by knowing w/b and WC, the result is compared with a graph that was produced at the laboratory and finds the corresponding binder weight.

Fig. 13 shows the relation between measured electrical resistivity during the first 3 days of curing and 28 days of compressive strength. Each line shows a linear correlation between ER and UCS regarding w/b in which the lower bound shows samples with WC=291 %, the middle part shows samples with WC=185 %, and the upper part points show samples with 138 % water content. The sample with higher compressive strength has higher resistivity. Previous scholars used electrical resistivity measurement to predict the compressive strength of concrete after 7 days of ER measurement [70] and predicted 28 days of compressive strength of cement paste after 24 h of ER measurement [71] with w/b = 0.4, and found linear regression between ER and UCS. In the Solidification/Stabilization (S/S) project for dredged sediment, the dry solids (DS) exhibit significant variability in water content. Therefore, it is essential to determine the water content before each mixing batch to optimize the binder content. The electrical resistivity (ER) measurements, as previously mentioned, can be conducted in the laboratory under controlled conditions, including varying water content (WC), water-to-binder ratios (w/b), and temperatures matching those in the field. These measurements are used to produce diagrams like Fig. 13.

In the field, by measuring the temperature, ER, w/b, and WC, it would be possible to predict the 28-day compressive strength after 24 h of curing. This prediction would allow for an evaluation of the mix's



Fig. 12. Electrical resistivity measurement during first 3 days of curing period against binder weight (g). Note difference in resistivity scale.



Fig. 13. Electrical resistivity measurement during first 3 days of curing period against 28-day compressive strength. Note difference in resistivity scale.

quality before the treated DS hardens. By comparing the field data with the laboratory-produced diagrams, as shown in Fig. 13, one can estimate the compressive strength.

This estimation process using ER measurement follows the same procedure outlined previously in Fig. 12, where the binder weight was estimated. Essentially, the field measurements are plotted against the laboratory reference curves to determine the expected compressive strength of the mix.

4. Conclusion

In this study, sediment that was dredged from Gothenburg harbour was utilized. Three distinct batches with varying water content levels of 138 %, 185 %, and 291 % were prepared. These batches were mixed with a binder that contained GGBS (ground granulated blast furnace slag) and cement, with five different water-binder ratios of 4, 5, 6, 7, and 8. Compressive wave velocities with non-destructive FFR tests were determined after 7, 14, and 28 days of curing, and 28-day UCS tests were performed. Non-destructive electrical resistivity measurements were done to allow the same samples to be used for UCS test. The results show that:

- Water content has a more significant impact on compressive strength and compressive wave velocity than cement content.
- During the hydration process, the resistivity of treated DS increases. At the first three days of hydration, the ER rises from 0.6 Ω m to 2.5 Ω m and then increases to 22 Ω m after 28 days of hydration. The increase depends on water content and water-binder ratio.
- Monitoring electrical resistivity allows for controlling the binder content at an early stage of curing. This could be done by performing this test during the primary phase of the laboratory tests and comparing it with field measurements.
- Electrical resistivity measurements taken for 24, 48, or 72 h, along with water content and w/b ratio, can be used to predict the 28-day strength.

5. Limitation and future study

All the quantitative results from UCS, FFR, and ER measurements are valid for the dredged sediment used in this study. This means that changing DS properties would change the results, but the procedure of using ER as a non-destructive quality control method could be valid for all kinds of DS.

For future studies, the water content could be varied between 200 % and 400 % stepwise, 50 %, to see which water content causes the ER measurement to not follow the theory, as in Fig. 10 with WC=291 %.

CRediT authorship contribution statement

Mohammadhossein Gholampoor: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Torleif Dahlin: Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition. Mikael Lumetzberger: Writing – review & editing. Per Hedblom: Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Paper III

METHODOLOGY FOR SAMPLE PREPARATION FOR QUALITY CONTROL OF STABILIZED DREDGED SEDIMENT

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KEYWORDS

Stabilization/Solidification, Dredged sediment, Quality control, Calorimetry, Electrical resistivity

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 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.

Batch number	Dredged sediment	Water content		Density	
		Mean%	COV%	Mean (kg/m ³)	COV%
1	Stavanger harbor, Norway	349	1.98	1130	0.79
2	Oslo Harbor, Nor- way	88	0.9	1510	0.73

Table 1. Dredged sediment water content and density

The binders used for the mixing process were CEM IIIB 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 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 DISSCUSSION

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	P wave velocity			Unconfined compressive strength		
time (minu-	Days after	Mean value	Coeffici-	Days after	Mean value	Coeffici-
tes)	treatment	of FFR	ent of va-	treatment	of UCS	ent of va-
		(m/s)	riance (%)		(kPa)	riance (%)
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		P waya valaa	ity	Unconfined compressive strength			
wirxing	r wave velocity			Uncontined compressive strength			
time (mi-	Days	Mean	Coeffi-	Days	Mean	Coeffi-	
nutes)	after	value of	cient of va-	after	value of	cient of va-	
	treatment	FFR (m/s)	riance (%)	treatment	UCS (kPa)	riance (%)	
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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