Methods to Investigate the Quality of Stabilized Dredged sediments

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2024

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Gholampoor, M. (2024). *Methods to Investigate the Quality of Stabilized Dredged sediments*. [Licentiate Thesis, Division of Building Materials]. Division of Building Materials, LTH, Lund University.

Total number of authors:
1

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Mohammadhossein Gholampoor

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Licenciate DISSERTATION

Licenciate Thesis, Report TVBM-3193, for the degree of Licanciate (Lic) at the Faculty of Engineering at Lund University to be publicly defended on Monday, 25th of November 2024, at 14:00, Room V:D, John Ericssons väg 1, Lund.

Faculty opponent
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Organization:

LUND UNIVERSITY, Department of Building and Environmental Technology, Division of Building Material

Document name: **Licenciate Thesis**

Date of disputation 2024-11-25

Author(s): **Mohammadhossein Gholampoor**

Sponsoring organization: **SBUF, Trafikverket, PEAB**

Title and subtitle:**Methods to Investigate the Quality of Stabilized Dredged sediments**

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.

Key words: Stabilization/Solidification, High water content, Quality control, Iso thermal calorimetry test, Electrical resistivity test, Mixing time

Language: **English**

ISSN and key title: 0348-7911 TVBM

Price

ISBN:
978-91-8104-292-4 (Print)
978-91-8104-293-1 (Pdf)

Number of pages: **71**

Security classification

Recipient’s notes

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Coverphoto by Mohammadhossein Gholampoor

Faculty of Engineering
Department of Building & Environmental Technology Division of Building Material
ISBN 978-91-8104-292-4 (Print)
ISBN 978-91-8104-293-1 (Pdf)
ISSN 0348-7911 TVBM

Printed in Sweden by V-huset, Lund University
Lund 2024

Printed matter
3041 0903
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Acknowledgments

I would like to express my deepest gratitude to my supervisory team, Prof. Lars Wadsö, Dr. Per Lindh, and Dr. Peter Johansson for their exceptional guidance and unwavering support throughout my studies. A special thanks to Lars Wadsö, my main supervisor, for his insightful feedback and continuous guidance. His expertise and encouragement have been vital to my academic progress.

I am profoundly grateful to Dr. Torleif Dahlin and his team for their invaluable insights into resistivity measurement. The knowledge I gained from them was crucial to the successful completion of my third article. Their willingness to listen and provide support whenever I needed it was indispensable, and I cannot thank them enough.

I would also like to extend my heartfelt thanks to Dr. Nils Ryden, my former manager at PEAB. His belief in me opened the door to pursuing my PhD at Lund University. Nils has been one of the best colleagues I have ever had, always supportive and positive, and I am immensely grateful for the opportunity he provided.

I am equally thankful to my current manager, Michael Sabattini, for his unwavering support during this period. His encouragement to continually develop myself has been greatly appreciated. My colleagues at PEAB Anläggningsteknik have also played a crucial role in my journey, and I sincerely thank them for their support and assistance.

I am immensely grateful for the financial support provided by the Development Fund of the Swedish Construction Industry (SBUF), Trafikverket, and PEAB. This project would not have been possible without their generous contributions. I would also like to acknowledge the valuable input from all the reference group members, whose feedback was instrumental in shaping my research.

Finally, I wish to express my deepest appreciation to my family, especially my parents, whose unconditional love and constant support have been the foundation of my academic pursuits. To my beloved wife, Mahsa, and my wonderful children, Elina and Arvid—words cannot adequately express the depth of my gratitude for your unwavering love, patience, and encouragement.

Lastly, I want to extend my thanks to all my Iranian friends—I would like to specifically mention Iman, Mohammad, Koroush, Hossein, Kavan, Amir, Alireza,

Amirhossein, Marzieh, and Behshid—for their kindness, guidance, and support during my studies. Your friendship has been a source of strength throughout this journey.

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 assesments for a port in Sweden, Nordic Geotechnical Meeting, 2024, Göteborg.

Abbreviations

S/S	Stabilization/Solidification
UCS	Unconfined compressive strength
FFR	Free-free resonance test
DS	Dredged sediment
IC	Isothermal calorimetry
ER	Electrical resistivity
QC	Quality control
QA	Quality assurance
w/b	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 QC/QA 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?

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.

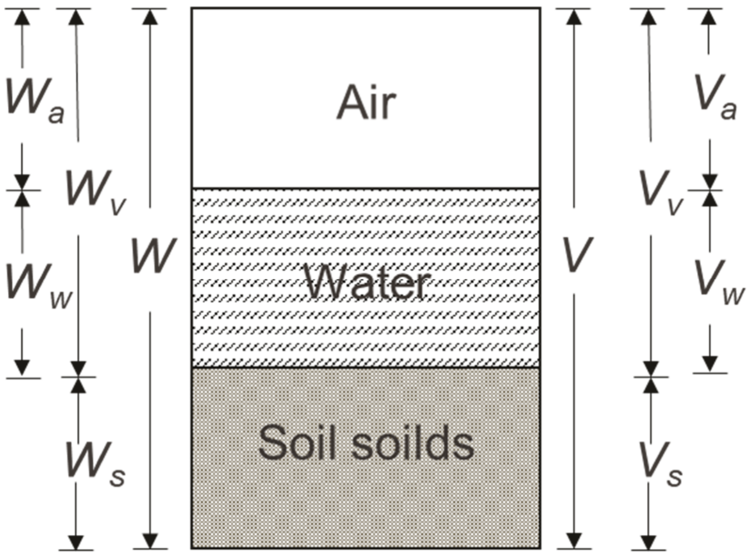

Figure 1: Weigh-volume relationships for soil aggregate

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:

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

Here, M_S represents the weight of dry DS in grams, M_w signifies the water in grams, and M_b is weight of binder (g), while G_w, G_s and G_b are the specific gravity of water, soil and binders, respectively in (g/cm^3).

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 (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and calcium aluminoferrite (C_4AF) [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:

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

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

$$C_3A + H_2O \longrightarrow C_3AH_6 \qquad (9)$$

$$C_4AF + H_2O \longrightarrow C_3AH_6 + CF_4 \qquad (10)$$

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 (C_3S) 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].

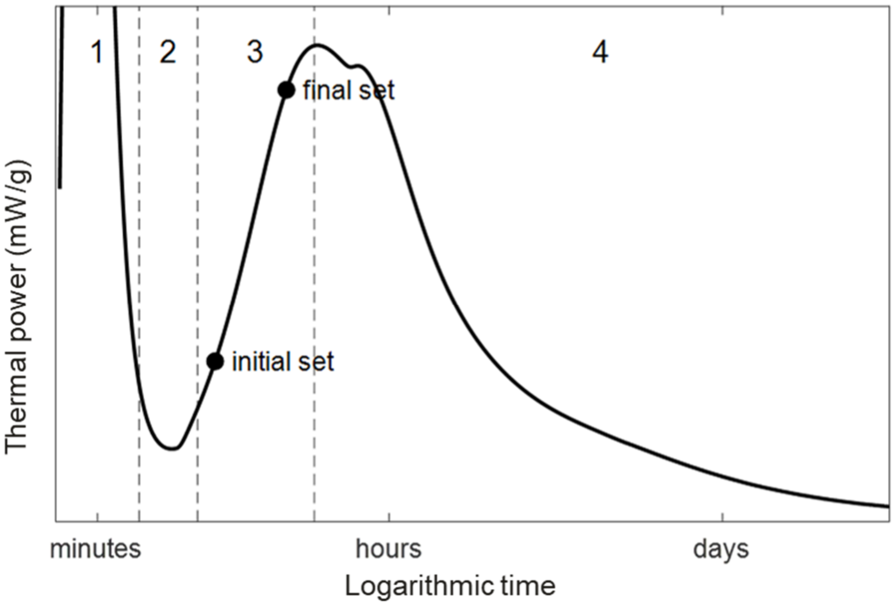

Figure 2: Typical thermal power (rate of heat of hydration) of a Portland cement as a function of time.

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.

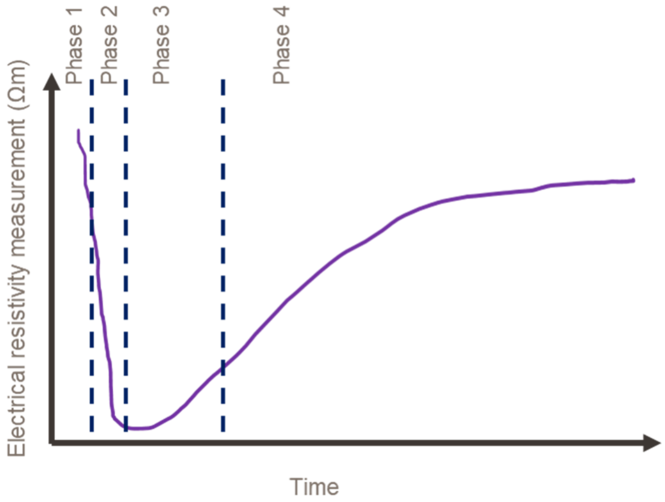

Figure 3: Schematic result of electrical resistivity measurement on stabilized soil material

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 Ca^{2+}, K^{+}, Na^{+}, OH^{-}, and SO_4^{2-} 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 mm^2. 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 (m^2) 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.

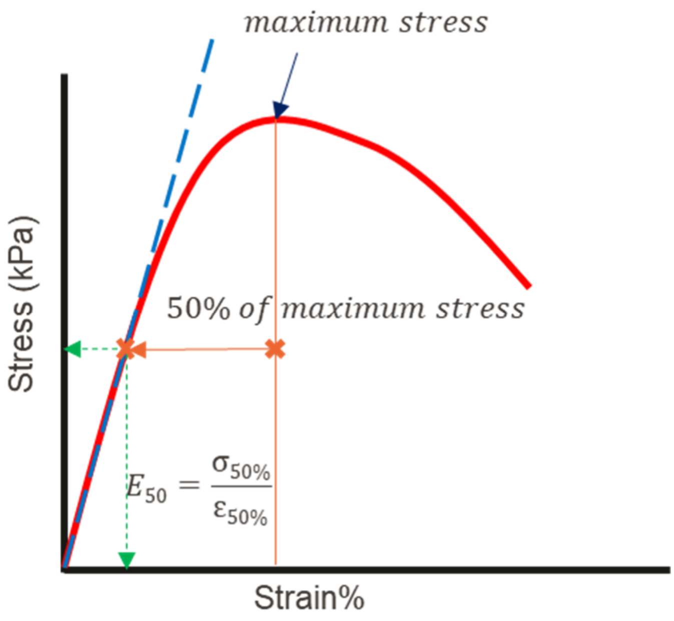

Figure 4: Schematic stress-strain results from UCS test and elastic modulus calculations (see the test).

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].

$$q_u = \frac{A}{B^{\frac{w}{b}}} \tag{12}$$

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

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 (m^3).

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/m^2) 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.

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

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 non-destructive 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/m^3, 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/m^3, 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	**Sio$_2$ %**	**Al$_2$O$_3$ %**	**CaO %**	**MgO %**	**SO$_3$ %**	**Na$_2$O %**	**K$_2$O %**	**TiO$_2$ %**	**Fe$_2$O$_3$ %**
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)

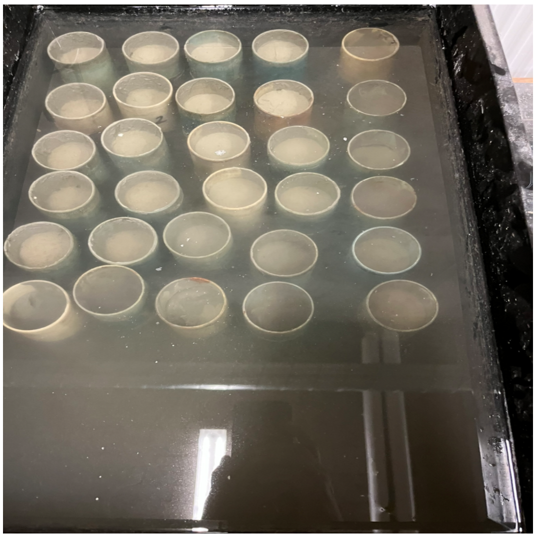

Figure 8: Submerged samples in water bath (photo by author)

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 ºC. 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 ºC; 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.

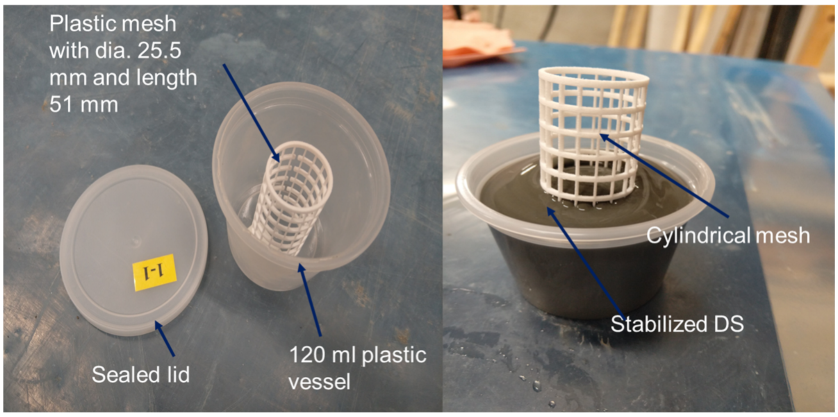

Figure 11: Plastic vessel for calorimetry test with cylindrical plastic mesh that simplified the extraction of a cylindrical sample for FFR testing after hardening; in the right hand image, the mesh is only half inserted into the sample (photos by Lars Wadsö)

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.

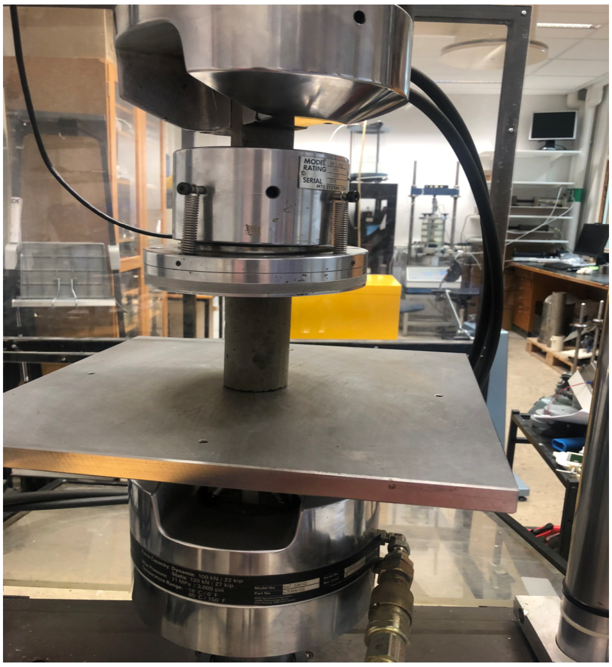

Figure 13: MTS810 machine during testing (photo by author)

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 one-dimensional 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 measurement conducted during the test. By selecting the primary dominant 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.

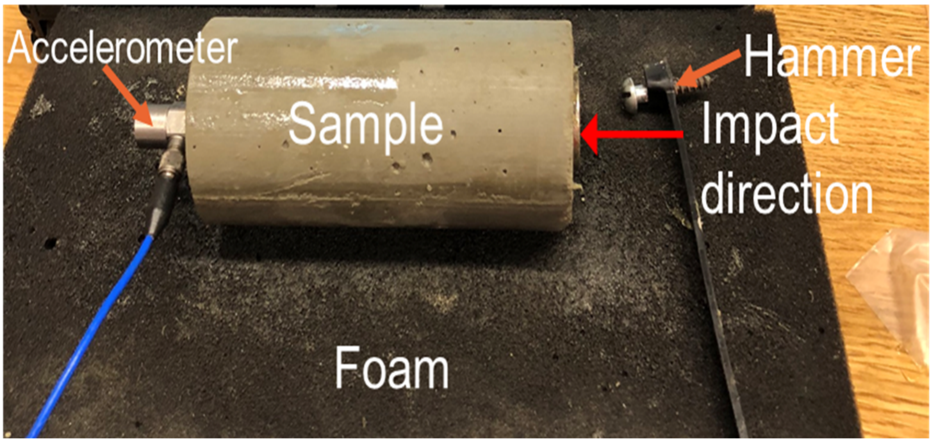

Figure 14: Longitudinal FFR test (photo by author)

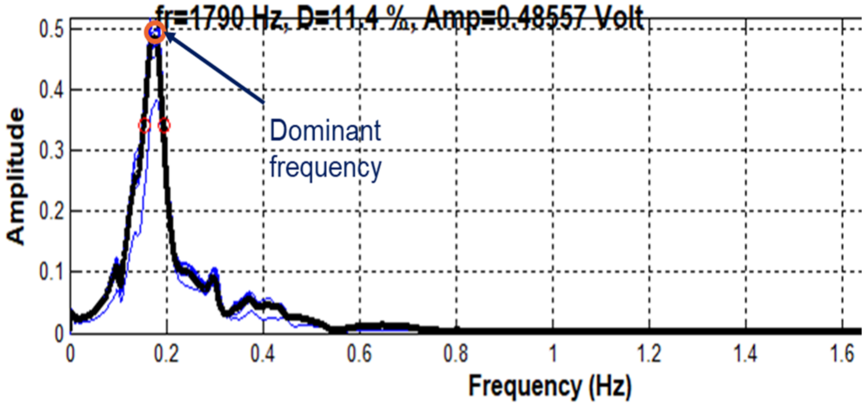

Figure 15: Sample frequency measurement in FFR test (photo by author)

$$V_p = 2f_pL \tag{18}$$

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

f_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/m^3) 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.

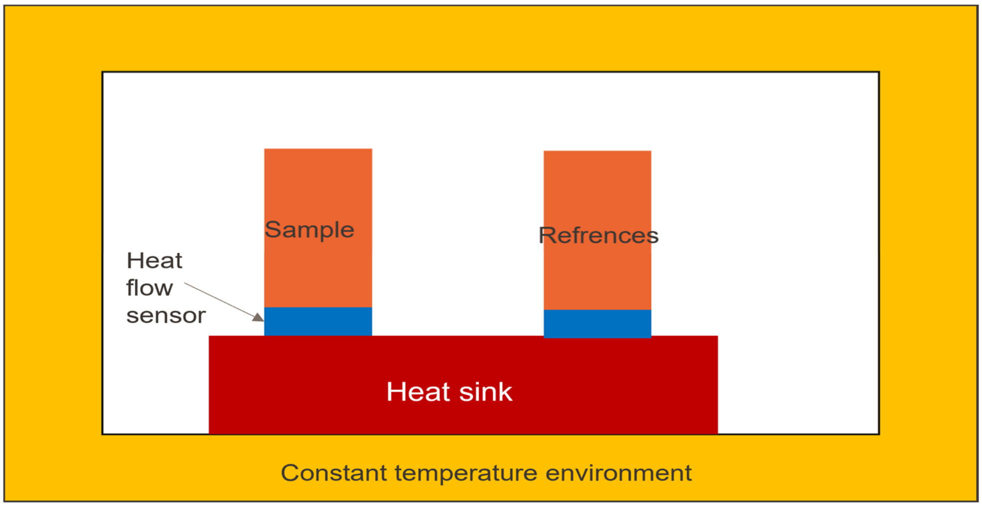

Figure 16: Isothermal calorimetry measurement concept

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.

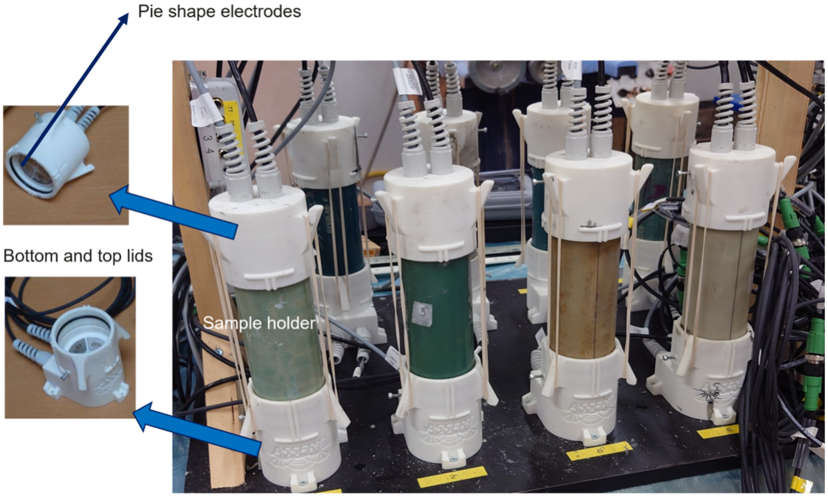

Figure 17: Electrical resistivity sample holders with electrode lids (Photo by Torleif Dahlin)

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 (m^2), and ρ is the electrical resistivity (Ωm).

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 enhances 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 sediment collection site**	**Water content**		**Density**	
		Mean (%)	**Coefficient of variation (%)**	**Mean (kg/m^3)**	**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/m^3 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.

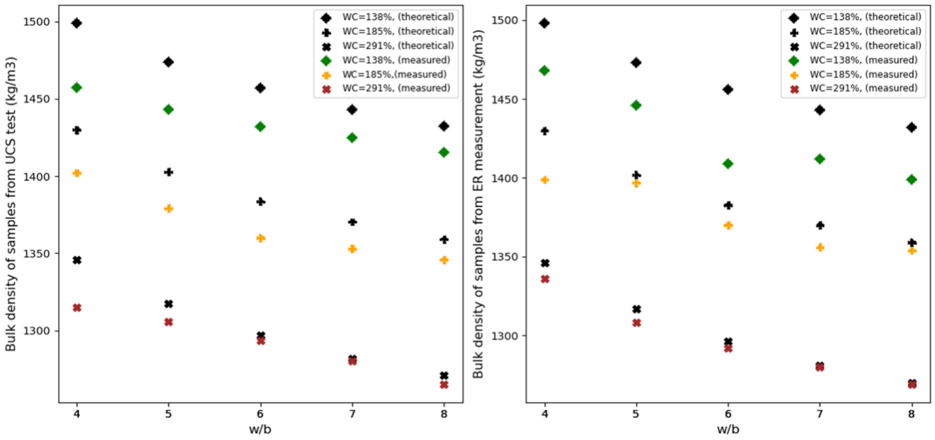

Figure 18: Theoretical and measured bulk density against water-binder ratio, left: samples from UCS test, right: samples from ER test

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.

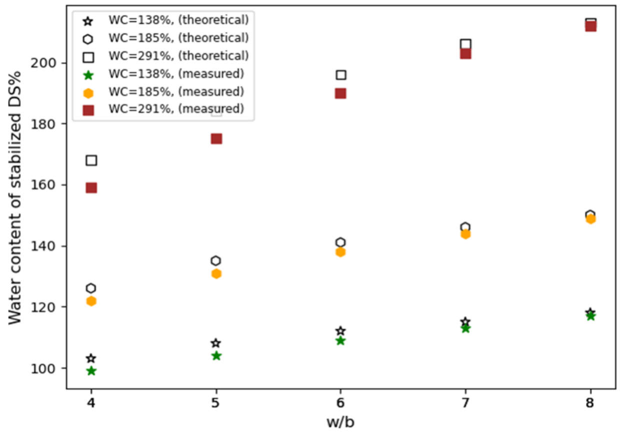

Figure 19: Theoretical and measured water content against the water-binder ratio of treated DS

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.

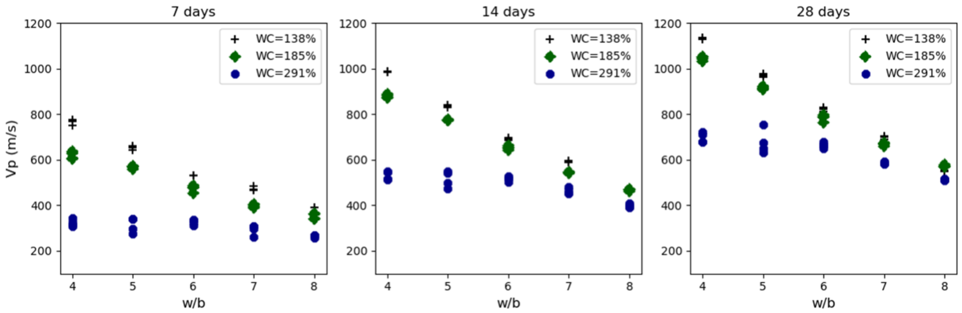

Figure 20: P-wave measurement in different curing times (7, 14, and 28 days) against water-binder ratio for samples from UCS test

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].

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

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.

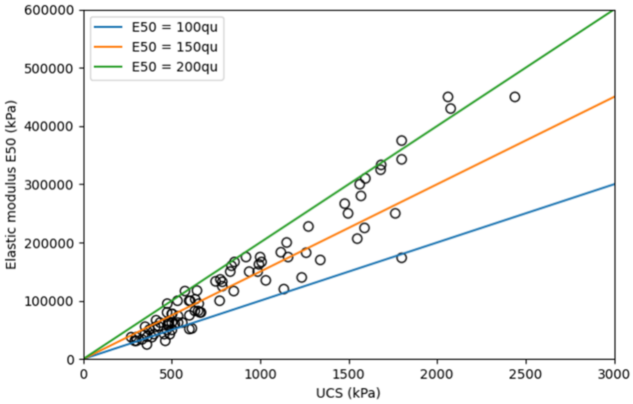

Figure 21: Correlation between elastic modulus (E_{50}) and compressive strength

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.

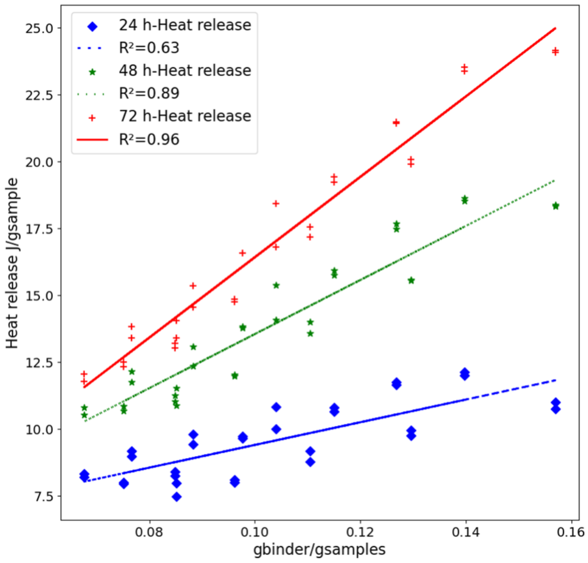

Figure 22: Correlations between binder content and heat-release, both normalized with weight of samples

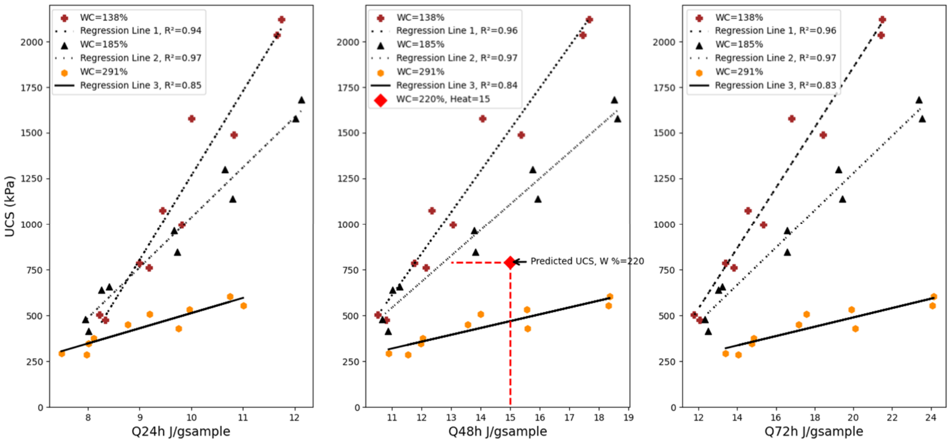

Figure 23: Correlations between heat release after 24 h, 48 h, and 72 h of curing normalized with weight of samples against 28-day compressive strength.

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%.

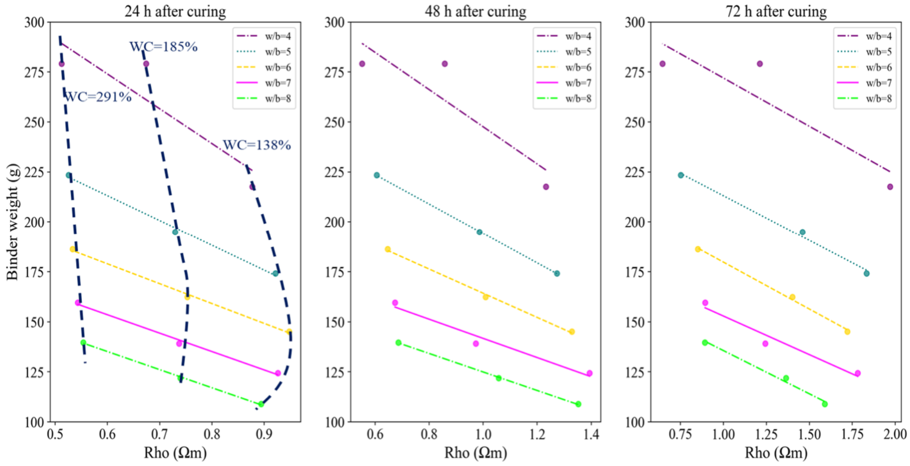

Figure 24: Electrical resistivity against binder content for different curing time periods.

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

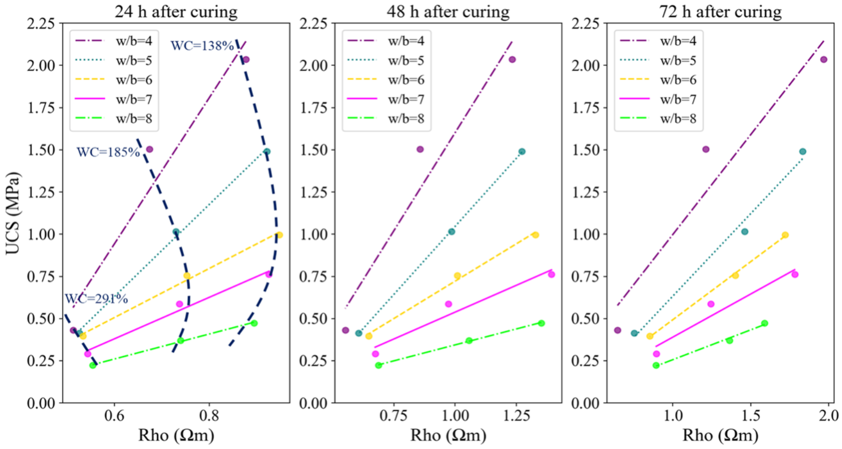

Figure 25: Electrical resistivity against compressive strength for different curing time periods.

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 velocity***			***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 time (minutes)	***P_Wave velocity***			***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 (%)
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 time (minutes)	***P_Wave velocity***			***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	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			

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

Mixing time (minutes)	***P_Wave velocity***			***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	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			

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×q_u to 200×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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