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Master’s Programme in Geoengineering

Effect of Binder Content on the Carbon Sequestration Capacity of Stabilized Soft Clays

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Abstract

Deep mixing method (DMM) is one of the most used methods to stabilize soft clay in Finland. DMM is a process that involves combining soil at its inherent moisture content with stabilizing agents such as cement and lime. Nevertheless, it can be noted that both lime and cement have a high carbon footprint. This has a negative effect on the environment and ecosystem. To deal with this problem, Aalto University has been studying the effect of carbonation on the reaction of alternative binders.

The main objective of this research is to assess how the amount of binder and carbonation duration affects the ability of stabilized soft clays to carbon sequestration capacity. Four different binders were used in laboratory for stabilizing soft clay from Malmi area of Helsinki, Finland. These binders are GTC (a mixture of gypsum, slaked lime, and cement type I) provided from Nordkalk Oy, CEMI (cement type I), CEMIII (cement type III) sourced from Finnsementti Oy, and UPM (fly ash) obtained from UPM-Kymmene Oy + CEMII (cement type II) sourced from also Finnsementti Oy.

Unconfined compression strength (UCS) tests and thermogravimetric analysis (TGA) were performed. The aim was to observe the effect of carbonation on the strength of the soft clay based on UCS tests. In addition, TGA was used to determine temperature range that weight loss of the soft clay occurs. The amount of carbon dioxide that was sequestered can be established by measuring the weight reduction that occurs during TGA.

CEMI binder was the most effective binder on the strength of the soft clays with 18% and 10% increasing strength due to carbonation for 150 kg/m^3 and 175 kg/m^3, respectively. In addition, CEMI binder had the second highest amount of carbon dioxide (CO_2) absorption. However, the highest amount of net CO_2 was found for CEMI due to CO_2 emissions from manufacturing. GTC binder absorbed the most amount of CO_2 with between 12 and 17 kg CO_2 eq. e. /m^3 compared to other binders, and the amount of CO_2 emissions from manufacturing of it was the least. Nevertheless, GTC binder did not show any positive effect on strength of the soft clay due to carbonation. The amount of weight loss of the samples increased by carbonation for all binder types, and it was seen that the amount of weight loss of the samples increased by rising binder content of the samples, except UPM+CEMII binder. Based on the UCS tests results, it was observed that higher amounts of binder, particularly at concentrations of 150 kg/m^3 and 175 kg/m^3, positively impacted the strength of the stabilized soft clays, except GTC binder.

Keywords deep mixing method, soft clay stabilization, binder content, carbon sequestration capacity, unconfined compression strength, thermogravimetric analysis

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Contents

Preface

The research presented in this thesis focuses on the effect of binder content on the carbon sequestration capacity of stabilized soft clays. Throughout this research, I have been fortunate to work with experienced knowledgeable advisors who have provided invaluable guidance and support. I would like to express my gratitude to my supervisor, Professor Leena Korkiala-Tanttu, for her support and mentorship during my master's thesis. I would also like to thank my advisors Raghuram Ammavajjala and Henry Gustavsson for their guidance and insightful feedback. In addition, I would like to thank Jukka Piironen and Matti Ristimäki for their technical support and help.

I would like to thank my family and my friends who have provided support and encouragement throughout my academic career.

Finally, I would like to dedicate this thesis to my dear grandmother Şerife Ceran, and my dear friend Yunus Emre Balcı.

Abbreviations

CEM I	Cement type I/52.5 R
CEM II	Cement type II/B-M (S-LL) 42.5 N
CEM III	Cement type III/A 52.5 L
CO_2	Carbon dioxide
$Ca(OH)_2$	Calcium hydroxide
$CaCO_3$	Calcium carbonate
CS	Carbonation sludge
DDM	Dry deep mixing method
DMM	Deep mixing method
DTA	Differential thermal analysis
DTG	Derivative thermal gravimetric curve
F-T	Freezing-thawing
GCMC	Grand canonical Monte Carlo
GGBFS	Blast furnace slag
GTC	Gypsum, slaked lime, and cement type I
GTK	Geological Survey of Finland
$H2CO_3$	Carbonic acid
HCO_3	Bicarbonate
HNO_3	Nitric acid
MIP	Mercury intrusion porosimetry
$MgCO_3$	Magnesium carbonate
MgO	Magnesium oxide
SEM	Scanning electron microscopy
TG	Thermogravimeter
TGA	Thermogravimetric analysis
UCS	Unconfined Compressive Strength
UPM	Fly ash
XRD	X-ray powder diffraction

1 Introduction

Soil stabilization refers to the enhancement of the physical and chemical characteristics of soil to enhance its strength and stability. There are several ways to achieve this objective, which may involve the addition of cement, lime, or other agents that enhance stability, compaction of the material, or blending it with other substances.

Finnish clays were formed by pulling away the Fennoscandian Ice Sheet of the Weichselian glaciation (Di Buò, et al., 2019). Soft clays from Scandinavia are frequently somewhat overconsolidated or nearly normally consolidated. Overconsolidation is typically a side effect of aging (Bjerrum, 1972), cited by (D'Ignazio, et al., (2016)).

One of the most used method for soil stabilisation in Scandinavian countries is Dry Deep Mixing (DDM) method. The DDM is a way of soil stabilization that involves blending soil in its natural water content with stabilizing agents like cement and lime. This method is commonly used in Finland particularly, due to its suitability for the country's cold, arctic climate and high water content of the soft clays. Soft clays in Finland typically have a high water content due to the cool and moist climate of the region.

Deep mixing method (DMM) works often by using lime and cement as binders, but their production process generates a significant amount of carbon dioxide emissions. The thermal decomposition of limestone during the production of lime and a chemical reaction during the manufacturing of cement both release CO_2 into the atmosphere. As a result, it is necessary to explore alternative binders with lower carbon emissions for use in DDM works. Alternative binders with lower CO_2 emissions and therefore more environmentally friendly can be used instead of lime and cement in DDM works. By utilizing these alternative binders in DDM works, the construction industry can greatly reduce its carbon footprint and contribute to mitigating the negative impacts of climate change. This research is a continuation of research at Aalto University on the CO_2 sequestration capacity of Malmi clay stabilized with different types of binders.

To address this issue, the thesis has two primary objectives. The first objective is to evaluate the impact of binder content on the ability of stabilized clays to carbon sequestration. The second objective is to demonstrate how the strength of these clays is affected by the duration of carbonation at varying levels of binder content. The findings of this research could provide valuable insights into the optimal binder content that balances both carbon sequestration and strength requirements in DDM works, while also reducing their environmental impact.

This thesis present a new storage method for CO_2 by using four different binder types to stabilize Malmi Clay which was taken from Malmi Airport, Southern Finland. These binders were GTC from Nordkalk Oy, CEM I, CEM II and CEM III from Finnsementti Oy, and UPM ash from UPM-Kymmene Oy.

The experiments involved the use of different binder contents. Dry mixing method was used to mix the clay and binders.

Carbonation process of the samples were done in the carbonation chamber with various duration time and pressure. After carbonation thermogravimeter analysis (TGA) was used to evaluate the weight change of the carbonated samples as it is exposed to different temperatures and periods of time. With weight loss during TGA, the amount of sequestrated CO_2 can be determined.

The following study presents the findings and analysis obtained from unconfined compression tests conducted after carbonation for each sample, which were aimed at determining the strength and deformation of the stabilized clay.

2 Literature Review

In literature review of this thesis ground improvement and soil stabilization mentioned. CO_2 emissions from cement, lime and CO_2 emissions from the binders used in this research were compared and clarified. Additionally, carbon sequestration capacity and microstructural characteristic of clay were referred. In addition, the tests that were performed in this research such as CO_2 carbonation, thermogravimetric analysis and unconfined compressive strength were explained.

2.1 Ground Improvement

Any approach or process that enhances the engineering properties of the treated soil mass is referred to as ground improvement. Shear strength, stiffness, and permeability are often changed attributes. Raju, (2010) suggested that ground improvement is typically done in accordance with the following principles:

- Consolidation (e.g. prefabricated vertical drains & surcharge, vacuum consolidation, stone columns)
- Chemical Modification (e.g. deep soil mixing, jet grouting, injection grouting)
- Densification (e.g. vibro compaction, dynamic compaction, compaction grouting)
- Reinforcement (e.g. stone columns, geosynthetic reinforcement) (Raju, 2010)

Moreover, ground improvement method categories presented by such as ground improvement without admixtures in non-cohesive soils or fill materials, ground improvement without admixtures in cohesive soils, ground improvement with admixtures or inclusions, ground improvement with grouting type admixtures, and earth reinforcement are mainly used in Europe.

By adding a chemical binder, chemical modification modifies the physical characteristics of the soil material. Common chemical adhesives include fly ash, cement, and lime. The soil is intended to be made stronger and more rigid. In some situations, the aim is to decrease permeability. The method of injecting the binder into the soil matrix is a common way to classify ground improvement through chemical modification (Raju, 2010).

The process of ground improvement plays a vital role in geotechnical engineering. It involves many methods that are employed to tackle various issues associated with the use of soil as a structural material. This vast and important field involves various procedures and technologies that can improve soil properties, making it more suitable for construction and other purposes. Many soils treatment and improvement techniques exist, with many of them primarily utilized to address clayey soils, which are structurally weak soils. Soft clays are regarded as one of the most problematic because of its low shear strength, high compressibility, and vulnerability to volumetric change. As a result, soft clays often must be treated before they may be used for engineering purposes (Afrin, 2017).

2.2 Soil Stabilization

Soil stabilization is the process of modifying soils to strengthen their physical and mechanical characteristics. Stabilization can improve the soil shear strength and durability (Manzoor & Yousuf, 2020) of a soil, load bearing capacity, filter, drainage system (Prabakar, et al., 2004) and/or manage its shrink-swell characteristics, which increases capacity of subsoil to support foundations and pavements by increasing the load bearing capacity. It is possible to define soil stabilization as the modification or preservation of one or more soil properties in order to improve the engineering properties and performance of the soil. When some stabilizing substances are introduced to the soil to strengthen its properties, the process is referred to as soil stabilization. In order to obtain a more thorough comprehension of the specific changes in soil properties resulting from the addition of soil admixtures, these stabilizers in varying proportions when mixed with the soil is utilized. This method allows for the observation of how different soil characteristics, such as strength, durability, and erosion resistance, are impacted. Using this approach, the ideal amount of stabilizer needed to achieve the desired soil properties for a particular application can be determined. This helps to ensure that soil stabilization is done in an effective and efficient manner. (Khan , et al., 2020).

According to Bowles, (1979) although heat and electrical methods have occasionally been applied, mechanical or chemical stabilization is more common. Compaction, a number of proprietary vibration techniques, and blasting are all examples of mechanical stability. In chemical stabilization process, into the soil is injected dry powder or thin slurry of different binders, e.g.

- Portland cement
- Asphalt
- Sodium chloride
- Lime
- Calcium chloride
- Paper mill waste.

2.2.1 Deep mixing method

The deep mixing method (DMM) entails the addition of binder solidifying materials into the soil, followed by agitation and mixing. This process results in the development of a stable, enhanced soil structure (improved soil column) in the treated area. Deep mixing methods are classified into two types based on the qualities of the solidifying material to be supplied: slurry agitating methods and powder agitating methods (Nakao, et al., 2021).

The development of the DMM dates to the late 1960s when lime was first used as a hardening agent. In the mid-1970s before it was widely accepted across the globe, DMM was initially adopted in Japan and the Nordic countries. In Japan, cement has replaced lime as the preferred hardening agent, while lime-cement blends are still commonly used in the Nordic countries. In recent years, there has been a growing interest in using combinations of lime or cement with materials such as gypsum, fly ash, and slags, which have proven effective for specific applications (Terashi, 1999).

Deep mixing methods have been in use since the middle of the 1970s, beginning in Sweden, Finland, and Japan at around the same time. Both in Nordic countries and Japan, the usage of techniques has significantly increased in the 1980s and 1990s. In Nordic countries, dry deep mixing method (DDM) is used. The DDM technique generates stabilized soil with better engineering qualities by mixing stabilizing material with soft soil. Many variables, including the characteristics and conditions of the soil layer, the characteristics of the binders, the mixing parameters, and the curing conditions, influence these qualities (Bredenberg, et al., 1999).

The main purposes of lime and lime/cement columns are to increase the durability and reduce settlement of railroad and road embankments. In order to increase the stability of trenches for sewage lines, water mains, and heating pipes, these columns are used as well (Moseley & Kirsch, 2004).

Unslaked lime alone has not proved efficient in stabilizing organic soils, hence lime/cement columns have been utilized. Lime columns have the benefit of having a high permeability and ductility. Furthermore, the heat released during slaking increases the ground temperature (Moseley & Kirsch, 2004). The heat generated during the slaking process of lime increases the ground temperature. This increase in temperature can be beneficial in cold climates or during winter, when the ground is frozen, making it easier to work with the soil. The increase in shear strength generated by a decrease in water content is generally considerable (Moseley & Kirsch, 2004). Lime reacts with clay particles in the soil, creating a cementitious material that binds the soil particles together. This results in an increase in shear strength.

According to the results of earlier studies, cation exchange, flocculation, and pozzolanic reactions occur when lime is added to clay soils in the presence of water. It is claimed that when clay soils are treated with even a small amount of lime, flocculation plays a major role in changing the engineering properties of the soil (Guney, et al., 2007).

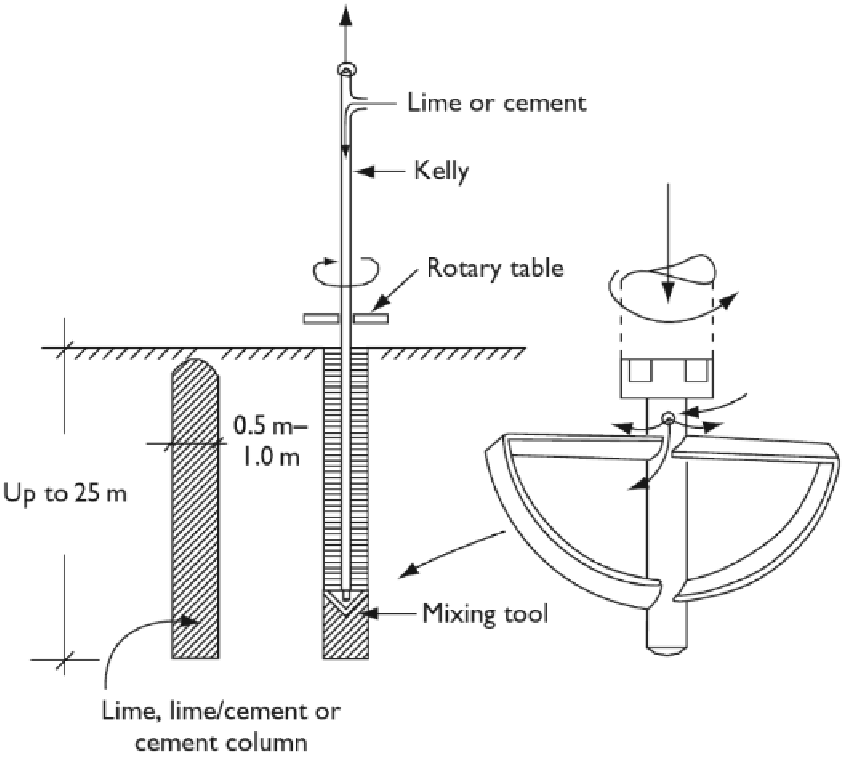


Figure 1. Lime and cement columns installation *(Moseley & Kirsch, 2004)*

The use of cement for soil stabilization triggers pozzolanic reactions that are similar to those occurring during lime stabilization. As a result, the chemical bonding of cement particles with soil occurs, leading to the formation of a stronger and more stable material. This chemical reaction improves the strength and stability of the soil, making cement stabilization an effective solution for preventing soil liquefaction and increasing the load-bearing capacity of foundations and structures constructed on the soil. The calcium needed for pozzolanic reactions to happen is present in both lime and cement, but the silica needed for those reactions to happen comes from different sources. When lime is added to the clay particle the chemical reaction occurs, causing it to disintegrate into smaller components, and silica is produced. However, for cement stabilization this process does not happen because cement has silica as a component. As a result, unlike lime stabilization, cement stabilization is largely independent of the characteristics of the soil; the only prerequisite for the hydration process to start in the soil is that it contains some water. Carbonation can also happen when using cement-based stabilization, which is similar to lime stabilization. When cement is exposed to air, it reacts with carbon dioxide to form a calcium carbonate that is comparatively insoluble (Asgari, et al., 2015).

2.2.2 Mass Stabilization

Stabilization can improve the geotechnical characteristics of soft soils. Scandinavia has been using deep stabilization (dry deep mixing) since the end of the 1970s. The mixing of stabilizers creates stronger columns during the deep stabilization procedure. A different approach has been created since the beginning of the 1990s that does away with some of the drawbacks of soil replacement techniques. Mass stabilization is the term for this technique. Peat can also be used with this technique, which was not possible before (Jelisic & Leppänen, 2003).

In order to apply mass stabilization, stabilizer agents can be mixed with soil that has been dug up and lifted to the surface. Mass stabilization enhances the characteristics of the excavated, subpar masses so that, rather than being transported to a dump, this material can instead be used for other construction projects like filling in openings, building roads, creating noise barriers. Mass stabilization eliminates the traditional way of replacing the soil, which involves replacing the soft soil layers with granular materials like gravel or blasted rock (Andersson, et al., 2001).

2.3 CO_2 emissions from cement production

According to Ma, et al., (2016), the decomposition of the limestone during cement production releases CO_2 (Carbon dioxide). Calcium carbonate ($CaCO_3$), along with a few other carbonates (such as $MgCO_3$), is the primary component of limestone. Equations (1) and (2) illustrate the chemical process from limestone decomposition,

$$CaCO_3 = CaO + CO_2 \uparrow \qquad (1)$$

$$MgCO_3 = MgO + CO_2 \uparrow \qquad (2)$$

Ma, et al., (2016), indicated that chemical Equation (1), limestone typically contains about 65% $CaCO_3$, and it can be calculated that for every kg of $CaCO_3$ consumed, 0.44 kg of CO_2 will be produced. As a result, it is possible to calculate the CO_2 emissions from decomposition during the cement production phase as follows: 65% times 0.44 kg equals 0.2860 kg. Similar to how limestone has a 1.5% $MgCO_3$ content and emits 7.8 g of CO_2. In other words, the CO_2 emission from limestone decomposition is the sum of 0.286 kg and 7.8 g, or 0.2938 kg, per 1 kg of cement production (Ma, et al., 2016).

2.4 CO_2 emissions from lime

Due to its efficiency and cost-effectiveness, stabilization, particularly with lime, is a widely used technique among the others (Guney, et al., 2007).

Cho, et al., (2019) pointed out that understanding the fractions of dissolution caused on by strong acids (such as H_2CO_3) and carbonic acid (H_2CO_3) is necessary to address the fate of carbon (C) in liming materials during dissolution (i.e., HNO_3). First, calcium (Ca^{2+}) and bicarbonate ($2HCO_3$) ions can be formed from the $CaCO_3$ that has been added to the soil.

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2HCO_3^- \quad (3)$$

For every mole of gaseous CO_2 absorbed in this reaction in soil solution, two molecules of HCO_3 are produced. Either the HCO_3^- is flushed out or it stays in the soil profile. It is predicted that any remaining bicarbonate in the soil will react with any hydrogen (H+) that is available to form carbonic acid (H_2CO_3). By converting into CO_2, this H_2CO_3 can be released into the atmosphere. For every mole of $CaCO_3$ that dissolves in this reaction, 1 mol of CO_2 can be released (Cho, et al., 2019).

$$2H_2CO_3 \leftrightarrow 2CO_2 + 2H_2O \quad (4)$$

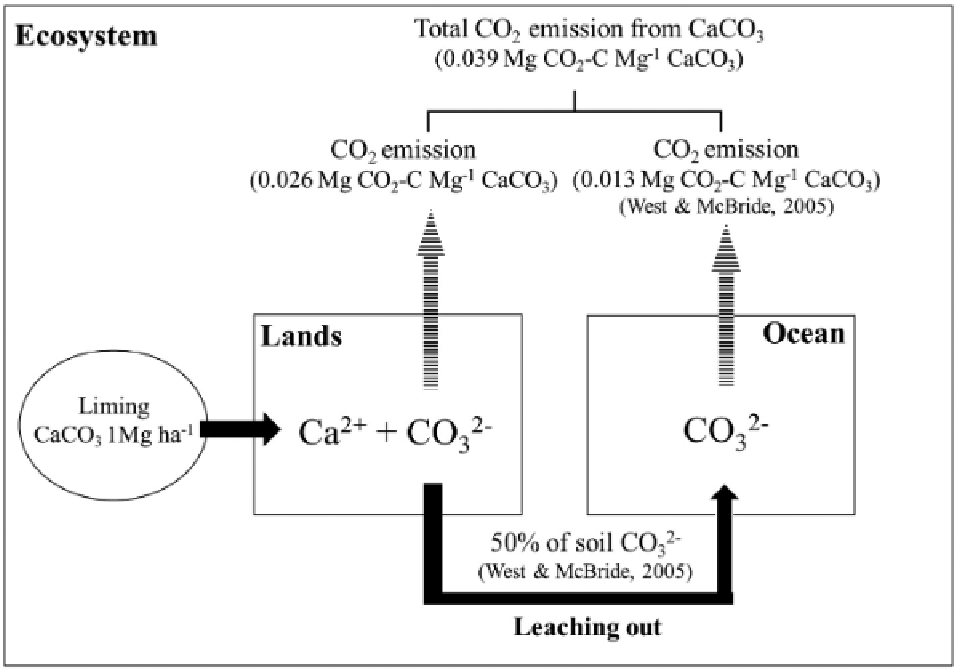


Figure 2. CO_2 flow diagram from $CaCO_3$ application in an ecosystem *(Cho, et al., 2019)*

2.5 CO_2 emissions from various binders

Although lime is efficient and cost-effective for soil stabilization, it is high in carbon dioxide emissions compared to the binders that were used in this research. In this research, the strength and carbon dioxide sequestration capacity of stabilized clay were evaluated using four different types of binders. These binders were GTC (gypsum, slaked lime, and cement type I), UPM (Fly ash) +CEM II (Cement type II), CEM I (Cement type I) and CEM III (Cement type III). Nguyen, (2021) indicated the emission coefficients of CO_2 for the production of these binders in his thesis, Figure 3.

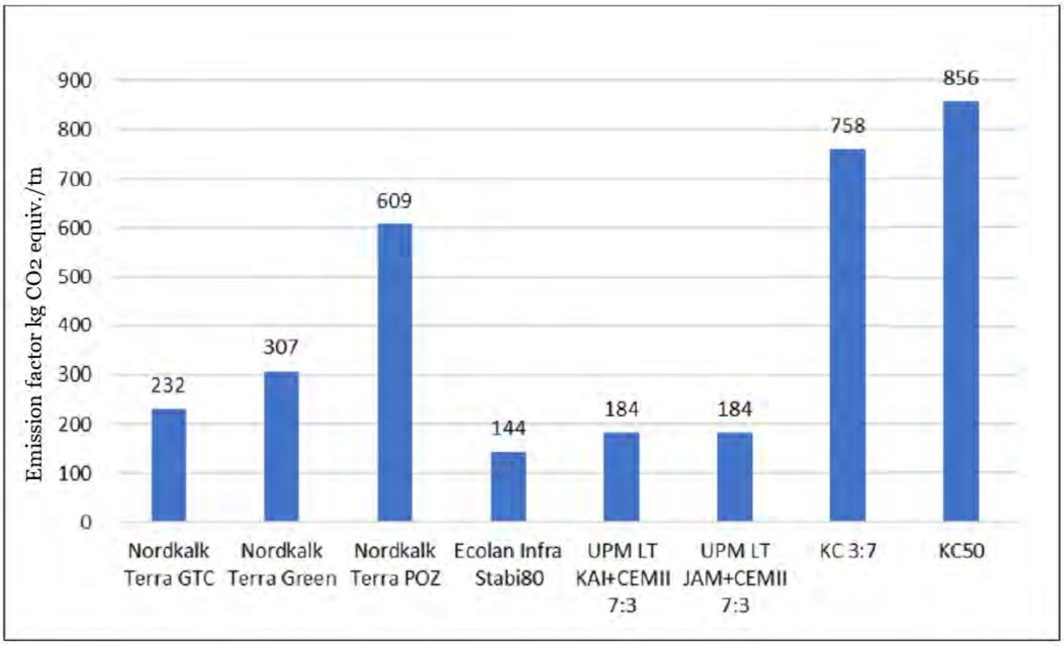


Figure 3. Emission coefficients for the production of binders (Nguyen, 2021)

2.6 Carbon Sequestration

Carbon dioxide sequestration is the long-term confinement of carbon dioxide from the atmosphere via physical, chemical, biological, or engineered processes (Friedmann, 2007). There are three basic methods of carbon storage proposed: geological storage, ocean storage, and mineral carbonation (Oelkers & Cole, 2008).

2.6.1 Geological storage

The injection of CO_2 into porous rock formations is the basis for geological storage. Sedimentary basins, drained oil reservoirs, and non-economic coal beds are examples of CO_2 storage reservoirs. Because CO_2 density is generally less than that of water, buoyancy tends to pull CO_2 upwards, back to the surface, hence an impermeable cap rock is required (Oelkers & Cole, 2008).

According to Friedmann, (2007), the most significant issue/challenge with underground storage is the long-term viability of the solution, as there will always be a possibility of leaking.

2.6.2 The Behavior of Carbon Dioxide Sequestration Capacity Under Different Pressures and Temperatures

Kang, et al., (2020), investigated absorbed CO_2 in different pressure and temperature by using Grand Canonical Monte Carlo (GCMC) simulations and results of experiments. The experiments were made in at the same temperature of 25 C◦ (298.15 K), and various degree of temperature under different pressures.

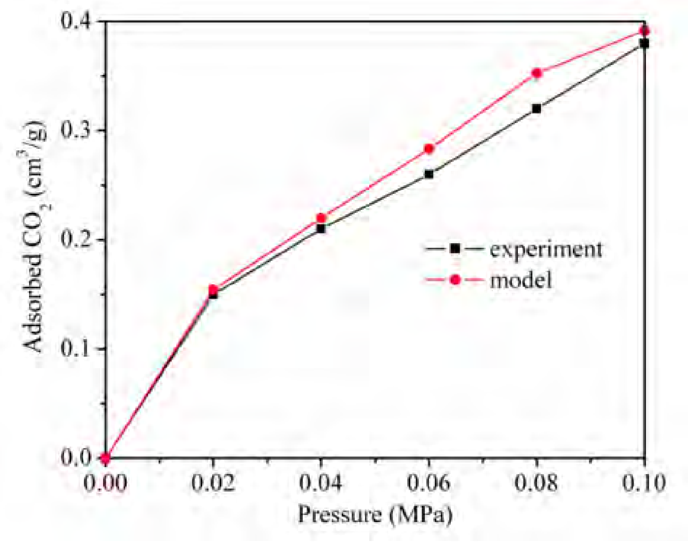


Figure 4. CO_2 adsorption isotherms based on simulated results and outcomes from experiments at 25 C◦ (298.15 K) *(Kang, et al., 2020)*

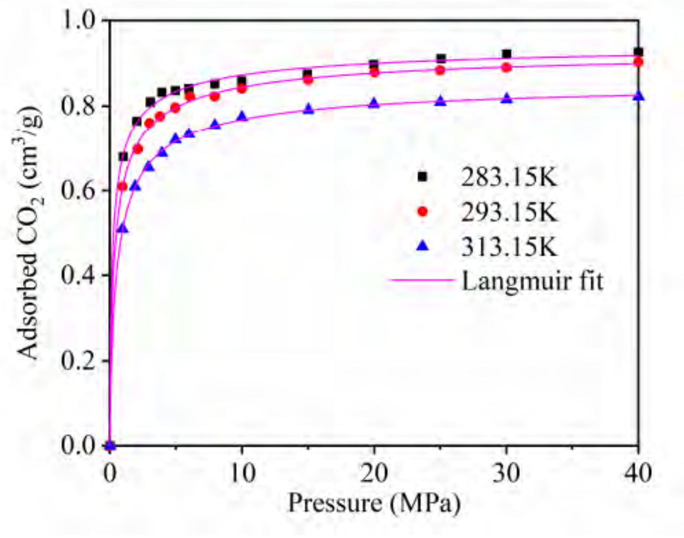


Figure 5. The CO_2 adsorption isotherms at various temperatures (Kang, et al., 2020)

Kang, et al., (2020) remarked based on the results that CO_2 adsorption capacity increased with increasing adsorption equilibrium pressure and decreased at low pressure. As the temperature increases, CO_2 adsorption capability drops, Figure 5.

2.6.3 Carbon Dioxide Sequestration Capacity Behavior Related to Time

Karacan & Mitchell, (2003), investigated dynamic behavior of CO_2 adsorption in coal. The three different CO_2 pressures used in the adsorption studies were 1.7, 3.06, and 4.42 MPa. Examples for 3.042-mm and 4.68-mm points along the center profile are shown in Figure 6. The amount of adsorbed gas (CO_2) increased with increasing exposure time for each CO_2 pressure. Then it slightly decreased and remained almost constant.

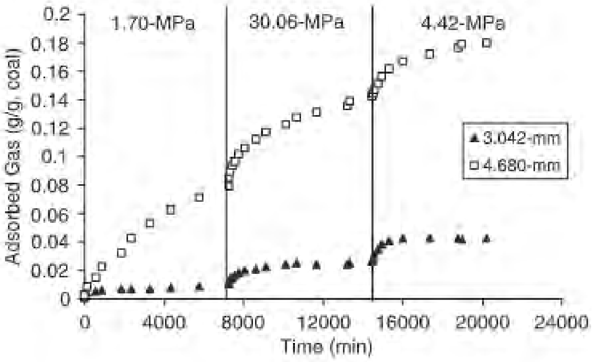


Figure 6. Time-Dependent CO_2 adsorption in Coal (Karacan & Mitchell, 2003)

Liu, et al., (2021) researched the carbonation mechanism and CO_2 curing technology. The experiments were done on cement and concrete. The effect of the moist and dry curing conditions of the concrete and the pre-curing time on the degree of CO_2 were examined. Pre-curing is a crucial step because it directly affects the moisture content of samples. Carbonization degree of the sample is very low if it is initially after molding exposed to CO_2 gas.

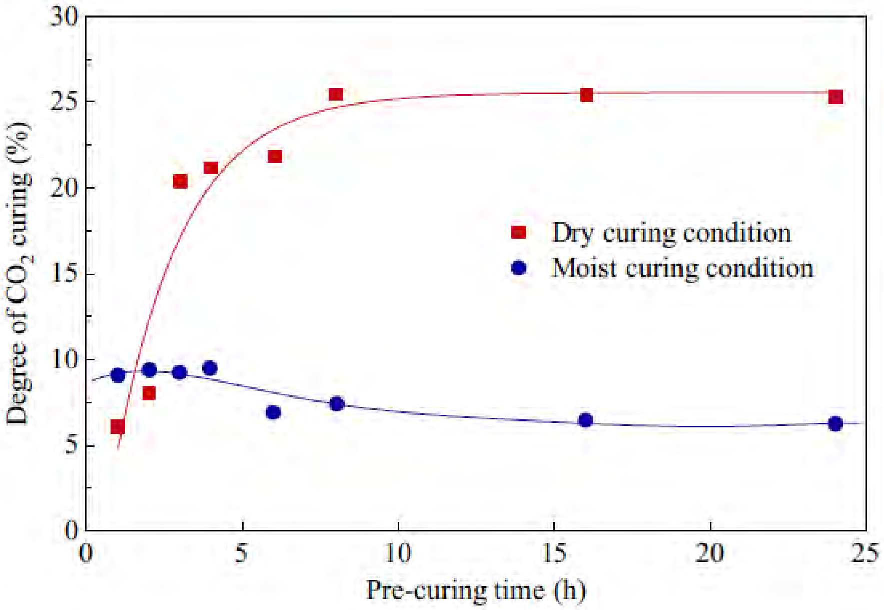


Figure 7. The impact of the pre-curing time on concrete CO_2 curing degree (Liu, et al., 2021)

2.7 CO_2 Carbonation

The term "carbonation" describes the phenomenon in which carbon dioxide seeps through soil that has undergone lime treatment, dissolves in the water present in pores of the soil and reacts with dispersed calcium (Ca^{2+}) ions to create calcium carbonates ($CaCO_3$) (Das, et al., 2022 as citied by (Arandigoyen, et al., 2006; Bandipally, et al., 2018; Padmaraj & Arnepalli, 2021; Vitale, et al., 2018 and Deneele, et al., 2021)).

Additionally, carbonation alters the material's permeability, gas diffusivity, capillarity, and other qualities that are directly related to its microstructure (Arandigoyen, et al., 2006). Depending on when the reaction occurs, carbonation affects the chemo-mineralogical evolution of lime-treated soils (Vitale, et al., 2018).

According to research made on cement and lime binders by Arandigoyen, et al., (2006), calcite crystals, $CaCO_3$, are created when the carbonation reaction between portlandite crystals, $Ca(OH)_2$, and CO_2 occurs. The microstructure of lime and lime-cement pastes alters, such that crystals combine to form a net and the material's strength rises because calcite crystals have various crystal structures and molar volumes.

$$Ca(OH)_2 + CO_2 \leftrightarrow CaCO_3 + H_2O \quad (5)$$

Fasihnikoutalab, et al., (2016) used carbonation method to stabilize clayey soil which is mixed with olivine. According to the research, it was concluded that the bearing capacity increased as a result of the carbonization of the soil. The production of $MgCO_3$(Magnesium carbonate) due to the CO_2 leads carbonated soil-olivine to become stronger and has higher bearing capactiy.

2.8 Thermogravimetric Analysis

Thermogravimetric analysis (TGA) is an experimental method that evaluates the weight of a sample as it changes in relation to temperature or time. This approach is used to accurately measure the mass of a sample throughout the course of a temperature or time dependent experiment. The sample may be subjected to non-linear temperature programs, as those used in sample controlled TGA research, but is normally heated at a constant heating rate or maintained at a constant temperature. A TGA measurement's results are typically shown as a TGA curve, which plots mass or mass percentage against temperature and/or time. The first derivative of the TGA curve with respect to temperature or time can be used as an alternate and complementary presentation. The differential thermogravimetric curve, or derivative thermal gravimetric (DTG) curve, illustrates the rate of mass change (Gabbot, 2008).

Yaras, et al., (2019) studied on the use of carbonation sludge (CS) on the preparation and characterization of highly porous bricks. A type of industrial waste called carbonation sludge (CS) is created during the carbonation process in sugar producing facilities. CS comprises of mostly calcium carbonate ($CaCO_3$) (Vaccari, et al., 2005).

Yaras, et al., (2019) did thermogravimetric analysis for both CS and clay materials. As a result of thermogravimetric analysis, Figure 8 makes it clear that the total mass loss for CS is %47.57 from 0°C to 1000°C. The reason of the weight loss at 100 °C dehydration. While between 150°C and 500 °C the organic materials burning, decomposion of $CaCO_3$ was observed at between 600°C and 800 °C.

For clay the mass loss in total is around 8% between 0°C and 1000°C based on TGA results. The reasons of the weight loss were dehydration of the physical water at 100°C , burning of the organic material in the clay at between 150°C and 250°C , dehydration chemical water in clay structure at 250°C and 450 °C, and hydroxylation reaction of chlorite-type clay minerals at 600 °C and 700°C (Yaras, et al., 2019).

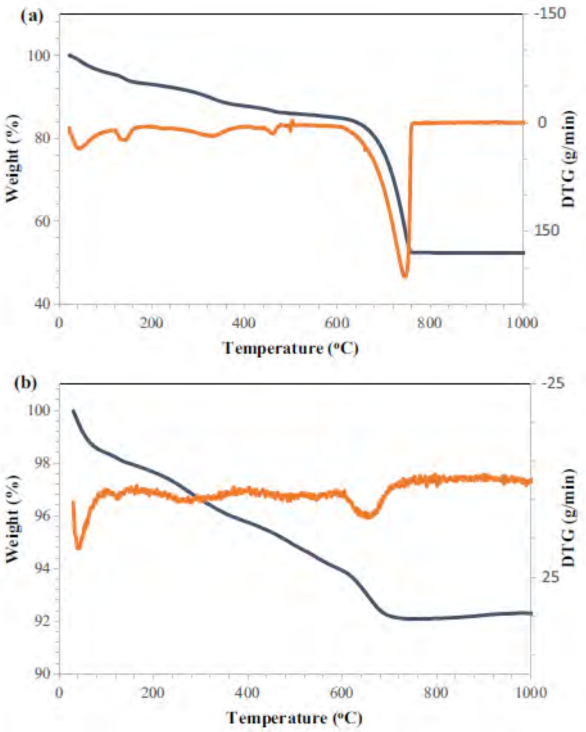


Figure 8. TGA and DTG results of carbonation sludge (a) and clay (b) (Yaras, et al., 2019).

Unluer & Al-Tabbaa, (2013) indicated that the temperature ranges of decarbonation of carbonated hydrated magnesium carbonates (HMCs) samples are between 520-550 ◦C and 750-800 ◦C (Table 1).

Table 1. Thermal decomposition of the HMCs mixture (Unluer & Al-Tabbaa, 2013)

Range of temperature (◦C)	Peak temperature (◦C)	Step	Reaction (e.g.hydromagnesite)
100-350	240-280	Removal of water of crystallization of the included and formed HMC	$4MgCO_3.Mg(OH)_2.4H_2O \rightarrow 4MgCO_3.Mg(OH)_2 + 4H_2O$
300-400	390-460	Decomposition of brucite within the included and formed hydrated HMC to MgO	$4MgCO_3.Mg(OH)_2 \rightarrow 4MgCO_3 + MgO + H_2O$
350-500		Decomposition of the uncarbonated brucite to MgO	$Mg(OH)_2 \rightarrow MgO + H_2O$
400-600	520-550	Decarbonation of included magnesium carbonate to MgO	$4MgCO_3 \rightarrow 4MgO + 4CO_2$
600-1000	750-800	Decarbonation of formed magnesium carbonate to MgO	$4MgCO_3 \rightarrow 4MgO + 4CO_2$

Ideally, only weight changes during heating are seen on the TGA curves. The DTG curve, which is the derivative of the TGA curve, reveals modifications in the TGA slope that may not be apparent from the TGA curve. As a result, processes like desorption, dehydration, and dehydroxylation that include changes in weight and enthalpy may exhibit remarkable similarity between the DTG curve and the differential thermal analysis (DTA) curve (Guggenheim & Koster van Groos, 2001).

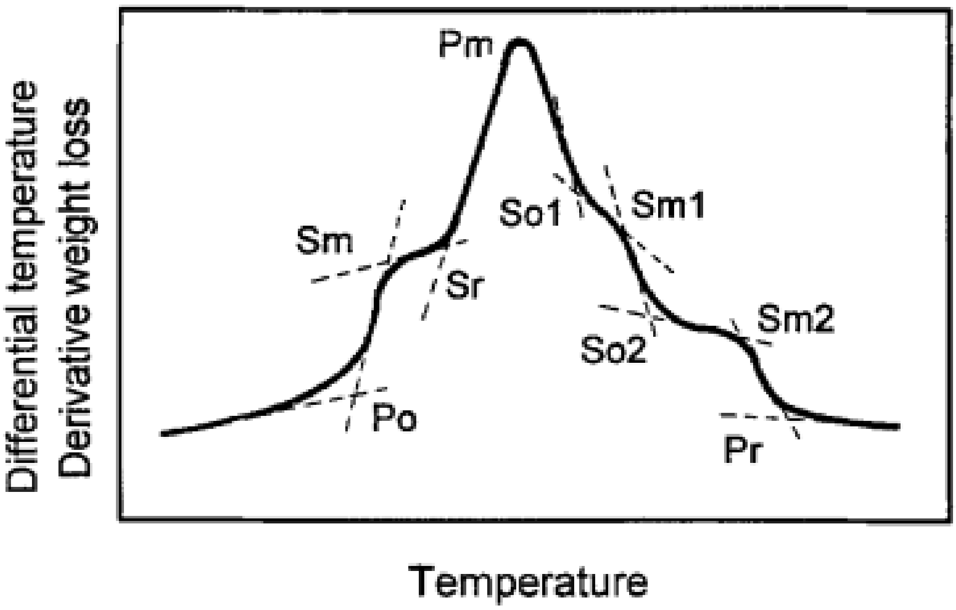


Figure 9. DTA and DTG curve (Guggenheim & Koster van Groos, 2001)

In Figure 9, the DTA and DTG peaks are shown. The basic peaks are extrapolated onset (Po), maximum peak (Pm) and peak return (Pr). In addition to these peaks, shoulder peaks are defined as complex peaks of the DTA and DTG curves. For lower temperatures, while Sm is identified as a maximum shoulder temperature, Sr is return shoulder temperature. In terms of higher temperatures, So1 and So2 are described as onset of the shoulder temperatures. Whereas Sm1 and Sm2 are maximum shoulder temperatures (Guggenheim & Koster van Groos, 2001).

2.9 Unconfined Compressive Strength Test

Unconfined compressive strength is the force per unit area where an unconfined prismatic or cylindrical specimen of soil with standard dimensions fails at straightforward compression test (Ranjan & Rao, 2000).

Wang, et al., (2019) conducted a study on dredged sludge mixed with binder MgO-fly ash and exposed to CO_2 carbonation. The study involved fixating binder contents at 5%, 10%, and 15% of sludge, with reactive weight ratio of MgO and fly ash ranging from 50% to 100%. The pressures of CO_2 for carbonation were set at 200, 300, and 400 kPa, while carbonation durations of 0.5, 1, 3, 6, and 24 h were selected for evaluating the time-dependent behavior. Their study also showed the impact of CO_2 carbonation on the difference in UCS~ε_f and UCS~E_{50} relationships, as depicted in Figure 10(a). Results showed a significant linear association between UCS and E_{50}, with E_{50} is 34.5 UCS and E_{50} is 38.2 UCS obtained for uncarbonated and carbonated specimens, respectively.

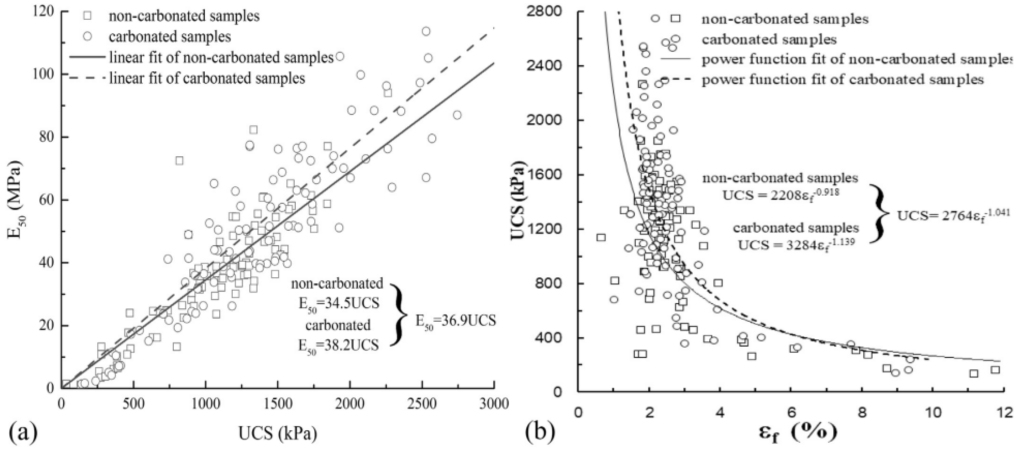


Figure 10. UCS~ ε_f and UCS~ E_{50} relationships changes due to carbonation (Wang, et al., 2019).

The results of UCS tests on uncarbonated and carbonated samples under the 300 kPa confining pressure and 150 kPa carbonation pressure are presented in Figure 11. Analysis of the non-carbonated specimens revealed that the weight ratio of MgO and fly ash (Mg:F) has the most significant effect on UCS evolution with binder amount. For samples of carbonated sludge, the same behavior might be observed (Wang, et al., 2019). While only fly ash was used as a binder in the samples in Figure 11a, only MgO was used as a binder in the samples in Figure 11d. The samples contained 50% MgO and 50% fly ash in Figure 11b, and 70% MgO and 30% fly ash in Figure 11c.

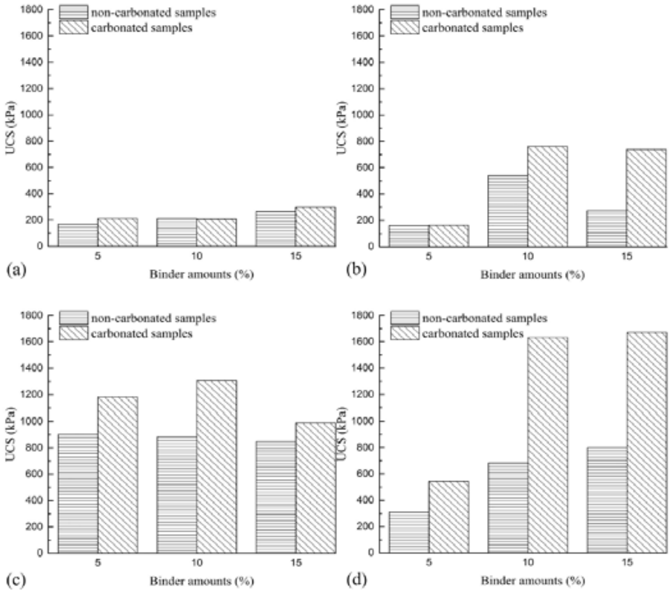


Figure 11. Strength of samples with and without carbonation and various amounts of binder (Wang, et al., 2019)

2.10 Microstructural characteristics of clay

The microstructure of clays affects their physical characteristics, and studies in soil mechanics and pedology have focused on how this microstructure relates to transport and rheology (Pusch, 1999).

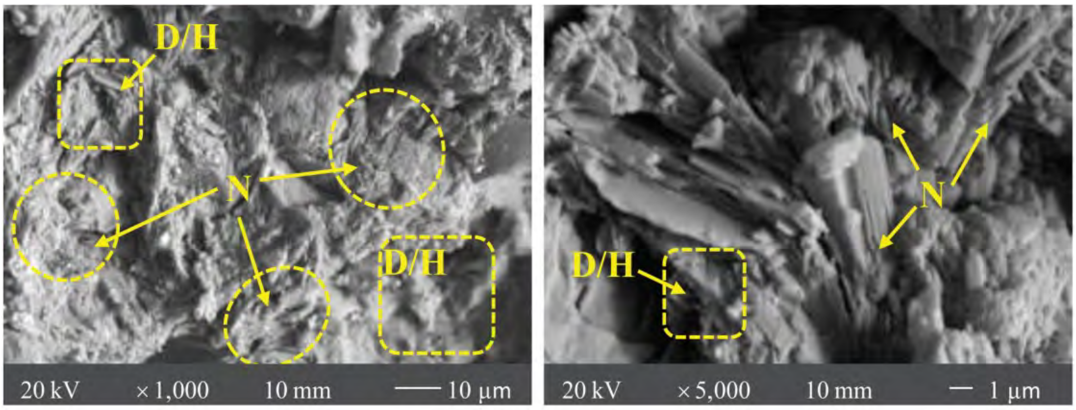
X-ray powder diffraction (XRD), mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM) analyses are used in order to examine the microstructural mechanisms of soils.

Clay minerals can be analyzed qualitatively and quantitatively using XRD to provide information on the mineral compositions, alteration histories, effects of parent material, provenances, and the kind and degree of weathering in soil (Hugbes, et al., 1994). XRD analysis of soil clay mineralogy is generally performed on orientated clay fraction specimens since this sort of preparation amplifies signals originating from the 001-cleavage plane, a process that helps in the identification of specific clay mineral phases (Kahle, et al., 2002).

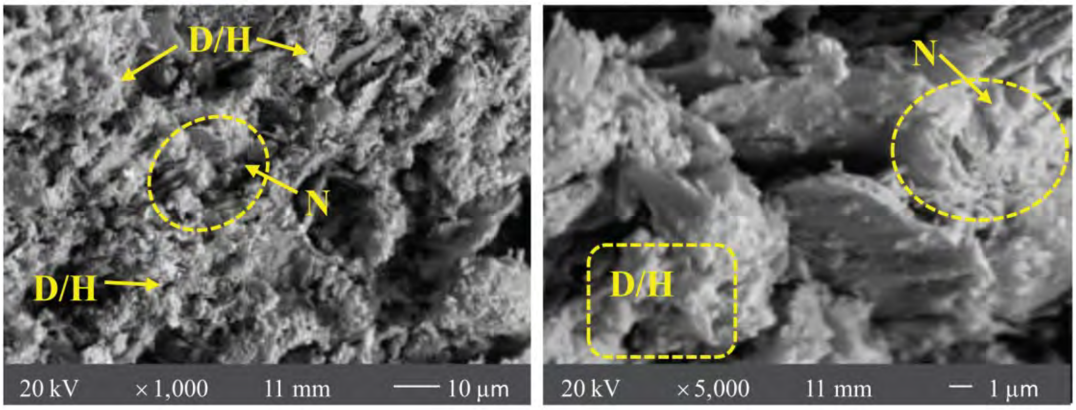
The pore-size distribution of powdered and bulk materials having open and linked pore structures has been frequently assessed using mercury intrusion porosimetry (MIP) (Penumadu & Dean, 2000). A number of studies have used MIP to examine the structure that develops in clays under various circumstances, such as their natural, remolded, compacted, or consolidated states (Sasanian & Newson, 2013).

One of the most essential instruments for examining the microstructural characteristics of sediments is the scanning electron microscope (SEM). In order to study soil microstructure, the SEM has a major advantage due to the high resolution that can be attained. SEM has grown in significance as a tool for investigating clay. According to SEM research, the bonding structure between the additives and the clay particles is visible (Ural, 2021).

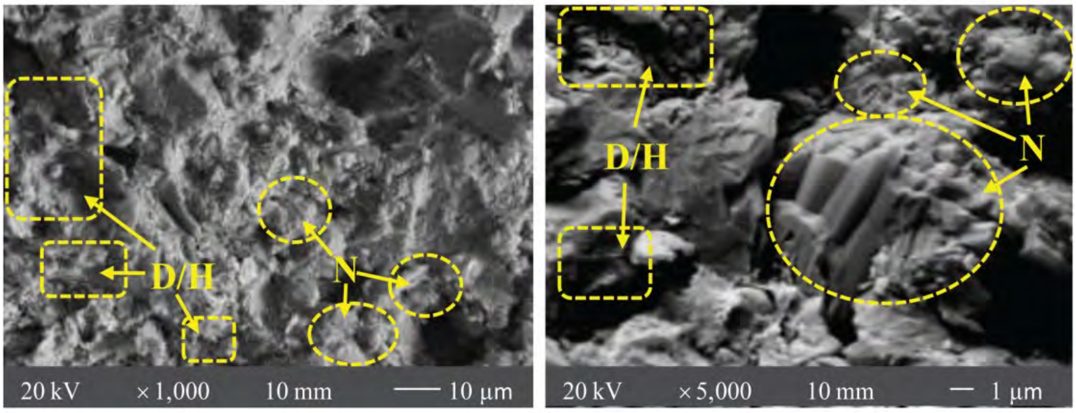
Cai, et al., (2021) studied on carbonated reactive MgO-admixed silty clay to observe freezing-thawing performance. The microstructural behavior of carbonated MgO-silty clay samples was examined using SEM. Figure 12 displays the MgO-carbonated silty clay SEM structures after cyclic freezing-thawing (F-T) of 0, 6, and 10. At zero F-T cycles, soil particles were closely linked and connected by crystalline carbonation products, successfully filling the pores between soil particles and generating a dense structure, as seen in the low-magnification image in Figure 12a. However, with increasing F-T cycles, the microstructure of carbonated silty clay changed from dense to loose, with dense grains breaking into numerous loose fragments. The size of pores in the clay particles also increased with the number of F-T cycles, as shown in Figure 12 b-c.



(a) $N_{F\text{-}T}=0$



(b) $N_{F\text{-}T}=6$



(c) $N_{F\text{-}T}=10$

Figure 12. The structures of MgO-carbonated silty clay as observed through SEM were analyzed after undergoing varying cycles (N) of freezing and thawing (F-T) (Cai, et al., 2021).

Liu, et al., (2018) used reactive magnesia (MgO) as a binder to carbonate and stabilize silty clay in their research. Different carbonation duration on stabilized clay were experimented which were 0 h, 3 hours, 6 hours and 12 hours. After carbonation of silty clay which is mixed with MgO, the model of carbonated clay was formed (Figure 13).

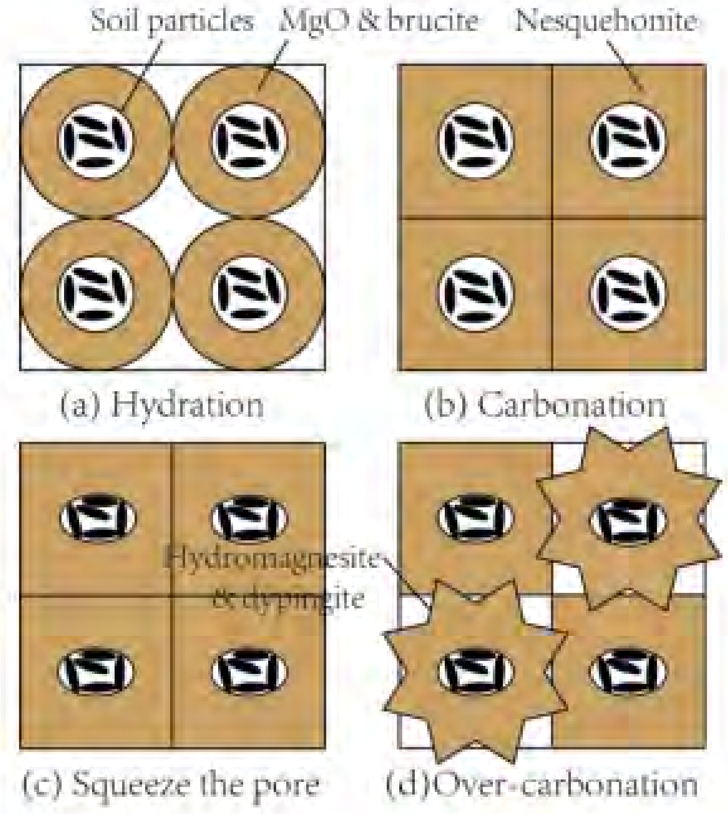


Figure 13. Carbonated reactive MgO stabilized silty clay micro mechanistic model (Shang, et al., (2020) as cited by (Liu, et al., 2018))

Silty clay is sensitive to ion exchange reactions and aggregation reactions when it is combined with magnesium oxide because of the comparatively high concentration of clay particles in the soil. As a result, the clay particles compact into bigger soil aggregates. The MgO binders interact with cohesive soil particles. Small porous soil particles comprised with hydration of MgO (Figure 13a). Under the carbonation the soil expanded and strengthened (Figure 13b). After carbonation the soil particles compacted (Figure 13c). The expansion of the soil particles, CO_2 pressure and the carbonation time duration effects the form of the soil. It can cause deterioration of the soil and occurs cracks on the soil (Figure 13d) (Liu, et al., 2018).

3 Research Materials and Methods

In this research, Malmi clay was used as soil, and some binders were used in the clay mixing. Firstly, the mixed clay was carbonated by exposing CO_2 into the carbonation chamber. After carbonation, the UCS test and TGA were done for each sample respectively.

3.1 Materials

3.1.1 Malmi Clay

Malmi is located on the north-eastern part of Helsinki, Finland. The clay samples are taken from the Malmi Airport region (Figure 14& 15). The samples are obtained at the depth of 2.8 m from the ground surface level.

Figure 14. Location of obtained Malmi Clay (Google Map)

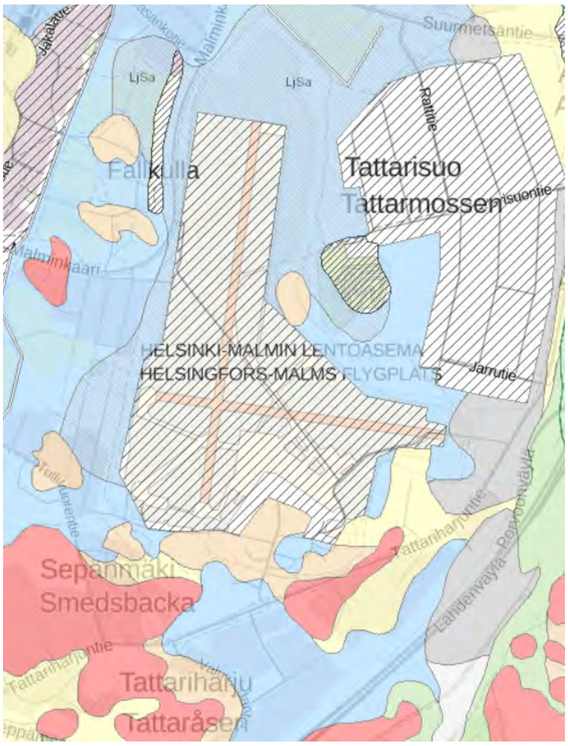


Figure 15. The Soil Map of Malmi Area (Geological Survey of Finland (GTK)).

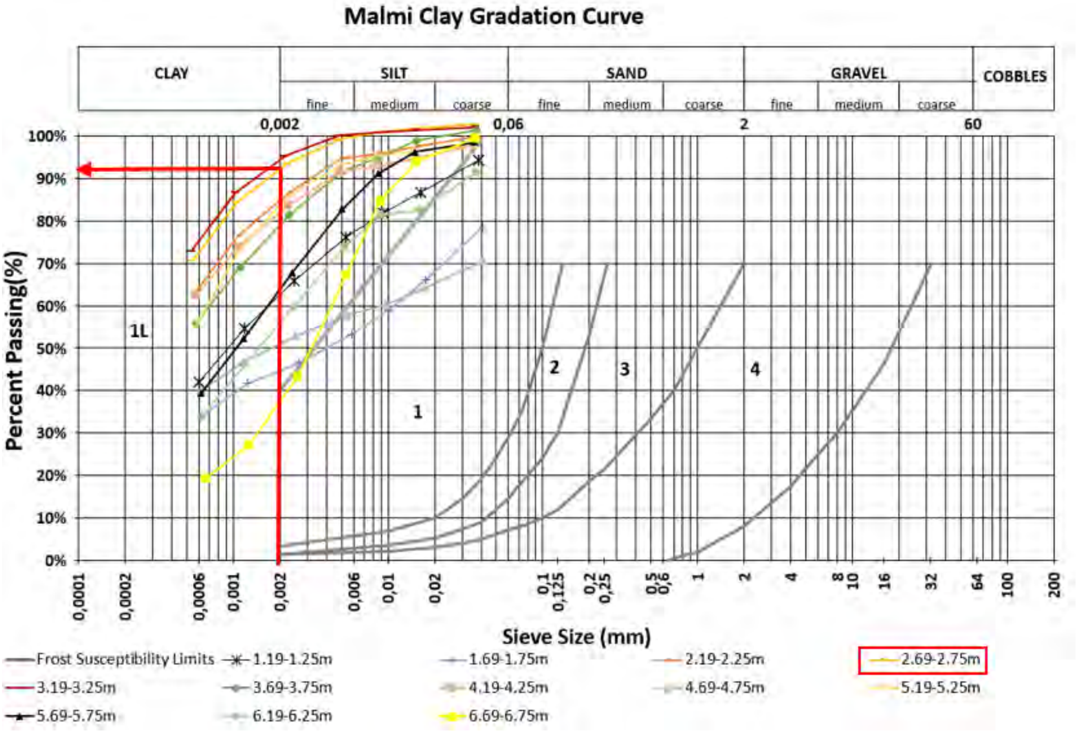
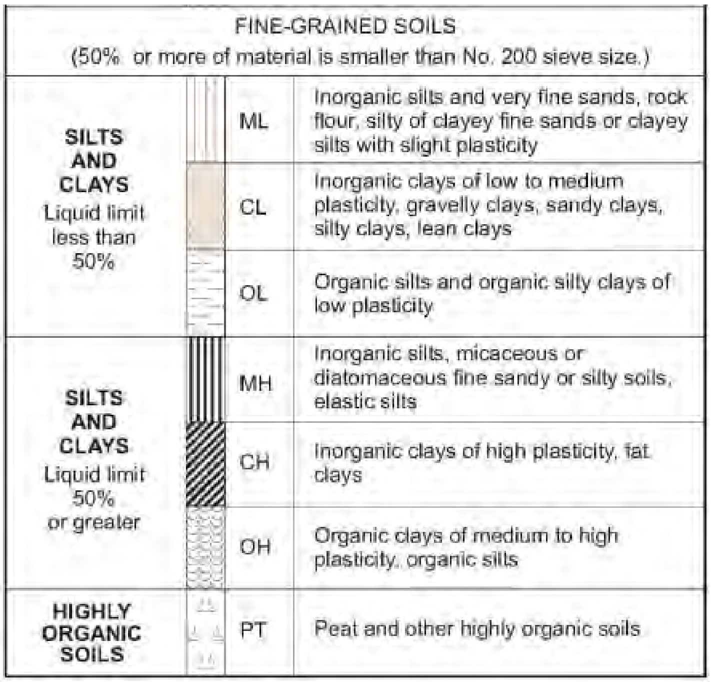


Figure 16. Grain size distribution of the Malmi Clay (The analysis was done by Yinning Zhang at the laboratories of Aalto University.)

Table 2. Fine-grained soil classification depending on clay content (Korhonen, et al., 1974).

Clay Content %	Name	List of Abbreviations (in Finnish)
<10	Does not affect the designation	-
>10...30	Clayey silt	saSi
>30...50	Lean clay	laSa
>50	Fat clay	liSa



FINE-GRAINED SOILS (50% or more of material is smaller than No. 200 sieve size.)		
SILTS AND CLAYS Liquid limit less than 50%	ML	Inorganic silts and very fine sands, rock flour, silty of clayey fine sands or clayey silts with slight plasticity
	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
	OL	Organic silts and organic silty clays of low plasticity
SILTS AND CLAYS Liquid limit 50% or greater	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
	CH	Inorganic clays of high plasticity, fat clays
	OH	Organic clays of medium to high plasticity, organic silts
HIGHLY ORGANIC SOILS	PT	Peat and other highly organic soils

Figure 17. Unified Soil Classification and Symbol Chart (California Department of Transportation)

The grain size distribution of the Malmi Clay is shown in Figure 16. Korhonen, et al., (1974) described the fine-grained soils based on the clay content on Table 2. Fine grained soils (≤0.063 mm) is named silt or/and clay. For clay content the passing percentage of the 0.002 mm sieve size is taken into account. The passing percentage for 0.002 mm grain size was remarked with red arrow in Figure 16 that is around 92%. According to Table 2, 92% clay content is greater than 50%. In addition, the type of clay can be defined by looking liquid limit of the soil. For Malmi clay, it is 68.3. Based on Figure 17, the liquid limit of the Malmi clay is greater than 50. Thus, it can be said that the Malmi clay is a "fat clay" according to Table 2 and Figure 17.

The properties of the Malmi clay are shown in Figure 18 and Table 3. According to these data, the unit weight, the water content, the sensitivity, and the shear strength of the clay at 2.8 m depth are 14.15 kN/m^3,125%, 38 and 10 kN/m^2 respectively.

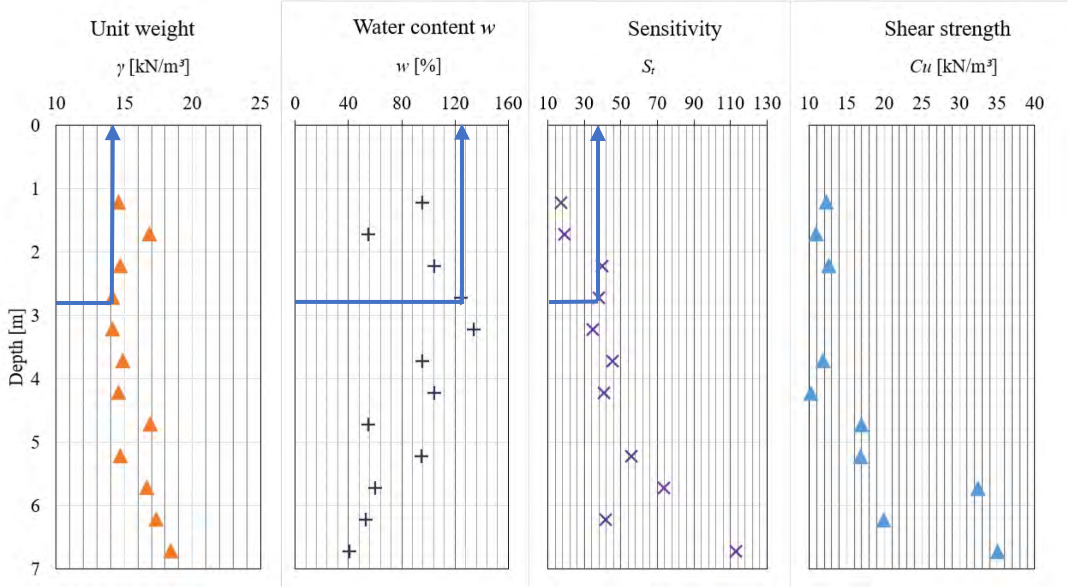


Figure 18. The properties of the Malmi clay (Löfman, 2022)

Table 3. Malmi clay properties according to the depth (Löfman, 2022)

Depth (m)						
Top	Bottom		Unit weight kN/m^3	Water Content (%)	Cu (kPa)	Sensitivity
0	1	1	14,56			
1,19	1,25	1,22	14,56	95,34	12,30	17,10
1,69	1,75	1,72	16,85	54,96	10,90	19,10
2,19	2,25	2,22	14,70	104,50	12,67	39,60
2,69	2,75	2,72	14,15	124,32	9,87	37,90
3,19	3,25	3,22	14,15	134,31	9,67	34,50
3,69	3,75	3,72	14,90	95,61	11,80	45,40
4,19	4,25	4,22	14,60	104,42	10,20	40,80
4,69	4,75	4,72	16,92	55,15	16,93	
5,19	5,25	5,22	14,73	95,16	16,80	56,00
5,69	5,75	5,72	16,68	60,28	32,40	73,60
6,19	6,25	6,22	17,33	52,89	19,97	41,60
6,69	6,75	6,72	18,40	40,90	35,10	113,20

3.1.2 Binders

Four different binder types were used into the mix clay to observe carbonation effects on strength and carbonation sequestration capacity of the clay. These binders are GTC, CEMI, UPM+CEMII and CEMIII.

GTC

GTC binder is produced by Nordkalk Oy, Finland. GTC consists of 33% slaked lime, 33% gypsum and 33% cement type I. The amount of recycled materials in GTC is around 40-45%. (Nguyen, 2021)

CEMI, CEMII and CEMIII

Cement type I (CEMI/52.5 R), cement type II (CEMII B-M (S-LL) 42,5 N) and cement type III CEMIII (A 52.5 L) are manufactured by Finnsementti Oy, Finland.

CEMI is very fast hardening Portland cement. The composition of this cement is between 95% and 100% of cement clinker. (Appendix 1)

CEMII is normally set Portland cement. CEMII contains with between 65% and 79% cement clinker, and between 21% and 35% additives (limestone and GGBFS (blast furnace slag). (Appendix 2)

CEMIII is blast furnace slag cement of high strength class 52.5. The cement composition of CEMIII is between 35% and 64% cement clinker and between 36% and 64% blast furnace slag (GGBFS). (Appendix 3)

UPM

UPM is a fly ash as using a binder that is produced by UPM-Kymmene Oy, Finland. The mix of binder for tests includes 70% fly ash and 30% cement (CEMII) (Lounais-Suomen Jätehuolto Oy, 2021).

Table 4. Binder types and amounts for Malmi clay stabilization.

	Binder Types			
	GTC	CEMI	CEMII+UPM	CEMIII
Binder Amounts (kg/m^3)	100			
	125			
	150			
	175			

3.2 Sample Preparation

The amount of the binder contents was taken into consideration when preparing samples. In this study, the binder contents were varied at 100 kg/m^3, 125 kg/m^3, 150 kg/m^3 and 175 kg/m^3 to stabilize the Malmi clay. For the clay and UPM+CEMII mixture, the amount of binder added to the clay mixture consists of 70% UPM and 30% cement type II (CEMII).

The samples were prepared into tubes of 150 mm in height and 50 mm in diameter. To determine the weight of the binder out of total weight of the sample, the volume of the tube was calculated, and the amount of the binder content was multiplied with volume to reach the weight of the binder. On the other hand, when the unit weight of the clay was multiplied by the volume of the tube, it gave the weight of the clay for filling a tube. When found weight of the binder was subtracted from this amount of clay, the weight of clay for mixing was reached.

The weight of the clay and the binder were measured on the scales (Figure 19a) for each sample. After that the soil was mixed for 5 minutes by using mixer (Figure 19b).

Figure 19. (a) The scale which was used for measuring the weight of the clay and binders, (b) The mixer which was used for mixing the clay and binders.

To prepare samples, a hammering method was utilized. In this method, 50 mm diameter and 150 mm height tubes were used, and the bottom of the tubes were covered with a plastic cap. After mixing the sample, the tubes were replaced into the tool which is shown in Figure 20a. The tubes were filled with 5-layer method. After adding each layer, 25 blows were made on the iron object by hammer. These blows helped the clay to compact well and prevent voids in the soil. After preparation of the samples, they were kept in plastic bags at room temperature for 24 hours (Figure 20 c). Finally, they were extracted from the tubes after 24 hours. (Figure 20d).

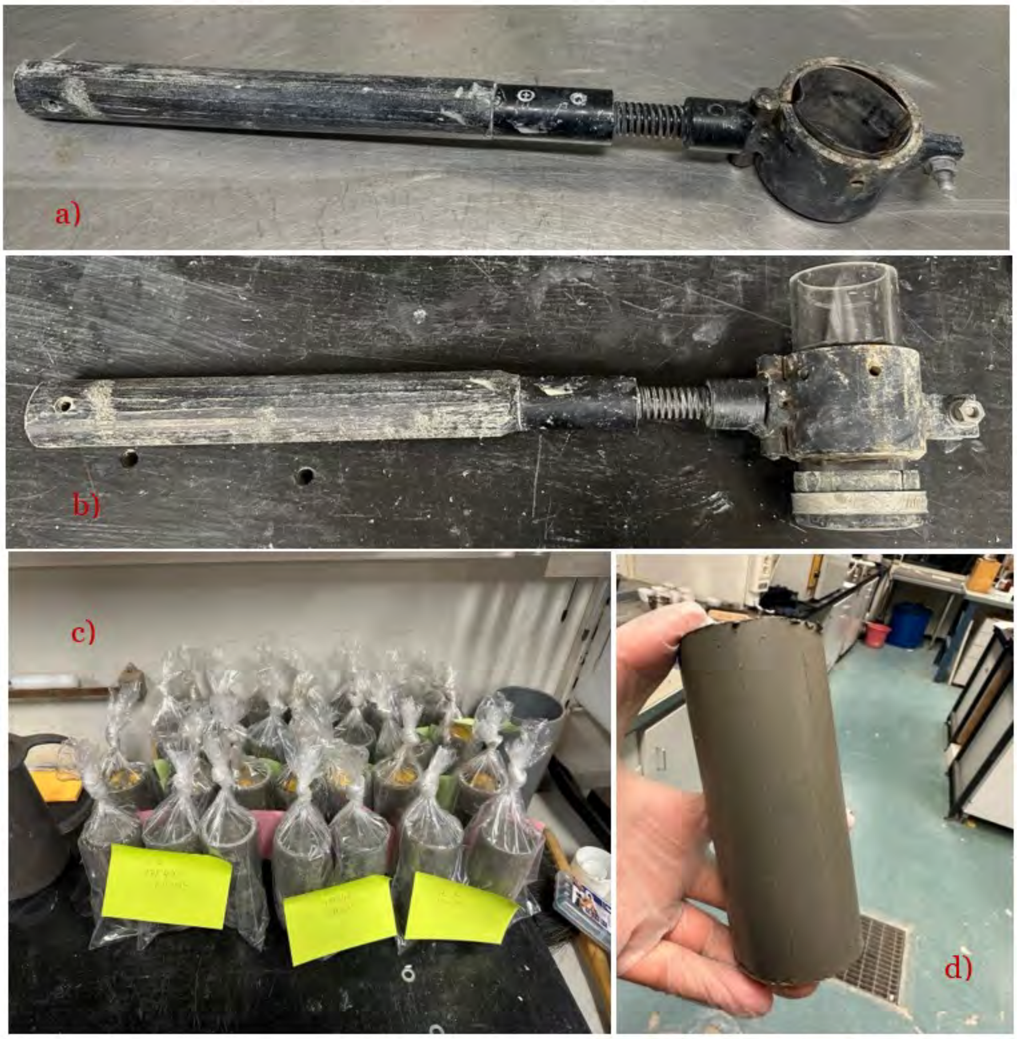


Figure 20. (a) The tool that is used as a hammer, (b) The tube is replaced into the hammer, (c) Samples into the plastic bags (d) The sample after extraction from the tube.

As shown in Figure 21, the samples were trimmed to 100 mm height after extraction from the tubes.

Figure 21. Trimmed samples to 100 mm height.

3.3 Methods and Analysis

After preparation, the samples were allowed to cure for a duration of 24 hours at room temperature. After carbonation samples were kept in a cold room (2.9 ◦C) for 7 days except samples with binder GTC (the curing time was 1 day). The samples were tested thermogravimetric analysis after carbonation, and unconfined compression tests.

3.3.1 Carbonation Chamber

Figure 22 shows the carbonation chamber equipment. The CO_2 which was used for the carbonation chamber is stocked in the CO_2 tube (Figure 22a). The valve that is shown in Figure 22b helps to adjust the CO_2 pressure. The inlet and outlet pressure gauges display the inlet and outlet CO_2 pressure as shown Figure 22c and 22e. The carbonation chamber is presented in Figure 22d, and it has heavy cover and screws. The valve can be released to empty the CO_2 pressure in the chamber as presented in Figure 22f, and Figure 22g displays the CO_2-meter.

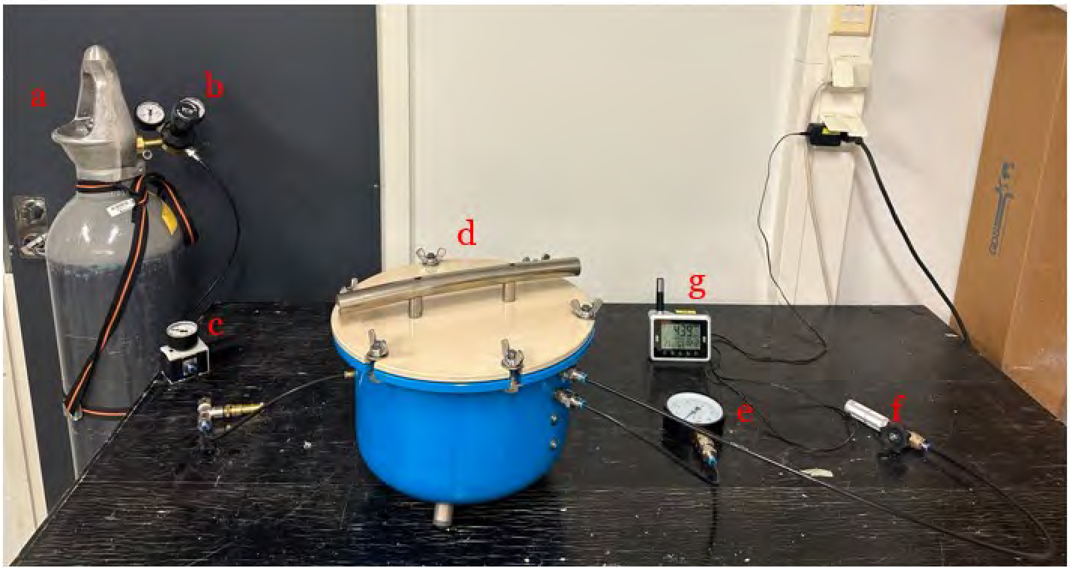


Figure 22. (a) CO_2 tube (b)Pressure adjustment (c) Pressure indicator (d)Carbonation chamber (e) Pressure indicator (f) valve to release the inside CO_2 pressure (g) CO_2-meter.

Figure 23 displays the samples that were placed into the carbonation chamber.

Figure 23. Samples in the carbonation chamber

The process of carbonation was that:

1. The carbonation chamber screws, and cover were opened.
2. The samples were placed into the chamber.
3. The carbonation chamber cover was closed, and the screws were tightened up.
4. The CO_2 tube was opened, and the adjustment was set for the specified CO_2 pressure.
5. The CO_2 pressure into the chamber was checked from the indicators.
6. The storage time of the samples in carbonation chamber was variable such as 1,2,4 and 6 hours to reach the optimum carbonation time. After finding the optimum carbonation time (mentioned in section 4), the specific time was used for carbonation duration.
7. After the test, the tube was closed, and the CO_2 in the chamber was released before opening the cover.
8. When the indicators showed the pressure was zero in the chamber, the screws and cover were opened, and the samples were taken from there.

Unsuccessful tests and methods

At the beginning of the research the Malmi clay stabilization was made by using GTC binder, and different preparation method (method which is used in Ramboll company, Finland) rather than method which is mentioned in section 3.2. Samples were prepared by filling the tubes by hand in this method. The results of the UCS tests were not reliable in this method because the force which is applied for filling the tubes in preparation was not constant and depended on the person who prepared.

Moreover, the curing time of the samples after carbonation was 7 days for stabilized clay with GTC binder. However, it was observed that the samples were dried due to the carbonation. Therefore, UCS tests could not be performed for carbonated samples nor compared with the UCS results of uncarbonated samples. After carbonation, two storage methods were applied to prevent drying and reduction of the water content of the samples. Firstly, the samples were stored in the 95% humidity room. Second, water was filled under the glass bell jar and the samples placed on a plate above water. Despite of these storage methods, it was seen that the samples dried after carbonation. For this reason, although the accuracy of the curing time after carbonation of clay samples stabilized with GTC is not certain, it was decided as 24 hours.

Successful tests and content of tests

Carbonation tests were done to observe the effects of carbonation on different carbonation duration time for 100 kg/m^3 amount of GTC binder content as shown in Table 5. The optimum duration time was found according to results of the stabilized clay with GTC binder, and it was used for other tests with different binder. The temperature of the chamber was room temperature (around 23 °C). The pressure of the CO_2 was 100 kPa for every tests. Since it was the closest pressure to the pressure in the site. In addition to these tests, the four different binders with various binder contents were used in the tests to investigate the effects of the binder amount under the carbonation and without the carbonation (Table 6).

Table 5. Content of the carbonation chamber tests on different duration time for GTC binder.

Binder Amount (kg/m^3)	Number of Samples	Duration Time of CO_2 Carbonation (hour)
100	3	1
	3	2
	3	4
	3	6

Firstly, the samples with 100 kg/m^3 GTC binder content were put into the carbonation chamber for 100 kPa CO_2 pressure for 1,2,4 and 6 hours, respectively. Three samples were prepared for each duration time. Optimum duration time was decided by looking the strength of the samples and the weight loss of the samples due to decarbonation reaction. After reached the optimum duration time for carbonation, the different binder contents tests were done by using this carbonation time.

Table 6. Content of the carbonation tests for different binder types with various binder amounts

		Number of Samples	
Binder Types	Binder Amounts (kg/m^3)	Carbonated	Uncarbonated
GTC	100	3	3
	125	3	3
	150	3	3
	175	3	3
CEM I	100	3	3
	125	3	3
	150	3	3
	175	3	3
UPM+CEM II	100	3	3
	125	3	3
	150	3	3
	175	3	3
CEM III	100	3	3
	125	3	3
	150	3	3
	175	3	3

3.3.2 Thermogravimetric Analysis

The equipment which was used for the thermogravimetric analysis that is shown in Figure 24 is 951 Thermogravimetric Analyzer.

Figure 24. Thermogravimetric Analyzer

The process of the thermogravimetric analysis was that:

1. The first step of the analysis was turning on the thermogravimetric analyser and the computer.
2. The valve of the helium bottle was opened (Figure 25).

Figure 25. Helium bottle

3. The helium flow was adjusted to 110 l/min (Figure 26).

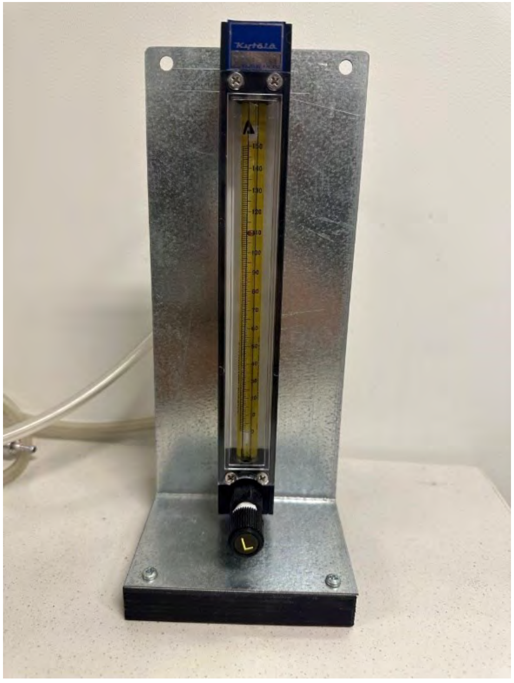


Figure 26. 110 l/min helium flow

4. The experiments method was selected, and the button of the 'start experiment' was pressed.

5. The chamber was unscrewed and pulled.
6. When the value of the voltage was stable, 'ok' button was pressed.
7. 50 mg sample was filled into the metal swing. The white rod helped the weight of the sample to be measured. The black stick behind the white rod measured the temperature of the chamber and samples. (Figure 27)
8. After filling the sample, the experiment was started.

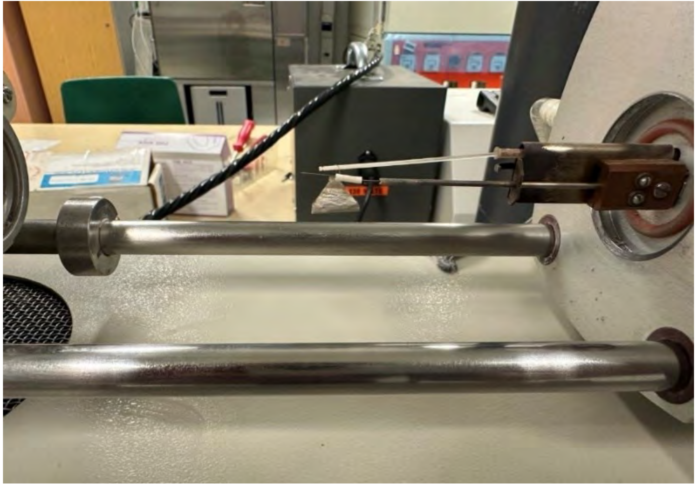


Figure 27. Inside of the TG analyzer chamber

For thermogravimetric analysis, the method that Dejenie, (2022) used in his research was selected. Dejenie, (2022) explained the method in his thesis. The temperature was between +50 and 950°C, and the heating speed was 20°C per minute. The heating process was split into two parts to allow time for water loss at 100°C. First, increase the temperature from +50 °C to +100 °C and maintain it there for 10 minutes. The temperature increases from +100°C to +950°C in the second phase.

3.3.3 Unconfined Compression Test

Unconfined compression test equipment is shown in figure below (Figure 28).

Figure 28. UCS test equipment

The UCS tests were made for each carbonated sample which had different amount of binder contents, exposed CO_2 for various duration times and pressure of 100 kPa. Figure 29 displays the sample after UCS test.

Figure 29. The sample after UCS test

4 Results and Discussion

In this section of the thesis, UCS and TGA results of different carbonation duration and the results of various binder types with different binder contents were presented. Through the results some discussions and inferences were made.

4.1 Unconfined Compressive Strength Tests

4.1.1 UCS Tests Results of Different Carbonation Duration

The UCS tests were performed for samples that were carbonated 1,2,4 and 6 hours under 100 kPa CO_2 pressure. These samples consisted of a GTC binder with 100 kg/m^3 binder content. The strength tests were done after CO_2 carbonation for samples.

The samples were prepared following the process that is mentioned in section 3.2. Furthermore, at the beginning of the study, the samples were placed in plastic bags after carbonation and kept in a cold room at 2.9 ◦C for 7 days. However, after 7 days of curing, it was observed that the carbonated GTC stabilized clay samples were getting dry due to the carbonation. Since this situation affected the results of the UCS tests, the curing time for the GTC stabilized clay samples were decreased and UCS tests were performed after carbonation. The UCS values were calculated as the maximum force divided by per area of the specimen, and the unit of the UCS was kPa.

The UCS results for different carbonation time (GTC binder, 100 kg/m^3) were shown in Figure 30. The results of UCS tests represented an average of 3 samples for each carbonation duration time except 1 hour duration results (Appendix 4). For 1 hour carbonation duration results, the average of the two parallel UCS results were taken into account. According to the results, the average of the UCS for samples under the 1-hour carbonation was 44.07 kPa, for samples under the 2 hours carbonation was 49.57 kPa, for samples under the 4 hours carbonation was 52.16 kPa, and for samples under the 6 hours carbonation was 45.53 kPa.

Based on the results, it can be said that the strength of the samples slightly increased by increasing the carbonation time up to 4 hours. At 6 hours carbonation, it was observed that the strength of the carbonated samples decreased. Thus, the optimum carbonation time was decided to be 4 hours for the other binders and all different binder amounts.

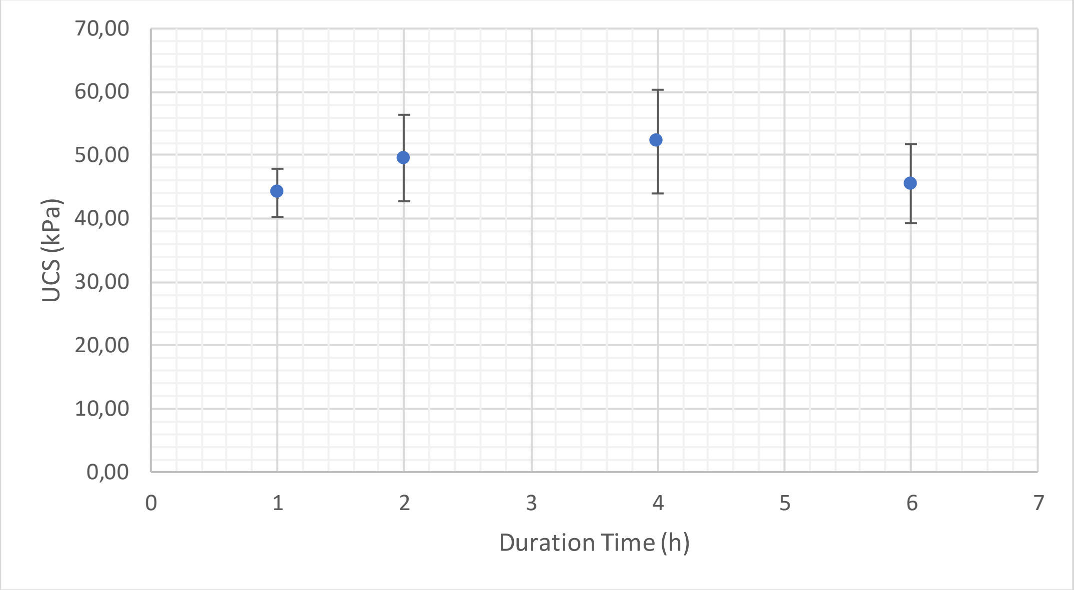


Figure 30. The average UCS results for different carbonation time (GTC binder (100 kg/m^3))

4.1.2 UCS Tests Results of Different Binder Types with Various Binder Amounts

In terms of different binder amounts, the UCS tests were performed for four binder types. The content of the samples was presented in Table 5. As the optimum carbonation time was found to be 4 hours in section 4.2.1., the tests were done for 4 hours carbonation time under 100 kPa CO_2 pressure.

For these tests, the samples were prepared as following the sample preparation methods in section 3.2. While the curing time after carbonation was 7 days for CEMI, UPM+CEMII and CEMIII stabilized clay samples, it was 24 hours for GTC stabilized clay samples. The average of the 3 samples UCS results were taken for each binder type and amounts in both carbonated and uncarbonated condition.

Figure 31 presents the comparison of the UCS results between carbonated and uncarbonated samples of stabilized clay with GTC. It can be seen in the figure, that the uncarbonated samples were stronger than carbonated samples.

Based on these results, it can be seen that increasing binder amount raised the strength of the carbonated samples. When the binder content was 100 kg/m^3, the UCS was 51,54 kPa. When the amount of binder increased to 125 kg/m^3 binder content, the UCS was 81,18 kPa. For 150 kg/m^3 binder content the UCS was 111,37 kPa and for 175 kg/m^3 binder content the UCS was 139,67 kg/m^3 (Appendix 5).

The strength of the uncarbonated samples that were stabilized clay with GTC binder increased when the amount of binder content was enhanced. The strengths of the sample with 100 kg/m^3 and 125 kg/m^3 binder content were 77.20 kPa and 98.50 kPa, respectively. For 150 kg/m^3 binder content, the strength was found 138 kPa, while it was 174.67 kPa for samples with 175 kg/m^3 binder amount (Appendix 6).

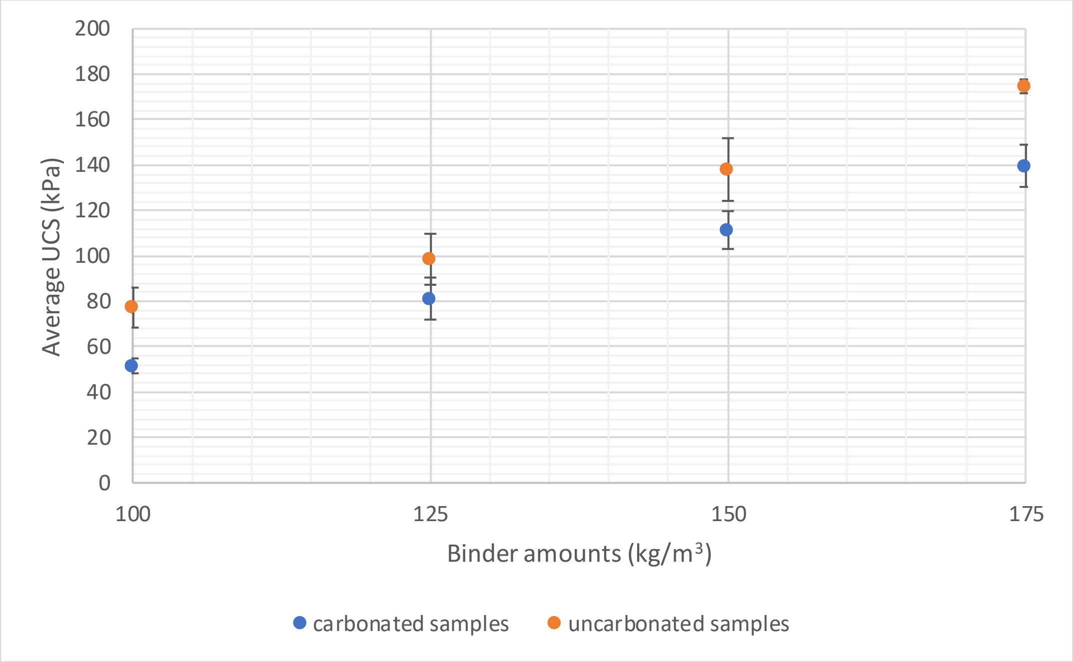


Figure 31. Comparison of the average UCS results for uncarbonated and carbonated samples for stabilized clay with GTC.

The results of the UCS tests for both carbonated and uncarbonated stabilized clays with CEMI for different binder amounts are presented in Figure 32. According to the graph, the UCS was 325.7 kPa for 100 kg/m^3 and 422.16 kPa for 125 kg/m^3.When the amount of binder was increased to 150 kg/m^3, the UCS was 657.81 kPa, and it was 853.96 kPa for 175 kg/m^3 (Appendix 7).

For carbonated samples of stabilized clays with CEMI the results were 222.08 kPa for 100 kg/m^3, 427.66 kPa for 125 kg/m^3. Moreover, the UCS were 777.83 kPa and 941.82 kPa for 150 kg/m^3 and 175 kg/m^3, respectively (Appendix 8).

In terms of increment of the binder amounts, the strength of the CEMI stabilized clays increased for both uncarbonated and carbonated conditions. The results indicate that carbonation generally improved the strength of the stabilized samples for all binder contents except for 100 kg/m^3. It was observed that the strength of the carbonated samples for 100 kg/m^3 binder content were 103.61 kPa less than strength of the uncarbonated samples. Although, the strength of the carbonated samples for 125 kg/m^3 binder content was greater than the strength of the uncarbonated samples, the difference between them was only 5.5 kPa. The difference in strength between carbonated and uncarbonated samples was more significant for higher binder amounts, with a difference of 120.02 kPa for 150 kg/m³ and 87.86 kPa for 175 kg/m³.

Therefore, it can be concluded that high binder amounts, such as 150 kg/m³ and 175 kg/m³, had a favorable influence on the strength of the stabilized clay with CEM I when carbonated.

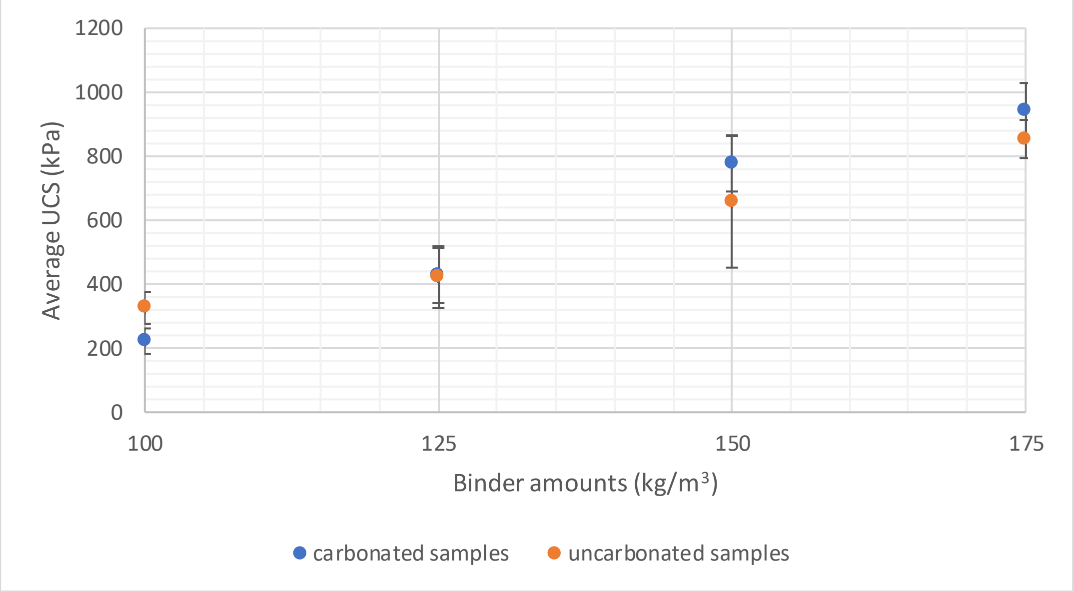


Figure 32. Comparison of the average UCS results for uncarbonated and carbonated samples for stabilized clay with CEM I.

The strengths of the stabilized clay with UPM+CEM II for uncarbonated and carbonated samples were shown in Figure 33. As a result of the UCS tests, the strength of the 100 kg/m³ binder content was 54.28 kPa for uncarbonated, and 58.58 kPa for carbonated conditions. Whereas the strength of the 125 kg/m³ binder amount stabilized clay sample was 120.81 kPa for uncarbonated situation, it was 105.05 kPa for carbonated situation. For 150 kg/m3 binder content, the UCS was 141.14 kPa for uncarbonated samples, and it was 143.41 kPa for carbonated samples. Similarly, the UCS was 153.52 kPa for uncarbonated samples of 175 kg/m³ binder content, and 165.16 kPa for carbonated samples of it.

Therefore, the strengths of the samples after carbonation were higher than the strengths of the uncarbonated samples for all binder contents, except for 125 kg/m³. In addition, the strength of the samples significantly increased (almost two times) between 100 kg/m³ and 125 kg/m³ binder contents.

Although, the UCS results were greater for carbonated samples, the difference between uncarbonated samples and carbonated samples results were not significant.

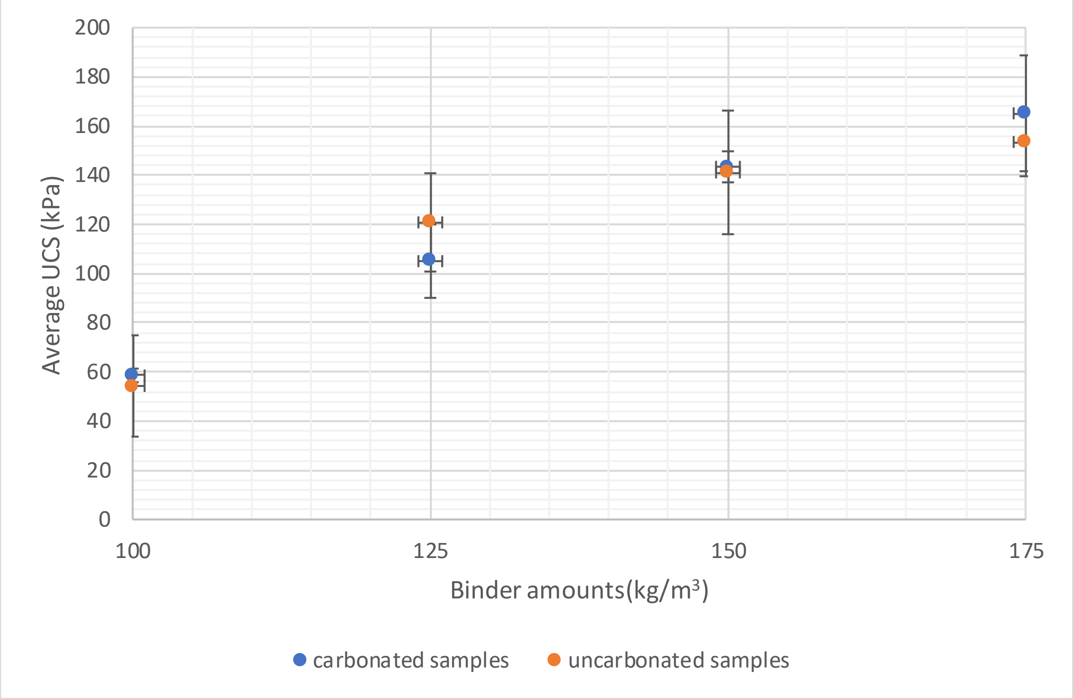


Figure 33. Comparison of the average UCS results for uncarbonated and carbonated samples for stabilized clay with UPM+CEMII.

Figure 34 shows the results of the uncarbonated and carbonated stabilized clay samples with CEMIII. The 100 kg/m^3 binder content samples had 163.59 kPa and 153.34 kPa strength for uncarbonated and carbonated situation, respectively. For uncarbonated samples of the 125 kg/m^3 binder content the UCS was 227.47 kPa, while it was 195.62 kPa for carbonated samples. The UCS was 320.93 kPa for 150 kg/m^3 in uncarbonated condition, it was 340.86 kPa for carbonated condition. When the binder content was increased to 175 kg/m^3, the UCS was 311.04 kPa for uncarbonated samples, and 334.50 for carbonated samples. The results were presented in Appendix 11 and 12.

The strength of the samples increased with the increase in the amount of binder for both carbonated and uncarbonated condition until 175 kg/m^3 binder content. It decreased from 320.93 kPa to 311.04 kPa for carbonated samples and decreased from 340.86 kPa to 334.50 kPa when the binder amount was increased from 150 kg/m^3 to 175 kg/m^3.

As an effect of carbonation, it was observed that the strength of the samples decreased after carbonation for all binder content, except for the 175 kg/m^3 binder content. The strength increased up to 334.5 kPa from 311.04 kPa in 175 kg/m^3 after carbonation.

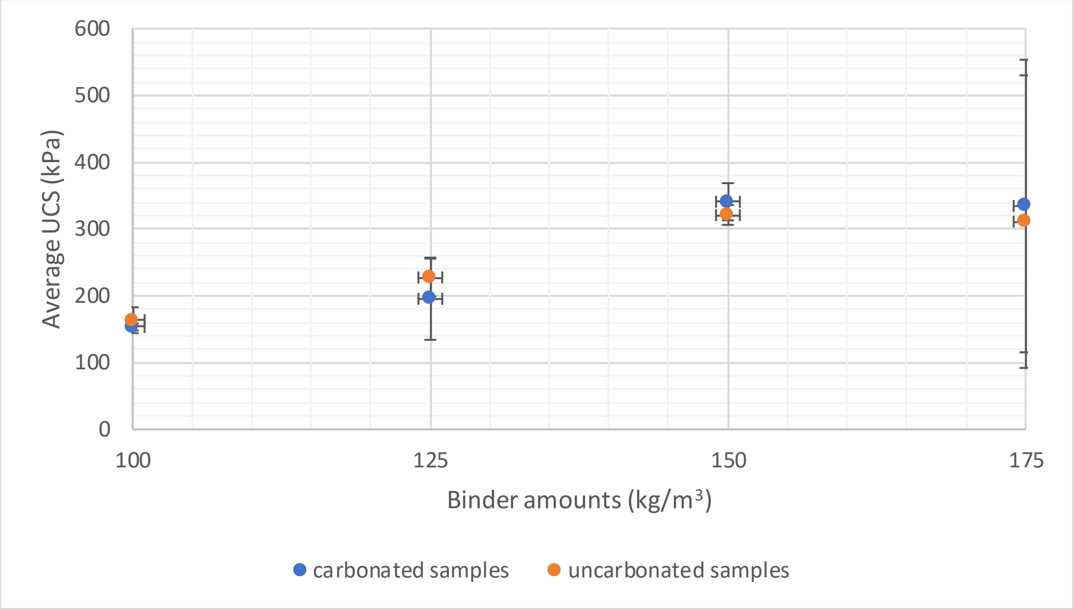


Figure 34. Comparison of the average UCS results for uncarbonated and carbonated samples for stabilized clay with CEMIII.

Overall, CEMI (cement type I) was found to be the most effective type of binder for stabilizing Malmi clay, while GTC was the least effective. This may be due to the duration of the curing time after carbonation. The carbonation process had a positive impact on the strength of stabilized clay samples for binder amounts of 150 kg/m^3 and 175 kg/m^3, except for GTC binder and 150 kg/m^3 CEMIII binder content. However, for lower binder amounts such as 100 kg/m^3 and 125 kg/m^3, carbonation has not had a significant effect on the strength of the samples, especially those that contained cement. Moreover, it was noticed that the strength of the samples generally rose as the binder amounts increased for both carbonated and uncarbonated samples, with respect to each type of binder.

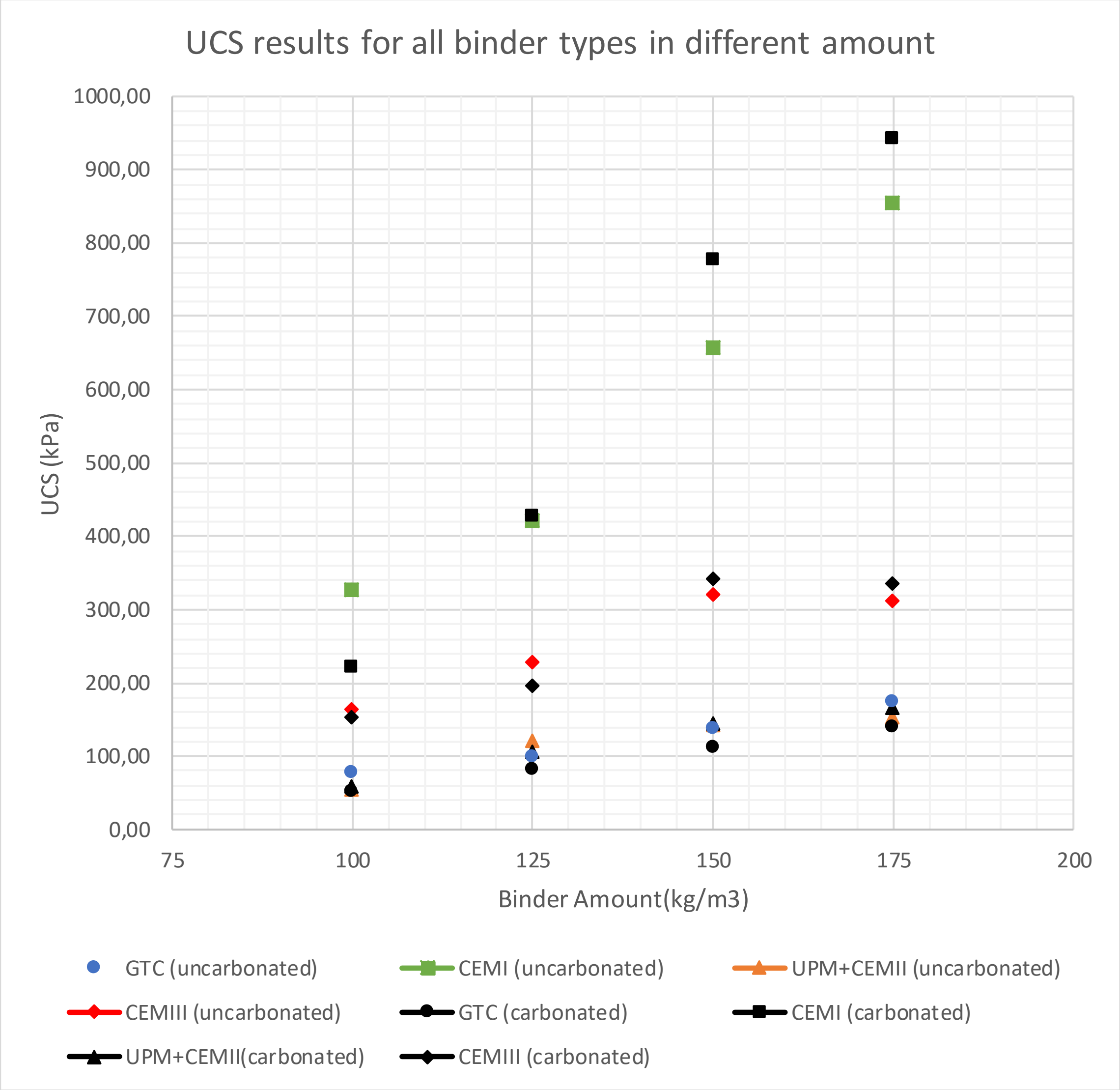


Figure 35. UCS results for all binder types in different amounts.

One of the stress-strain curves of the stabilized soft clay samples with 100 kg/m^3 GTC binder is shown in Figure 36. Based on stress-strain curves, deformation modulus (E_{50}) was found for each binder type and amounts for both carbonated and uncarbonated conditions. It can be seen in Figure 36, the slope of the midpoint of the linear line in the elastic region gave the E_{50} values of the samples. Figure 37 and 38 present E_{50} values for carbonated and uncarbonated samples, respectively. While deformation modulus for CEMI had the greatest in all binder content among the other binder types, GTC and UPM+CEMII had the lowest deformation modulus (Appendix 13 and 14).

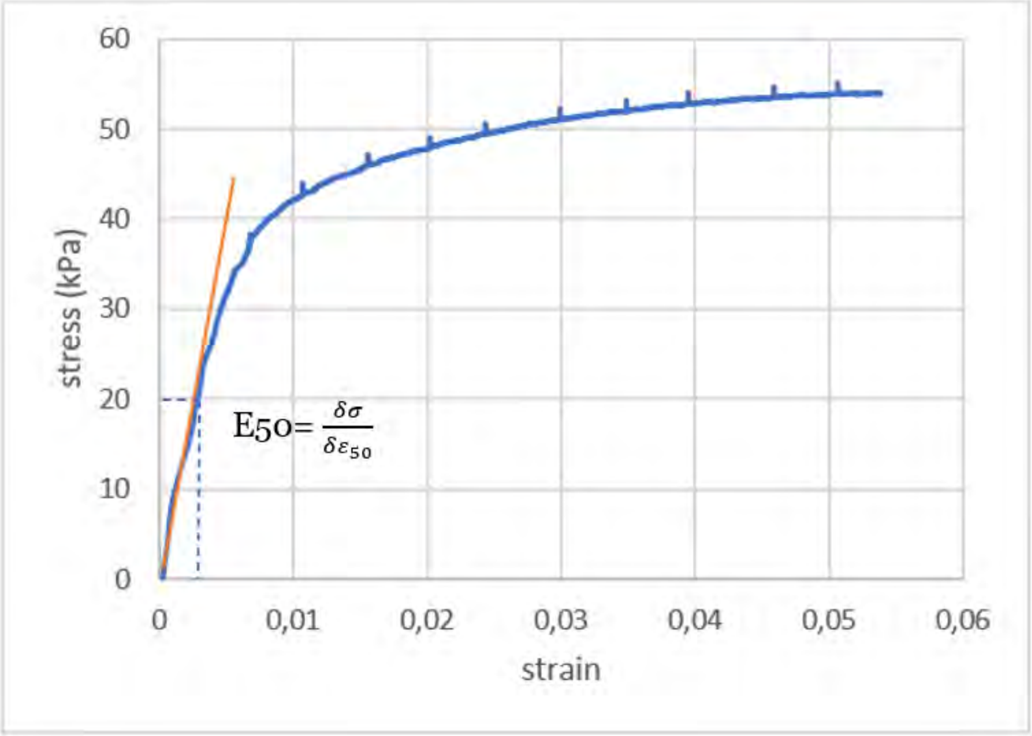


Figure 36.Stress-strain curve of the carbonated stabilized soft clay with GTC binder (100 kg/m³)

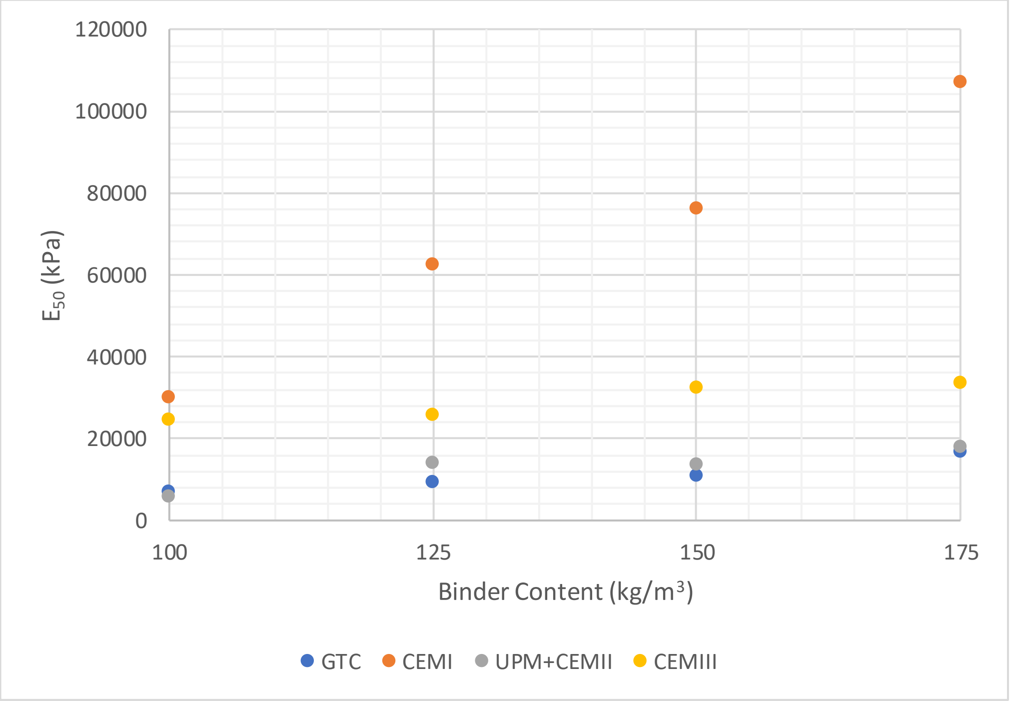


Figure 37. Deformation modulus (E_{50}) of carbonated samples

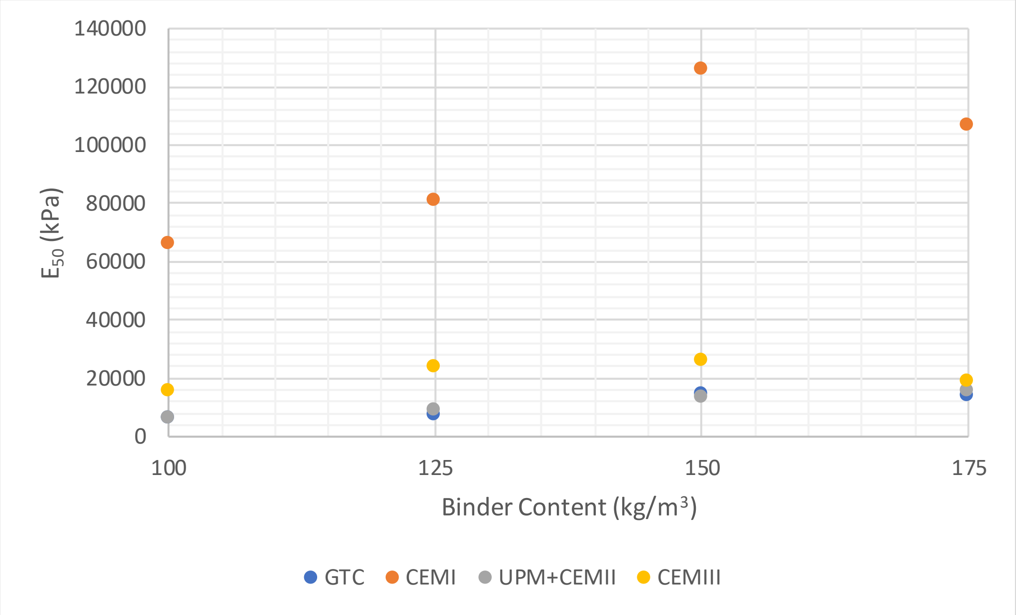


Figure 38. Deformation modulus (E_{50}) of uncarbonated samples

4.2 Thermogravimetric Analysis

4.2.1 Thermogravimeter Analysis Results of Different Duration Time of Carbonation

The samples which were formed 100 kg/m^3 GTC binder content were performed in TGA to find optimum carbonation duration. 3 samples were tested for each duration time such as 1 hour, 2,4 and 6 hours carbonation. The average of the weight loss was calculated from each 3 samples results for different carbonation duration.

The weight loss of the carbonated samples at between 520 ◦C and 800 ◦C was taken into consideration in this research. The percentage of the weight loss of the carbonated stabilized clay with GTC (100 kg/m^3 binder content) for different carbonation duration is shown in Figure 39.

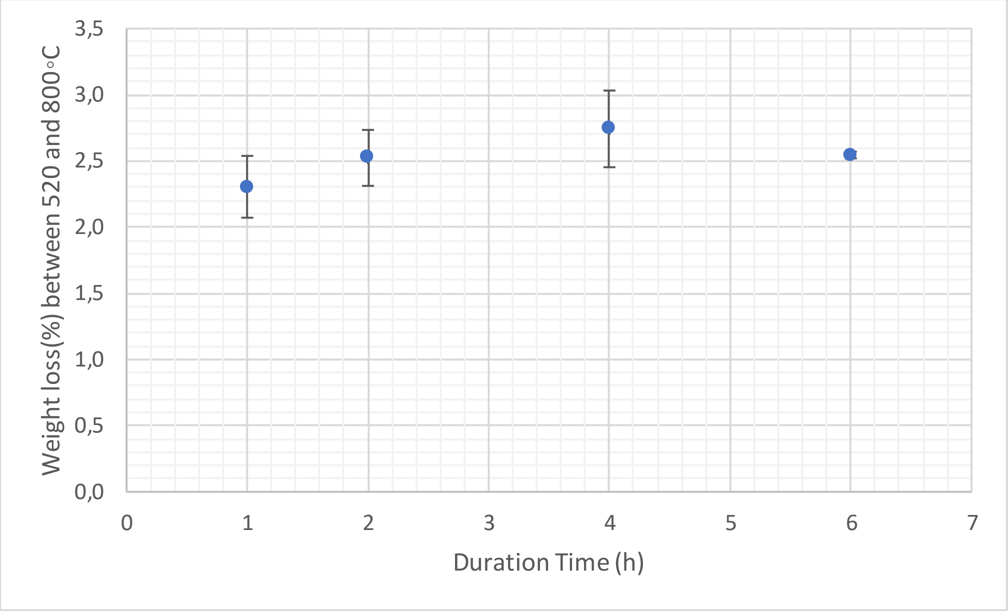


Figure 39. The average weight loss (%) between 520 and 820 ◦C for carbonated stabilized clay with different carbonation duration for GTC binder

The weight loss of the stabilized clay with 1 hour carbonation was 2.30% and 2.52% for stabilized clay with 2 hour carbonation. It increased up to 2.74% for 4 hour carbonation. However, for 6 hour carbonation the weight loss was 2.55%. Thus, the reaction of the decarbonation increased by increasing carbonation duration of the samples from 1 hour to 4 hours (Appendix 15). It can be said that the optimum time of the carbonation was 4 hours. So, this conclusion was supported with the UCS results which was mentioned in section 4.2.1.

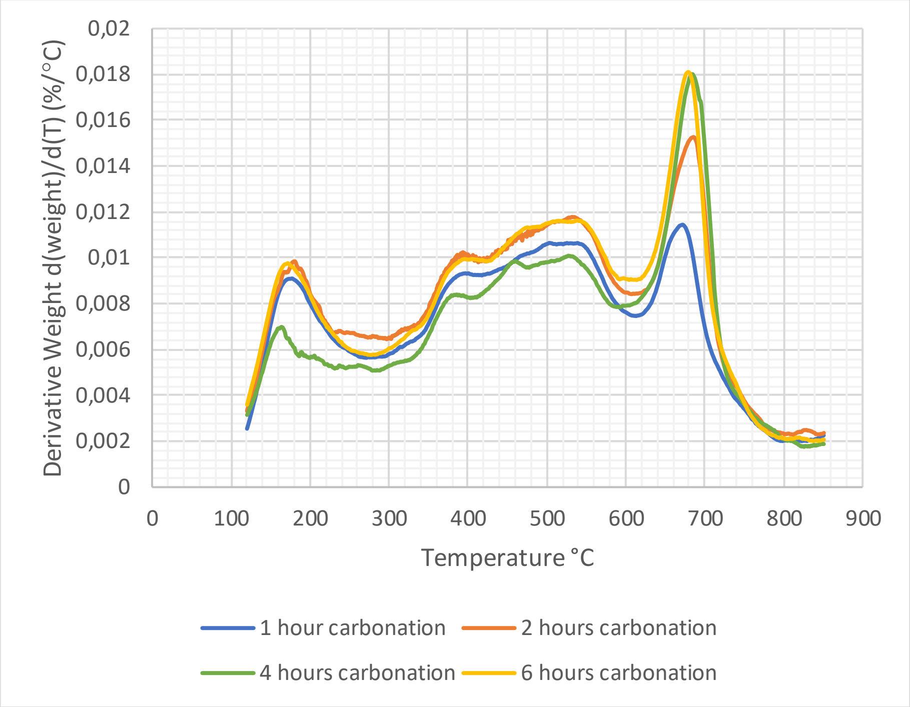


Figure 40. TG derivative (%/ºC) results of carbonated stabilized clay with different carbonation duration for GTC binder

Figure 40 displays the DTG curve of the carbonated stabilized clay samples for different carbonation time. There were three peaks in the graph at 100 ± 20 ◦C to 300± 20 ◦C, 300± 20 ◦C to 600± 20 ◦C and 600± 20 ◦C to 800± 20 ◦C. The first peak can be associated with the removal of the water from the specimen (Unluer & Al-Tabbaa, 2013) and (Yaras, et al., 2019)). The second peak at 300 ◦C to 580 ◦C can be caused by decomposition of the calcium carbonate to calcium oxide. The third peak can be formed due to the decarbonation of the calcium carbonates to calcium oxide (Unluer & Al-Tabbaa, 2013). Moreover, it can be seen that clays exposed to more carbon dioxide lose more weight at between 600 ◦C to 800 ◦C.

4.2.2 Thermogravimeter Analysis Results of Different Binder Types with Various Binder Amounts

The weight loss of the carbonated and uncarbonated samples at between 520 ◦C and 800 ◦C increased when the binder amount was enhanced for stabilized clay with GTC binder (Figure 41). The carbonation affected the samples by raising the weight loss of the samples at specified temperatures. While the weight loss of the carbonated samples was 3.34% and 3.71% for 100 kg/m^3 and 125 kg/m^3 binder contents, respectively. It was 1.71% for uncarbonated samples with 100 kg/m^3, and 1.76% for uncarbonated samples with 125 kg/m^3. When the binder amount was increased to 150 kg/m^3, the weight loss was 3.80% for carbonated samples, and 1.96% for uncarbonated samples. Similarly, for stabilized clay samples at 175 kg/m$_3$ the weight loss was 4.18% and 2.15% with carbonation and without carbonation, respectively.

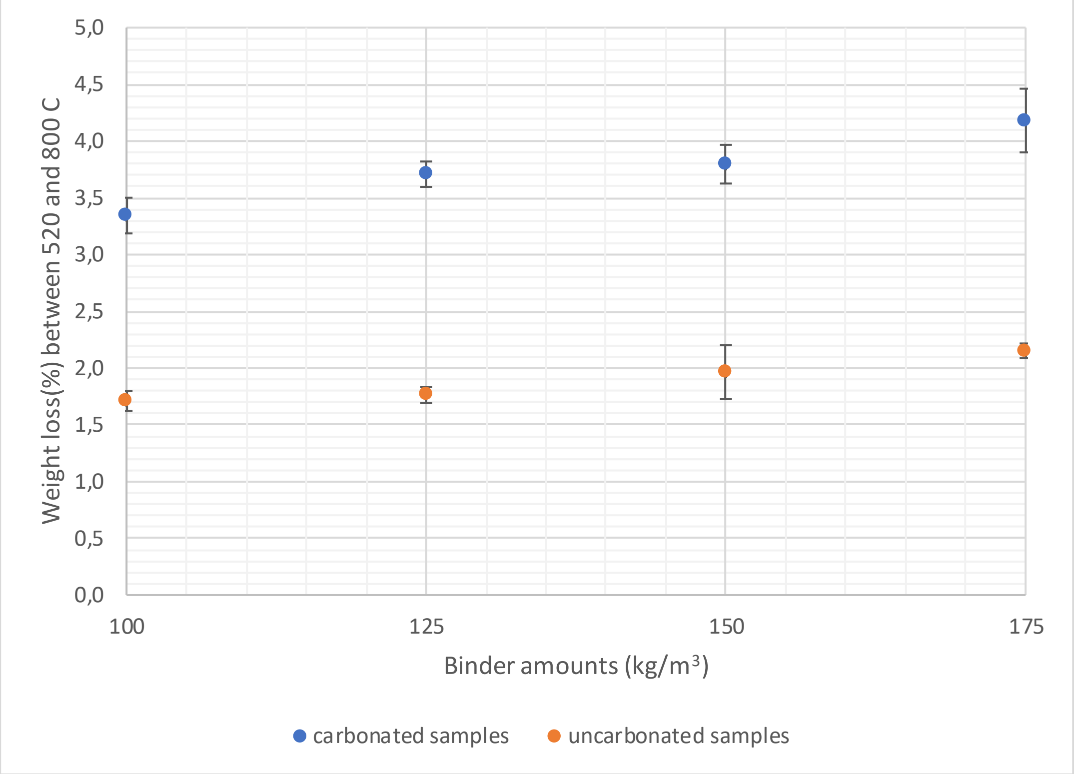


Figure 41. The average weight loss of the carbonated and uncarbonated stabilized clay with GTC

For stabilized clay with CEM I, the weight loss of the samples growth when the binder amount was increased for both carbonated and uncarbonated samples. Figure 42 displays comparison of the TGA results for carbonated and uncarbonated samples of stabilized clay with CEM I. The percentage of weight loss for 100 kg/m^3 and 125 kg/m^3 was 3.07% and 3.11%, respectively. When the binder amount was increased to 150 kg/m^3, the weight loss of the sample was 3.17%. While it was 3.23% for 175 kg/m^3 binder content (Appendix 18). In terms of uncarbonated samples the weight loss was 1.80% for 100 kg/m^3. It was 1.89% and 2.26% for 125 and 150 kg/m^3 binder contents respectively. The percentage of weight loss rose to 2.36% when the binder amount was 175 kg/m^3 (Appendix 19). It can be seen in Figure 42; the weight loss of the carbonated samples was greater than the weight loss of the uncarbonated samples for each binder content.

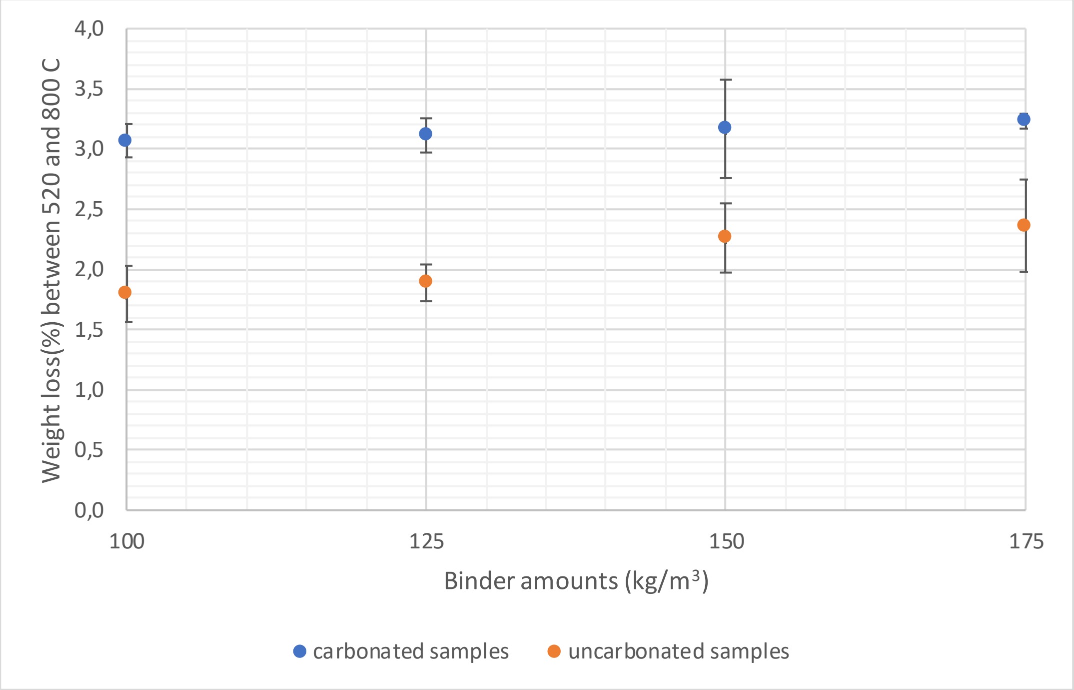


Figure 42. The average weight loss of the carbonated and uncarbonated stabilized clay with CEMI

According to the TGA results of stabilized clay with UPM+CEMII, no linear increasing or decreasing graph was not observed by increment of binder content for both carbonated and uncarbonated samples. However, the weight loss of the carbonated samples was greater than the weight loss of the uncarbonated samples for each binder content. As it can be seen in the Figure 43, the weight loss of the carbonated samples was almost same for all different binder content, while the weight loss of the uncarbonated samples with 100 kg/m^3 binder content was higher than other the weight loss of the uncarbonated samples. Thus, it can be said that although carbonation had an impact on the reaction of the stabilized samples by increasing the weight loss, the increment of the binder content did not affect the weight loss of the samples at all.

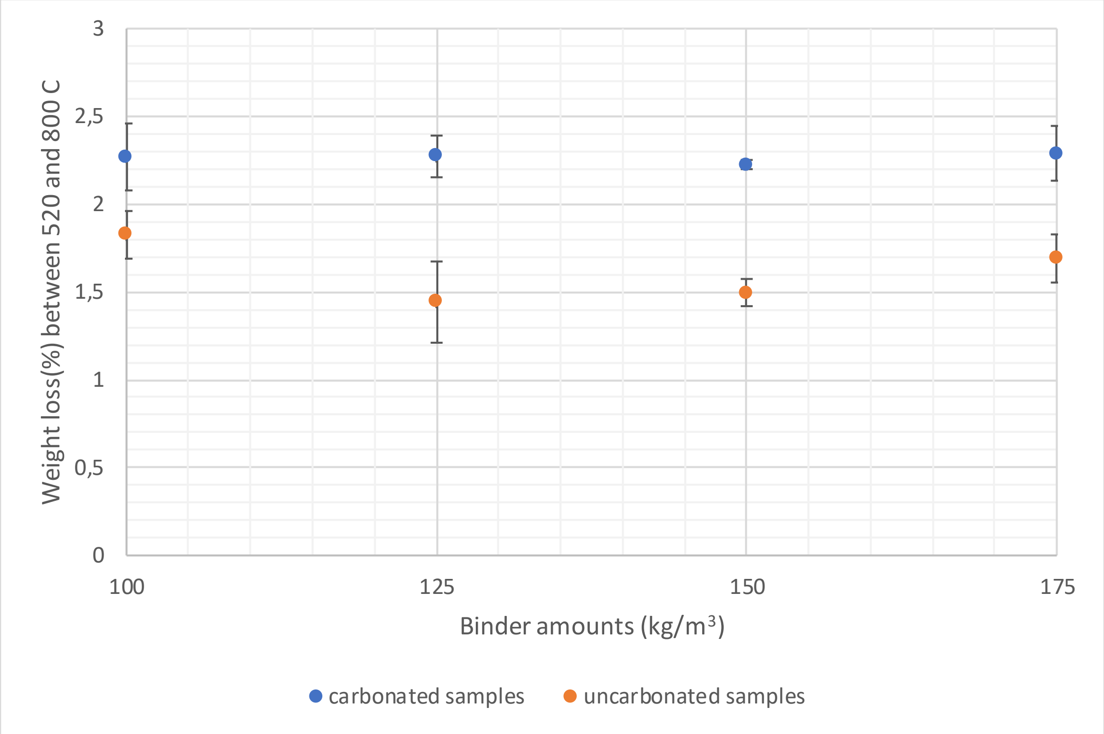


Figure 43. The average weight loss of the carbonated and uncarbonated stabilized clay with UPM+CEMII

Figure 44 presents the results of the weight loss (%) between 520 and 800 ◦C of the stabilized clay with CEMIII for both uncarbonated and carbonated samples. As it can be seen in the graph, reduction of the weight of the carbonated samples were more (around 1%) than uncarbonated samples weight loss for all binder content. While the amount of weight loss was rising with increasing binder content for carbonated samples, the weight loss of the uncarbonated samples with various binder amount were very close to each other.

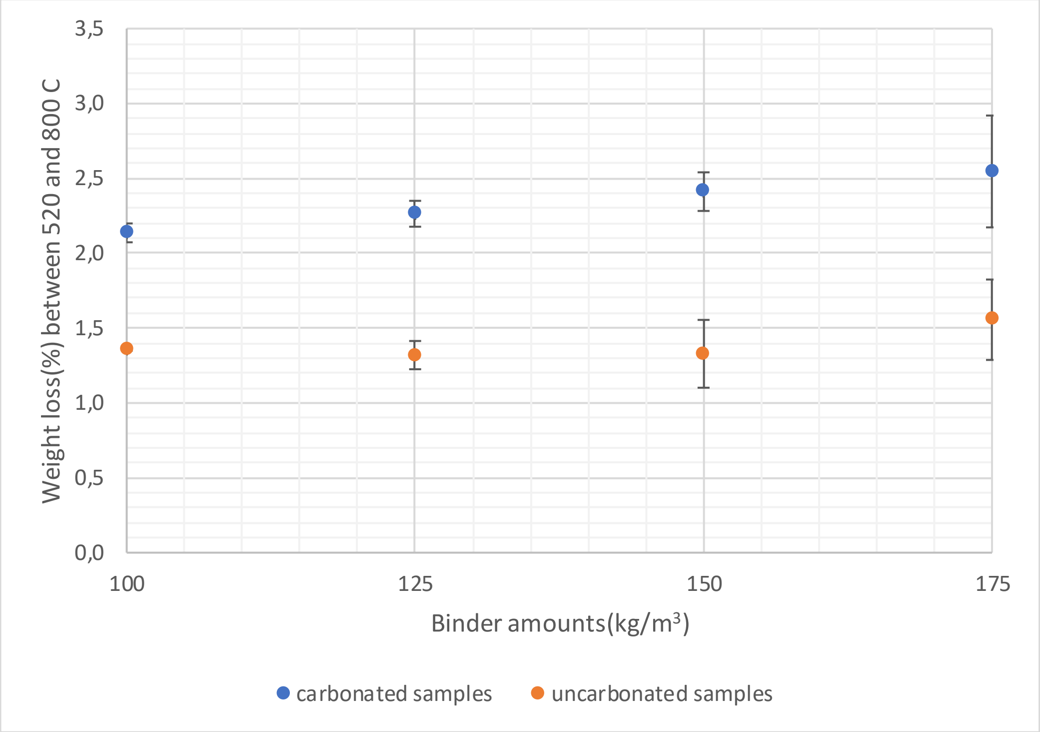


Figure 44. The average weight loss of the carbonated and uncarbonated stabilized clay with CEMIII

The DTG curves of the carbonated stabilized clay samples by using different binders with various contents are shown in Figures 45,46,47 and 48 for binders GTC, CEMI, UPM+CEMII and CEMIII, respectively. Similar observations have been made with the DTG curve results of different duration time of carbonation which at there were three peaks for all samples with different binder types and amounts. Thus, the first peak was observed at between 100 ± 20 ◦C and 300 ± 20 ◦C due to the loss of hydration (Yaras, et al., (2019), Unluer & Al-Tabbaa, (2013)). The second peak was at between 300 ± 20 ◦C and 600 ± 20 ◦C because of the decomposition of the $CaCO^3$ (dos Santos, et al., 2014). The third peak was related to the decarbonation of the $CaCO_3$ (Unluer & Al-Tabbaa, 2013).

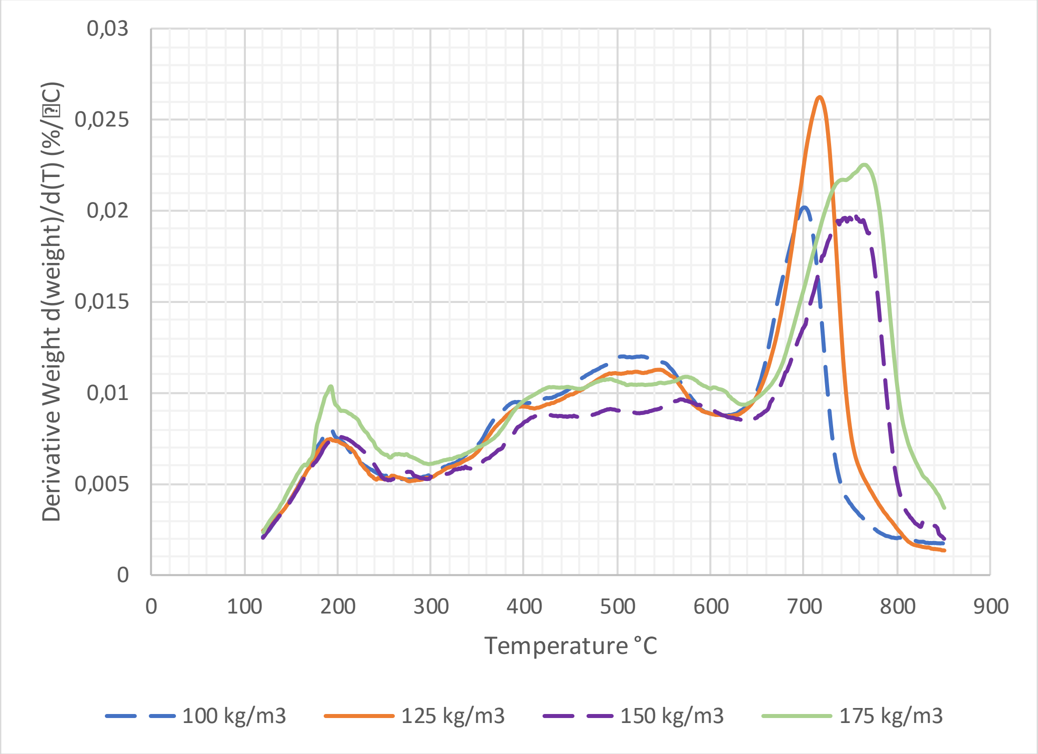


Figure 45. TG derivative (%/°C) results of carbonated stabilized clay with GTC for different binder amounts

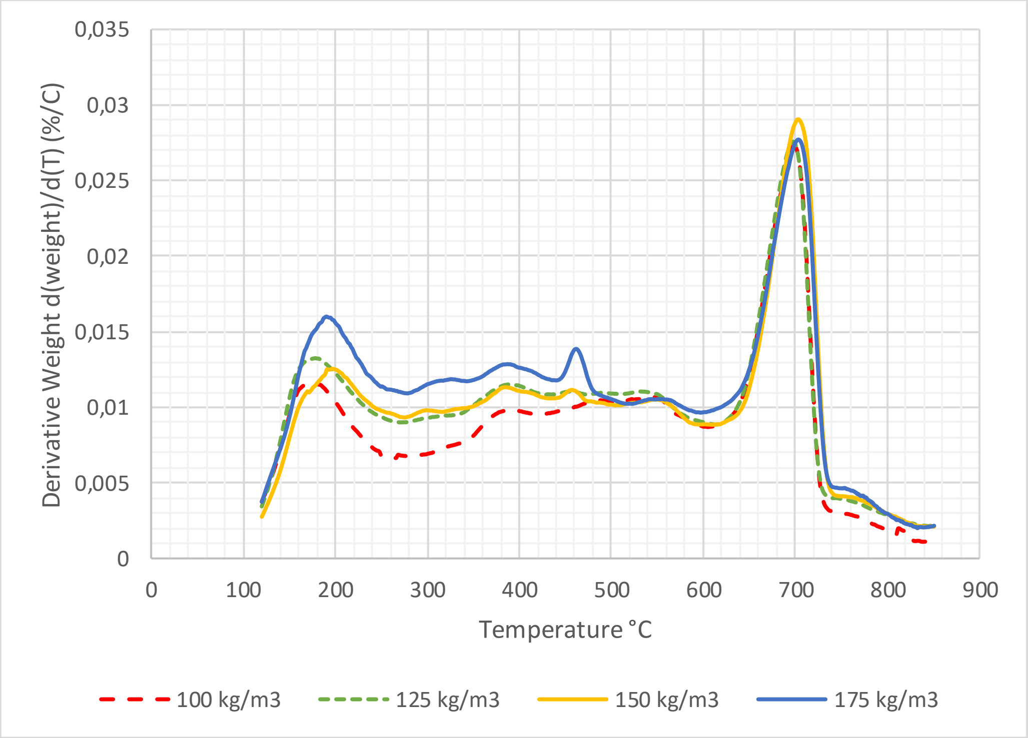


Figure 46. TG derivative (%/°C) results of carbonated stabilized clay with CEM I for different binder amounts

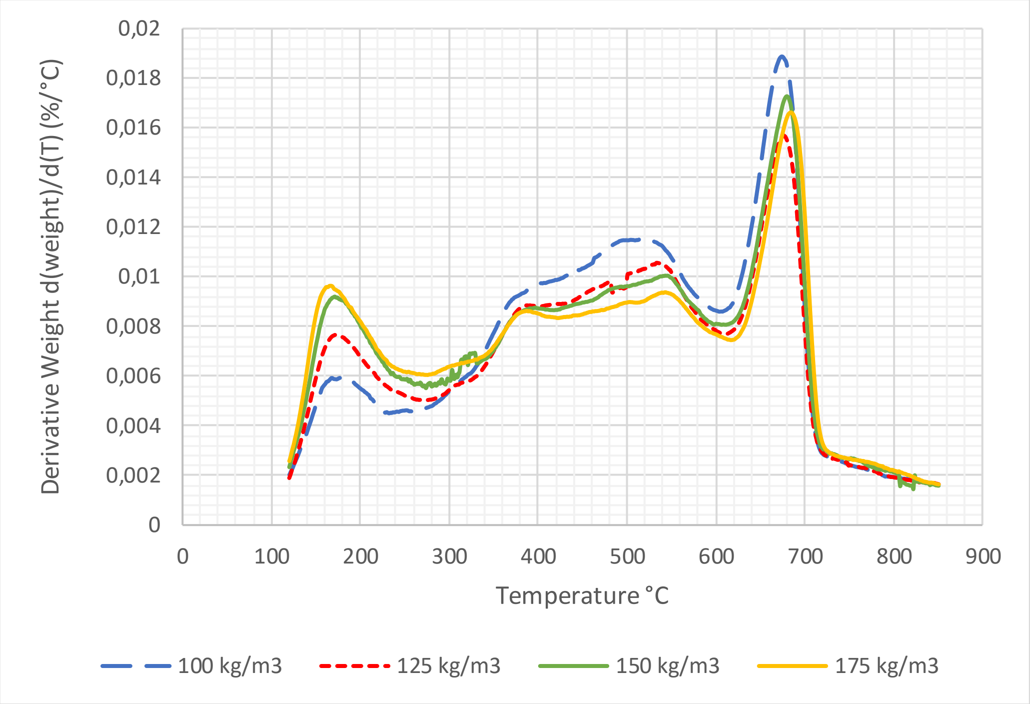


Figure 47. TG derivative (%/ºC) results of carbonated stabilized clay with UPM+CEMII for different binder amounts

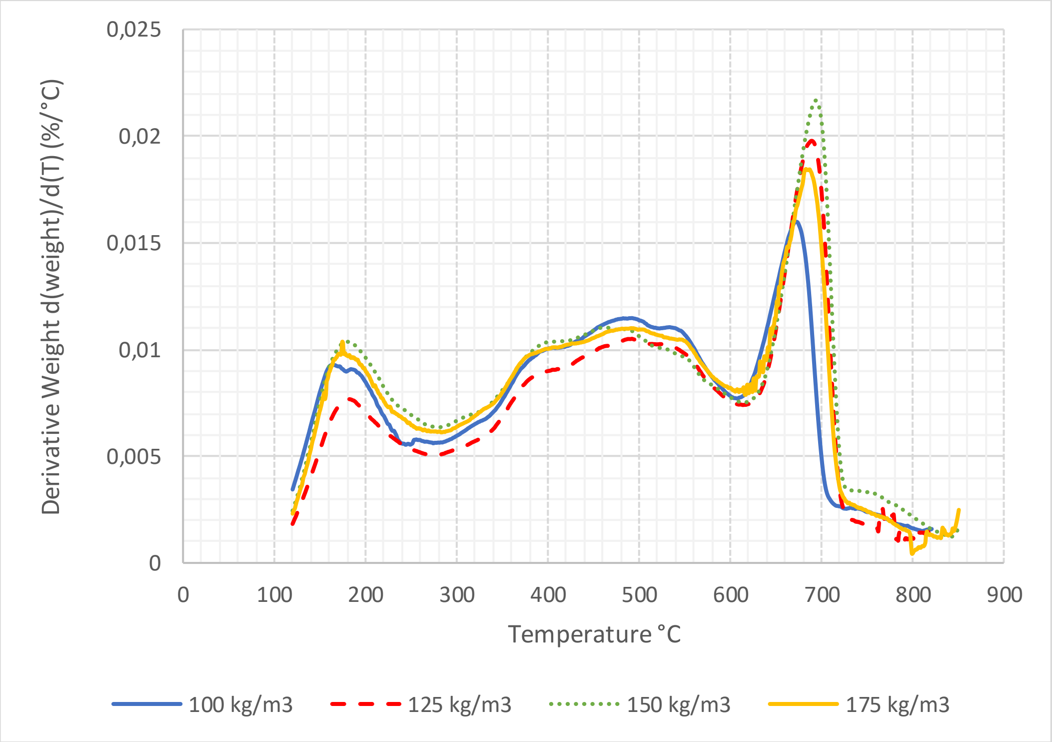


Figure 48. TG derivative (%/ºC) results of carbonated stabilized clay with CEMIII for different binder amounts

Weight loss of the carbonated samples from decarbonation for all four binder types and amounts are shown in Figure 49. GTC binder had the most weight loss for each binder type compared to the other binders. The least weight loss was observed for stabilized clay samples with UPM+CEMII and CEMIII binders. While the weight loss due to decarbonation increased with increasing binder amount for GTC and CEMIII binders, it was nearly same for CEMI and UPM+CEMII binders in each binder amounts.

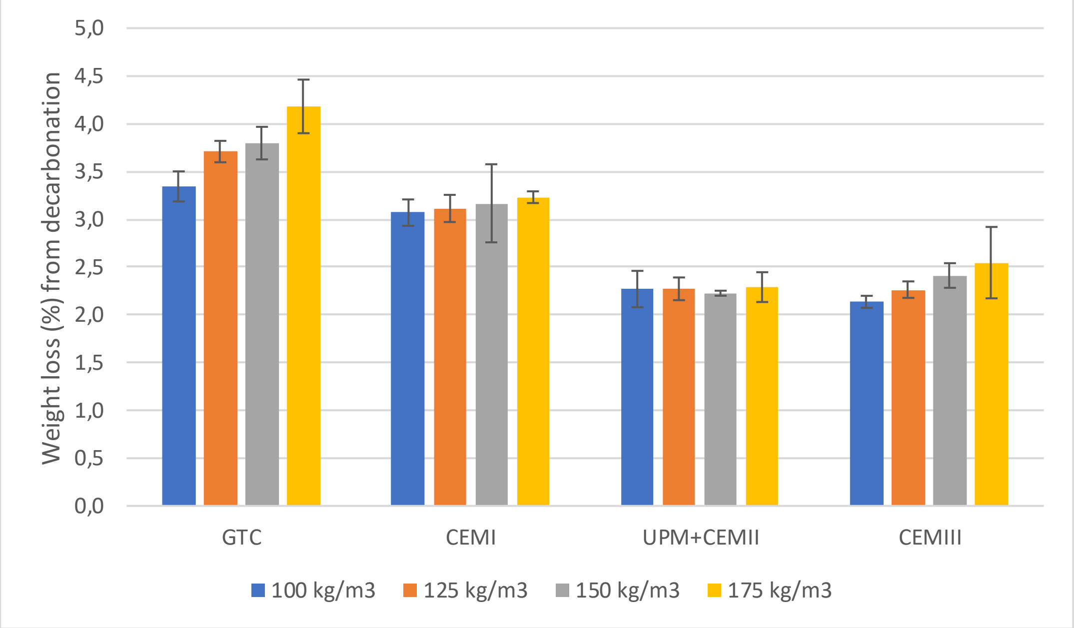


Figure 49. Weight loss due to decarbonation for each binder types and amounts

The amount of CO_2 bound of the samples was calculated for various binder types and amounts by comparing the weight loss of the carbonated and uncarbonated samples in decarbonation reaction. It can be seen in Figure 50, the highest amount of CO_2 bound was for GTC binder, and the least amount of CO_2 bound belonged to UPM+CEMIII binder. Based on the results it was not observed linear effects of the binder amounts on amount of CO_2 bond. Because the results were fluctuated for all binder types on different binder amounts. The binder with the most amount of CO_2 bond was the (175 kg/m^3) GTC binder with 2%, while the binder with the least amount of CO_2 bond was (100 kg/m^3) UPM+CEMII with 0.44%.

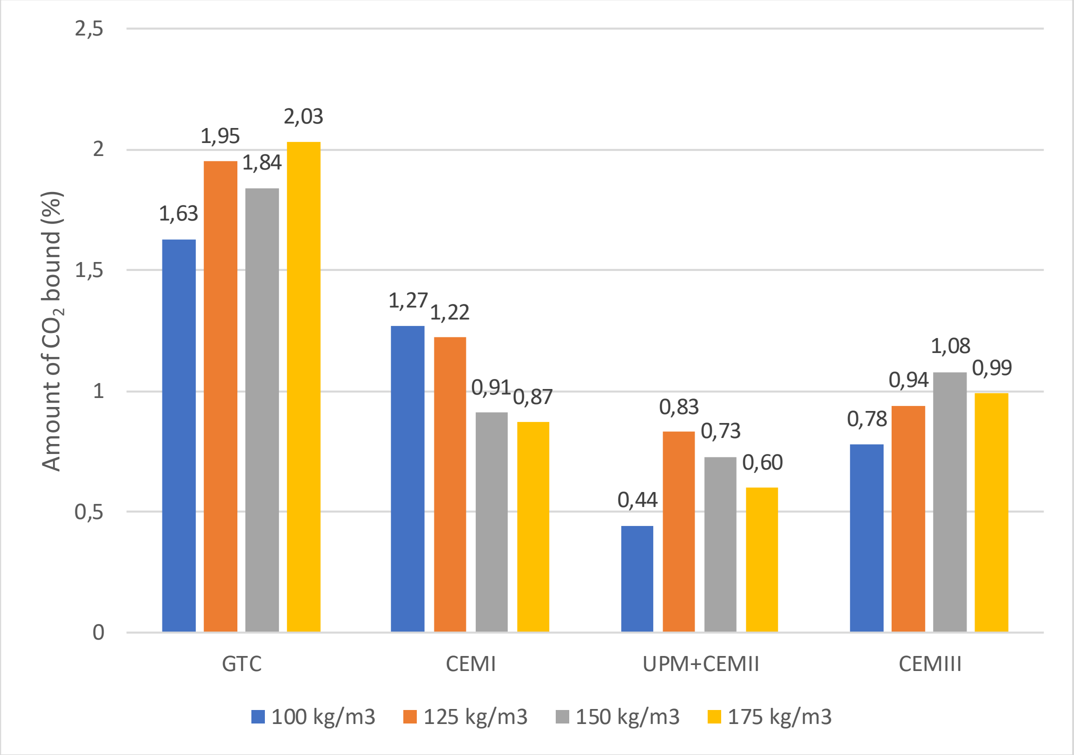


Figure 50. Amount of CO_2 bound for all binder types and amounts.

In Figure 51, CO_2 absorption capacity, and CO_2 emissions from manufacturing and net CO_2 for all binder types and amounts are shown. The dry density of the stabilized clay samples was used to calculate and make an estimation CO_2 absorption capacity (kg/m^3) for per cubic meter of the samples. The difference between CO_2 absorption capacity and CO_2 emissions from manufacturing the binders was net amount of CO_2 (kg/m^3) per cubic meter. The CO_2 emissions from manufacturing were taken from the thesis by Dejenie, (2022) and Nguyen, (2021) as 23 .2 kg CO_2 eq. e. /100kg of GTC, 77.6 kg CO_2 eq. e. /100kg of CEM I, 18.4 kg CO_2 eq. e. /100kg of UPM+CEM II, and 47 kg CO2 eq. e. /100kg of CEM III. For other binder amounts assumptions were made for all binder types by using values for 100 kg/m^3 binder content. GTC and UPM+CEM II binders had the lowest CO_2 emissions from manufacturing. The highest amount of CO_2 absorption was for GTC binder between 12 kg CO_2 eq. e. /m^3 and 17 kg CO_2 eq. e. /m^3. While the CEM I binder had the most amount of CO_2 emissions from manufacturing data, it had the second highest CO_2 absorption amount which was between 8 kg CO_2 eq. e. /m^3 and 10 kg CO_2 eq. e. /m^3. Net CO_2 was between 11 and 24 kg CO_2 eq. e. /m^3 for GTC binder, and it was between 15 and 27 kg CO_2 eq. e. /m^3 for UPM+CEM II. For CEM I binder net CO_2 was between 67 and 128 kg CO_2 eq. e./m^3, whereas it was between 41 and 73 kg CO_2 eq. e. /m^3 for CEM III.

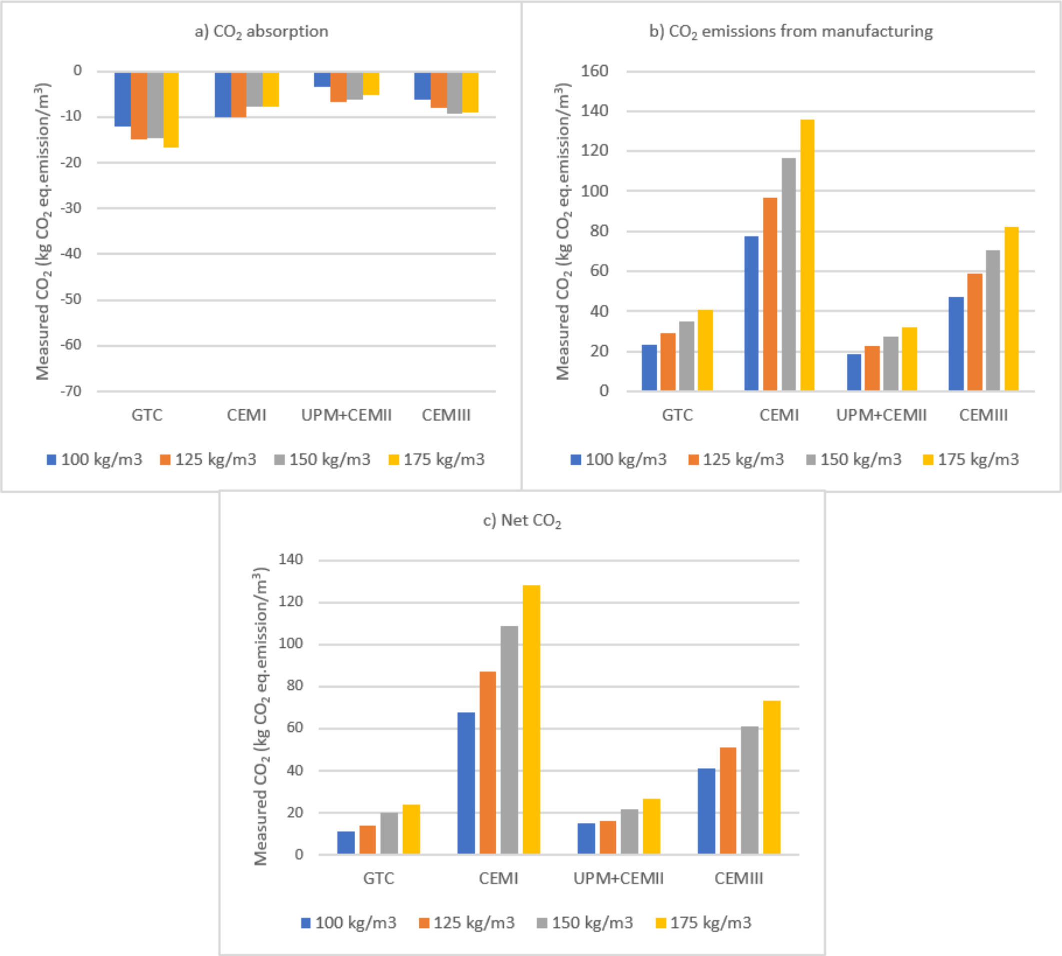


Figure 51. a) CO_2 absorption of all binders and binder amounts, b) CO_2 emissions from manufacturing of all binders and binder amounts, c) Net CO_2 of all binders and binder amounts

5 Conclusions and Recommendations for Future Research

The effect of the binder content on the carbonation sequestration capacity of stabilized soft clays was investigated in this research. The objectives of this thesis are to observe the effect of binder content on the ability of stabilized clays to carbon sequestration, and to explain how the strength of these clays is affected by the duration of carbonation at different levels of binder content. Four different binder types were used to stabilize soft clay with various binder amounts. The stabilized soft clays were exposed to CO_2 into the carbonation chamber. Unconfined compressive strength tests and thermogravimetric analysis were performed to observe the strength and carbonation sequestration capacity of the stabilized soft clays, respectively.

In research, it was observed that the stabilized clay samples with GTC binder dried due to carbonation. Despite the methods that were applied to prevent drying, it was seen that the carbonated samples continued to dry. Thus, curing time after carbonation was decreased from 7 days to 24 hours to prevent drying for stabilized clay samples with GTC binder. Optimum carbonation time was found by only using GTC binder with 100 kg/m^3 binder content. The stabilized soft clays were exposed to CO_2 carbonation 1,2,4 and 6 hours, and the CO_2 pressure was adjusted as 100 kPa into the carbonation chamber. As a results of UCS and TG analysis, the optimum carbonation for stabilizing soft clays was decided as 4 hours. This carbonation time was used in tests for all binder types and contents.

After that the impact of the carbonation on stabilized clay samples were examined for different binder types and amounts. According to the UCS results, binder CEMI (cement type I) was found to be the most effective binder type among the binders used in the experiments for stabilizing Malmi clay. While GTC binder had the least impact on the strength of the stabilized soft clay samples. The reason for this might be the curing time of the samples after carbonation. Because the curing time was 24 hours for stabilized clay with GTC binder, while it was 7 days for other binders after carbonation. When the binder contents were used as 150 kg/m^3 and 175 kg/m^3, the CO_2 carbonation provided beneficial outcomes in terms of strength of the samples for all different binder types, except GTC binder. However, the strength of the samples was not considerably impacted by carbonation for smaller binder levels like 100 kg/m^3 and 125 kg/m^3.

Both carbonated and uncarbonated samples were heated from 50 ◦C to 950 ◦C in thermogravimeter analyzer. Carbonation sequestration capacity and decarbonation of the samples were detected when the temperature was between at 520 ◦C and 800 ◦C. TGA results showed that the carbonated stabilized samples lost more weight than uncarbonated samples regardless of the binder types and amounts. The weight loss of the carbonated stabilized soft clay samples between specified temperatures increased by increment of the binder content for all binder types, except for UPM+CEMII binder. Although the carbonation affected the weight loss of the samples upward direction, the trend of the weight loss was almost constant for both carbonated and uncarbonated samples with UPM+CEMII binder.

Moreover, GTC and UPM+CEMII binders had the least amount of CO_2 emissions from production. While CEMI binder had the most amount of CO_2 emissions from production. It was observed that GTC and CEMI binders had the highest amount of CO_2 absorption, whereas UPM+CEMII binder was the lowest binder for amount of CO_2 absorption.

As a result of the TGA, binder of GTC had the most CO_2 sequestration capacity, while CEMI was the second. On the other hand, UPM+CEMII and CEMIII had similar CO_2 sequestration capacity.

To sum up, it can be said that increasing of the amount of binder had a positive impact on the strength of the stabilized soft clays for especially higher amounts of binder such as 150 kg/m^3 and 175 kg/m^3, and it effected the CO_2 sequestration capacity of the stabilized soft clay samples favorable. Although the carbonated stabilized soft clay with GTC binder had the highest CO_2 sequestration capacity based on the TG analysis, the carbonation did not affect the strength of the soil. Thus, according to the UCS and TGA results the most effective binder based on the strength of the soil and CO_2 sequestration capacity was found CEMI binder. However, for amount of net CO_2 CEMI was the binder that had the highest amount due to CO_2 emissions from manufacturing.

The curing time of the stabilized soft clay with GTC binder can be increased for accurate comparison with other binder types. To prevent drying after carbonation, the carbonated soft clay samples with GTC binder samples can be stored in a controlled environment with stable temperature and humidity conditions, and these conditions can be monitored. In addition to this recommendation, moisture barrier that reduces moisture loss can be added in the storage area.

The reactions of stabilized soft clays with various binder contents to long-term carbonation conditions can be investigated. The current study concentrated on short carbonation timeframes, however examining the behavior of these materials over longer timescales could provide useful data for practical applications.

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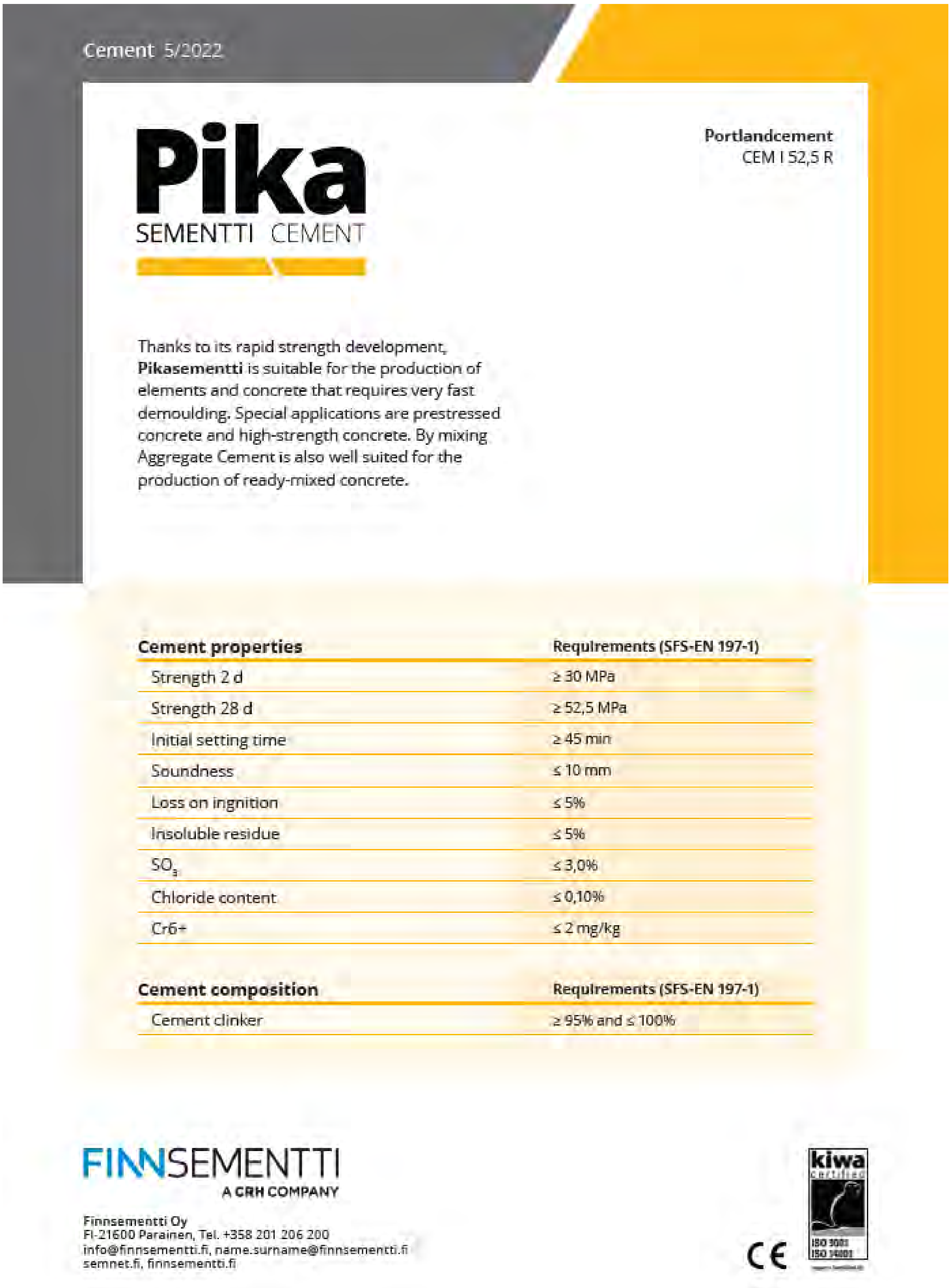
List of Appendices

Appendix 1: Technical data sheet of instant cement CEM I 52.5 R



Cement 5/2022

Pika

SEMENTTI CEMENT

Portlandcement
CEM I 52,5 R

Thanks to its rapid strength development, **Pikasementti** is suitable for the production of elements and concrete that requires very fast demoulding. Special applications are prestressed concrete and high-strength concrete. By mixing Aggregate Cement is also well suited for the production of ready-mixed concrete.

Cement properties	**Requirements (SFS-EN 197-1)**
Strength 2 d	≥ 30 MPa
Strength 28 d	≥ 52,5 MPa
Initial setting time	≥ 45 min
Soundness	≤ 10 mm
Loss on ingnition	≤ 5%
Insoluble residue	≤ 5%
SO_3	≤ 3,0%
Chloride content	≤ 0,10%
Cr6+	≤ 2 mg/kg

Cement composition	**Requirements (SFS-EN 197-1)**
Cement clinker	≥ 95% and ≤ 100%

FINNSEMENTTI
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Appendix 2: Technical data sheet of Oiva cement CEM II/B-M (S-LL) 42,5 N

Cement 5/2022

Oiva
SEMENTTI

Portland composite-cement
CEM II/B-M (S-LL) 42,5 N

Oiva cement is an economical and versatile cement.
Cement properties are its best in ready-mixed concrete, but there are also applications for Oiva-cement in various concrete products and element production.

Oiva cement is also an excellent cement for stabilization.
The relatively high admixture content of cement makes it a more environmentally friendly solution to concrete construction.

Cement properties	**Requirements (SFS-EN 197-1)**
Strength 2 d	≥ 10 MPa
Strength 28 d	≥ 42,5 MPa
Initial setting time	≥ 60 min
Soundness	≤ 10 mm
SO_3	≤ 3,5%
Chloride content	≤ 0,10%
Cr6+	≤ 2 mg/kg

Cement composition	**Requirements (SFS-EN 197-1)**
Cement clinker	≥ 65% and ≤ 79%
Additives (limestone and GGBFS)	≥ 21% and ≤ 35%

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CE

kiwa certified
ISO 9001
ISO 14001

Appendix 3: Technical data sheet of triple cement CEM III/A 52.5 L

Cement 5/2022

Blast furnace cement
CEM III/A 52,5 L

Kolmossementti is a high-strength blast furnace cement.
Mainly used is in ready-mixed concrete, but applications can be found in various concrete products and element applications.

Kolmossementti is also excellent for stabilization.
The high amount of GGBFS makes it an environmentally friendly

Cement properties	**Requirements (SFS-EN 197-1)**
Strength 2 d	≥ 10 MPa
Strength 28 d	≥ 52,5 MPa
Initial setting time	≥ 45 min
Soundness	≤ 10 mm
Loss on ingnition	≤ 5%
Insoluble residue	≤ 5%
SO_3	≤ 4,0%
Chloride content	≤ 0,10%
Cr6+	≤ 2 mg/kg

Cement composition	**Requirements (SFS-EN 197-1)**
Cement clinker	≥ 35% and ≤ 64%
GGBFS	≥ 36% and ≤ 65%

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Appendix 4: The UCS results of different carbonation duration for GTC 100 kg/m^3 content.

Sample No	Duration Time (h)	Diameter (mm)	Force max(kN)	UCS (kPa)	Average Force Max(kN)	Average UCS (kPa)
1	1	50,06	0,08	40,28	0,09	44,07
2*		49,92	0,15	75,19		
3		50,04	0,09	47,87		
1	2	49,92	0,09	47,20	0,10	49,57
2		49,9	0,09	44,24		
3		50,06	0,11	57,26		
1	4	49,97	0,08	42,72	0,10	52,16
2		49,94	0,11	56,46		
3		49,84	0,11	57,29		
1	6	49,74	0,10	52,56	0,09	45,53
2		49,99	0,09	43,37		
3		49,91	0,08	40,66		

2* was not included in the average values calculations.

Appendix 5: UCS results for different binder contents of carbonated GTC stabilized clay samples.

Sample No	Binder Amount (kg/m³)	Diameter (mm)	Force max(kN)	UCS (kPa)	Average Force Max(kN)	Average UCS (kPa)
1	100	49,73	0,09	48,84	0,10	51,54
2		49,9	0,11	55,20		
3		49,86	0,10	50,58		
1	125	50,01	0,16	83,75	0,16	81,18
2		49,97	0,14	70,91		
3		50,02	0,17	88,88		
1	150	49,87	0,23	118,67	0,22	111,37
2		49,92	0,20	102,28		
3		49,91	0,22	113,17		
1	175	49,9	0,29	149,45	0,27	139,67
2		49,78	0,27	138,65		
3		50,14	0,26	130,93		

Appendix 6: UCS results for different binder contents of uncarbonated GTC stabilized clay samples.

Sample No	Binder Amount (kg/m^3)	Diameter (mm)	Force max(kN)	UCS (kPa)	Average Force Max(kN)	Average UCS (kPa)
1	100	50,45	0,14	68,45	0,15	77,20
2		50,03	0,17	86,07		
3		50,08	0,15	77,09		
1	125	50,02	0,18	91,75	0,19	98,50
2		50,44	0,22	111,46		
3		50,04	0,18	92,28		
1	150	50,02	0,24	123,91	0,27	138,03
2		50,45	0,30	151,51		
3		50,11	0,27	138,66		
1	175	50,39	0,34	171,68	0,35	174,67
2		49,9	0,35	177,78		
3		50,32	0,35	174,56		

Appendix 7: UCS results for different binder contents of uncarbonated stabilized clay samples with CEM I.

Sample No	Binder Amount (kg/m^3)	Diameter (mm)	Force max(kN)	UCS (kPa)	Average Force Max(kN)	Average UCS (kPa)
1	100	49,93	0,65	333,90	0,64	325,69
2		49,87	0,53	272,57		
3		50,19	0,73	370,59		
1	125	50,14	0,61	311,40	0,83	422,16
2		49,88	0,96	491,01		
3		50,18	0,92	464,06		
1	150	50,17	1,26	635,93	1,30	657,81
2		50,13	0,92	463,85		
3		50,12	1,72	873,65		
1	175	50,18	1,74	880,26	1,68	853,96
2		50,04	1,76	895,82		
3		49,99	1,54	785,80		

Appendix 8: UCS results for different binder contents of carbonated stabilized clay samples with CEMI.

Sample No	Binder Amount (kg/m^3)	Diameter (mm)	Force max(kN)	UCS (kPa)	Average Force Max(kN)	Average UCS (kPa)
1	100	49,72	0,52	268,10	0,44	222,08
2		50,25	0,39	197,90		
3		50,15	0,40	200,23		
1	125	50,1	0,70	353,96	0,84	427,66
2		49,93	0,80	407,30		
3		49,8	1,02	521,72		
1	150	49,98	1,35	690,00	1,53	777,83
2		50,01	1,53	777,43		
3		50,19	1,71	866,08		
1	175	50,33	1,71	858,58	1,85	941,82
2		49,74	2,01	1032,45		
3		50,06	1,84	934,43		

Appendix 9: UCS results for different binder contents of uncarbonated stabilized clay samples with UPM+CEMII.

Sample No	Binder Amount (kg/m³)	Diameter (mm)	Force max(kN)	UCS (kPa)	Average Force Max(kN)	Average UCS (kPa)
1	100	49,71	0,13	66,67	0,11	54,28
2		49,92	0,06	30,49		
3		50,26	0,13	65,69		
1	125	50,13	0,23	114,64	0,24	120,81
2		50,29	0,21	104,64		
3		50,2	0,28	143,16		
1	150	50,2	0,27	136,33	0,28	141,14
2		49,87	0,33	168,33		
3		49,77	0,23	118,75		
1	175	49,99	0,28	143,34	0,30	153,52
2		50,08	0,29	147,79		
3		50,1	0,33	169,42		

Appendix 10: UCS results for different binder contents of carbonated stabilized clay samples with UPM+CEMII.

Sample No	Binder Amount (kg/m³)	Diameter (mm)	Force max(kN)	UCS (kPa)	Average Force Max(kN)	Average UCS (kPa)
1	100	49,93	0,11	55,50	0,11	58,58
2		50	0,12	59,38		
3		49,91	0,12	60,85		
1	125	49,8	0,22	111,91	0,21	105,05
2		50,28	0,17	87,91		
3		50,06	0,23	115,33		
1	150	50,06	0,28	139,87	0,28	143,41
2		49,76	0,29	150,70		
3		50,1	0,28	139,67		
1	175	50,02	0,35	178,16	0,32	165,16
2		49,78	0,35	179,37		
3		50,06	0,27	137,97		

Appendix 11: UCS results for different binder contents of uncarbonated stabilized clay samples with CEMIII.

Sample Number	Binder Amount (kg/m^3)	Diameter (mm)	Force max(kN)	UCS (kPa)	Average Force Max(kN)	Average UCS (kPa)
1	100	49,83	0,31	159,01	0,32	163,59
2		49,81	0,36	184,76		
3		50,28	0,29	146,99		
1	125	49,95	0,40	201,75	0,45	227,47
2		50,29	0,51	257,74		
3		50,28	0,44	222,93		
1	150	49,96	0,61	310,46	0,63	320,93
2		50,21	0,66	331,41		
3*		49,99	0,81	413,64		
1	175	49,76	0,37	192,01	0,61	311,04
2		49,95	0,37	186,41		
3		49,9	1,08	554,70		

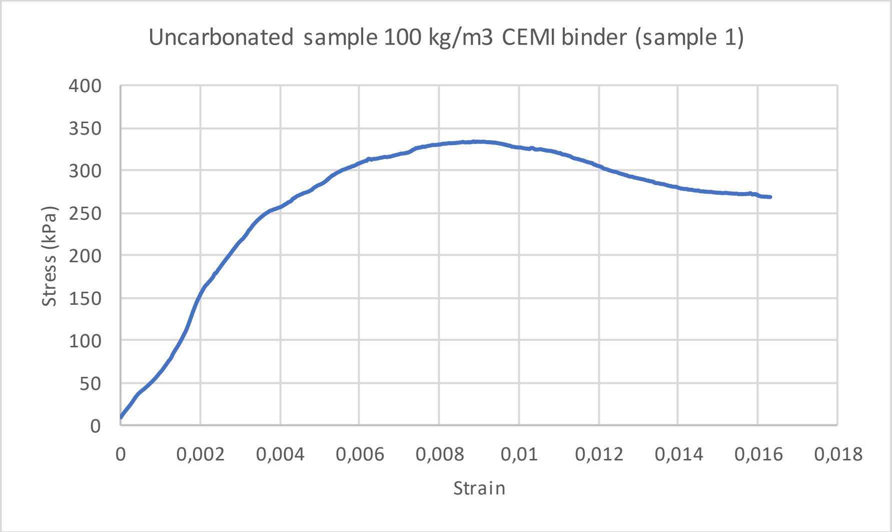
3* was not included in the average values calculations.

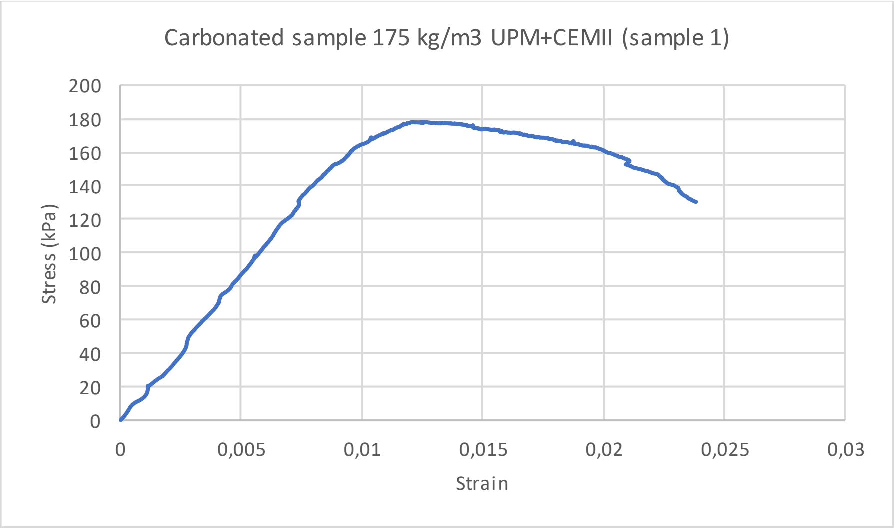
Appendix 12: UCS results for different binder contents of carbonated stabilized clay samples with CEMIII.

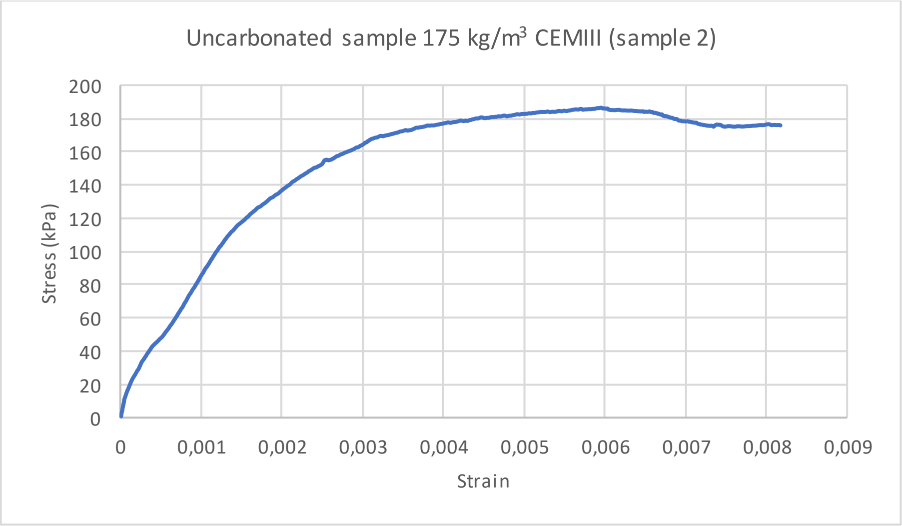
Sample Number	Binder Amount (kg/m^3)	Diameter (mm)	Force max (kN)	UCS (kPa)	Average Force Max(kN)	Average UCS (kPa)
1	100	49,94	0,31	156,13	0,30	153,34
2		50,02	0,31	156,41		
3		49,77	0,29	147,48		
1	125	49,98	0,27	138,86	0,38	195,62
2		49,81	0,36	187,05		
3		49,83	0,51	260,95		
1	150	50,22	0,64	321,20	0,67	340,86
2*		50,11	0,49	250,72		
3		50,12	0,71	360,53		
1	175	49,76	1,14	584,80	0,66	334,50
2		50,29	0,48	240,54		
3		50,21	0,35	178,15		

2* was not included in the average values calculations.

Appendix 13: Stress-strain curves of different binders







Appendix 14: Deformation modulus (E_{50}) of carbonated and uncarbonated samples

			Carbonated		Uncarbonated	
Binder Type	**Binder content(kg/m^3)**	**Sample number**	**E50 (kPa)**	**Average E50 (kPa)**	**E50 (kPa)**	**Average E50 (kPa)**
GTC	100	1	7458	7212	7271	6327
		2	7006		6514	
		3	7172		5196	
	125	1	9637	9252	5159	7383
		2	8443		9403	
		3	9677		7588	
	150	1	9149	10826		14446
		2	8535		17624	
		3	14793		11268	
	175	1	15631	16699	17540	14265
		2	17766		13059	
		3			12195	
CEMI	100	1	25016	30035	69940	66285
		2	39972		69478	
		3	25116		59438	
	125	1	82743	62493		81278
		2	59953			
		3	59930		81278	
	150	1	67596	76274	127236	126009
		2	84951			
		3	20244		124781	
	175	1	103507	107241		107050
		2	129983			
		3	88234		107050	
UPM+CEMII	100	1	4587	5827	5231	6395
		2	7797			
		3	5098		7559	
	125	1	14585	13872	8168	9268
		2	8632		7157	
		3	16984		12480	
	150	1	16001	13844	16506	13326
		2	9757		18064	
		3	15775		5409	
	175	1	17588	17878	16016	15647
		2	30195		15227	
		3	5850		15697	
CEMIII	100	1	28788	24433		15698
		2	20077		16160	
		3			15235	
	125	1	15040	25766	15204	24264
		2	14491		26040	
		3	47768		31548	
	150	1	36671	32249	21808	25941
		2	27827		39180	
		3	50078		16836	
	175	1	22972	33685	19168	19168
		2	33669			
		3	44414			

Appendix 15: The weight loss (%) between at 520 and 800 ◦C of stabilized clay with GTC (100 kg/m^3) for different carbonation duration

Duration Time(h)	Sample Number	Weight loss (%) between 520 and 800 ◦C	Average weight loss (%)
1	1	2,49	2,30
	2	2,04	
	3	2,38	
2	1	2,77	2,52
	2	2,43	
	3	2,37	
4	1	2,97	2,74
	2	2,42	
	3	2,83	
6	1	2,53	2,55
	2	2,56	
	3	3,24	

Appendix 16: Weight loss of the carbonated stabilized clay with GTC

Binder Content(kg/m^3)	Sample Number	Weight loss (%) between 475 and 800 ◦C	Average weight loss (%)
100	1	3,51	3,34
	2	3,33	
	3	3,20	
125	1	3,58	3,71
	2	3,77	
	3	3,77	
150	1	3,66	3,80
	2	3,99	
	3	3,75	
175	1	3,86	4,18
	2	4,31	
	3	4,37	

Appendix 17: Weight loss of the uncarbonated stabilized clay with GTC

Binder Content(kg/m³)	Sample Number	Weight loss (%) between 520 and 800 ◦C	Average weight loss (%)
100	1	1,78	1,71
	2	1,62	
	3	1,73	
125	1	1,68	1,76
	2	1,81	
	3	1,80	
150	1	1,80	1,96
	2*	2,48	
	3	2,13	
175	1	2,11	2,15
	2	2,20	
	3*	2,00	

2* and 3* were not included in the average values calculations.

Appendix 18: Weight loss of the carbonated stabilized clay with CEM I

Binder Content(kg/m^3)	Sample Number	Weight loss (%) between 520 **and 800 °C**	Average weight loss (%)
100	1	3,17	3,07
	2*	3,38	
	3	2,97	
125	1	3,27	3,11
	2	2,99	
	3	3,08	
150	1	3,21	3,17
	2	2,74	
	3	3,55	
175	1	3,27	3,23
	2	3,19	
	3*	3,00	

2* and 3* were not included in the average values calculations.

Appendix 19: Weight loss of the uncarbonated stabilized clay with CEM I

Binder Content(kg/m³)	Sample Number	Weight loss (%) between 520 and 800 ◦C	Average weight loss (%)
100	1	1,59	1,80
	2	2,05	
	3	1,75	
125	1	1,72	1,89
	2	2,00	
	3	1,95	
150	1	2,58	2,26
	2	2,19	
	3	2,01	
175	1	2,77	2,36
	2	2,30	
	3	2,01	

Appendix 20: Weight loss of the carbonated stabilized clay with UPM+CEMII

Binder Content(kg/m³)	Sample Number	Weight loss (%) between 520 and 800 ◦C	Average weight loss (%)
100	1	2,42	2,27
	2	2,06	
	3	2,33	
125	1	2,15	2,27
	2	2,38	
	3	2,28	
150	1	2,21	2,23
	2	2,24	
	3*	1,99	
175	1	2,40	2,29
	2	2,18	
	3*	1,95	

3* and 3* were not included in the average values calculations.

Appendix 21: Weight loss of the uncarbonated stabilized clay with UPM+CEMII

Binder Content(kg/m^3)	Sample Number	Weight loss (%) between 520 and 800 ◦C	Average weight loss (%)
100	1	1,85	1,83
	2	1,95	
	3	1,68	
125	1	1,40	1,44
	2	1,69	
	3	1,23	
150	1	1,54	1,50
	2	1,54	
	3	1,41	
175	1	1,82	1,69
	2	1,55	
	3	1,70	

Appendix 22: Weight loss of the carbonated stabilized clay with CEMIII

Binder Content(kg/m³)	Sample Number	Weight loss (%) between 520 and 800 ◦C	Average weight loss (%)
100	1	2,14	2,14
	2	2,19	
	3	2,07	
125	1	2,30	2,26
	2	2,32	
	3	2,16	
150	1	2,44	2,41
	2	2,27	
	3	2,52	
175	1	2,98	2,55
	2	2,29	
	3	2,37	

Appendix 23: Weight loss of the uncarbonated stabilized clay with CEMIII

Binder Content(kg/m^3)	Sample Number	Weight loss (%) between 520 and 800 ◦C	Average weight loss (%)
100	1	1,35	1,36
	2*	1,62	
	3	1,36	
125	1	1,38	1,32
	2	1,21	
	3	1,37	
150	1	1,49	1,33
	2*	1,09	
	3	1,17	
175	1	1,33	1,56
	2	1,85	
	3	1,48	

2* and 2* were not included in the average values calculations.

Appendix 24: Amount of CO_2 absorption, emissions from manufacturing and net CO_2 for all binder types and amounts

GTC

Binder content (kg/m^3)	Wet density (kg/m^3)	Water content (%)	Dry density(kg/m^3)	CO_2 bound (%)	CO_2 absorption for 1m^3 (kg)	CO_2 emission (kg) from manufacturing	Net CO_2 (kg)
100	1419,0	92,7	736,5	1,6	12,0	23,2	11,2
125	1429,0	86,8	765,2	2,0	14,9	29,0	14,1
150	1430,9	80,6	792,4	1,8	14,6	34,8	20,2
175	1441,1	74,0	828,1	2,0	16,8	40,6	23,8

CEM I

Binder content (kg/m^3)	Wet density (kg/m^3)	Water content (%)	Dry density(kg/m^3)	CO_2 bound (%)	CO_2 absorption for 1 m^3 (kg)	CO_2 emission (kg) from manufacturing	Net CO_2 (kg)
100	1454,2	81,28	802,2	1,27	10,2	77,6	67,4
125	1478,5	80,99	816,9	1,22	10,0	97,0	87,0
150	1494,5	73,80	859,9	0,91	7,8	116,4	108,6
175	1495,3	68,93	885,2	0,87	7,7	135,8	128,1

UPM+CEM II

Binder content (kg/m^3)	Wet density (kg/m^3)	Water content (%)	Dry density(kg/m^3)	CO_2 bound (%)	CO_2 absorption for 1 m^3 (kg)	CO_2 emission (kg) from manufacturing	Net CO_2 (kg)
100	1453,6	85,91	781,87	0,44	3,5	18,4	14,9
125	1470,7	81,61	810,15	0,83	6,7	23,0	16,3
150	1493,9	74,62	855,58	0,73	6,2	27,6	21,4
175	1502,6	68,91	889,94	0,60	5,3	32,2	26,9

CEM III

Binder content (kg/m^3)	Wet density (kg/m^3)	Water content (%)	Dry density(kg/m^3)	CO_2 bound (%)	CO_2 absorption for 1 m^3 (kg)	CO_2 emission (kg) from manufacturing	Net CO_2 (kg)
100	1477,1	85,85	794,8	0,78	6,2	47	40,8
125	1511,0	78,70	845,6	0,94	7,9	58,75	50,8
150	1490,7	73,55	859,0	1,08	9,3	70,5	61,2
175	1516,8	67,03	908,2	0,99	9,0	82,25	73,3