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Feasibility of biochar for low-emission soft clay stabilization using CO_2 curing

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ABSTRACT

Use of traditional lime-cement binders on stabilizing soft sensitive clays pose a significant challenge for the construction sector to reach Finland's carbon neutrality goals by 2030. Traditional stabilization recipes consisting of cement as binders contributing significantly to CO_2 emissions (≅ 500 kg CO_2 eq./ton in deep mixing alone). This laboratory study explores the feasibility of achieving near carbon-negative stabilization of soft clay leveraging accelerated CO_2 curing (ACC) in biochar (BC) enhanced cementitious composites. BC, a by-product of the biofuel industry, is used as partial replacement of cement (0 %, 10 %, and 50 % of binder) in developing precast cementitious piles. One non-carbonated treatment and two ACC treatments are employed to assess their uniaxial compressive strength, thermogravimetric properties and CO_2 sequestration capacity. The results demonstrate that synergistic effects of using BC with ACC not only enhances the compressive strength of the composites but also promotes CO_2 uptake due to formation of stable carbonates. BC due to its surface functional groups, honeycomb porous structure, and hydrophilicity facilitated uniform CO_2 diffusion in the clay matrix and likely improved internal curing. In ACC treated composites, the replacement of 50 % of cement with BC resulted in sufficient load-bearing capacity (≥50 kPa as per Finnish Guidelines) for both shallow and deep clay layers, making a suitable subgrade media for many types of geotechnical applications. The measured bound CO_2 increased gravimetrically from 2 % to 41 % when cement was partially replaced by BC. In case of non-carbonated samples, 10 % partial replacement of BC provided high strength (≥ 200 kPa). Life Cycle Assessment (LCA) of a case study of utilizing BC stabilized clay in deep mixing operations can potentially reduce net carbon emissions to −50 kg CO_2 eq./ton.

Introduction

In Finland, introduction of the new 2023 Building act mandates the construction companies in the geotechnical sector to lower their CO_2 footprint by more than 50 % than existing values. Finland has major CO_2 emissions from soft clay stabilization particularly in installing cementitious piles. The construction industry emits nearly 10 % of the global CO_2 emissions. In particular, the addition of ordinary Portland cement (OPC) as a mixing agent in cementitious composites contributes to a major increase in CO_2 emissions (0.8–1 tonne CO_2 per tonne of concrete). The European Commission as well as the Finnish parliament targets a net reduction in greenhouse gases by 55 % before 2030 and ultimately achieve net-zero CO_2 emissions by 2050 [43],Wang et al. [69],Wang et al. [71]. The Finnish Geotechnical Society reports that the geotechnical sector utilizes cement for ground improvement applications (through mass stabilisation, deep mixing, piling) for soft clay stabilization [66] accounting for 90 % of cement usage [29]. Finnish soft clays are notoriously known for its low shear strength ($\leq 25kPa$). Before any construction on stratum having these soft clays, it is required to be stabilized by lime-cement mixtures as binder material or otherwise requires excavation followed by landfilling. In Helsinki alone around 340000 m^3 of soft clay and fine silt are transported to landfill sites annually (Ollila et al., 2012). Both strategies of stabilization and landfilling involve enormous CO_2 emission issues due to cement manufacturing and logistical transport, respectively [56],Nguyen [48]. Finland is the highest exporter of forest-based products (e.g., furniture,

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paper, and pulp industry) in Europe and consequently produces tons of organic side streams that requires valorisation. For instance, in 2018 alone, 19.9 million m^3 of wood-based side streams was generated from the furniture industry out of which 7.7 million m^3 were tree barks, 7.4 million m^3 were wood chips, and 2.5 million m^3 were saw dust [41]. The current practice of incinerating this organic biomass has an associated CO_2 footprint. There is scope to further reduce the CO_2 footprint through alternate combustion practices like pyrolysis having a low to net negative CO_2 emissions [38].

Accelerated CO_2 curing (ACC) in cementitious materials has been identified by Intergovernmental Panel on Climate Change as one of the fastest strategies to sequester stable carbon [42]. The mechanism can be viewed as artificially injecting CO_2 (gaseous or dissolved liquid form) which react with hydrated and un-hydrated cement paste, ultimately transforming into stable carbonates (Fig. 1). During the ACC process, high-concentration CO_2 diffuses into the cementitious matrix during or after early curing stage and ultimately precipitates as mineralized $CaCO_3$. $CaCO_3$ particles formed through the process of carbonation are finer than those of OPC particles resulting in better packing [70,72]. This packing consequently improves cement hydration rate and is likely to improve compressive strength of composite. Although ACC has been used in precast concrete to increase compressive strength, there are pertinent issues such as reduced pH (leading to rebar corrosion) and pore blockage along the edges that restricts uniform CO_2 diffusion [75]. The utility of ACC in cementitious materials can be enhanced by utilizing a material that can improve CO_2 diffusion uniformly throughout the cementitious matrix.

A pyrolysis by-product- biochar (BC) is identified as a stable carbon sink material having tuneable properties such as high specific surface area, high pH, hydrophilicity, CO_2 adsorption potential and high porosity. Pyrolysis is the process of heating up organic materials up to 350–600 °C under no to limited oxygen conditions [80]. The liquid and gaseous products emanate as biofuel, and biogas used for energy generation while the solid by-product is the BC. Even though structurally, BC has low stiffness, which reduces the compressive strength of concrete under normal air curing, the incorporation of ACC with BC addition has been recently reported to amplify the mechanical and durability properties of concrete while significantly improving the CO_2 mineralization [76]. The size, structure, and application rate of BC results in either increased [2,17] or decreased [63] compressive strength (CS) with respect to control by 25 % and 35 %, respectively. Unlike in concrete wherein the strength requirements are in the range of 10–50 MPa, the strength requirement for soft clay stabilization piles is between 50 kPa to 1 MPa [13,32,51]. Previous studies have indicated that BC addition in clay can help improve CO_2 diffusion under relatively unsaturated conditions and result in enhanced $CaCO_3$ precipitation [6,23]. Thus, utility of biochar as an additive material for developing pre-cast cementitious composite piles using ACC can be a sustainable strategy in reducing CO_2 emissions associated to soft clay stabilization in Finnish conditions.

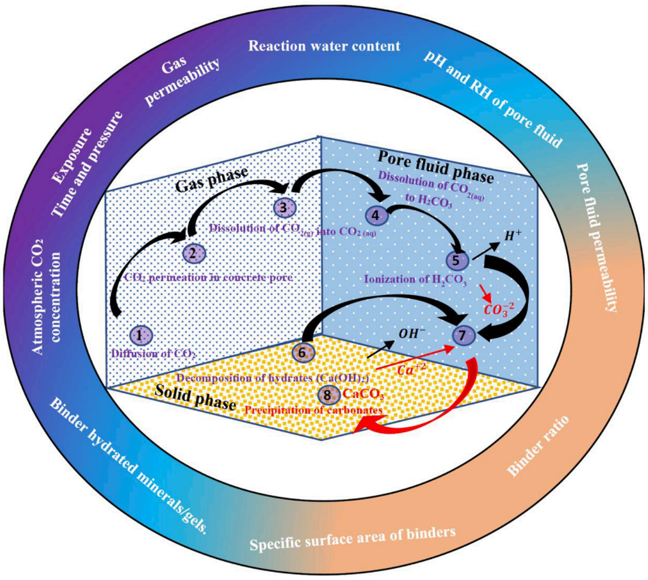


Fig. 1. Conceptual figure for accelerated CO_2 carbonation in cementitious materials.

The majority of biochar applications in cementitious composites, combined with accelerated carbon curing (ACC), have focused on concrete, with an array of supplementary cementitious materials (Table 1). The current study is unique as it explores whether CO_2 mineralization can be utilized in the case of extremely soft clays. Compared to traditional stabilization methods, using biochar with carbonation offers significant advantages. It relies not only on hydration to enhance strength [18] but also on the formation of mineralized carbonates. This approach also reduces net CO_2 emissions by lowering cement usage and capturing CO_2 in a stable form. Additionally, applying ACC in soil stabilization eliminates the risk of corrosion, which is a concern in concrete [10]. However, its field application remains limited due to the need for further research on CO_2 injection, monitoring, and potential impacts on groundwater.

The unique utilization of biochar in Finland as a partial replacement to cement in soft clay stabilization is suitable due to three major reasons. First, the abundant organic waste from the forest sector is highest in all Europe [62]. The anaerobic pyrolytic conversion of this decomposable feedstock into carbon negative biochar makes it a low-cost material to reduce the CO_2 emission of cement. Second, biochar has been shown to enhance the mechanical properties of cementitious materials, making these methods applicable to a wide range of field applications as explored in this study for soft clay stabilization. Third, since soft clay stabilization does not involve the use of rebar, any drop of pH during carbonation process can be carried out without the risk of corrosion which is a factor of concern in reinforced concrete applications.

The overarching objective of the current study is to explore the feasibility of developing ACC induced precast cementitious piles that can be potentially used for soft clay stabilization. The study investigates the effects of BC replacement rates (0, 10 %, and 50 % of binder proportions) and two CO_2 diffusion methods in developing precast cementitious piles. The major measured properties of these stabilized cementitious materials studied included compressive strength, thermal properties, and bound CO_2 of the material. A conventional life cycle assessment (LCA) as per contemporary Finnish regulations was conducted to assess the overall net CO_2 emissions. This research is motivated by the goal of lowering the existing CO_2 emissions or working towards CO_2 −neutral emissions in soft clay stabilization. The current study offers preliminary data on the potential use of biochar and for soft clay stabilization utilizing ACC.

Methods

Materials

Soft sensitive clay, in its natural state, was collected from the Malmi airfield, situated in the northeastern sector of Helsinki, Finland. The clay designated in this study as Malmi clay is classified as a post-glacial clay, typically exhibiting normal consolidation and is geologically fully saturated. The clay samples were drilled and obtained from two distinct depths, first, ranging from 2 to 3.5 m and second, from 6 to 8.5 m. The shallower depth is saturated at a higher water content due to its relatively loose overburden pressure while the deeper depth has higher density and lower moisture content. All the sampling points are located at the northern part of the airfield (refer Appendix A). The index properties exhibited very little variation in the basic properties for each depths considered. Table 2 presents the average physical properties of the clay samples for the two selected depth ranges. In total, three

Table 1
Summary of studies on the use of biochar in cementitious materials.

Reference	Country of study	CO_2 measurement for ACC	pH before and after carbonation	Raw materials or SCM used	Final Application
[50]	New Zealand, China	√	×	PC – fly ash – corn stover biochar	Concrete
Wang et al. [69],Wang et al. [71]	Hong Kong	√	×	Magnesia cement – softwood biochar	Concrete
[77]	Korea	√	×	PC – commercial biochar	Mortar
Wang et al. [70],Wang et al. [72]	Korea/Hong Kong	√	×	Calcium silicates binders –	Cement-based products
[9]	China	√	×	PC – corn straw biochar	Mortar
[40]	China	√	×	GGBFS – PC – steel slag – sawdust biochar	Artificial aggregates
[44]	United States	√	×	PC – fly ash – nano silica – commercial biochar	Concrete
[45]	United States	√	×	PC – fly ash – commercial biochar	Mortar
[33]	Singapore	√	×	PC – wood biochar	Mortar
[76]	China	√	√	PC – steel slag – Corn stover biochar	Lightweight aggregates
[1]	India	√	×	PC – rice husk biochar	Mortar
[74]	Switzerland	×	×	PC – wood branches biochar	Aggregates & concrete
This study	*Finland*	√	√	soft clay, biochar, PC	Soft Clay stabilization

Table 2
Physical and chemical properties of Malmi clay.

Properties	Depth (m)	
	2—3.5	6—8.5
Clay content (%)	71	73
Classification	Fat clay	Fat clay
Average water content (%)	105	55
Average unit weight (kN/m^3)	13.73	16.68
Average specific gravity	2.68	2.70
Sensitivity	35.4	40.1
Undrained shear strength (kPa)	14.0	18.4
Average Organic content (%)	1.3	1.3
Average pH	7.5	7.5

samples were tested for plotting the average values. The clay is classified as a fat clay due to its high clay content (>70 %) [31]. The average water content of the clay was determined in accordance with [61] as 105 % for the shallow layer and 55 % for the deeper layer. The specific gravity was measured with accordance to [58] and was found around 2.7. The sensitivity and the undrained shear strength were determined from the fall cone method [59]. The elemental oxides of the clay were determined by the use of X-ray fluorescence (XRF) and presented in Table 3. Commercial CEM III – A (Finnsementti) was used in this study. CEM III – A is a high-strength class 52.5 blast furnace slag cement, with a composition ranging of (35–64 %) cement clinker and (36–64 %) blast furnace slag. The cement complies with [57] requirements.

Table 3
Elemental oxides of materials.

Oxides	CEM III – A (%)	BC (%)	Malmi clay (%)
CaO	49.46	43.33	2.86
SiO_2	25.51	10.41	52.29
Al_2O_3	9.54	2.74	15.97
MgO	5.82	2.06	2.97
SO_3	3.63	5.17	0.26
Fe_2O_3	2.03	15.81	15.72
K_2O	1.16	11.79	6.01
TiO_2	1.22	0.55	1.40
Na_2O	0.67	0.54	1.07
P_2O_5	0.40	3.99	0.81

The feedstock for the biochar production used in this study was collected from the side stream of HSY Helsingin Seudun Ympäristöpalvelut (HSY) Helsinki. HSY primarily produce biogas and heat from the pyrolysis process while the biochar produced is stored in a nearby disposal site (Fig. 2). The feedstock is woodchip waste (Fig. 2) from the forest industry, primarily consisting of spruce and broad-leaved trees. The biochar was produced at an onset temperature of 500 °C, with a residence time of 70 min under a limited supply of Nitrogen (N_2) gas. The pyrolysis setup for producing the biochar is shown in Fig. 2. The biochar had an organic material content of 82,4%, a pH of 7.85, an electrical conductivity of 1.135 m S. The elemental oxides of the BC are presented in Table 3. The BC had abundant CaO which is a good source for ACC such that $CaCO_3$ are precipitated.

Numerous intrapore on the biochar surface were observed (Fig. 3a) by the scanning electron microscope (SEM) micrographs which indicate that most of the hemicellulose and cellulose were thermally degraded leaving behind a honeycomb structured carbonaceous material. On visual inspection, these intrapore size were roughly lower than 20μ m. These intrapore could suitably allocate for internal curing sites and also facilitate the individual clay particles ($\leq 2\mu$ m) (Fig. 3a). They also allocate as tortuous spaces for CO_2 transport when the samples are carbonated. SEM micrograph of the stabilized samples indicate that the clay and hydrated/carbonated products during the curing stages remain ingrained in these intrapore (Fig. 3b). Fig. 3c presents the surface functional groups of biochar characterized by Fourier Transform Infrared (FTIR) analysis. Hydrophilic functional groups, such as amido (–NH_2) and hydroxyl (–OH) were observed distinctly which would help in water retention. Presence of –NH, –NH_2, –OH and carboxyl C=O groups have strong affinity for CO_2 gas and can adsorb them through Lewis's acid-base interaction [23].

Sample preparation

The sample preparation for mixing and moulding the binder stabilized clay in this study was carried out in accordance with the Finnish Guidelines for deep soil mixing [13]. These guidelines are provided in

Wood based feedstock from the forest sector used for pyrolysis at HSY facility

Biochar production unit at HSY

Produced biochar dumps in HSY facility

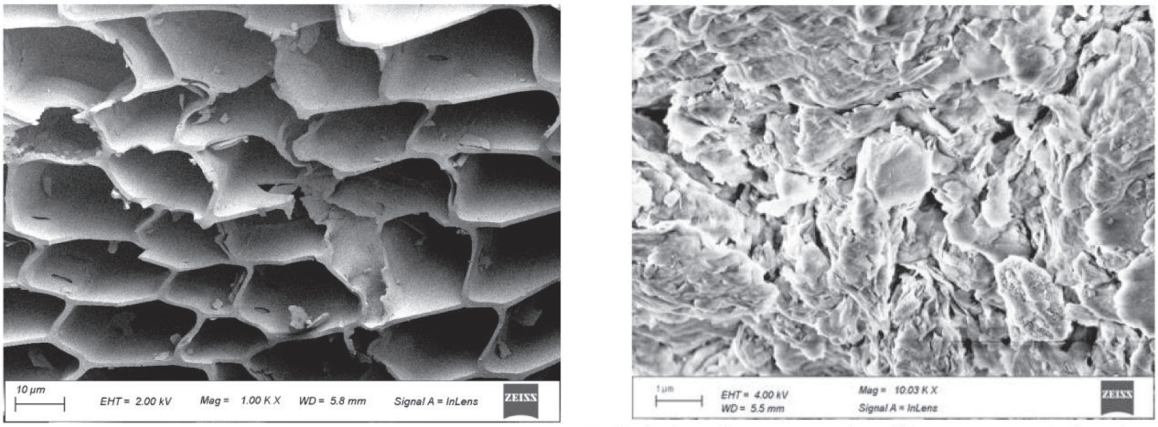
Fig. 2. BC production in Helsingin Seudun Ympäristöpalvelut (HSY) Helsinki.

English in previous literature [30]. Eurocode guidelines as well as previous studies [12,51]) clearly indicate that the binder is mixed with the soft clay under the natural water content of the in-situ sample, inherently resulting in disturbance of the sample during the process. This approach has been widely adopted in literature for Finnish soft sensitive clays [3,51,55]. As per Finnish Transportation Agency guidelines, before conducting any in-situ stabilization directly on clays the binders are tested in the lab to estimate the compressive strength under the designed binder amount used [39]. This guide is provided in English by [30]. Unlike estimation of soft clay geotechnical properties like shear strength, compressibility and hydraulic conductivity wherein samples shouldn't be disturbed [81], stabilization of soft clay necessitates samples being disturbed. Initially, the natural clay is homogeneously mixed using an electric mixer. No water adjustment as suggested by other standards such as [4] was performed as we intended to see the reaction kinetics of in-situ mixing of binder, biochar, and clay. Secondly, the binder is mixed with the Malmi clay that accounted for 100 kg per cubic meter of clay. This is the binder rate generally used in practice for Finnish soft clays. Biochar added is also considered as a binder for the developed mixes in this study as it provides suitable elemental oxides, alkalinity, and reaction sites for internal curing. Upon determining the binder quantity at 100 kg/m^3, a designated portion of biochar (by weight) was substituted with that of the cement. This study employed three varying percentages in the overall used binder at 0 %, 10 %, and 50 %. 0 % was used as a control to highlight biochar effect on the material properties of the cementitious composite. Trial tests were conducted on the samples, and it was observed that beyond 50 % of partial biochar replacement, the mixture was not uniform wherein the biochar forms clusters in the clay matrix. Moreover, beyond 50 % partial replacement of biochar, the 28 days compressive strength in these trial tests were lower than permissible strength values of Finnish Transportation Agency (30 kPa) for shallow infrastructures. The selected binder and clay constituents are blended for approximately 5 min in accordance with the Finnish guidelines. Mixing durations may vary across different standards. However, both the European Committee for Standardization [11,12] recommend a sufficient duration for achieving homogeneity in the admixture. After the mixing process is concluded, a portion of sample (roughly 10 g) is extracted to determine the actual water content of the mixtures using an oven before proceeding with the moulding of the samples. Plastic cylindrical moulds measuring 50 mm in diameter and 100 mm in height were utilized for the moulding process. Upon completion of moulding, the samples are enclosed in nylon bags and kept for 24 h in desiccator for moisture homogenisation in a temperature-controlled room. Following that the cylindrical samples (50 x 100) mm are extracted using an in-house extruder developed at Aalto for assessing clay-binder mixes for deep mixing [51]. In the final step, the samples are labelled for identification and again placed in sealed desiccators where full humidity was ensured to facilitate curing. Three replicates are used for assessing the properties measured in the current study and average values are used for discussion. The desiccators containing the samples were stored in cold rooms where the temperature is controlled to 6 °C as per field conditions experienced in Finland. Table 4 provides the overall experimental matrix adopted in this study. The design of the current study is unique than existing studies discussed in Table 1. The final application is for soft clay stabilization which is different than studies reported in literature. Comprehensive analytical techniques were utilized to validate the materials studied in the current study. Chemical analyses were conducted to assess the carbonation potential of the materials, including the evaluation of available oxides, pH levels, and functional groups as also conducted in majority of the studies conducted in Table 1. Additionally, microstructural analyses were performed both before and after the stabilization process to examine the mineralized carbonates. Thermogravimetric analysis was employed to quantify the amount of CO_2 sequestered within the soil matrix. Lastly, mechanical analyses in the form of uniaxial compressive strength test were conducted to evaluate the practicality and usability of the proposed methods.

Experiment protocol

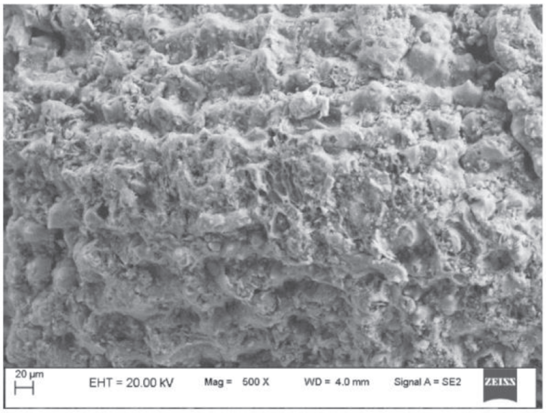
Carbon Sequestration and strength assessment of stabilized clay samples

Fig. 4 provide a diagram of the procedure followed for preparing the samples. This ACC protocol consisted of two carbonation conditions, denoted as C1 and C2 as shown in the figure. The accelerated carbonation curing conditions was conducted using two different protocols to assess the efficacy of gas diffusion and subsequent precipitation in the stabilized clay. After three days of natural curing in the desiccator, one third of the samples were subjected to ACC on the fourth day. This ACC protocol consisted of two carbonation conditions, denoted as C1 and C2 in the current study. Under C1 conditions, the samples received no prior treatment, and the gas diffusion occurred at the actual mixing water content, while under C2 conditions, the samples underwent partial drying in an oven at 105 °C for 1 h. This was intended to increase the moisture gradient that would facilitate for more CO_2 diffusion within the clay matrix without inducing desiccation induced cracks [23]. This step also aimed to explore the impact of internal water content during ACC on calcium carbonate generation potential, as previous studies have highlighted [19,20,21]. Nevertheless, the ACC conditions on the samples involved putting them in a sealed chamber with a CO_2 gas



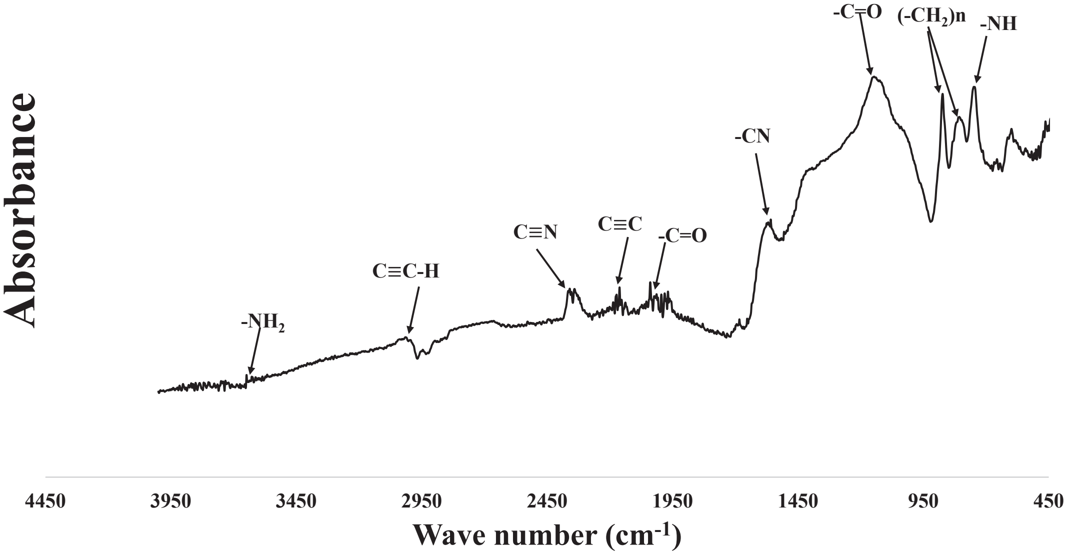
BC with honeycomb intra pores (≤ 20μm) Dried clay showcases plate like structure (≤2μm)

(a)



Stabilized clay with BC and cement indicates that intrapore are filled hydrated/carbonated material

(b)

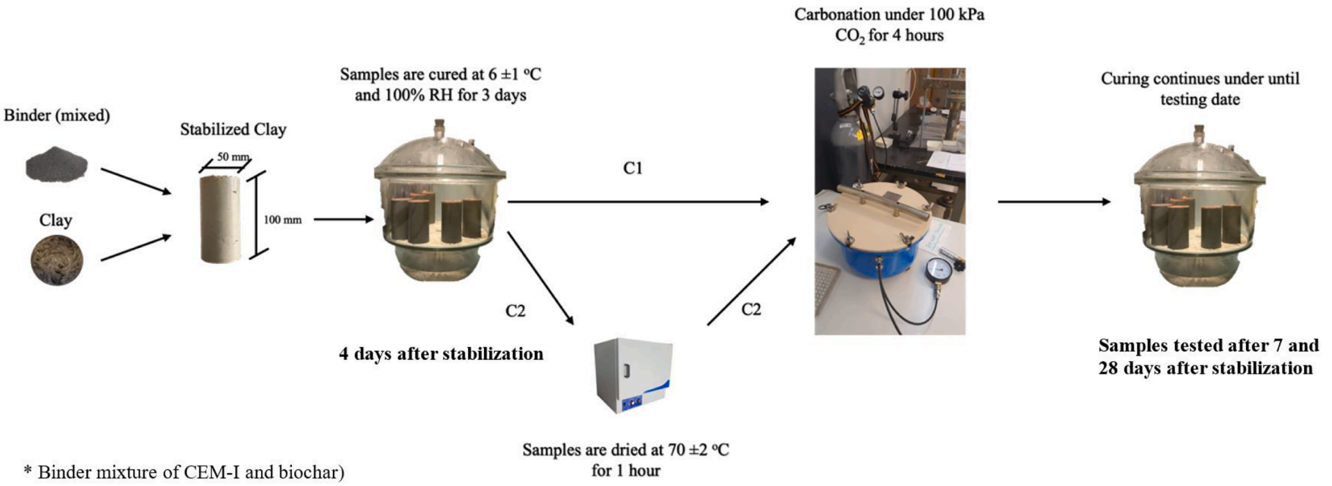


(c)

Fig. 3. (a) Micrographs of BC and clay and (b) Micrographs of Stabilized Clay-BC mixes at 10% partial replacement (c) FTIR spectra of BC.

Table 4
The experimental matrix adopted in this study.

Soil	Average density (g/cm^3)	Binder amount (kg/m^3)	Partial replacement of BC in binder (%)	Curing time (days)	Carbonation method	Tests
Malmi clay	1.4	100	10 %	7, 28	100 % Concentration	UCS
	1.7		50 %		100 % Concentration with 1 h partial drying	TGA
						pH



* Binder mixture of CEM-I and biochar)

Fig. 4. Illustrative visualization of sample preparation for compressive strength testing.

concentration of 100 % (refer Appendix B). The chamber was equipped with a control valve connected to a CO_2 storage cylinder with a knob to adjust the pressure within the chamber. Initially, the prepared samples were removed from sealed desiccators after three days of curing. These samples that would undergo pre-treatment in case on C2 were separated and placed in the oven for 1 h. Once preparation was finalized, the specimens were introduced into the chamber, where CO_2 was applied at a pressure of 1 bar for 4 h. Following completion of carbonation, the specimens were extracted from the chamber, their weights were recorded, and they were returned to their respective desiccators for completion of the curing duration. The humidity in these chambers is 100 %, so any further curing occurs at 100 % relative humidity.

Upon completion of curing, the samples after 7 and 28 days were tested for its compressive strength, pH and thermal properties. The unconfined compressive strength (UCS) test was conducted to assess the compressive strength of the stabilized clay in accordance with the European standard [60]. Initially, the weight and dimensions of each specimen were remeasured to account for any changes in volume during carbonation and hydration process. Subsequently, the specimen was positioned in the load frame, which was connected to a data acquisition system. A constant strain rate of 1 mm per minute, corresponding to 1 % of the sample's height, was applied until a minimum axial deformation of 7 % was reached or clear shear failure was observed. Once the test concluded, a portion of the specimen was extracted for the determination of the pH and to assess the thermal properties. A drop in pH accounted for increase in H^+ ions and was used as an indirect indicator for relative carbonate formation (refer Fig. 1).

Thermogravimetric analysis (TGA) was conducted on the stabilized samples to determine the phases formed due to hydration as well as carbonation [46,79]. The analysis was performed using a Thermogravimetric instrument TGA 951 (TA Instruments, USA). The stabilized samples were exposed to temperature up to 950 °C. Initially, the sample was ground to a particle size smaller than 1.18 mm through a sieve. Subsequently, approximately 50 mg of the sample was placed into the instrument. The temperature was then systematically increased at a rate of + 20 °C per minute. Upon reaching 100 °C, the temperature was maintained constant for 10 min to facilitate water loss. Following this, the temperature was further increased to 950 °C at the same rate. Three main phases are formed from the decomposition curves of the hydrated and carbonated products Kumar Mishra and Kumar [34], Wang et al. [69], Wang et al. [71]. They correspond to thermal decomposition of C-S-H and ettringites (Aft, Afm) at 100-200°C, hydroxides of Ca and Mg at 400-500°C, and Ca carbonates at 525-800°C. The decomposed $CaCO_3$ and subsequent bound CO_2 content were measured from the thermal decomposition curves based on Eqs. (1) and (2) Kumar Mishra and Kumar [34].

$$CaCO_3\,(\%) = \frac{M_{525} - M_{800}}{M_c}\,x\,2.27\,x\,100 \tag{1}$$

$$CO_2\,(\%) = \frac{M_{525} - M_{800}}{M_c}\,x\,100 \tag{2}$$

Where M_{525}, and M_{800} represent the sample masses (g) at their respective ignition temperatures. M_c is the mass of anhydrous cement heating to 1000 °C and corrected for the loss of ignition of cement, biochar and clay used in the study. CO_2 emissions data for CEMIII-A were obtained from the manufacturer (Finnsementi), while emissions from biochar were assumed to be zero [36]. The net emission is determined by subtracting the amount of bound CO_2 for each mixture from the emissions originating from the manufacturing process.

Statistical Analysis

Statistical analysis was conducted on each measured parameter in the current study to assess the significance level of effects. The experimental results were interpreted by adopting two-way analysis of variance (ANOVA) for estimating statistical significance level values. A significant value of $p < 0.05$ was ensured before conducting further theoretical interpretation.

Life Cycle Assessment for implementing biochar in dry deep soil mixing

Life cycle assessment (LCA) serves as a valuable tool for estimating the overall carbon dioxide (CO_2) emissions associated with the DDSM method [32,52]. According to the European Committee for Standardization (2019), the LCA evaluation of construction activities comprises five distinct stages, denoted as A1 to A5. The initial three stages primarily focus on the production of the binder. Stage A1 involves the procurement of raw materials, while stage A2 encompasses the costs associated with transforming these materials to the manufacturing site, and stage A3 accounts for emissions stemming from the manufacturing process itself. On the other hand, stages A4 and A5 pertain to the construction activities, with A4 addressing the transportation of construction materials to the site and A5 covering the construction activities themselves, such as excavation and the use of machinery. Hence, to conduct an LCA for the DDSM method, essential data includes emissions factors for binder production, transportation of materials to the site, and fuel consumption by construction equipment. These factors are crucial for accurately assessing the environmental impact of the DDSM method throughout its life cycle. In our study, the LCA factors were adopted based on geotechnical department of Ramboll Oy guidelines for estimating CO_2 footprint in DDSM accounting for Finnish conditions.

Fig. 5 outlines the workflow for estimating CO_2 emissions from DDSM using LCA analysis across all stages. The process is divided into three sections as per established literature in Finnish conditions. They are discussed below, and their factors are provided in Table 5.

Section 1 (Stages A1, A2, A3): This includes the extraction and procurement of raw materials for binder manufacturing, their transportation to the factory, and the manufacturing process. The input required is the mass of the binder (in tons) needed for the DDSM design. Emission factors for this stage are sourced from the Environmental Product Declaration of the binder [53].

Section 2 (Stage A4): This stage involves transporting materials from the factory to the construction site. Two approaches are documented in the literature: the activity/distance-based approach and the energy-based approach [52]. The method selection depends on the data availability in the application country. For dry deep soil mixing, the activity index approach is preferred due to its reliance on the mass of the binder to be transported. Inputs for stage A4 include the binder mass, travel distance, and road type assessment, expressed in kg CO_2 eq./t-km (where t-km represents one ton of material transported for 1 km). Data for this factor can be sourced from national databases, LCA databases, or transport operators.

Section 3 (Stage A5): This section covers the construction stage, including excavation, injection, and mixing of the binder. An energy-based approach is used, where fuel consumption (in liters) is converted to kg CO_2 equivalents using conversion factors, which vary by fuel type. The European standard [67] provides these values. The total estimated CO_2 emissions are calculated by summing the emissions from all these stages. CO_2 equivalents for futuristic equipment installation for in-situ CO_2 curing has not been accounted in this study. As the LCA study is considered within Helsinki and the lightweight biochar is also locally produced in HSY Helsinki, the emissions due to transportation is considered negligible in this case.

Results and discussion

Strength and pH characteristics of the stabilized clay samples

Fig. 6 provides the average q_u and pH results of the stabilized clay samples at 7 and 28 days of mixing the constituents as put forth in Table 4. The results demonstrate the effect of biochar percentage on the strength characteristics and pH variations with and without carbonation curing conditions. Fig. 6a corresponds to the samples prepared from the deep clay layer at 6.5–8 m depth. In the case of the samples with no biochar, the effect of carbonation condition (C1) had no effect on the strength characteristics after 7 days. However, for C2 carbonation condition, the samples showed a 50 % increase in q_u as compared to the control, which indicates a relatively higher CO_2 diffusion in the sample. In the case of the biochar amended samples at 10 % and 50 % amendment rate, similar response of q_u was observed for C1 condition with no significant strength increments with respect to the uncarbonated samples. On the contrary, the C2 condition exhibited an increase in q_u for the biochar amended samples. At biochar amendment rate of 10 % and 50 % there was an increase of q_u by 52 % and 170 % with respect to uncarbonated samples, respectively. From the 7-day q_u results, the C2 conditions potentially facilitate higher CO_2 diffusion in biochar amended samples even at 50 % biochar amendment rate. This phenomenon can be indirectly inferred based on the pH results for the 7-day samples. That sample showcased the lowest pH at 9.1 with respect to the control samples with no biochar addition (pH=11.3), indicating higher H^+ ion dissociation. Nevertheless, without CO_2 curing, the biochar amended samples at 7 days demonstrate a decrease in q_u with respect to the samples without biochar with strength reduction up to 60 %.

In the case of 28 days cured samples, which includes the initial hydration curing, carbonation curing and slow hydration curing stages, the q_u results seemed to change based on the biochar amendment rate. The samples without biochar amendment and C1 curing resulted in the highest strength of almost 1 MPa. This can be explained by optimum

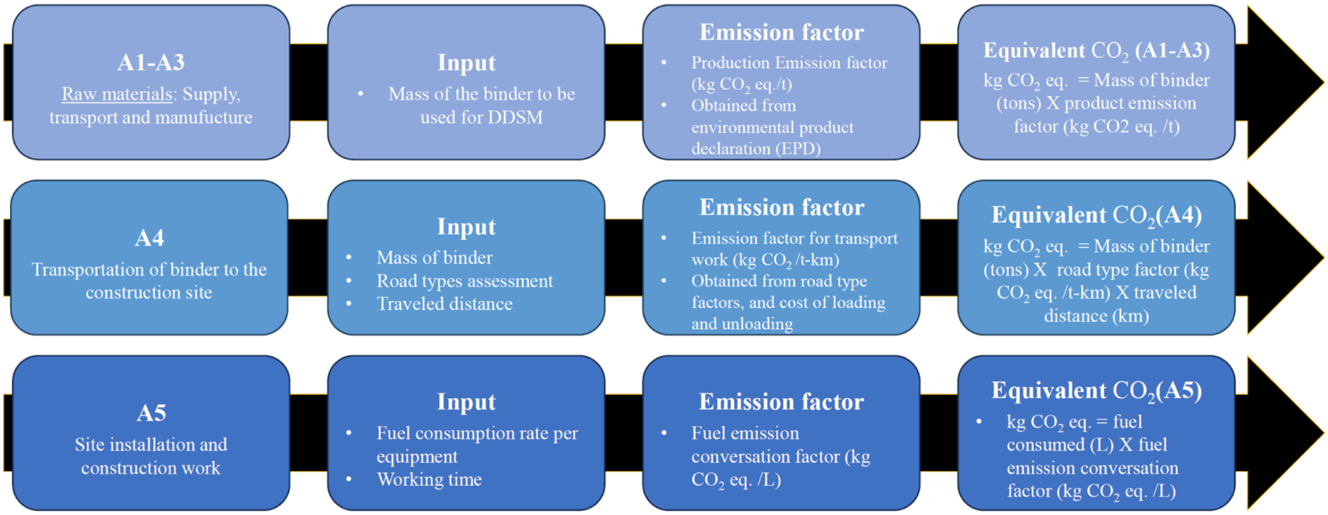


Fig. 5. The LCA workflow for estimating carbon emissions in deep soil mixing.

Table 5

LCA analysis: stages A1, A2, A3, and the CO_2 sequestration potential of the used binders.

	A1 – A3	A4 – Transportation			CO_2 sequestration potential due to carbonation				
Used binder	Production emission factor	Factory location	Distance to Malmi airfield	Transportation emission factor per factory	Carbonation method	Binder density	Sequestered CO_2	Sequestered CO_2	Production emission factor (After carbonation)
	(kg CO_2 e/t-binder)		km	(kg CO_2-eq/ton)	0	(kg/m^3)	(kg/m^3)	(kg CO_2 e/t-binder)	(kg CO_2 e/t-binder)
CEM III – A	426	Finnsementi Oy	15	0.62	NC	100	0	0	426
					C1	100	2.28	22.8	403.2
					C2	100	10.64	106.4	319.6
90 % CEM III – A+10 % BC	383.4	HSY Helsinki	9.3	0.38	NC	100	0	0	383.4
					C1	100	18.41	184.1	199.3
					C2	100	21.12	211.2	172.2
50 % CEM III – A+50 % BC	281				NC	100	0	0	281
					C1	100	38.67	386.7	−105.7
					C2	100	41.31	413.1	−132.1

conditions facilitated for slow hydration. After carbonation, it is likely that on the boundary of the samples, the partially formed $CaCO_3$ films may potentially reduce the pore size which reduces the k_{co_2} and further lowers the ingress of CO_2 inside the sample [49]. Thus, there is still an adequate amount of non-hydrated constituents of the cement clinker or clay that would undergo slow hydration resulting in the high compressive strength. On the contrary, C2 conditions showcase relatively lower q_u than both uncarbonated samples and C1 samples. This can be understood based on the rapid and higher CO_2 diffusion occurring in the materials. This lowers the pH significantly (pH=9.6) and reduces the availability of non-hydrated constituents for subsequent slow hydration. This can be also seen based on the difference in q_u at 7 days and 28 days for C2 condition. In the case of biochar amended soil, the q_u response is directly observed to be the function of the biochar percentage. At 10 % biochar amendment, in non-carbonated condition the q_u was highest among all conditions and almost equivalent to the C1 condition wherein no biochar was amended. This high q_u for 10 % biochar amendment facilitated for optimum slow hydration curing due to three major reasons. Those are, (1) Internal curing effect due to biochar intra-pores [65]; (2) Pore filling effect in the macropores of the cementitious composites [50]; (3) Available CaO in the biochar (refer Table 3) which facilitates both slow hydration and natural CO_2 curing [73]. In the case of C1 and C2, the q_u progressively decreases with respect to uncarbonated sample mainly because the samples undergo higher CO_2 mineralization during the accelerated CO_2 curing. C2 demonstrates the lowest pH at 8.8 which means most of the metal oxides are mineralized into carbonates during CO_2 curing. Naturally, biochar being very low stiff material, at higher amendment rate at 50 %, the q_u reduces by 28 % with respect to its control samples without biochar amendment and CO_2 curing. In this case, the pH without accelerated CO_2 curing resulted in low pH at 9.58 which showcases the CO_2 affinity of biochar [14]. This is also reflected in C1 conditions with a drastic reduction in qu by almost 50 % when compared to the control uncarbonated samples. However, at 50 % biochar amendment rate at C2 conditions the q_u values were highest and is equivalent to that of the control samples (without biochar amendment and CO_2 curing). This can be explained based on high CO_2 mineralization which is indicated with the rapid drop of pH (8.9) and resultant increase in the true cohesion component of the samples [35]. In the case of ACC (refer Fig. 1), the precipitation of CO_2 as carbonates from decomposition of available hydrates have a pore filling effect and densifies the cementitious matrix [35]. Thus, densification increases the compressive strength of the cementitious clay matrix in the current study as also observed in the literature related to concrete structures (refer Table 1). However, if samples have a very effective CO_2 mineralization there is a natural reduction of pH due to excess release of H^+ ions. Low pH is not conducive for subsequent hydration in the later stages which likely produces less hydration phases. Thus, the compressive strength may decrease as compared to uncarbonated samples of same mixtures. The mineralization process exhausts the oxides in the stabilized clay which leads to less optimal conditions for hydration curing [8]. The results for this figure inferred that compressive strength of soft clay at deeper depths can be improved by utilizing biochar alone at 10 % partial replacement. This can have implications in developing CO_2 adsorbents or low CO_2 intensive aggregates for construction industry using locally sourced biochar and readily available soft clay.

Fig. 6b shows the q_u and pH results for the stabilized clay samples that were prepared from the shallow depth layer between 2–3.5 cm depth. It is clear from the overall q_u values for all composites that the shallow clay having relatively high-water content (85–95 %) showcased lower strength than those at deeper depths. This is expected as the pore water pressure would be higher due to excess moisture content, resulting in lower strength [5]. Moreover, the initial water-to-cement ratio being higher for these composites would ideally delay the onset time considerably as reported by [28]. The results of the 7-day samples show that on the short-term, the C1 carbonation had no significant effects ($p \leq 0.5$) from those that were not carbonated regardless of the treatment type. In the control samples, the 7-day strength increased by merely 11 % due to C1 carbonation at around 125 kPa which does not satisfy as a stratum for construction Jyoti Bora et al. [26]. The results for the C1 conditions can also be observed based on the pH values which did not change significantly indicating the CO_2 diffusion was minimal for samples without biochar and 10 % biochar amendment. The effect of partial drying and consequent CO_2 diffusion with respect to biochar amended samples can be seen by comparing the pH drop and consequent q_u values. Whereas the pH remains constant (11.3) for non-biochar amended samples with respect to control hydrated samples (11.5), there is a relatively high drop in pH for the biochar amended samples (9.5 – 10.8). From the q_u results at both 7 and 28 days, one can infer that up to 10 % biochar amendment, the q_u (≥ 200 kPa) of the biochar amended soft clay can be used as a subgrade material even for shallow clay with higher water content. Nevertheless, the Finnish guidelines allocate the even lower values of q_u (≥ 40 kPa) for other geotechnical applications such as shallow embankment stabilization. At 50 % biochar amendment, there is scope for CO_2 mineralization for non-geotechnical applications wherein

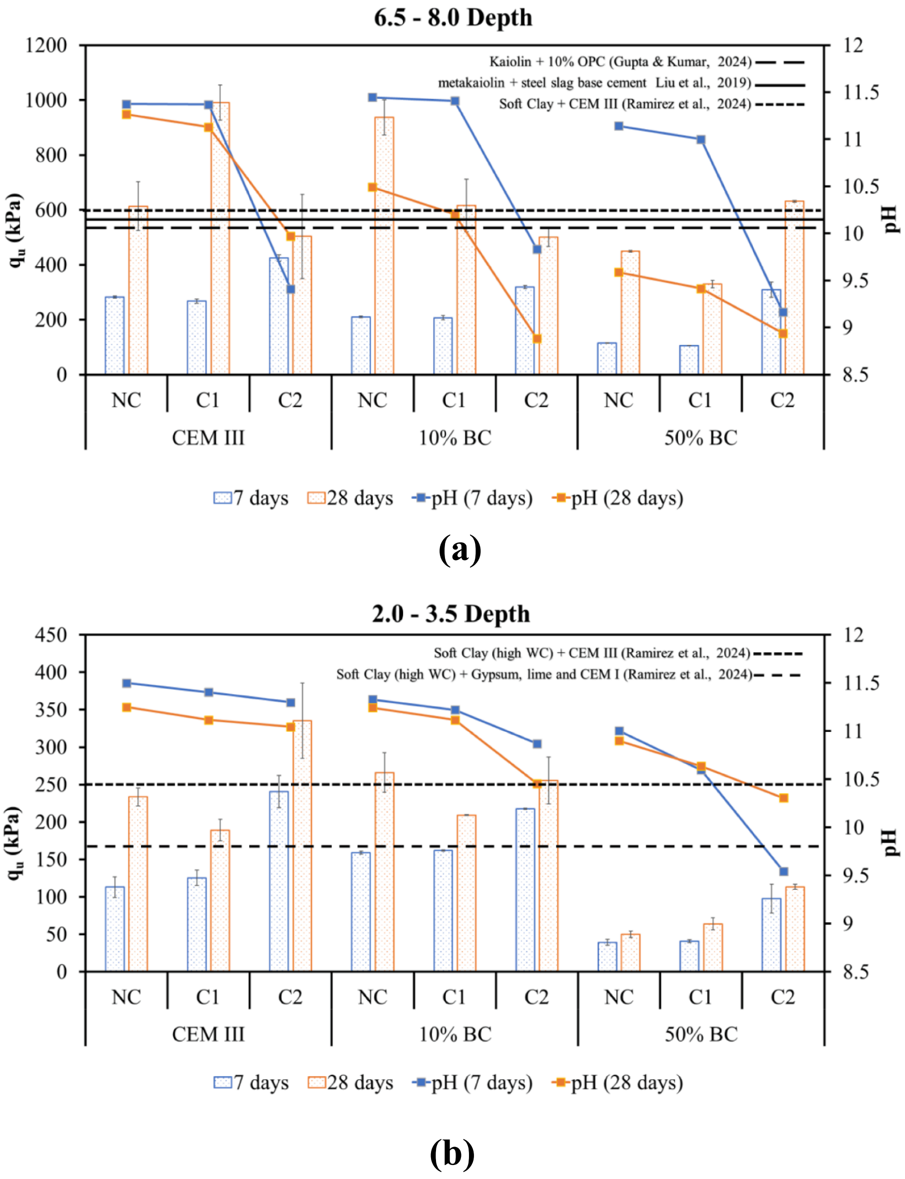


Fig. 6. Peak unconfined compressive strength and pH of the stabilized clay samples sourced from (a) deep and (b) shallow depths.

strength is not a priority, and the end goal is low CO_2 emission sustainable materials.

Thermogravimetric analysis of the stabilized clay samples

Fig. 7 presents the TGA spectra for the stabilized samples at deep stratum clay with 50 % biochar amendment cured for 28 days. This sample was chosen as that sample incorporate both the high percentage of biochar, and the benefit of carbonation, where the C2 sample showed similar strength to the control sample stabilized with 100 % cement (Fig. 6a). The TGA profile for 50 % biochar for normally hydrated and C1 carbonated condition were relatively identical up to 500 °C. After 500 °C, the C1 condition degraded slightly more than that of the normally hydrated samples. The TG curves are separated to three zones indicative of three different hydrated phase [47,68,78]. The first zone spans between 50 and 200 °C is associated with breakage of crystallization water related to C-S-H gel and ettringite products (Aft, Afm). The second zone spanning between 400 and 500 °C, is associated with dihydroxylation of the hydroxides ($Ca(OH)_2$ and $Mg(OH)_2$). The temperature range between 520 °C and 800 °C is associated with the decomposition of the carbonates. This phase is associated with the amount of sequestered carbon dioxide in the stabilized sample. The amount of decomposed $CaCO_3$ and CO_2 uptake can be calculated from Eqs. (1) and (2), as described in experimental protocol, from the TGA curves of individual samples.

The NC and C1 samples show a similar reduction in the weight percentage in the first zone (0.89 % and 0.81 % respectively), on the other hand, the C2 curve shows that, almost half of those percentages were lost before 200 degrees (0.42 %). Moreover, the C2 curve shows slightly more reduction in mass in the second phase, indicating a higher amount of calcium hydroxide in the partially dried sample. Both NC and C1 reduced by 0.77 %, while C2 reduced by 0.85 %. The carbonate content of the uncarbonated sample (NC) was relatively high. This implies that the biochar improves the natural carbon capture of the soil without the need to apply additional CO_2. This is also evident when comparing with the control sample (non-carbonated and no biochar amendment) wherein no significant degradation occurs in the carbonate decomposition range. Similar results were observed from concrete amended with biochar [25,27]. Moreover, based on the TGA analysis the C1 sample showed similar carbonate content when compared to the

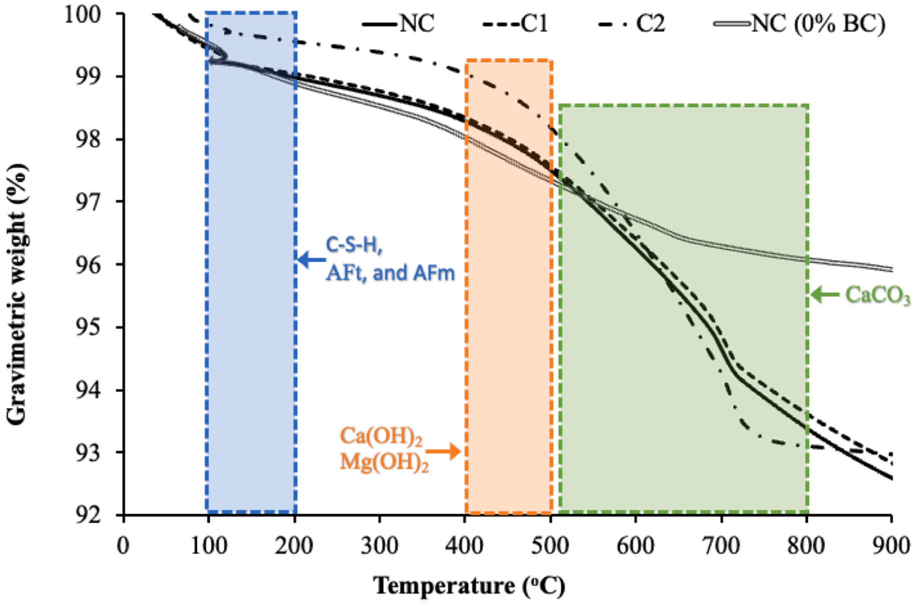


Fig. 7. Thermogravimetric curve for 50 % biochar amended stabilized clay samples at 28 days.

uncarbonated sample (3.74 % and 3.89 % respectively). This infers that the application of 4 h of CO_2 in 100 % condition might not be enough for the gas to penetrate in the samples. The additional pore water hindered the CO_2 gas diffusion and therefore, not much difference in the carbonate content was observed. On the other hand, the C2 sample showed a high increase in the carbonate content. The carbonate content increased up to around 30 % when compared to the uncarbonated sample with the same amount of biochar and up to 330 % when compared to the uncarbonated, stabilized sample with only cement. This highlights the significance of biochar in increasing the carbon sequestration capacity in soil stabilization. Moreover, As was shown in Fig. 6a, the C2 strength of samples up to 50 % replacement level, showed a similar strength compared to the samples stabilized with 100 % cement. Thus, the incorporation of biochar can significantly impact the carbon footprint without deteriorating the engineering properties of the soil.

CO_2 mineralization potential of the stabilized clay samples

Fig. 8a shows the weight loss from decarbonation (i.e., $CaCO_3$) and bound CO_2 for stabilized samples at deep depth with biochar replacement levels of 0, 10, and 50 %. Similarly, the bound CO_2 for each mixture is presented by subtracting the CO_2 corresponding to the control

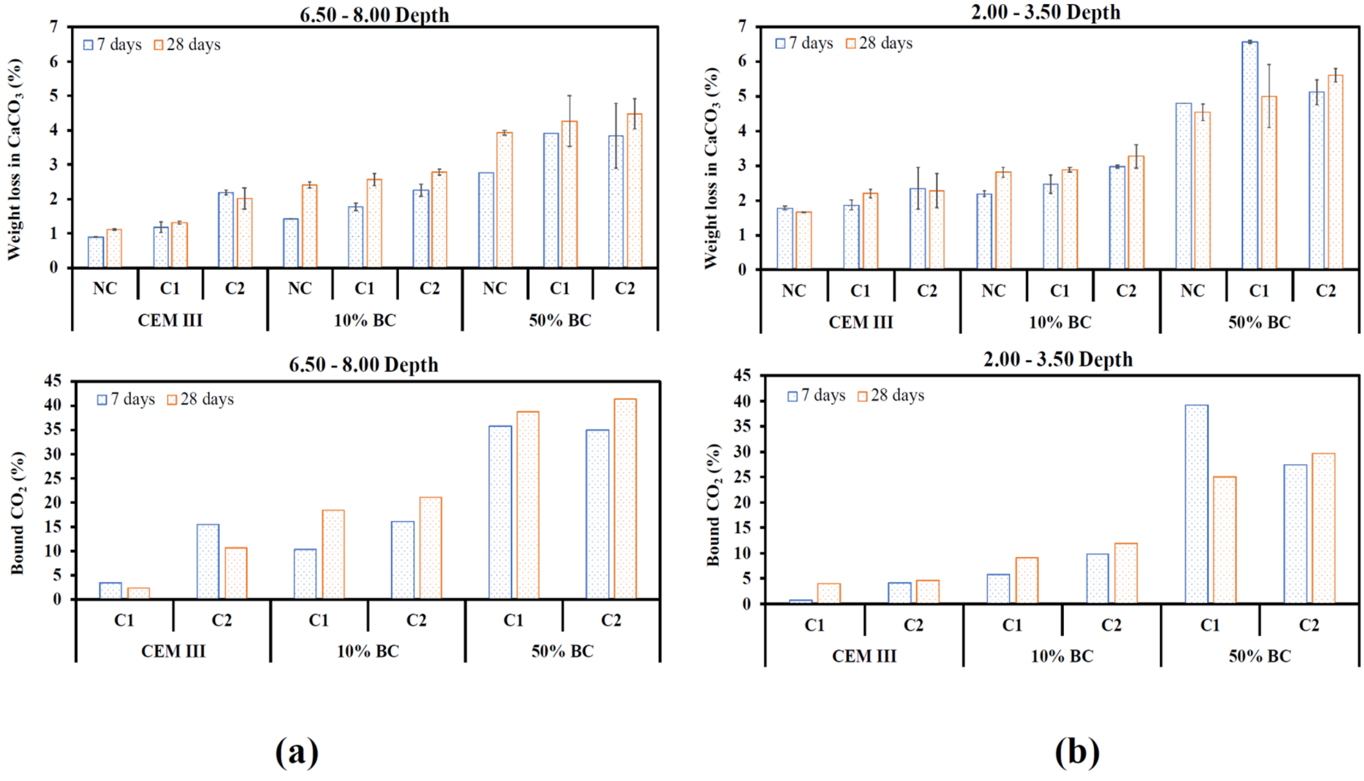


Fig. 8. Total CaCO3 and bound CO2 in stabilized clay samples sourced from (a) deep and (b) shallow depths.

non-carbonated sample at 0 % biochar amendment considering Eq. (1). The control samples with no biochar amendment showed increase in the weight loss under both C1 and C2 conditions. The carbonate content for the 7 days samples increased from 0.9 % to 1.2 % for C1, and up to 2.2 % for the C2. On the other hand, the weight loss for the samples that incorporated 10 % of the biochar increased from 1.4 % to 1.77 % and 2.25 % due to C1 and C2, respectively. The samples prepared at 50 % biochar also increased weight loss when applying the CO_2 environments. The weight loss due to decarbonation of those samples cured for 7 days increased around 30 % for both C1 and C2 at 4 % for each. The 28-day cured samples also showed a similar behavior with a noticeable increase in the carbonate content at C1 condition. It is likely that the carbonation kinetics increases with lower pore water content of deep clay layers. Similar behavior was also observed in the samples cured for 28 days. Nonetheless, the weight loss was shown to be higher than the 7 days samples for majority of the samples. The reason for that is the natural carbonation process that occurs with time even after the accelerated carbonation induced at 4th day [7]. This process takes place due to the available CO_2 in the surrounding atmosphere. Furthermore, including biochar as a replacement for cement, increased the carbon capture potential significantly, for both the uncarbonated and carbonated samples. At 28 days after mixing, the weight loss due to the loss of $CaCO_3$ in the stabilized clay samples with 10 % biochar amendment was higher by 120 % as compared with the control samples without any CO_2 curing (NC). Increasing the biochar content to 50 % further increased the weight loss by more than 250 % at both C1 and C2 conditions. This implies that the biochar could play an effective role in mineralizing the CO_2 gas in clays even if these kind of samples at 50 % amendment would not facilitate a subgrade stratum particularly taking high water content samples.

The bound CO_2 refers to the amount of the sequestered CO_2 gas in the stabilized samples [54]. As the TGA analysis was conducted on the dried samples, the dried density is used to calculate the amount of the bound CO_2 for each sample. The bound CO_2 was calculated based on the difference in the uptake CO_2 between each mix and the uncarbonated reference samples with no biochar replacement. This method allows for the consideration of the natural carbon content of the biochar, which is considered as a negative carbon material [64]. In case of the samples from the deep stratum clay (Fig. 8a), the samples with no biochar showed a relatively small amount of the bound CO_2. This is especially true for the samples with C1 carbonation condition where only 2.3 % CO_2 were stored back in the 28-day sample. The bound CO_2 percent increased to 10 % for the C2 method in the 28-day sample. The bound CO_2 increased significantly in the samples having 10 % of biochar replacement. The 28-day samples increased by 682 % and 850 % for C1 and C2 method, respectively. The increment of the biochar up to 50 % markedly amplified the sequestration of CO_2. At this high biochar amendment rate, the 28-day samples increased by 1639 % and 1726 % for C1 and C2 method, respectively. Judging the very high increase in mineralized CO_2, the scope of utilizing biochar as a carbon capture strategy in clay can be manifested in different applications. For instance, the use of cold-bonded aggregates using these mixtures can translate as an excellent CO_2 adsorbent in CO_2 storage/utilization facility.

The samples that were sourced from shallower clay depth (Fig. 8b) depicts the same range of $CaCO_3$ formation (0.8–3 %) as the samples prepared at the deeper depth for 0 and 10 % biochar amendment. However, the amount the bound CO_2 sequestered in these samples is relatively lower than that of the deeper layers for 0 and 10 % biochar amendment. This is expected as the natural geological water content is relatively higher (around 85 to 100 %) in shallow layers. This adsorbed and capillary water naturally pose resistance against CO_2 diffusion into the porous matrix even when biochar is present at 10 %. Comparing the 28 day bound CO_2 results, even though CO_2 is sequestered in 10 % biochar amendment more than that of the cement stabilized samples (5 %), the stored CO_2 is at around 10 %. On the contrary, both $CaCO_3$ and bound CO_2 at 50 % biochar amendment results in CO_2 sequestration even at high water content level. This indicates that the hypothesis that biochar facilitates uniform and higher CO_2 diffusion pathways must hold some weight. This is also backed up by the lowest pH observed in these samples (refer Fig. 6). Nevertheless, one should keep in mind that these high moisture content clay may not be suitable as a geotechnical base layer for all construction applications (as $q_u \leq 200$ kPa) while for low-load bearing applications like shallow embankment this kind of stratum is still acceptable as per Finnish Transportation guidelines ($q_u \geq 50$ kPa) [13].

Fig. 9 depicts a comparison of the CO_2 emission profiles linked to the final composite properties at 28 days after curing. These values indicate the CO_2 footprint with respect to the cradle-to-gate phase (mining, transport to factory, clinker production and grinding). The CO_2 emission includes the three stabilized clay composites with pure cement (designated as CEM-III); a mixture containing 90 % CEM-III and 10 % BC (designated as 10 % BC); and another blend comprising 50 % CEM-III and 50 % BC (designated as 50 % BC). Fig. 9 shows the CO_2 emissions of the samples prepared from the deep clay layers (6.5–8.0 m depth). Overall, the total CO_2 emission when no carbonation was done showed a lowering of the CO_2 footprint from 42.6 kg CO_2/m^3 (for CEM-III) to 28.1 kg CO_2/m^3 (for 50 % BC) which accounts for 34 % reduction. Moreover, the net CO_2 emission which accounts for the bound CO_2 in mineralized form, the utility of biochar is apparent as the net CO_2 emission shows marked reduction from 32 % (for CEM-III stabilized clay) to −13 % for (50 % BC stabilized clay). Thus, at 50 % BC usage, the CO_2 is sequestered in stable carbonates than the overall CO_2 emission related from cradle-to-gate phase. For 10 % BC stabilized samples, even though negative emissions were not reached, the overall net-CO_2 emissions were reduced by 46 % considering the C2 carbonation procedure. The results imply that for deeper clay layers with low water content, biochar addition up to 50 % in the binder can be utilized to achieve high UCS requirement of 200 kPa while reaching carbon negativity from cradle-to-gate considerations. However, similar results were not evident for shallow clay layers with high water content when biochar was added more than 10 % (Fig. 9b).

Estimation of CO_2 equivalents in deep mixing design– case study

Site-specific data are essential for estimating emissions from stages A4 and A5, as discussed in Fig. 5. Consequently, this case study focuses on Malmi airfield, where deep soil mixing is utilized to stabilize the site. Tables 5 and 6 presents the LCA data for the stabilization process, encompassing all stages shown in Fig. 5. For stages A1 to A3, emission factors were derived from the Environmental Product Declaration (EPD) provided by Finnsementi. The emission factor for CEM III – A production is reported as 426 kg CO_2 eq. per ton. Conversely, biochar emission factors were assumed to be zero, despite literature indicating negative emission factors [15,16]. This assumption aligns with common practice for LCA calculations in stages A1 to A3 [64]. The negative emissions of biochar were considered in the bond CO_2 calculations, as previously mentioned.

The study primarily examined carbon sequestration potential, incorporating the CO_2 sequestration capacity for each binder, as shown in Fig. 9. These values were converted to equivalent sequestered CO_2 per ton and subtracted from the manufacturing emissions (Stage A1). Emission factors for stage A4 were calculated based on the distances between the field and manufacturing sites for cement and biochar, which are 15 km and 9.3 km, respectively. The road emission factors were derived from the Handbook Emission Factor for Road Transport [24]. Given that biochar is available within Helsinki (less than 4 km), the transport emission factors are relatively low and considered zero.

For stage A5, emission factor calculations depend primarily on the deep mixing design as per recommendations by Ramboll Finland Oy. However, some design data allow for comparison of the environmental performance of binders without a complete LCA. These indicators include the emission factors per linear meter of deep mixing stabilized

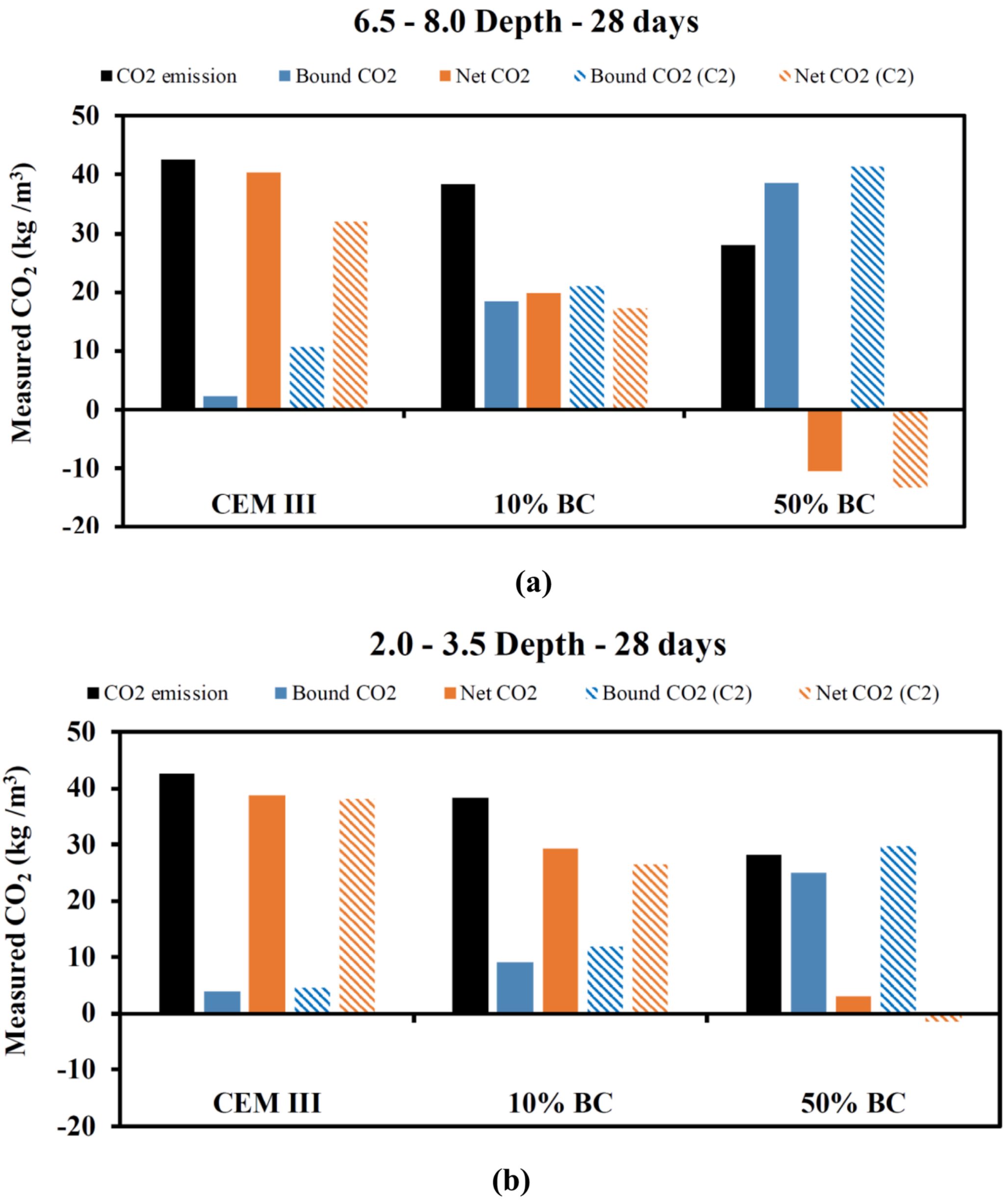


Fig. 9. CO2 emissions of all stabilized clay samples considering 28 days of curing.

Table 6
LCA analysis: the construction phase (stage A5) for Malmi airfield deep soil stabilization.

A5 – emissions factors from DDSM design											
Column diameter (m)	Total number of columns	Column length (m)	Achieved undrained cohesion (kPa)	Achieved shear strength (kPa)	Targeted strength (kPa)	Binder amount (kg)	Total emissions (kg CO$_2$ eq/ton-binder)	Binder consumption (kg/m-column)	Sequestered CO$_2$ per column (kg CO$_2$ eq./m-column)	Emission factor per m Of column (kg CO$_2$ eq./m)	Design emission factor (kg CO$_2$ eq./m/kPa)
0.7	321	1874	613	306.5	150	72,120	81.51	38.48	0.00	16.39	53.49
0.7	321	1874	900	450	150	72,120	81.51	38.48	0.88	15.52	34.48
0.7	321	1874	503	251.5	150	72,120	81.51	38.48	4.09	12.30	48.91
0.7	321	1874	936	468	150	72,120	81.51	38.48	0.00	14.75	31.53
0.7	321	1874	615	307.5	150	72,120	81.51	38.48	7.08	7.67	24.94
0.7	321	1874	501	250.5	150	72,120	81.51	38.48	8.13	6.63	26.46
0.7	321	1874	449	224.5	150	72,120	81.51	38.48	0.00	10.81	48.17
0.7	321	1874	329	164.5	150	72,120	81.51	38.48	14.88	−4.07	−24.73
0.7	321	1874	632	316	150	72,120	81.51	38.48	15.90	−5.08	−16.09

column (kg CO_2 eq./m-column), per linear meter per 1 kPa of achieved binder strength and carbonation method (kg CO_2 eq./m/kPa), and the sequestered CO_2 potential per linear meter of column. These factors are useful for evaluating the CO_2 emission rates for a given binder formula, including accelerated carbon curing. Similar factors without carbon sequestration were reported by [22,37]. The adopted and calculated values discussed in LCA estimation are provided in Tables 5 and 6. The incorporation of biochar, along with carbonation, significantly reduced the emission factor per meter column per 1 kPa from 53.5 kg CO_2 eq./m/kPa to −24.73 kg CO_2 eq./m/kPa. Tables 5 and 6 demonstrates the substantial potential of biochar combined with accelerated carbonation to stabilize soil according to industry standards while achieving overall negative greenhouse gas emissions.

Fig. 10 provides a graphical representation of the LCA evaluation of the deep mixing method applied to soft Finnish clay stabilized with cement and biochar binder formulas. Samples stabilized solely with cement exhibit relatively high net emissions, despite using a modified cement formula containing up to 64 % blast furnace slag. The estimated net emissions without carbon sequestration exceed 500 kg CO_2 per ton. After carbonation, net emissions decrease to 485 and 400 kg CO_2 per ton for C1 and C2 carbonation methods, respectively. Conversely, samples incorporating biochar as a cement replacement show a significant reduction in overall emissions. Replacing 10 % of the cement mass with biochar reduces net emissions to 400 kg CO_2 per ton without accelerated carbon curing. Applying carbonation further decreases emissions to 281 and 254 kg CO_2 per ton under C1 and C2 conditions, respectively, likely due to biochar's enhanced CO_2 sequestration capability within the soft clay-cement composite. Increasing the biochar replacement to 50 % of the cement mass results in even greater emission reductions. CO_2 sequestration of the binder increases from 22.2 kg CO_2 per ton for control samples to 386 kg CO_2 per ton with C1 carbonation and 413 kg CO_2 per ton with C2 carbonation, resulting in negative overall emissions for the stabilized soft clay. The overall emissions of the binder containing 50 % biochar and carbonated under C1 and C2 conditions are –23.7 and −50 kg CO_2 per ton, respectively. These preliminary results from the case study demonstrate a significant potential to reduce CO_2 emissions in the soft clay stabilization niche of geotechnical designs. The methods applied here provide a hypothetical means to continue essential construction activities while offering an opportunity to sequester CO_2 rather than emit it to atmosphere. Nevertheless, further research is needed to develop tools to initiate CO_2 injection in actual field methods for curing stabilized soil.

Summary and Conclusions

The current study aimed at developing precast cementitious composites cured with concentrated CO_2 gas. These composites constituted of waste soft clay, biochar and cement and left for hydration for 3 days followed by CO_2 curing. The biochar was used as a partial replacement of cement at 10 % and 50 %. The developed cementitious composites were cured using two CO_2 diffusion techniques and physio-chemical properties of the composites were measured. The results from UCS tests, sequestered CO_2, and overall CO_2 footprint are briefly summarized below pointwise.

1) The replacement of 10 % of cement with biochar resulted in sufficient load-bearing capacity (≥200 kPa) for both shallow and deep clay layers, making the material suitable for high load bearing geotechnical applications. Increasing the biochar content to 50 % and employing accelerated carbon curing still produced materials meeting standard strength requirements. Specifically, samples with 50 % biochar in deep clay layers achieved 620 kPa strength comparable to control samples (600 kPa) when partial drying carbonation was used. However, samples with 50 % biochar in shallow clay could only achieve strength just above 100 kPa, which can be applicable for low load bearing infrastructures as per Finnish guidelines (≥40 kPa).
2) Thermogravimetric analysis revealed a substantial increase in bound CO_2 due to carbonation when 50 % of cement was replaced with biochar. For shallow clay samples, bound CO_2 increased from 2 % to 39.2 %, and for deep clay samples, it increased from 3 % to 41 %. Partial drying before carbonation enhanced both CO_2 capture efficiency and material strength.
3) Life Cycle Assessment (LCA) of a case study demonstrated that incorporating up to 50 % biochar and applying accelerated carbon curing could potentially make deep soil mixing carbon negative. Net carbon emissions reduced from 508 kg CO_2 eq./ton to −50 kg CO_2 eq./ton. However, further research is needed to implement carbonation techniques in real field conditions for stabilized columns.

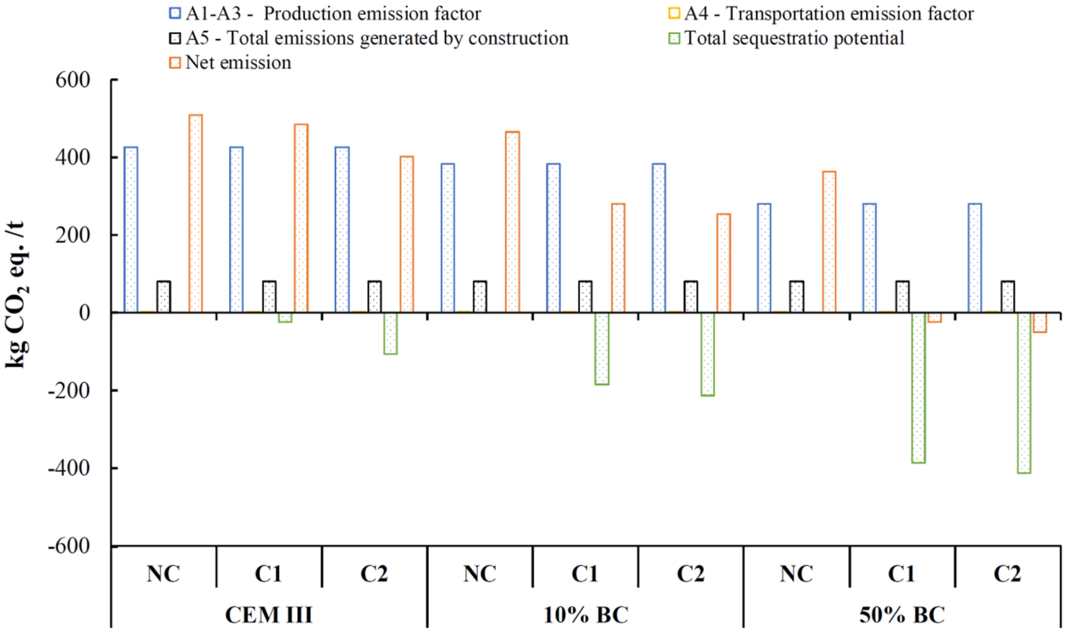


Fig. 10. CO2 emissions from the different LCA stages and the net emissions of the binders used, along with their respective carbonation methods.

CRediT authorship contribution statement

Mohamad Hanafi: Writing – review & editing, Investigation, Data curation. **Sanandam Bordoloi:** Writing – original draft, Supervision, Project administration, Conceptualization. **Rinta-Hiiro Ville:** Writing – review & editing. **Oey Tandre:** Writing – review & editing. **Leena Korkiala-Tanttu:** Supervision, Resources, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Malmi airfield sampling programme and details

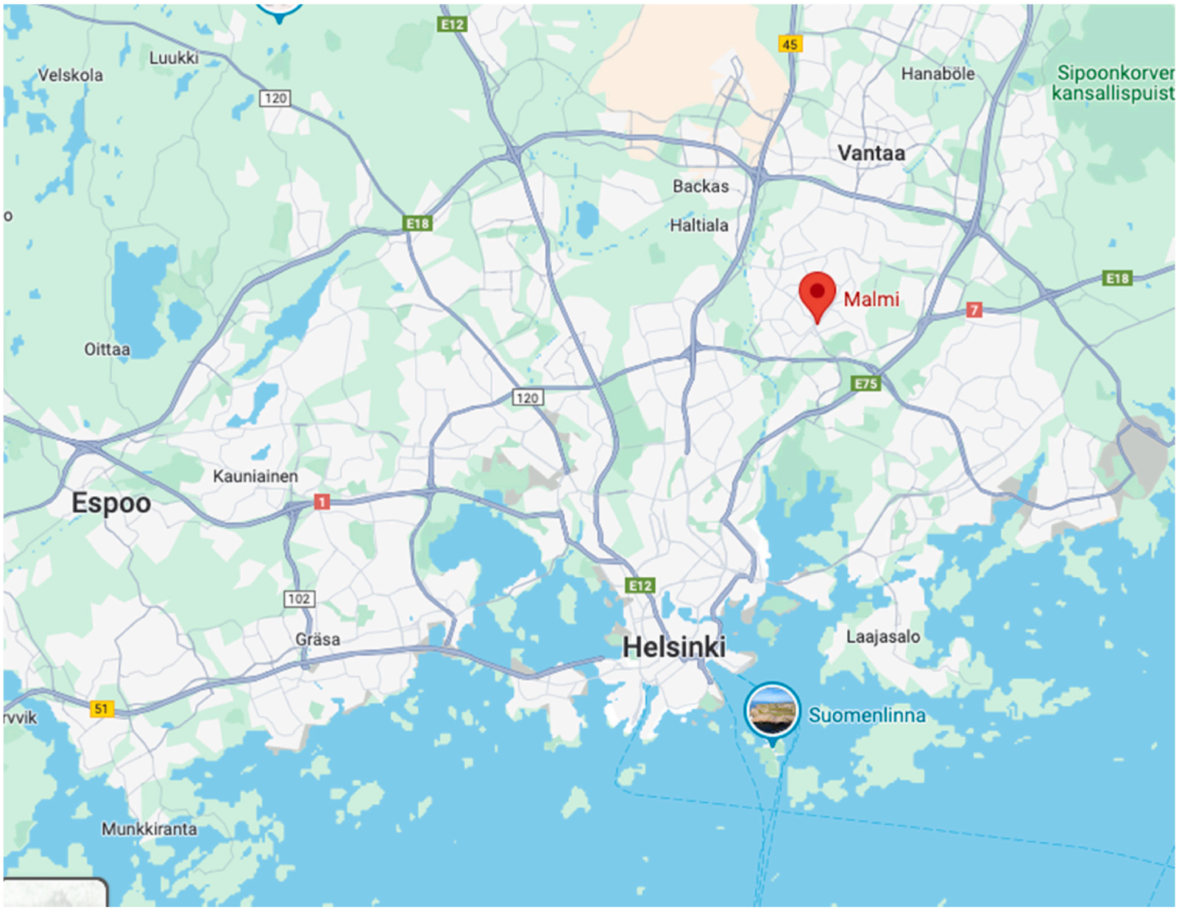

Fig. A1. The location of Malmi Airfield.

Fig. A2. The machinery used to obtain the clay samples from different depths.

Appendix B. CO_2 chamber setup

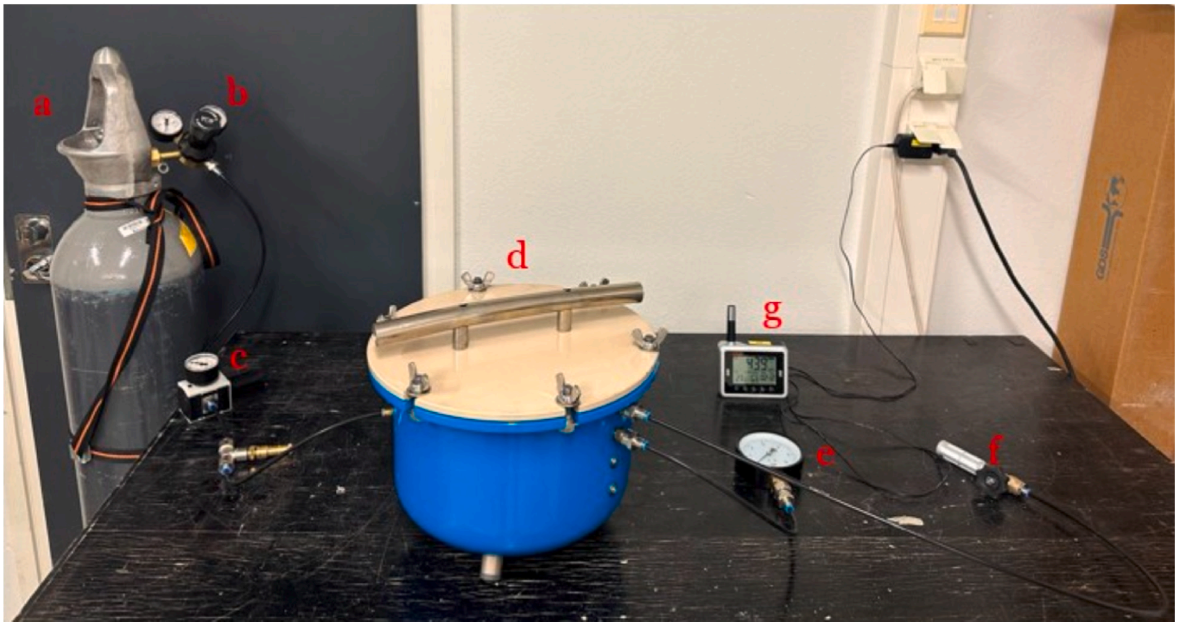

Fig. B1. The setup of the carbonation chamber at Aalto university.

a) CO_2 tube supplies the CO_2 gas to the chamber.
b) Pressure adjustment valve: adjust and maintain the gas pressure coming from the tube.
c) Pressure indicator: measure the pressure coming from the tube.
d) Carbonation chamber: A sealed and pressurized chamber where the samples can be placed.
e) Pressure indicator: to measure the pressure inside of the chamber.
f) Pressure value: to release the pressure from the chamber upon the end of carbonation.
g) CO_2 meter: to monitor gas percentage in the room and indicate any leak.

Fig. B2. Stabilized samples placed in the carbonation chamber.

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