KEYNOTE: RECENT DEVELOPMENTS IN DEEP MIXING IN FINLAND

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KEYWORDS

Deep mixing, deep stabilization, low-carbon binders, carbon emissions, environmental impacts, leaching, mechanical properties

ABSTRACT

Deep mixing has established its role as one of the most commonly used ground improvement methods in Finland over the last few decades. Research on deep mixing has been active, covering topics such as execution, quality control, design, design guidelines, and binder development. Although alternative low-carbon materials have been used as binders since the 1990's, their use has been modest. However, the pressure to apply low-carbon binders is now higher than ever. All research indicates that it is possible to decrease the carbon emissions of stabilised soils by using alternative binders without compromising structural performance or environmental impacts. This is important to demonstrate to the industry and stakeholders. This presentation highlights the results of recent studies and developments of low-carbon binders in Finland, concentrating on research conducted at Aalto University with partners.

1 INTRODUCTION

Deep mixing, or deep stabilisation, is one of the most widely used ground improvement methods in Finland [1]. The mean annual deep mixing volumes have stabilised at approximately 850,000 m^3 [2], of which about 83% involve mixing with columns and 17% involve mass stabilisation. In the Nordic stabilisation method, dry mixing is employed. Finnish design guidelines have been based for decades on the principle of equal settlement presented by Broms and Boman [3] and on the concept of elastic columns. The use of lime–cement mixtures as binders has predominated. However, the situation is changing rapidly, as it has been noted that lime–cement mixtures have significantly higher carbon emissions compared to other binder types [4,5]. According to Lehtovaara [5], on average, 2.6% of the total CO_2 emissions from Finnish

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infrastructure construction (57 kt CO_2eq annually) originate from the manufacturing of binder materials for deep mixing. Therefore, the city of Helsinki is now planning to relinquish the use of lime–cement in 2024.

The next Eurocode will also include ground improvement methods. Additional drivers for developing deep mixing methods and guidelines include the need to standardise the preparation of stabilisation test samples and their testing to improve quality control methods, to prove that low-carbon binders are environmentally acceptable, and to adapt and update Finnish design guidelines [10].

Researchers at Aalto University, formerly Helsinki University of Technology, have studied the behaviour of natural Finnish clays for decades. Since the late 1990s, the deep mixing of clays has also been a focus [6]. Early studies concentrated on the development of deep mixing techniques (e.g. mixing tools) and stabilisation test methodology [6]. Recent research topics have focused on the long-term performance of stabilised soil and peat, the performance of alternative binders in laboratory and field conditions, environmental impacts, and CO_2 emissions. The objective of this keynote lecture is to introduce the key findings of recently published Finnish research results.

2 PERFORMANCE OF ALTERNATIVE BINDERS COMPARED TO LIME–CEMENT MIXTURES

2.1 Laboratory tests

Material properties and tests

The performance of low-carbon binders has been reported in several laboratory studies. López Ramirez et al. collected and analysed the results of several researchers [7,8]. The stabilised soil presented is mainly soft, sensitive, non-organic Malmi clay from the northern part of Helsinki. The studied clays had a water content between 80% and 120% and undrained shear strength varying between 8 kPa and 20 kPa. The binder materials included lime–cement (LC or KC) as a reference and several commercial binders produced by Nordkalk, Finnsementti, and Ecolan. A binder mixture tailored by Oulu University was also tested (CSAB calcium sulfoaluminate belite). The binders consist of blast furnace slag, quick lime, Portland cement and cement mixtures, lime kiln dust, slaked lime, gypsum, fly ash, slags from the steel industry, and phosphogypsum [7]. The fly ashes are biobased from paper industry UPM and energy production (PVO). Table 1 includes the typical index properties of Malmi clay, and Table 2 lists the binder materials[3] and the associated raw materials. The extensive laboratory studies comprised index tests, uniaxial compression, fall cone,

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[3] Due to the existence of several sources, the naming of binders was not always possible to harmonise.

oedometer, and triaxial tests, and even autoradiography. The curing times varied from 7 to 91 days.

Table 1. Malmi clay index properties according to [8].

Property	Value	Standard
Depth (m)	3–4.5	-
Density (g/cm^3)	1.50	ISO 17892-2:2014
Specific gravity	2.70	ISO 17892-3:2015
Water content (%)	95	ISO 17892-1:2014
Clay content (%)	73	ISO 17892-4:2016
Plastic limit (%)	32.1	ISO 17892-12:2018
Liquid limit (%)	82	ISO 17892-12:2018
Undrained shear strength (kPa)	17.8	ISO 17892-6:2017
Sensitivity	35.4	ISO 17892-6:2017
Organic content	1.3	SFS-EN 15935:2021
pH	7.5	ISO 10390:2021

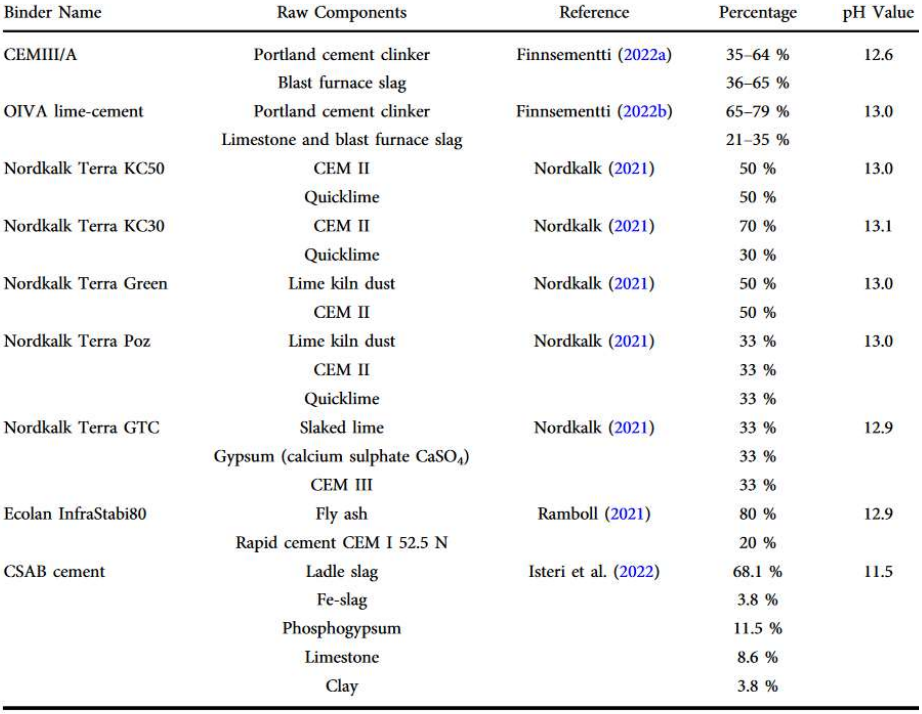
Failure modes

One study concentrated on radial deformations and failure modes using a photogrammetric method. Failure modes were divided into three categories: axial splitting, inclined shearing, and hybrid splitting–shearing. The results implied that most of the stabilised specimens remained ductile. Another conclusion was that the unconfined shear strength was predominantly determined by the composition and dosage of the binder rather than by the failure mode [9].

Porosity studies

The porosity of stabilised samples was compared at the age of 28 days for four binders provided by Nordkalk. The porosity stabilized clay samples mixed with LC50, Terra Green, and Terra Poz varied between 74% and 78%. However, Terra GTC had less porosity (around 64%). This difference might be explained by the presence of gypsum, a component that has been shown to have a significant closing effect on the porosity of stabilised clay samples with high water content [8].

Table 2. Raw materials and pH values of the tested binder materials [7].



Binder Name	Raw Components	Reference	Percentage	pH Value
CEMIII/A	Portland cement clinker	Finnsementti (2022a)	35–64 %	12.6
	Blast furnace slag		36–65 %	
OIVA lime-cement	Portland cement clinker	Finnsementti (2022b)	65–79 %	13.0
	Limestone and blast furnace slag		21–35 %	
Nordkalk Terra KC50	CEM II	Nordkalk (2021)	50 %	13.0
	Quicklime		50 %	
Nordkalk Terra KC30	CEM II	Nordkalk (2021)	70 %	13.1
	Quicklime		30 %	
Nordkalk Terra Green	Lime kiln dust	Nordkalk (2021)	50 %	13.0
	CEM II		50 %	
Nordkalk Terra Poz	Lime kiln dust	Nordkalk (2021)	33 %	13.0
	CEM II		33 %	
	Quicklime		33 %	
Nordkalk Terra GTC	Slaked lime	Nordkalk (2021)	33 %	12.9
	Gypsum (calcium sulphate $CaSO_4$)		33 %	
	CEM III		33 %	
Ecolan InfraStabi80	Fly ash	Ramboll (2021)	80 %	12.9
	Rapid cement CEM I 52.5 N		20 %	
CSAB cement	Ladle slag	Isteri et al. (2022)	68.1 %	11.5
	Fe-slag		3.8 %	
	Phosphogypsum		11.5 %	
	Limestone		8.6 %	
	Clay		3.8 %	

Preparation of samples and round-robin tests

The Finnish guidelines for preparing and storing laboratory samples were harmonised in 2018 [10]. Koivulahti et al. [11] presented these guidelines in English. To test the usability of these guidelines, three round-robin (interlaboratory) test series were conducted in Tankovainio (2018) and Topinpuisto (2020 and 2021). Eight anonymous (L1–L8) laboratories took part in this effort. The uniaxial compression test results were examined to determine the internal (within one laboratory) coefficient of variation (COV) of individual test series and the external variation between test series performed in parallel in different laboratories [12]. The internal variation ranged from 1% to 34%, depending on the laboratory. After the preliminary results from 2018, the laboratories with the highest variation re-evaluated their sample preparation techniques. In the next rounds (2020 and 2021), the internal variation percentages decreased to between 1% and 24%. Despite the new guidelines, a large external variation was found between laboratories, ranging from 13% to 36% [12]. Figure 1 shows the variations for the two binders and two dosages. The binder type did not have a clear effect on the variations, nor did the binder dosage [13]. Forsman et al. [12] stated that it is possible to achieve COVs of less than 10%. This can be accomplished if '(i) the instructions [are] followed, (ii) laboratory personnel [are] qualified to conduct stabilization, and iii) laboratory [are] equipped with proper test apparatus (mixing, compaction, curing, testing, etc.)'. In the concrete industry, the quality of accredited laboratories is monitored using annual round-robin tests. For comparison, the internal COVs in 2024 varied between 0.5% and 4.2%, with an average of 2.6% [14].

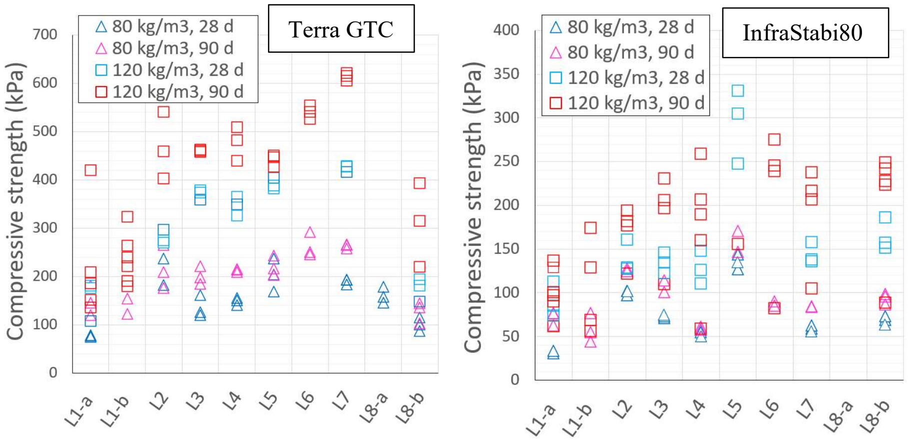


Figure 1. Topinpuisto (2021): the results of the unconfined compression tests of eight laboratories with Terra GTC and InfraStabi80 binders and two curing times and dosages [12].

Performance of low-carbon binders in triaxial tests

Different binder materials were tested in isotropically consolidated drained triaxial tests (CID) for Malmi clay with a binder content of 120 kg/m^3 [8]. The effective strength parameters were calculated for the maximum and residual strength values (see Figure 2). For the 28-day tests, the maximum effective friction angle (ϕ') varied between 35° and 37.2° and the residual effective friction angle (ϕ'_{res}) varied between 35.3° and 38°. The maximum effective cohesion (c') was estimated to be lowest for InfraStabi80 at 18.7 kPa and highest for Terra Green at 75.2 kPa. The residual effective cohesion (c'_{res}) varied from 6.5 kPa to 30.2 kPa. For a curing time of 60 days, ϕ' and ϕ'_{res} varied about 35–38.5°, but the maximum cohesion values c' clearly increased to 66.6–127.9 kPa, and ϕ'_{res} ranged from 8.3 kPa to 35.9 kPa. The Terra Green, Terra GTC, and Terra LC30 binders exhibited the best performance in the 28-day tests compared to the reference LC50 binder. In particular, the c' values were higher than for the reference. The Terra Green and Terra GTC binders were also tested for 60-day triaxial strength, showing further strength development that surpassed that of the reference binder. The LC50, Terra Green, and Terra Poz binders exhibited about 40% higher effective cohesion values than after 28 days, while the hardening of Terra GTC was much more significant, with 90% of the cohesion values being higher than after 28 days. The breakage of cementation bonds at maximum deviatoric stress and the consequent strength reduction were reflected in significantly smaller cohesion values for the fully softened state, especially for the GTC binder. It seems that the relationship between c’ and c’$_{res}$ depends entirely on the type of binder [8].

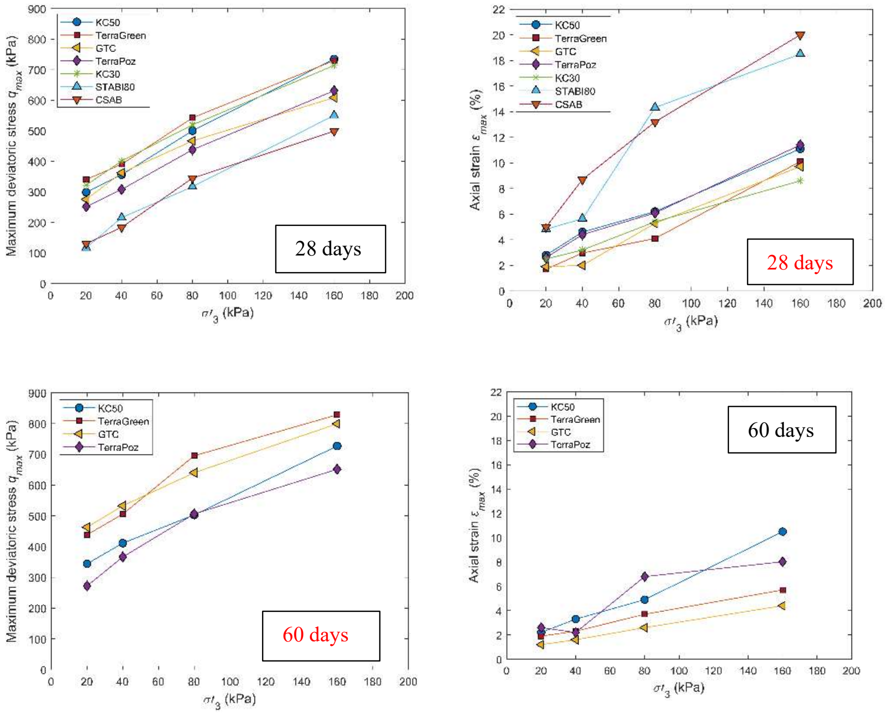


Figure 2. Malmi clay: triaxial test results for seven binders with a dosage of 120 kg/m^3 and curing times of 28 and 60 days [8].

Although the cohesion and strength of the GTC binder surpassed those of the reference binder LC50, this formula can result in a highly brittle admixture compared to the rest of the binders. The binder reactions used the water inside the samples, rendering them partially saturated. Therefore, it was decided to conduct drained triaxial tests with a back pressure of 20 kPa. Åhnberg [15] stated that the difference between drained and undrained test results with high water content can be small. Nonetheless, the samples in the study were assumed to be sufficiently saturated. The base soil had a high initial water content, and upon stabilisation, the samples had saturation degrees within the 94–96% range [8].

Fall cone tests compared to uniaxial compression test results

In the laboratory, the fall cone test can be used to evaluate, for example, the curing process. Lopez Ramirez et al. [7] studied the correlation between fall cone measurements and the undrained shear strength obtained from uniaxial compression tests. The results showed a relatively good correlation between these test types up to the shear strength level of 650 kPa in the fall cone test (Figure 3). Above 650 kPa, the fall cone is no longer sensitive enough. The fall cone overestimates the shear strength, giving values about three times larger than UCS. Therefore, there is a clear need to redefine the empirical fall cone correlations for stabilised in future. In this study, binder type and curing time did not affect the results.

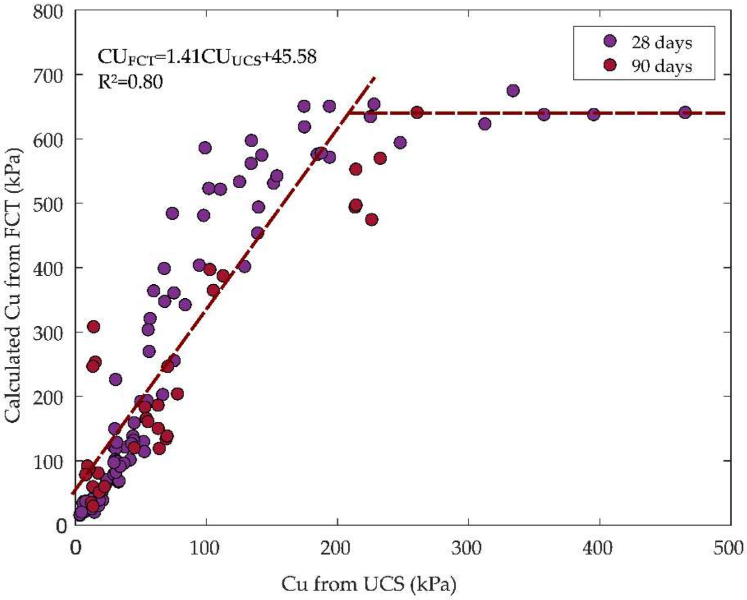


Figure 3. Correlation between the undrained shear strength C_u obtained from the fall cone test and that obtained from the uniaxial compression test [7].

Water content and binder dosage

Low-carbon binders are mixtures of several constituents that cause both pozzolanic and hydration reactions. Sometimes, binder mixtures are less active, or the development of strength might be slower. Typically, this is connected to the underlying chemical reactions: hydration reactions occur quicker than pozzolanic reactions [10]. In some cases, a slightly higher binder dosage for low-carbon binders is needed compared to traditional lime–cement mixtures. This trend appears to become more pronounced as the water content of the soil increases. Figure 4 illustrates the test results of several low-carbon binders for a curing time of 90 days, grouped based on the water content of the Malmi clay. The target compressive strength was 150 kPa. For lower water contents, it was possible to achieve this target value with a low dosage of binder (50–70 kg/m^3). When the water content exceeds 100%, it is challenging to achieve the target strength with a lower binder content. Only two InfraStabi80 samples out of three surpassed the target value with a binder dosage of 80 kg/m^3 and even 60 kg/m^3. For the other low-carbon binders, the dosage had to be at least 100 kg/m³. In this case, even the reference binder LC50 did not reach the target strength [7].

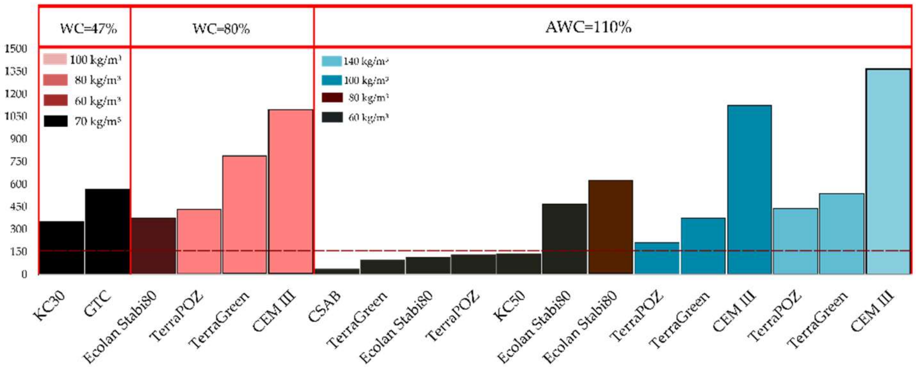


Figure 4. Uniaxial compression strength [kPa] for low-carbon binders grouped based on the water content of the Malmi clay 90 days [7].

Effect of curing time

All the stabilisation tests were stored according to the Finnish guidelines: the first two days at room temperature and then in a cold room at 6 to 10°C [10]. This temperature corresponds to the soil temperature, which is around 6°C in the Helsinki region. The effect of curing time has been investigated to some extent in nearly all studies. One way to estimate the time effect is by using time-strengthening coefficients normalised to the 28-day strength, as outlined in the design guidelines [10]. Nguyen [4] discovered that the time-strengthening coefficients for low-carbon binders differed from the guidelines. To better understand this behaviour, Aalto University has been collecting test results into a database, which will be analysed in future studies.

2.2 Field tests

Variations in field samples

The variation in undrained shear strength (COV) for some natural Finnish clays is between 22% and 32% [16]. Deep mixing makes the soil more heterogeneous than natural clay. In Savila's master's thesis [17], the field properties of stabilised soil of varying ages were tested using field samples extracted from columns. The coefficient of variation of the uniaxial compressive strengths of stabilised clays measured from field samples was typically around 70% [17]. Figure 5 addresses these variations in the shear strength of the Malmi field samples for five low-carbon binders, two dosages, and three clay depths. The results are challenging to interpret. However, it can be observed that as the strength increases, the variance also increases.

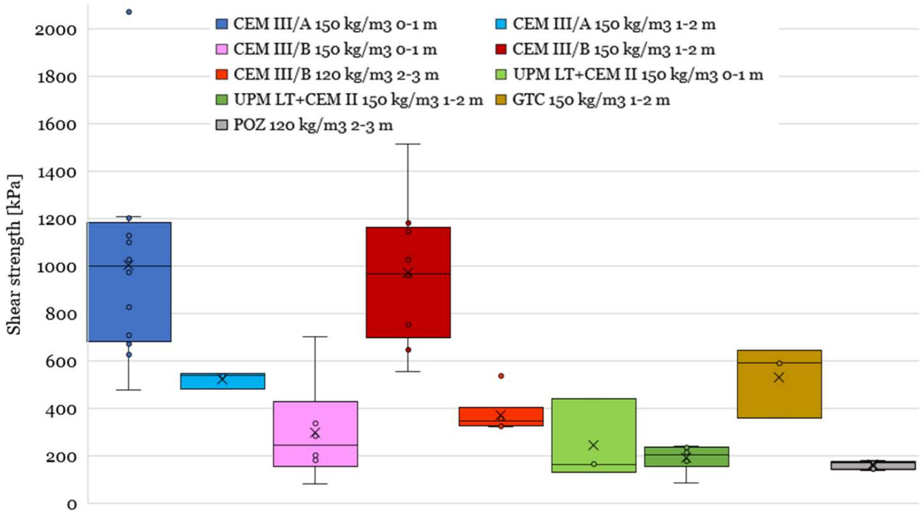


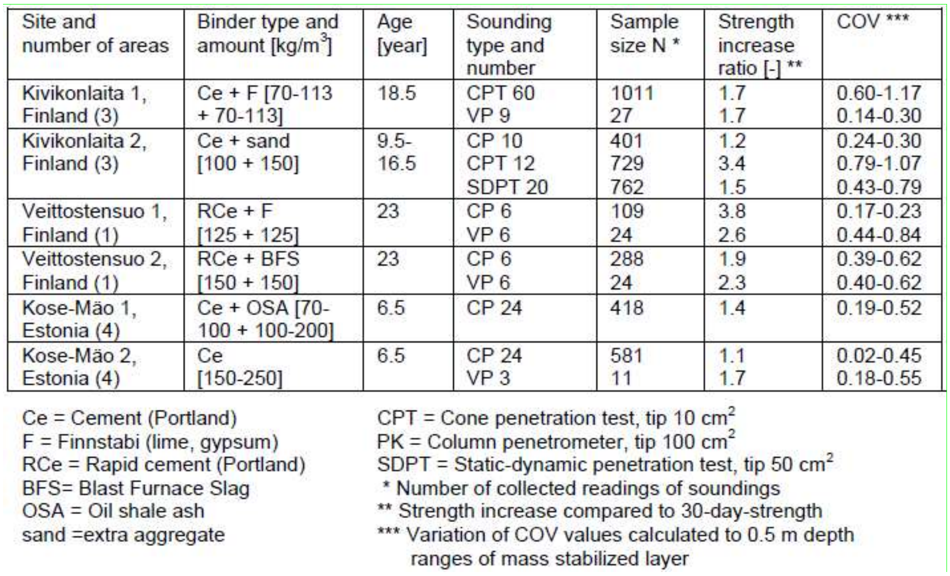
Figure 5. Malmi clay: variations in the shear strength of field samples for different binders, dosages, and depths [17].

Long-term performance of low-carbon binders

Piispanen et al. [18, 19] collected data to analyse the long-term performance of mass-stabilised soils, including peats, clays, and dredged sediments. The analysis was mainly based on strength comparisons from quality control / quality assurance (QC/QA) soundings. QC/QA sounding methods for mass-stabilised soil were studied by Melander in 2017 [20,21]. The studied sites are presented in Table 3. The quality control methods included the column penetrometer test, static-dynamic penetration test, and cone penetrometer test with tip areas of 100 cm^2, 50 cm^2, and 10 cm^2. Heterogeneity is common and typical for mass-stabilised soil due to variability in the mixing process and in the soil. Therefore, it is necessary to carry out sufficient QA tests. To determine shear strength, a minimum of approximately 10 representative soundings (e.g. column penetrometer) should be performed, and at least 3 vane shear tests should be carried out in a given subarea.

Piispanen [17] concluded that the strength of mass stabilised soil increased regardless of binder or soil type. Short-term strength development was faster in hydraulic binders than in pozzolanic or gypsum binders. Over a period of 6.5–23 years, the strength increased by an average of 1.6 times for hydraulic binders and by 2.0 times for pozzolanic or gypsum binders compared to their 30-day strength. This result – although obtained for mass-stabilised peat – is in line with the long-term results of Savila in 2024 [17].

Table 3. Sites of peat mass stabilisation. Binder type and amount, hardening time of the peat, sounding types and the number of sounding points, sample size, strength increase ratio, and COV variations [21].



Site and number of areas	Binder type and amount [kg/m^3]	Age [year]	Sounding type and number	Sample size N *	Strength increase ratio [-] **	COV ***
Kivikonlaita 1, Finland (3)	Ce + F [70-113 + 70-113]	18.5	CPT 60 VP 9	1011 27	1.7 1.7	0.60-1.17 0.14-0.30
Kivikonlaita 2, Finland (3)	Ce + sand [100 + 150]	9.5-16.5	CP 10 CPT 12 SDPT 20	401 729 762	1.2 3.4 1.5	0.24-0.30 0.79-1.07 0.43-0.79
Veittostensuo 1, Finland (1)	RCe + F [125 + 125]	23	CP 6 VP 6	109 24	3.8 2.6	0.17-0.23 0.44-0.84
Veittostensuo 2, Finland (1)	RCe + BFS [150 + 150]	23	CP 6 VP 6	288 24	1.9 2.3	0.39-0.62 0.40-0.62
Kose-Mäo 1, Estonia (4)	Ce + OSA [70-100 + 100-200]	6.5	CP 24	418	1.4	0.19-0.52
Kose-Mäo 2, Estonia (4)	Ce [150-250]	6.5	CP 24 VP 3	581 11	1.1 1.7	0.02-0.45 0.18-0.55

Ce = Cement (Portland)
F = Finnstabi (lime, gypsum)
RCe = Rapid cement (Portland)
BFS= Blast Furnace Slag
OSA = Oil shale ash
sand =extra aggregate

CPT = Cone penetration test, tip 10 cm^2
PK = Column penetrometer, tip 100 cm^2
SDPT = Static-dynamic penetration test, tip 50 cm^2
* Number of collected readings of soundings
** Strength increase compared to 30-day-strength
*** Variation of COV values calculated to 0.5 m depth ranges of mass stabilized layer

Correlation between laboratory and field tests

Ikävalko [13] investigated field test results from three test areas in Malmi and from five other test stabilisation sites. His objective was to define the ratio between the strengths determined in the field and in the laboratory. There are several reasons for the discrepancies between these two strengths. According to Piispanen and Åhnberg [18, 22], the following issues affect this ratio:

- the mixing is better in the laboratory;
- differences in temperatures in situ and in the laboratory;
- the temperature released during the binding reaction has a different effect in the laboratory compared to in situ;
- in dry mixing, the water content of the soil decreases after mixture and stays partly saturated in the laboratory, whereas in situ, the water content slowly increases.

Ikävalko [13] grouped the test results of low-carbon binders into three categories based on their strength properties: 1) Terra Poz, Terra Green, and LC; 2) Infrastabi80, Terra GTC, and Fly ash + CEMII; and 3) CEMIIIs. His results corresponded to 90 days of strength. As the target strengths of Finnish column stabilisation normally lie between 50 kPa and 150 kPa, the strengths gained in situ were clearly higher than in the laboratory, including for low-carbon binders, and than the guidelines [10] suggest.

3 ENVIRONMENTAL IMPACTS

3.1 Carbon emissions

Concerning climate change, the most important environmental impact of deep mixing is the reduction in carbon emissions. The issue of rising carbon emissions has gained increased attention over the last decade. The development of low-carbon binders has concentrated on low-carbon materials, which are typically recycled materials or by-products. This means that besides low CO_2 emissions, the use of these materials supports the circular economy. Several calculations of the carbon emissions of deep mixing have been conducted [4,7,23].

Binder producers have recently developed low-emission products and have succeeded in significantly reducing the carbon footprint of binders. The use of primary materials, such as Portland cement and lime, has decreased. This means that older carbon footprint calculations may be outdated. Nguyen [4] stated that transportation plays only a small role in the carbon emission comparisons of binder manufacturing. She estimated that the carbon emissions of the stabilisation work in the field were the same for all binder types (about 72 $kgCO_2$-eq/ton). Therefore, Figure 6 shows only a comparison of the carbon emissions from the production of different binders using the latest information obtained from binder producers and Nguyen [4].

3.2 Local impacts of deep mixing on groundwater and surface water

Deep mixing using the dry method has been used in Finland for about 50 years. No remarkable harmful local environmental effects were reported during this period. In the few studies conducted, the impact data originated mainly from leaching test results and field observations. No significant problems were observed in these studies, and the leaching tests also indicated low concentrations of harmful ingredients. Therefore, the need to monitor local impacts has been low. As the sector now uses more low-carbon binders, this need has been re-evaluated. In general, the stabilisation or solidification of soils has been used to treat contaminated soils or waste [24]. Therefore, the risk of large local environmental impacts can be estimated to be comparatively low.

In the southern part of Finland, local impacts on groundwater have been monitored in five deep-mixing areas. Additionally, the cities of Helsinki and Vantaa are constantly monitoring the quality of water in at least six other deep-mixing areas [25]. Valjakka's thesis also presented the current understanding of the effects of stabilisation through expert interviews [25]. In his study, Valjakka used data from 20 standpipes for groundwater sampling at the inspected sites. The standpipes were installed upstream and downstream of the column stabilisation. Groundwater samples were extensively studied using field and laboratory measurements for different concentrations and basic properties of water. The results showed no statistically significant differences between the upstream and downstream samples.

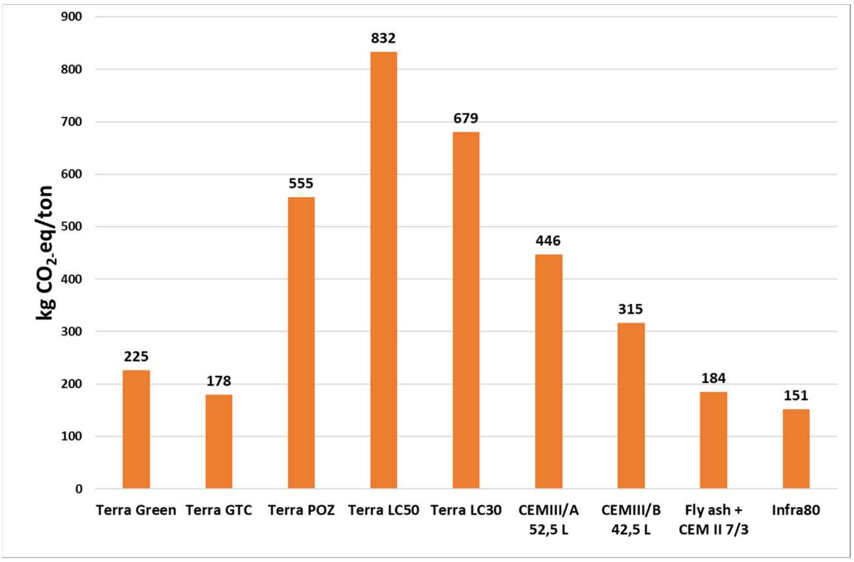


Figure 6. The unit carbon emissions associated with the manufacturing of the most used low-carbon binders and lime–cement binders (LC50 and LC30) in Finland.

Valjakka [25] found that soluble calcium dissolved from the column stabilisation in low volumes. In addition, there were indications that the concentrations of soluble cobalt, manganese, and nickel may also increase due to stabilisation. The conclusion was that the effects of column stabilisation on the groundwater were minor. The monitoring of water quality continues, and the results are reported annually. The situation has remained stable.

These conclusions are in line with earlier Finnish studies [26]. In Kuninkaantammi, Helsinki, several low-carbon binders were used. In addition to the water quality tests, samples of the clay surrounding the columns were also collected. The pH values of clay just around the column (<40 mm) have increased. In this case, the pH values of groundwater remained the same; calcium content increased slightly in some pipes but decreased in others.

4 MAIN CONCLUSIONS AND FUTURE RESEARCH

The mechanical and environmental performance of low-carbon binders has proven to be the same as that of traditional binders. Ductile behaviour was the dominant failure mode for all tested binders. The effective friction angles of different binders resemble each other. However, some differences exist in the effective cohesion values. The variation in strength values increases as the strength increases. Round-robin tests revealed that the variation between different testing laboratories was significant. However, the authors believe that it is possible to reduce this variation to less than 10%. In particular, field results can exhibit significant variances in strength. Long-term studies prove that stabilised structures have mainly kept on increasing strength.

The impacts of deep mixing with low-carbon binders on the quality of groundwater have been shown to be small or even non-existent in some cases. As the emissions of low-carbon binders are manifold lower compared to lime–cement mixtures, their environmental benefits are clearly higher and support the transition towards their use.

Research on the stabilisation of soil is ongoing. For example, Bruk et al. [27] studied the carbon sequestration capacity of stabilised soft clays with low-carbon binders, with promising results. Additional efforts include, for instance, the development of databases of stabilisation outcomes and the properties of stabilised soils.

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