Technical Paper

Lime-cement stabilisation of Trondheim clays and its impact on carbon dioxide emissions

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Abstract

Dry deep mixing is used throughout Norway to improve soft and sensitive clays. Traditionally, binders such as lime and cement have been used in combination with relatively high binder contents. The production of lime and cement causes large emissions of carbon dioxide, and it is therefore desirable to reduce the binder contents in engineering practice. This paper presents results from a comprehensive study of various lime-based binders, with the aim to improve the understanding of the engineering properties of such stabilised clays when using reduced binder contents. Results from analyses on pH, plasticity and mineralogy are presented, and it is concluded that fine-grained quartz particles exhibit relatively high pozzolanic properties giving a considerable strength development over time, also with low binder contents. A novel correction of the binder content has been used, based on the active CaO of the binders. This correction gives remarkably consistent results between the water-binder ratio and the strength development. These results have also enabled estimations of carbon dioxide emissions as a function of binder type and strength development. It is concluded that the type of lime-based binder has little influence on the carbon dioxide emissions per unit strength for binder contents higher than 30–40 kg/m^3. For lower binder contents, there is a tendency that binders with low active CaO-content give lower carbon dioxide emissions per unit strength, however, these low binder contents are difficult to obtain in field applications.

1. Introduction

Dry deep mixing (DDM) is widely used in the Nordic countries to stabilise soft sensitive clays to improve their strength and deformation properties (Karlsrud et al., 2015; Larsson, 2021). In the DDM method, a dry binder is mechanically mixed into the soil which over time reacts with water and soil particles and increases soil strength and stiffness.

The strength increase depends on several factors; however, for a given type of soil and its water content, the type and amount (α) of binder are the two most important factors (Åhnberg, 2006; Bergado et al., 1996; Kitazume and Terashi, 2013). The binders used in the Nordic countries for inorganic clays have historically consisted of cement

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Nomenclature

α	Binder content (kg/m³)
α_{corr}	Binder content corrected for K_{CaO} (kg/m³)
C	Cement as defined by EN 197–1
CaO	Calcium oxide
CKD	Cement kiln dust
CL	Type of quicklime as defined by EN 459–1
CO_2-eq	Carbon dioxide equivalent
E_{50}	Secant Young's modulus (kPa)
ε_f	Strain at failure (%)
I_p	Plasticity index (%)
K_{CaO}	Concentration of active CaO-content in binder (%)
LKD	Lime kiln dust
P	Proportion of a certain binder in composite binder mixture (%)

QL	Quicklime
s_{uA}	Undrained active shear strength (kPa)
S_t	Sensitivity (-)
SEM	Scanning electron microscope
τ_{max}	Maximum shear strength (q_{uf}/2) (kPa)
w_c	Water content of stabilised soil (%)
w_n	Natural water content (%)
w_p	Plastic limit (%)
w_l	Liquid limit (%)
wbr	Water-binder ratio (weight of water/weight of dry binder) (-)
wbr_{corr}	Water-binder ratio corrected by K_{CaO} (-)
XRD	X-ray diffraction
XRF	X-ray fluorescence

(C) and burnt unslaked quicklime (QL) with α around 80–120 kg per m³ soil (Karlsrud et al., 2015; Larsson, 2006). Although it is widely recognised in the Nordic deep mixing practice that field testing indicates considerably higher strengths than the typical target strengths, the use of these typical values of α seem to continue. It is thus not unlikely that there generally is an costly overconsumption of binders.

The production of C and QL also generates a considerable amount of carbon emissions, normally measured in carbon dioxide equivalents (CO_2-eq) (IPCC, 2006). For example, a recent study of the redevelopment of the E6 highway south of Trondheim, Norway, showed that around 26% of the total CO_2-eq emissions originated from the DDM works (NGI, 2020) – a number in the same proportion as the diesel emissions of the same project.

Thus, the incentive to reduce these emissions is very high. This can be achieved by either using a different type of binder or by reducing α. New binders or by-products such as lime kiln dust (LKD) and cement kiln dust (CKD) are also being used at an increasing rate. However, recent experience also suggests that sufficient shear strengths can be obtained with a considerably lower α than historically used, depending on the application (Al-Jabban, 2019; NGI, 2018). This is particularly the case for clays in the greater Trondheim area, which generally have low natural water contents (w_n) around 25–40%. Values of α down to around 30 kg/m³ have been tested in the laboratory with good results (NGI, 2018), and a few field applications with $\alpha = 30$ kg/m³ have also been performed (NGI, 2021). Although these changes are already being tested and implemented, the knowledge around the effects of low α in combination with the use of by-products on strength and stiffness properties are limited. It is also difficult to compare results of low α with international studies, partly because

the typical target strengths and thus α are both considerably higher (e.g., Kitazume and Terashi, 2013; Topolnicki, 2009; FHA, 2013), and partly because of the different types of clays which differ in the binder-soil reaction. It is also difficult to directly compare the dry mixing method to the wet mixing method which is more common internationally.

This paper presents results from a large number of laboratory tests performed at the Norwegian Geotechnical Institute (NGI) with α varying between 10 kg/m³, which is significantly lower than traditional α, and 110 kg/m³, which is in the range of traditionally typical values. This wide variation has allowed a comprehensive analyses of strength variation as a function of binder type and α. All clay samples have been stabilised with cement and/or lime-based binders, i.e. QL and LKD. The testing of strength and stiffness properties was performed with unconfined compression (UC) tests. In addition, analyses of pH, scanning electron microscope (SEM), X-ray fluorescence (XRF) and X-ray diffraction (XRD) were performed. Results from strength and stiffness tests on samples from six sites of marine clays in the Trondheim area have been compared, and the impact on carbon dioxide emissions is evaluated.

2. Materials and method

2.1. Types of soil

The Tiller-Flotten quick clay is a low plastic marine clay with a clay content (fraction < 2 μm) of ∼ 68% (L'Heureux et al., 2019). At the depth where samples were taken for stabilisation, the clay have a w_n of ∼ 45% and a unit weight ∼ 18 kN/m³. The pore water has a salt content (NaCl) of ∼ 2 g/l. The clay fraction is dominated by biotite

(26%) and illite/muscovite (23%), followed by chlorite (16%), plagioclase (13%), amphibole (7%), quartz (7%) and potassium feldspar (4–6%).

The other clays used in this study have similar composition and properties as the Tiller-Flotten clay, however, they generally have a lower clay content. For these clays, the clay content is around 35–55% which are typical values for Trondheim clays (Hilmo, 1989; Syversen, 2013; Paniagua and L'Heureux, 2019). The mineralogy of the clay fractions is similar for all marine clays in the Trondheim area, and the organic content is below ∼ 1%, i.e., negligible with regard to lime-cement stabilisation (Åhnberg, 2006).

Table 1 summarises the geotechnical properties of all clays discussed later in the manuscript.

2.2. Types of binder

The lime-based binders used in the tests, i.e., QL and LKD, were manually mixed in various proportions to fulfil the requirements of reactivity according to EN 495–1, i.e. the types of lime products designated CL 70, CL 80, and CL 90. The CL 90 contains pure burnt QL, i.e. ∼ 95–100 % CaO, whilst the CL 80 contains 80–85% QL and 15–20% LKD and CL 70 contains ∼ 70% QL and ∼ 30% LKD (Table 2). LKD consists mainly of CaO and calcium carbonate ($CaCO_3$) and is a by-product of the QL production.

For stabilisation purposes, it is important to distinguish between active and total CaO-content, the latter being measured in e.g., XRF analyses, while any calcite ($CaCO_3$) content is identified on XRD. The amount of CaO available for chemical reactions is, however, the active content. The difference can either be due to large CaO-particles where chemical reactions in the outer periphery prevents chemical reactions in the centre, or that a part of the total CaO-content already is chemically bonded to other constituents in the binder (Fällman et al., 2001). The concentration of active CaO in a binder is herein denoted by K_{CaO}, i.e., the dry weight percentage of the total α available to react with the soil. The total and active CaO-content of the various lime-based binders is shown in Table 2.

The total CO_2-eq emissions from QL production is around 1,027 kg CO_2-eq/ton, and for LKD around 356 kg CO_2-eq/ton (FMI, 2019). Around 68% of this orig-inates from calcination, 30% from combustion and 2% from electricity needed in the production (Stork et al, 2014).

The cement used in the investigation was a standard Portland cement designated CEM II/B-M 42.5R according to EN 197–1. It consists of around 78% cement clinker, 18% fly ash, 4% limestone and less than 4%, 1.5% and 0.085% of sulphate (SO_4^{2}), alkalis (Na_2O) and chloride, respectively. The amount of calcium oxide (CaO) in C is approximately 60–65%, the remaining being mainly silicon and aluminium oxides (Taylor, 1997).

According to the Environmental Product Declaration (EPD), the CEM II generates about 625 kg CO_2-eq per ton of binder (dry weight) (Norcem, 2016). This is slightly higher than the default value of 520 kg CO_2-eq per ton as recommended by IPCC (2006). About 60% of the total CO_2-eq emissions originate from the calcination and the remaining 40% from combustion and grinding (Norcem, 2016).

All binders used in this study are mixtures of C, QL and LKD. Most samples are stabilised using 50% C and 50% QL and/or LKD (in dry weight percentage). These are referred to as e.g. 50C/50QL or e.g. 50C/50CL90 (the denotation QL and CL70–90 is used interchangeably depending on the purpose). A few tests were done with a single binder, specifically 100C, 100QL (=100CL90) and 100LKD.

2.3. Laboratory testing

An overview of the laboratory tests of the Tiller-Flotten clay is given in Table 3. For all combinations, three identical samples were prepared, and pH, plasticity, SEM, XRF and XRD analyses were performed on selected samples (Table 3). The XRF and XRD analyses were performed on samples cured 28 days, while SEM was performed on samples cured for about 3 months.

A unifying factor is that all stabilisation and UC tests have been performed by the same laboratory (NGI) and lab technicians using the same laboratory procedures (NGF, 2012). This procedure consists of mixing the remoulded natural clay and the dry binder for 2–4 min. Specimens are thereafter manufactured by dynamically compacting layers of around 20 mm in plastic moulds. The compaction is done by tamping a brass rod with an energy of 0.2–0.25 Nm a total of 20 times. This coherent

Table 1
Physical properties of the clays used in the study.

Clay	Soil type	w_n(%)	w_p(%)	w_L(%)	I_p(%)	s_{uA}(kPa)	S_t(-)
Tiller-Flotten	Quick clay	45	21	36	15	∼60	250
Holvegen	Clay	30	20	34	14	∼25	7
	Sensitive clay	25	18	23	5	∼25	25
Holan	Clay	33	20	34	14	∼34	9
Vassmarka	Clay	34	21	35	14	∼15	12
Stokkan	Clay	30	19	31	12	∼23	8
Saksvik	Clay	31	18	28	10	∼33	7

Table 2
Chemical composition of the lime-based binders (values of CaO and MgO based on XRF analyses) (FMI, 2019; Norcem, 2016).

Binder	Proportion QL	Proportion LKD	CaO + MgO total	CaO active (K_{CaO})	Reactivity (EN 495–1)		CO_2e emissions (kg CO_2-eq /ton)
					t_{60}	ΔdT	
Quicklime CL90	100%	0%	>96%	~95 ± 5%	<180	>50	1,027
Quicklime CL80	~15–20%	~80–85%	>96%	~85 ± 5%	<180	<50	898
Quicklime CL70	~70%	~30%	>90%	~75 ± 5%	>500	>40	768
LKD	0%	100%	>70%	~30%	N/A	<20	356

Table 3
Laboratory programme for the Tiller-Flotten clay.

α [kg/m³]	Number of UC tests per binder type						
	50% C/50% LKD	50% C/50% CL 70	50% C/50% CL 80	50% C/50% CL 90	100% LKD	100% CL 90	100% C
10	–	3	3	3	–	–	–
15	–	3	3	3	–	–	–
20	–	3	3	3	–	–	–
25	–	3[1]	3[1]	3[1]	–	–	–
30	3	3[2]	3[2]	3[2]	–	–	–
35	3	–	–	–	–	–	–
40	3	–	–	–	–	–	–
45	3	–	–	–	–	–	–
50	3[1]	–	–	–	–	–	–
60	3[2]	3	3	3	3	3	3
90	3	3	3	3	3	–	–
110	3	–	3	–	–	–	–

1 One sample analysed by SEM (performed at the University of Oslo)
2 One sample analysed by XRD and XRF (performed at the Geological Survey of Norway's laboratory in Trondheim)

procedure eliminates to a large degree variation and hence uncertainties in sample preparation, curing conditions, and testing procedures. Samples were cured at 20 °C following the recent work of Bache et al., 2022, which showed that this temperature is more representative for field conditions than the previously curing temperature of 7 °C that has been in use in the Nordic countries. All samples have cured 28 days unless otherwise stated.

The XRF analysis was performed using a PANalytical Axios 4 kW equipped with a Rh X-ray tube. Analysis of major elements were performed on fused glass beads prepared by mixing the material with a lithium borate flux and heated to 1,000 °C, while minor element analysis was performed on pressed pellets.

Samples for bulk XRD analysis were hand-mortared prior to analysis. XRD analysis was performed with a BRUKER D8 Advance using CuKα radiation (40 kV/40 mA). Scans were acquired on a rotating disk using 2.5° soller slits and a fixed divergence slit (0.6 mm) in the range of 3-75°2θ with a steps size of 0.02°2 θ and 1 s count time. Mineral identification was done using the BRUKER Diffrac.EVA ver. 5.2 software and the Crystallographic Open Database (COD) and the International Centre for Diffraction Data (ICDD) databases. Mineral quantification was done using Rietveld modelling using the TOPAS 5.0 software.

3. Results and discussion

3.1. Basic properties

Results from measurements of Atterberg limits on the Tiller-Flotten clay on day 0, i.e., immediately after stabilisation, are shown in Fig. 1. w_p increases from around 21% for the natural clay to between 32% and 45% with an average of 40% for stabilised clay. The w_p increases with increasing α and increasing K_{CaO} in the QL. The general increase in w_p agrees with other studies (Diamond and Kinter, 1965; Åhnberg, 2006; Hilt and Davidson, 1960).

The increase in w_l is relatively high and increase from 36% in the natural clay to between 68% and 103% with an average of 86% in the stabilised samples. Similarly, the w_p and w_l increases with increasing α, as well as with increasing K_{CaO} in the QL. Moreover, there is a tendency for w_l to decrease between day 0 and day 1 (not shown in Fig. 1). On average, w_l decreased ~ 2.5 percentage points (*pp*) from day 0 to day 1.

Previous studies show both increases and decreases in w_l of stabilised clay (Diamond and Kinter, 1965; Åhnberg, 2006, Kitazume and Terashi, 2013; Kang et al., 2017). The high increase in w_l for the Tiller-Flotten clay is most likely due to the low NaCl content in the pore water, which is due to natural leaching by meteoric water for thousands
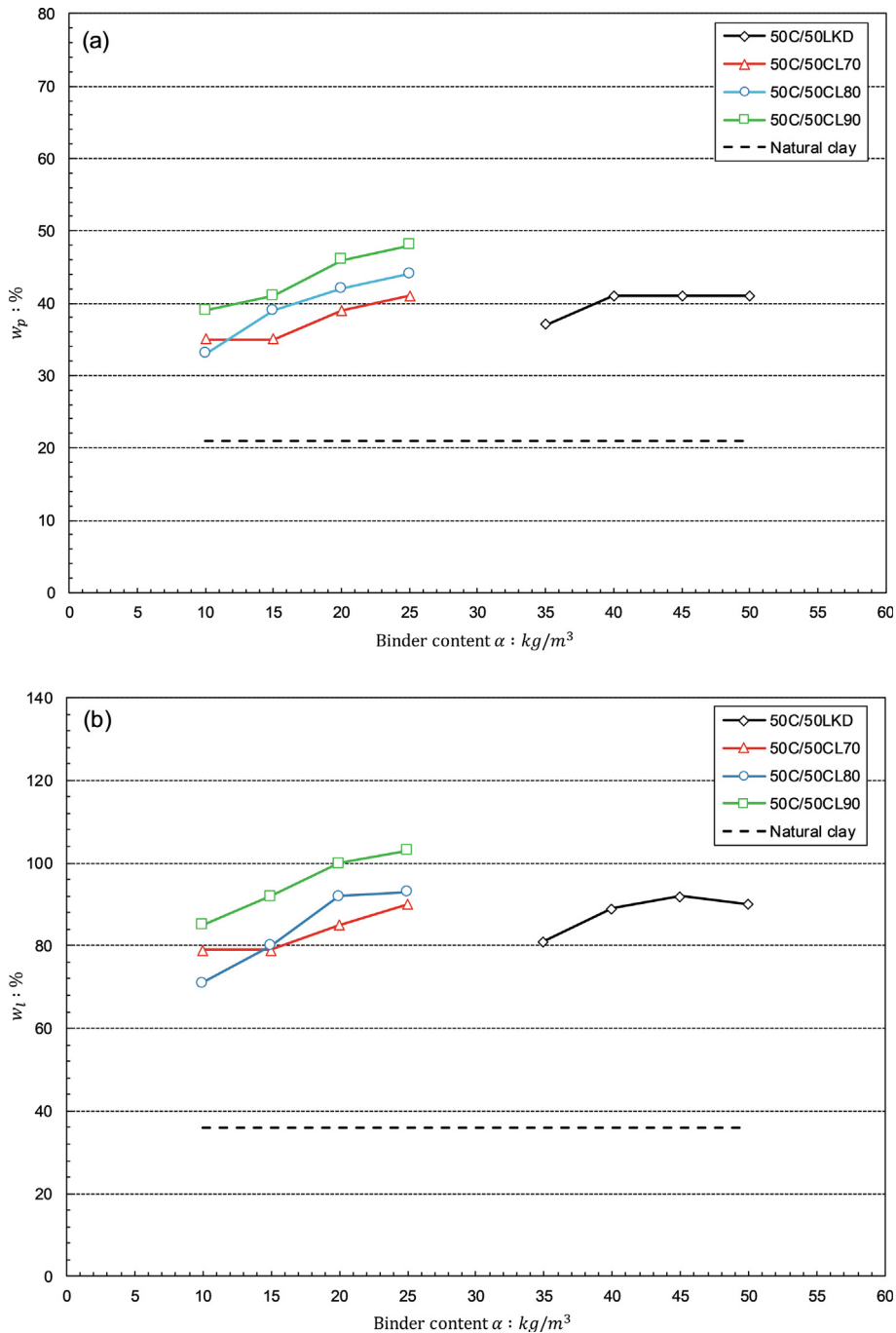
Fig. 1. Results from measurements of Atterberg limits on stabilised samples day 0 (Tiller-Flotten clay with $\alpha = 10$–50 kg/m³ with different binder types), a) plastic limit and b) liquid limit.

of years, and thus has a large potential to change properties when cations are added via a binder.

The I_p also increases from $\sim 15\%$ for the natural clay to between 36% and 56% with an average of 47% for the stabilised clay, a result which is due to the large increase in w_l. This increase contradicts most other findings by e.g. Diamond and Kinter (1965), Eades and Grim (1966) and Hilt and Davidson (1960).

Fig. 2 shows pH values measured up to 28 days after stabilisation of the Tiller-Flotten clay with different binder types and α. The pH increases immediately upon adding

the binder to values between 11.5 and 12.2; increasing with increasing α, as expected, but somewhat lower than the pH of a dissolved lime, which at 25 °C has a pH of ~ 12.5 (Eades and Grim, 1966). The high pH is due to the rapid increase of hydroxide ions (OH⁻) concentration in the water phase by the hydration reaction with CaO and the formation of calcium hydroxide $Ca(OH)_2$. The pH of the natural clay was measured at 8.48.

This hydration reactions give also high concentrations of calcium ions (Ca^{+2}) in the pore water, leading to cation exchange on the surfaces of the clay particles, and causes
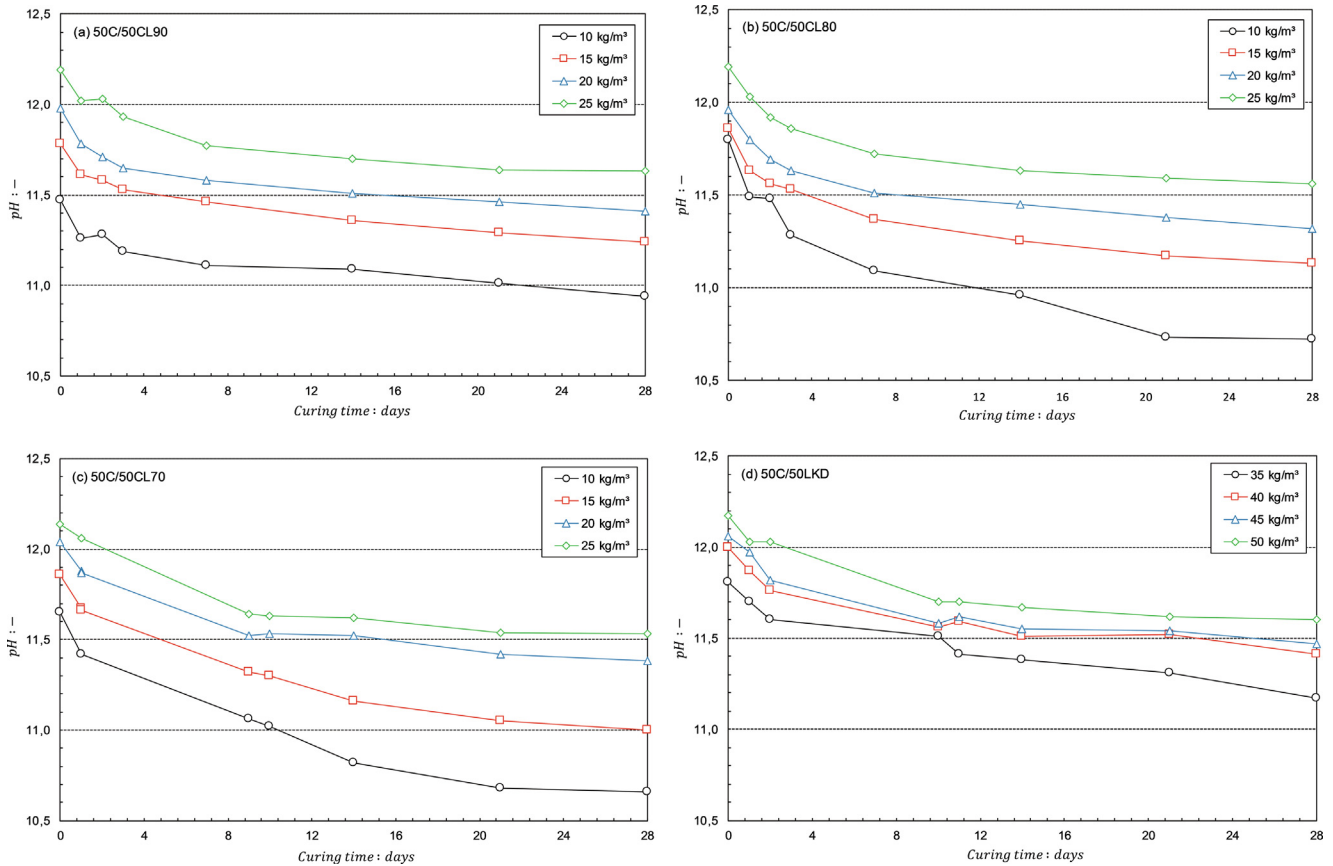
Fig. 2. Results from pH measurements on stabilised samples of Tiller-Flotten clay using 50% C and 50% QL, a) CL 90, b) CL 80, c) CL 70 and d) LKD (note the different α for LKD in (d)).

significant flocculation and agglomeration reactions, which commonly are reducing the I_p of the clay. Eades and Grim (1966) defined a threshold of lime content where I_p ceases to decrease, even though the lime content increases. This threshold was termed initial consumption of lime (ICL) and has been extensively researched by e.g. Eades and Grim (1966), Al-Mukhtar et al. (2010), DiSante et al. (2014) and Cambi et al. (2016). However, as seen for the naturally leached Tiller-Flotten clay, I_p increases. The concept of ICL is thus not necessarily applicable to quick clays. However, this has not been tested in detail with addition of 100QL with varying α.

The gradual decline in pH (Fig. 2) appears to be approximately logarithmic, with the majority of decrease in pH within the first 15–20 days of curing, whereupon the pH seems to stabilise. This is consistent with results by e.g. Eades and Grim (1966) but considerably faster than other studies (e.g. DiSante et al., 2014).

The decrease in pH corresponds to the decrease in OH^- concentration, which in turn is consumed as the QL reacts with the clay minerals in pozzolanic reactions (Bell, 1996; Eades and Grim, 1966, Firoozi et al., 2017). The cation exchange is a fast process, that does not affect OH^- concentration significantly, and hence not the pH (Cambi et al., 2016, Al-Mukhtar et al., 2010).

3.2. Micro-structure and composition

The XRD analyses of the stabilised clay in Table 4 shows the mineral composition of the crystalline phases present. Analyses were performed on samples containing 50% CL 70, CL 80 and CL 90 with $α = 30$ kg/m³ and one sample 50% LKD with $α = 60$ kg/m³. The analyses show that quartz (silicone dioxide, SiO_2) is reduced from 19% to around 12–13%, which indicates that some of the quartz is consumed in the pozzolanic reactions with the binder. The amorphous content, e.g., C-S-H or C-A-H, could not be analysed.

Such interactions between pozzolan and crystalline minerals in other types of clays have been observed by, e.g. Kamruzzaman et al. (2006) who discovered that the amount of kaolinite decreased in stabilised Singapore clay by pozzolanic reactions. Kamruzzaman et al. (2006) and Hilt and Davidson (1960) also noted that illite was considerably less pozzolanic, compared to other clay minerals.

Results from the XRF analyses are presented in Table 5. The amount of CaO increases from around 3.1% in the natural clay to around 4.1% for CL 70, CL 80 and CL 90 with $α = 30$ kg/m³ and to around 5.2% for C/LKD with $α = 60$ kg/m³, simply due to the added binder which contains CaO. The remaining oxides are unchanged.

Table 4
Results from XRD analyses on natural Tiller-Flotten clay and stabilised samples (all values in %).

Clay/binder	Quartz	K-feldspar	Plagioclase	Illite /muscovite	Biotite	Chlorite	Amphibole	Calcite	Dolomite
Tiller-Flotten clay (bulk)	19	4	17	21	19	9	8	2	1
Tiller-Flotten clay (clay fraction, <2 μm)	7	5	13	23	26	16	7	2	1
50% C/50% CL 90 ($\alpha = 30$ kg/m^3)	13	–	16	23	23	14	6	4	1
50% C/50% CL 80 ($\alpha = 30$ kg/m^3)	12	–	16	24	22	15	6	4	1
50% C/50% CL 70 ($\alpha = 30$ kg/m^3)	12	–	16	24	22	15	6	4	1
50% C/50% LKD ($\alpha = 60$ kg/m^3)	12	–	18	23	22	14	6	4	1

Table 5
Results from XRF analyses on natural Tiller-Flotten clay and stabilised samples (all values in %).

Clay/binder	SiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	CaO	MgO	CaO + MgO	K$_2$O	Na$_2$O	S	LOI
Tiller-Flotten clay	52.7	17.0	9.3	3.1	5.7	8.8	3.9	2.0	–	4.8
50% C/50% CL 90 ($\alpha = 30$ kg/m^3)	45.6	16.6	9.6	4.1	6.0	10.1	3.8	1.7	1.0	11.3
50% C/50% CL 80 ($\alpha = 30$ kg/m^3)	45.5	17.3	10.1	4.1	6.4	10.5	4.1	1.7	1.0	8.9
50% C/50% CL 70 ($\alpha = 30$ kg/m^3)	45.9	17.2	9.9	4.0	6.3	10.4	4.0	1.7	0.9	9.3
50% C/50% LKD ($\alpha = 60$ kg/m^3)	45.2	17.0	9.86	5.2	6.3	11.5	3.9	1.7	2.1	8.1

Images from the SEM analyses at two different magnifications are shown in Figs. 3 and 4. The images are showing samples stabilised with 50C/50LKD with $\alpha = 50$ kg/m^3. The needle shaped minerals are interpreted as ettringite crystals, formed by calcium aluminate and calcium sulphate (gypsum), present in the Portland cement. The ettringite crystals bind together clay minerals and hence increases the strength and stiffness properties.

3.3. General strength and stiffness properties

Results of τ_{max} from UC tests on all samples vs. α are shown in Fig. 5. As expected, τ_{max} increases with increasing α. τ_{max} varies from around 20 kPa for $\alpha = 10$ kg/m^3 up to around 700 kPa for $\alpha = 110$ kg/m^3. Some scatter is seen, however, depending mainly on the type of binder and to a certain degree variations in w_n, which varies between ∼ 25% and ∼ 45% (Table 1). It is noticed that the τ_{max} values are generally higher than most Norwegian clays according to Paniagua et al. (2019).

As the reactive ingredient in a lime-based binder is CaO, it is natural to assume that the shear strength increases with the amount of available CaO in the binder, i.e., depending on K_{CaO}, given a specific type of clay and α. To correct for this difference in reactivity between the different binders, Fig. 6 presents the same plot where α is corrected with K_{CaO} according to Eq. (1).

$$\alpha_{corr} = \alpha \times K_{CaO,C} \times P_C + \alpha \times K_{CaO,QL} \times P_{QL} \qquad (1)$$

where $K_{CaO,C}$ and $K_{CaO,QL}$ = available CaO-content in C and QL, respectively, and P_C and P_{QL} = proportion of C and QL in the binder, respectively. Eq. (1) thus calculates the content of active CaO per unit volume of soil (α_{corr}) from the active CaO contents in the respective binders and their proportions in the composite binder mixture.

The reaction of C is largely independent of reactions with minerals in the clay because it already contains chemical compounds of pozzolanic material, i.e., the silicon and aluminium oxides. The reaction is thus relatively fast and is only dependent on the content of water in the soil,
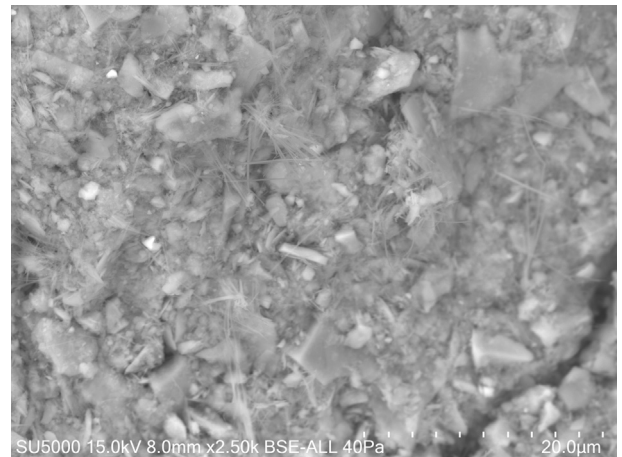

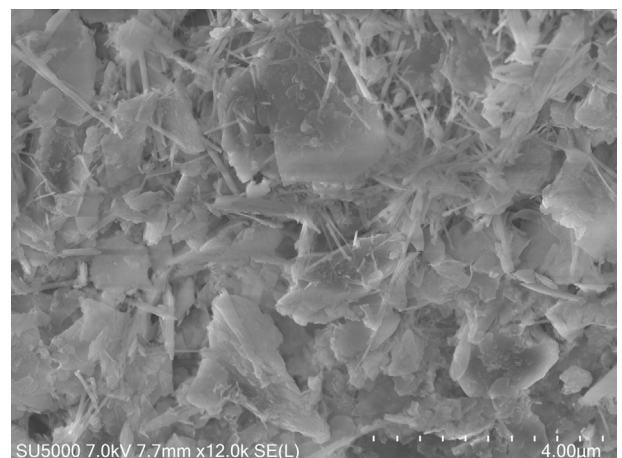Fig. 3. SEM analyses on 50C/50LKD with $\alpha = 50$ kg/m^3 (scale 20.0 μm).

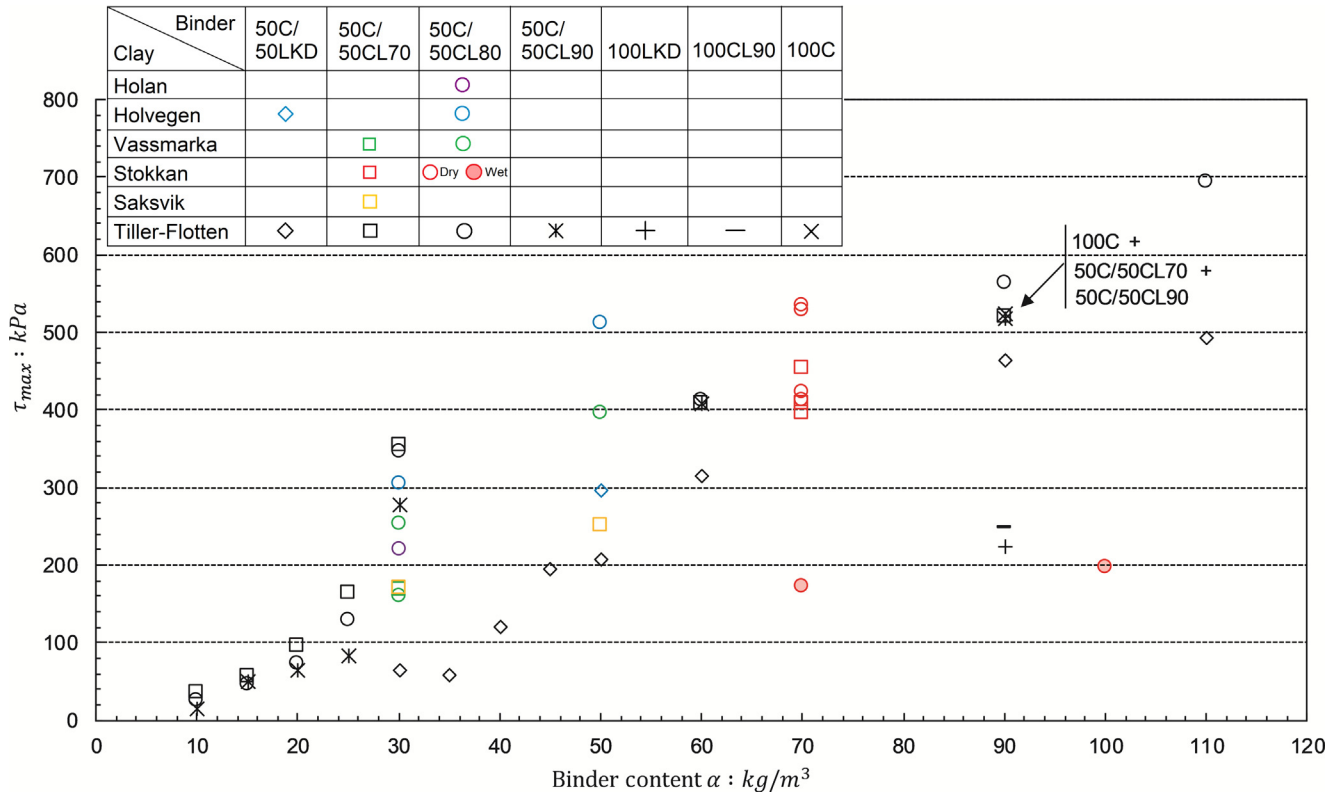Fig. 4. SEM analyses on 50C/50LKD with $\alpha = 50$ kg/m^3 (scale 4.0 μm).

Fig. 5. Results of τ_{max} vs. α from UC tests (all samples, all binder types, 28 days of curing).
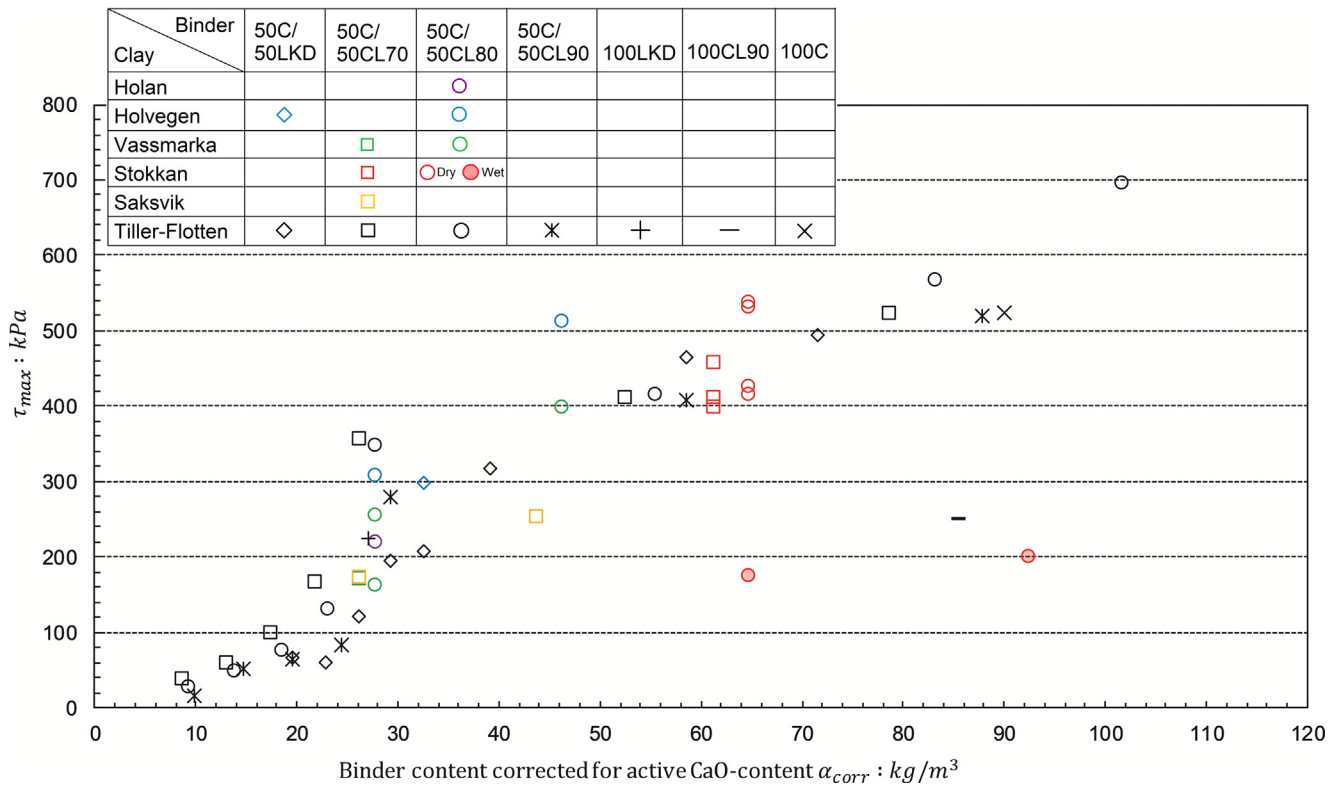

Fig. 6. Results of τ_{max} vs. α_{corr} from UC tests (all samples, all binder types, 28 days of curing).

although the reactions can be delayed by e.g. organic substances or sulphate content (Janz and Johansson, 2002; Firoozi et al. 2017). These types of substances are not found in the tested Trondheim clays. $K_{caO,C}$ is thus set to 1.0, i.e., 'full' reactivity.

$K_{CaO,QL}$ is set according to Table 2, i.e., with values lower than 1.0. This means that QL is assumed to be less reactive than C in 28 days of curing. This was also noted by Vervoorn and Barros (2021) for Swedish clays, however, they did not analyse this further. With values according to Table 2, α_{corr} equals α for 100C but is $0.3 \times \alpha$ for 100LKD. For e.g. 50C/50CL70, $\alpha_{corr} \approx 0.88 \times \alpha$.

Based on this, Fig. 6 shows results of τ_{max} vs. α_{corr}. There is here a significantly more unified trend where τ_{max} increases slightly for α_{corr} up to ~ 20–25 kg/m^3, whereupon it increases considerably. From α_{corr} around 40 kg/m^3 the τ_{max} increases linearly with increasing α_{corr}. There is a clear S-shaped curve (sigmoid growth curve), which was also noted by Barros (2019). The reason for this shape is unknown.

It is noted that the sample stabilised with 100CL90 (100QL) fall below the general strength trend (Figs. 5 and 6). The lower strength development of QL compared to C is expected as the C is known to react considerably faster than QL (e.g., Åhnberg, 2006). The value of τ_{max} for 100CL90 is approximately half that of 100C or 50C/50CL90, indicating that the effect of QL is about half that of C after 28 days of curing. Still, the τ_{max} for 100CL90 is relatively high ($\sim$260 kPa). This is discussed later in the paper. It is also noted that 100LKD is below general strength trend when analysing α, but fall within the general trend when analysing α_{corr}.

The strain at failure varied between 1.0% and 17.6%, however, the majority of the samples failed at a strain of 1.0% to 3.0%. Those with a strain at failure above 3.0% had τ_{max} below 60 kPa (samples with $\alpha = 10$–15 kg/m^3 for 50C/50CL70–90 and $\alpha = 35$ kg/m^3 for 50C/50KD). The ratio E_{50}/τ_{max} varied between ~ 50 and ~ 200 with an average of 104. This ratio is shown to vary considerably between different soils (Porbaha et al., 2000).

Fig. 7 presents the increase in shear strength over time for the Holan clay, together with the time dependency suggested by Åhnberg (2006) who studied Swedish clays. This time dependency is in practice equal to that suggested by e.g., Horpibulsuk et al. (2003). As can be seen, Trondheim clays are in agreement with the strength increase over time with other types of clays.

Fig. 7 also shows the decreasing strain at failure (ε_f) over time. This is thought to be caused by the strength increase and thus a stiffer response, i.e., a higher E_{50}. Consequently, there is an increase in the ratio E_{50}/τ_{max} over time, which increased from 30 to 60 at 3 days of curing to 130–140 at 28 days of curing. There is limited data on this ratio, however, stabilised Swedish clays show a clear tendency that the ratio E_{50}/τ_{max} increases with decreasing ε_f (LabMind, 2021). The results presented herein are thus in agreement with the properties of Swedish clays.
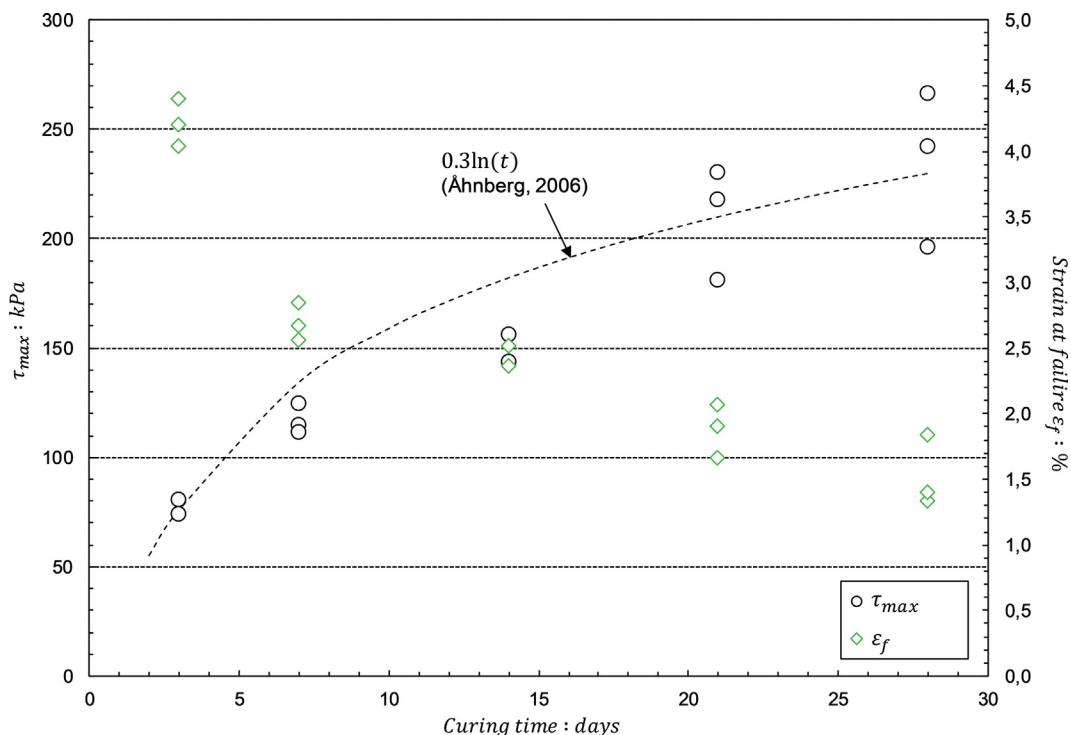

Fig. 7. Strength τ_{max} and strain at failure ε_f for curing times up to 28 days for the Holan clay ($\alpha = 30$ kg/m^3 and 50C/50CL80).
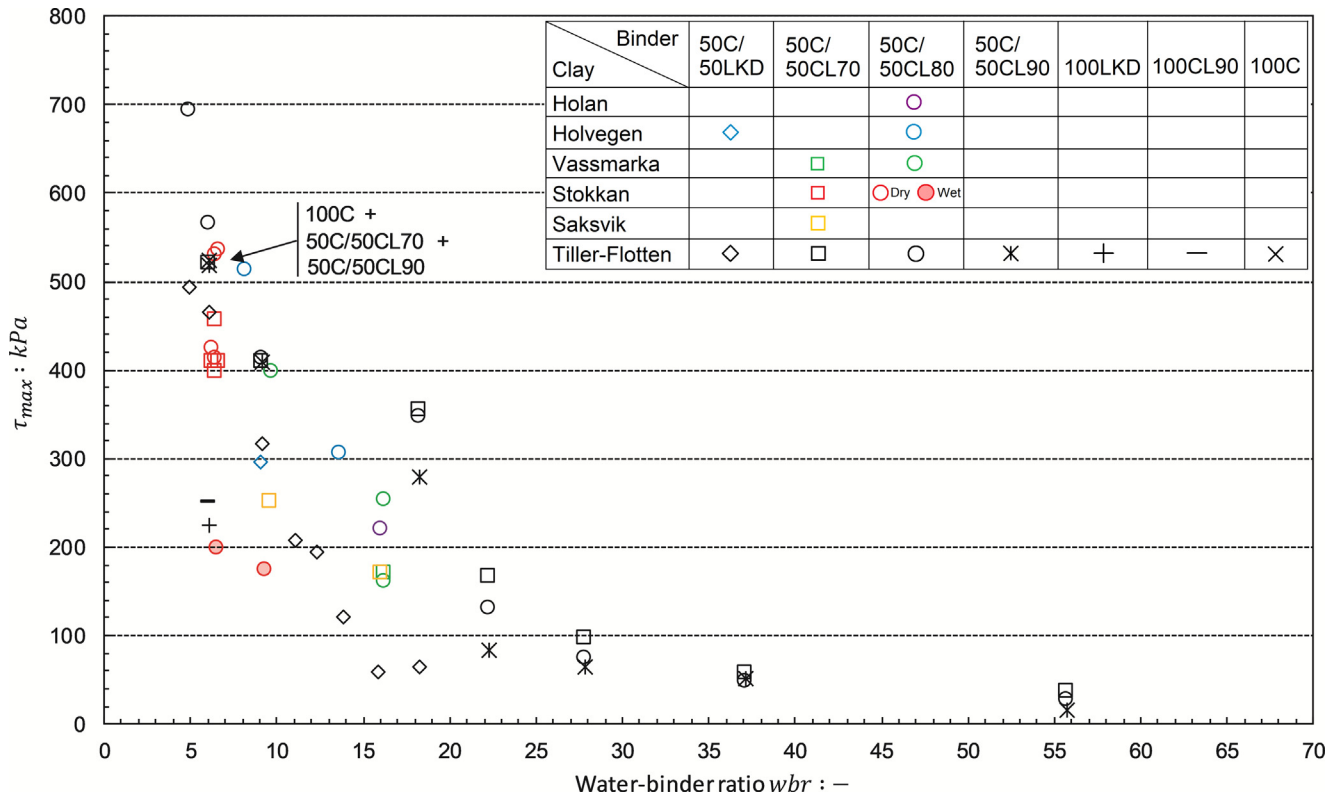
Fig. 8. Results of τ_{max} vs. α from UC tests on (all samples, all binder types, 28 days of curing).

3.4. Water-binder-ratios vs. Shear strength

An often-used parameter for shear strength estimation is the water to binder ratio (wbr), as defined in Eq. (2) (Kitazume and Terashi, 2013).

$$wbr = \frac{m_{w,s} + m_{w,a}}{m_b} \qquad (2)$$

where $m_{w,a}$ = mass of natural content of water in the soil, $m_{w,s}$ = mass of added water (if any), and m_b = mass of dry binder. The concept of wbr, or rather water to cement ratio when pure C is used as a binder, is extensively researched (Horpibulsuk et al., 2003; Kitazume, 2022; Åhnberg et al., 1995), however, the use in Nordic engineering practice is limited.

Values of wbr vs. τ_{max} for all Trondheim clays are shown in Fig. 8. The wbr has a large variation, ranging from ~ 5 to ~ 56. A clear decrease in τ_{max} as wbr increases is noted.

Similar as for α, wbr can be corrected by K_{CaO} in the binder by using $α_{corr}$ instead of α, giving wbr_{corr}. Values of wbr_{corr} vs. τ_{max} are shown in Fig. 9. It is seen that by using wbr_{corr} a unified and consistent relationship is obtained. This is notable since the data consists of stabilised clay with a variety of binder types and wide range of α and different clays from the Trondheim area. Some of the data points also consists of a single binder, e.g. 100C or 100LKD.

There are two exceptions to the unified trend line; a sample with 100QL and samples mixed with water, i.e., wet mixing method. The wet mixed samples are performed on the Stokkan clay. α was here increased to obtain the same wbr. Although there are only two samples with added water, it is clear that the strength increase is considerably lower than those without added water. Very few, if any, direct comparisons between the dry and wet method has been published to the authors knowledge, however, the relatively lower strength on wet mixed samples contradicts findings on some Swedish soils where equal strengths for both dry and wet mixing have been found (LabMind, 2021). The reason for this is not fully understood.

A commonly used formulation of the wbr vs. τ_{max} is based on Abrams (1918) relationship for concrete given by Eq. (3).

$$q \; or \; \tau_{max} = \frac{A}{B^{wbr}} \qquad (3)$$

where A and B are empirical constants. As A and B describes the strength development, these are naturally dependent on type of soil, type of binder, sample preparation, curing conditions and testing methods, among other things. However, for a given set of these 'influencing factors', the shear strength is only dependent on the weight ratio between water and binder.

A best fit trend line gives A = 950 and B = 1.09 for the Trondheim clays (using unconfined compressive strength (UCS) in Eq. (3) the constants are A = 1900 and B = 1.09). This trend line, particularly the parameter A, cannot directly be compared to other studies because of the aforementioned 'influencing factors'. The parameter
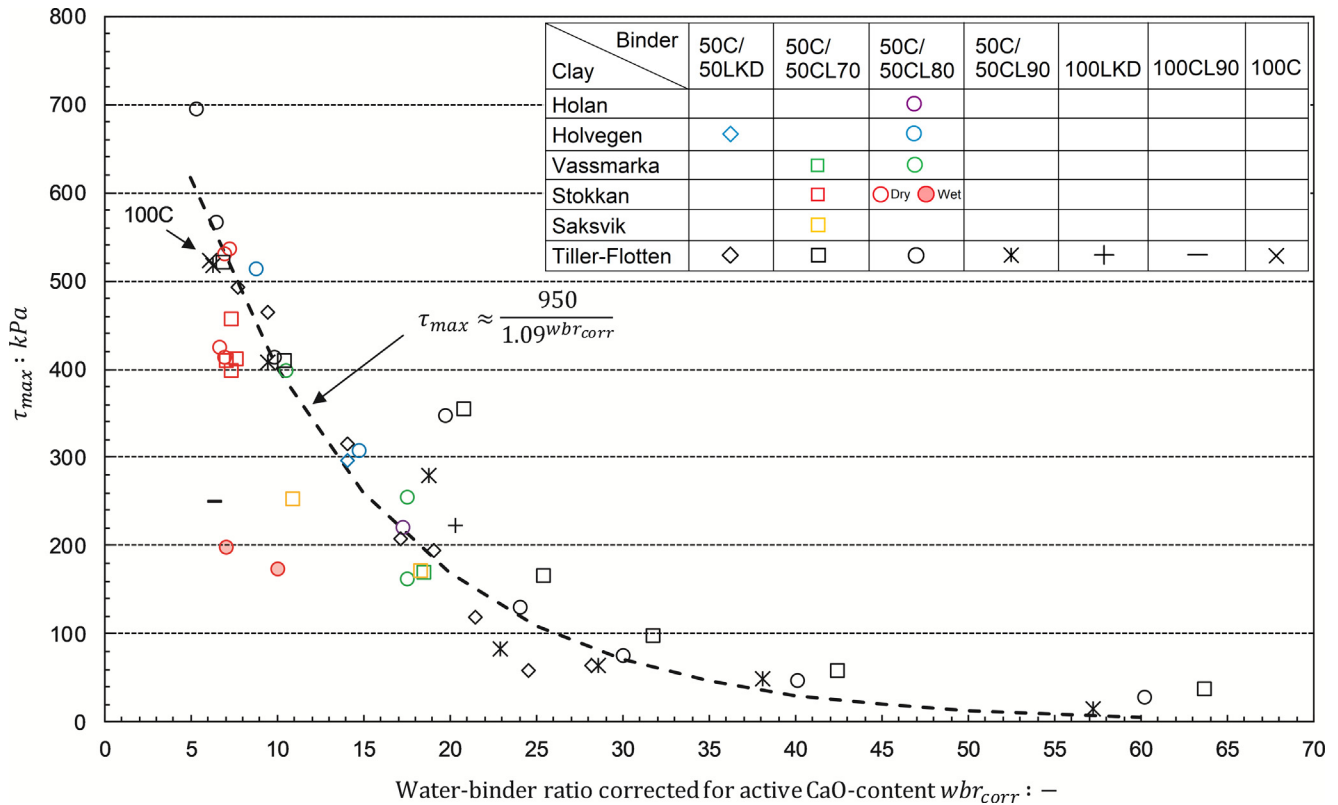
Fig. 9. Results of τ_{max} vs. α_{corr} from UC tests on (all samples, all binder types, 28 days of curing).

B, however, is less dependent of these influencing factors and it was found to be ~ 1.09 for the Trondheim clay (Fig. 9). This is to be compared with values of ~ 1.2 on Japanese clay by Yamashita et al. (2020), $\sim 1.23–1.24$ for Japanese and Thai clay by Horpibulsuk et al. (2003), ~ 1.22 by Miura et al. (2001) and ~ 1.27 by Jacobsen et al. (2005). Data from LabMind (2021) shows ~ 1.24 for east Swedish clays, and data presented by e.g. Åhnberg et al. (1995) on west coast Swedish clays shows ~ 1.15.

The concept of *wbr* is in principle similar to the void/cement ratio as defined by e.g. Consoli et al. (2007). However, due to the dry mixing method the specimens most probably contain some unknown amounts of entrapped air, and a void/cement ratio vs. strength analysis have therefore not been included in this paper. It is however probable that the unified trend as seen in Fig. 9 is inherently similar to that seen in e.g. Consoli et al. (2007).

It should also be mentioned that there are several other relationships between *wbr* and τ_{max} proposed in the literature as recently summarised by Yamashita et al. (2020), however, they have not been tested on data from Trondheim clays.

4. General discussion on strength development

Stabilisation of clays with C and QL are fundamentally based on the reaction between CaO in the binder and the soil containing water and particles. The reaction between unslaked QL and clay has in general five stabilising effects: hydration (i.e. a drying effect), flocculation/agglomeration, ion (cation) exchange, carbonation and pozzolanic reactions between Ca^{2+} and OH^- and clay minerals (Behnood, 2018; Bergado et al. 1996; Kitazume and Terashi, 2013; Åhnberg et al., 1995; Diamond and Kinter, 1965).

Ion exchange and flocculation/agglomeration take place within seconds, minutes or hours (Diamond and Kinter, 1965; Behnood, 2018; Vitale et al., 2016; Eades and Grim, 1966; Al-Mukhtar et al., 2010; Bell 1989; Arabi, 1987). Hydration can be on-going for a longer period, up to a roughly a week, but the majority of the drying effect takes place immediately upon adding the binder (Åhnberg, 2006; Sivapullaiah et al., 2000). In general, the effect on soil strength from these reactions, i.e. hydration, flocculation/agglomeration and ion exchange are, however, normally limited (Arabi, 1987; Diamond and Kinter, 1965; Al-Mukhtar et al., 2010; Behnood 2018; Bergado et al. 1996; Cherian and Arnepalli, 2015). Many chemical agents can flocculate clays but yields no strength development (Bergado et al., 1996), and the drying effect can be reversed as samples are wetted and thereby not contributing to any long-term strength (Janz and Johansson, 2002). Broms (1999) states that the undrained shear strength of purely lime-stabilised clays normally reaches the clays original intact strength one to two hours after mixing, indicating that the hydration and flocculation effect is small. Results

on the Tiller-Flotten clay (Fig. 7) indicate immediate strength development up to around 50 kPa. The strength effect of carbonation is not studied herein; however, studies have shown that this can be of some importance (e.g., Ho et al., 2017).

As seen from the results presented herein, e.g. Figs. 5 and 6, there is a relatively large strength increase for 100QL, reaching τ_{max} ~ 260 kPa after 28 days of curing. As the immediate strength increase from hydration, flocculation and ion exchange is limited, this indicates that a large proportion of the strength increase for lime-stabilised Trondheim clays is due to pozzolanic reactions. Notably, as the pozzolanic reactions consumes OH^-, the pH in the stabilised clay normally decreases, which is clearly seen for the Tiller-Flotten clay within days after stabilisation (Fig. 2). Similar fast pozzolanic activity is also seen by other authors on highly pozzolanic soils (Cambi et al., 2016; Al-Mukhtar et al., 2010). Further, as all the investigated Trondheim clays for all binder types fall on the same unique *wbr* vs. τ_{max}-line, this indicates that the pozzolanic reactivity for all the clays investigated herein are similar. This seems to be independent of engineering properties such as w_n, S_t, I_P, among others.

It is worth noting that a common property of all pozzolanic materials, whether natural soil particles, binders or binder additives such as fly ash or ground granulated blast-furnace slag, is the amorphous state which is needed for pozzolanic reactions to occur (Sabir et al., 2001; Bergado et al., 1996; Williams and van Riessen, 2010; Murray, 2007). In both natural soil particles and these types of binders and binder additives, the pozzolan consists mostly of silicon and aluminium oxides. The amorphous material can originate from a previously crystalline structure which has been dissolved by the highly alkaline conditions that occur upon adding a binder (Bell, 1996; Mitchell and Soga, 2005; Eades and Grim, 1966, Firoozi et al., 2017). It is, however, also possible that the amorphous material exists naturally in the soil due to geological conditions.

The XRD analyses (Table 4) indicates that the amount of the clay minerals illite/muscovite, biotite and chlorite are constant or increases. The amount of quartz, however, decreases from 19% in Tiller-Flotten clay, to 12–13% in the stabilised soil, i.e. a 6–7 percentage points (*pp*) decrease. This indicates that the main pozzolan in the soil-binder reaction is fine-grained particles of quartz (SiO_2) which is dissolved in the highly alkaline conditions. This is likely as the rate of solubility of quartz increases exponentially with decreasing particle sizes (e.g., Hendersen et al., 1970). No pozzolanic consumption of the other minerals in the clay is observed based on the XRD data.

The resulting components from the pozzolanic reactions are the cementitious calcium silicate hydrate (C-S-H) and/or calcium aluminate hydrate (C-A-H) which give the stabilised clay its increased strength. The loss on ignition (LOI) measured during sample preparation for the XRF analyses (Table 5) increases from ~ 5% for the natural Tiller-Flotten clay to ~ 8–11% for the stabilised soil. This increase in LOI represents the weight loss by dehydroxylation of C-S-H and C-A-H at temperatures from 110 °C to 1,000 °C.

It is noted that the strength from 100QL on the Tiller-Flotten clay is similar to that found on a west coast Swedish clay reported by Åhnberg and Pihl (1997) where τ_{max} reached ~ 300–400 kPa with the same α as used for the Tiller-Flotten clay. However, Åhnberg and Pihl (1997) also tested an east coast Swedish clay which gave around 6 times less strength. The two Swedish clays have similar mineralogy and engineering properties in terms of e.g. w_n (~80%) and S_t (~15), but their formation nonetheless represent different geological conditions. The clay properties are a function of the processes of their formation, e.g., the bedrocks in their 'hinterland', chemical and mechanical weathering, and conditions during erosion, transportation, and deposition. All these parameters can have a significant impact on their strength development, e.g., with respect to variations in pozzolanic reactivity. Because of this, it is to be expected that large differences are seen when comparing clays from various geological and climatic areas (e.g., Vitale et al., 2017; Bell, 1989; Mateos and Davidson, 1963).

It is also clear that neither w_n nor S_t alone has a defining effect on strength. It is also apparent that the pore sizes are largely irrelevant.

5. Impact on carbon dioxide emissions

In addition to the investigation of engineering properties, a study of its impact on CO_2-eq emissions has been made. Table 2 presented data on CO_2-eq emissions from C, QL and LKD which varies between 356 and 1,027 kg CO_2-eq per ton of dry binder. The commonly used α in Norway has been around 100 kg/m^3 using a binder 50C/50QL (NGF, 2012), which amounts to around ~ 76 kg CO_2-eq per m^3 stabilised soil. Normal construction equipment used in Norway generates around 0.5 kg CO_2-eq /m^3 stabilised clay (NGI, 2020), which is obviously negligible. In general, studies have shown that ~ 98–99% of total CO_2-eq emissions in DDM originates from the production of binder (mobilisation of equipment not included) (NGI, 2020).

Using this approach, values of CO_2-eq per unit strength τ_{max} have been calculated and presented vs. α in Fig. 10. Again, the α_{corr} is used and presented in Fig. 11. Notably, the CO_2-eq emissions is roughly proportional to the CaO-content.

As shown previously (Fig. 6), lower α_{corr} around 30 kg/m^3 do not contribute to a significant τ_{max}. This results in large $CO_2 eq/\tau_{max}$. A general trend is that the lowest $CO_2 eq/\tau_{max}$-values are found around ~ 30–50 kg/m^3 whereupon it increases slightly with increasing α_{corr}.

These results indicate that, from a climatic point of view, the type of binder and α_{corr} is not relevant given a certain target strength. It also indicates that a minimum α_{corr}
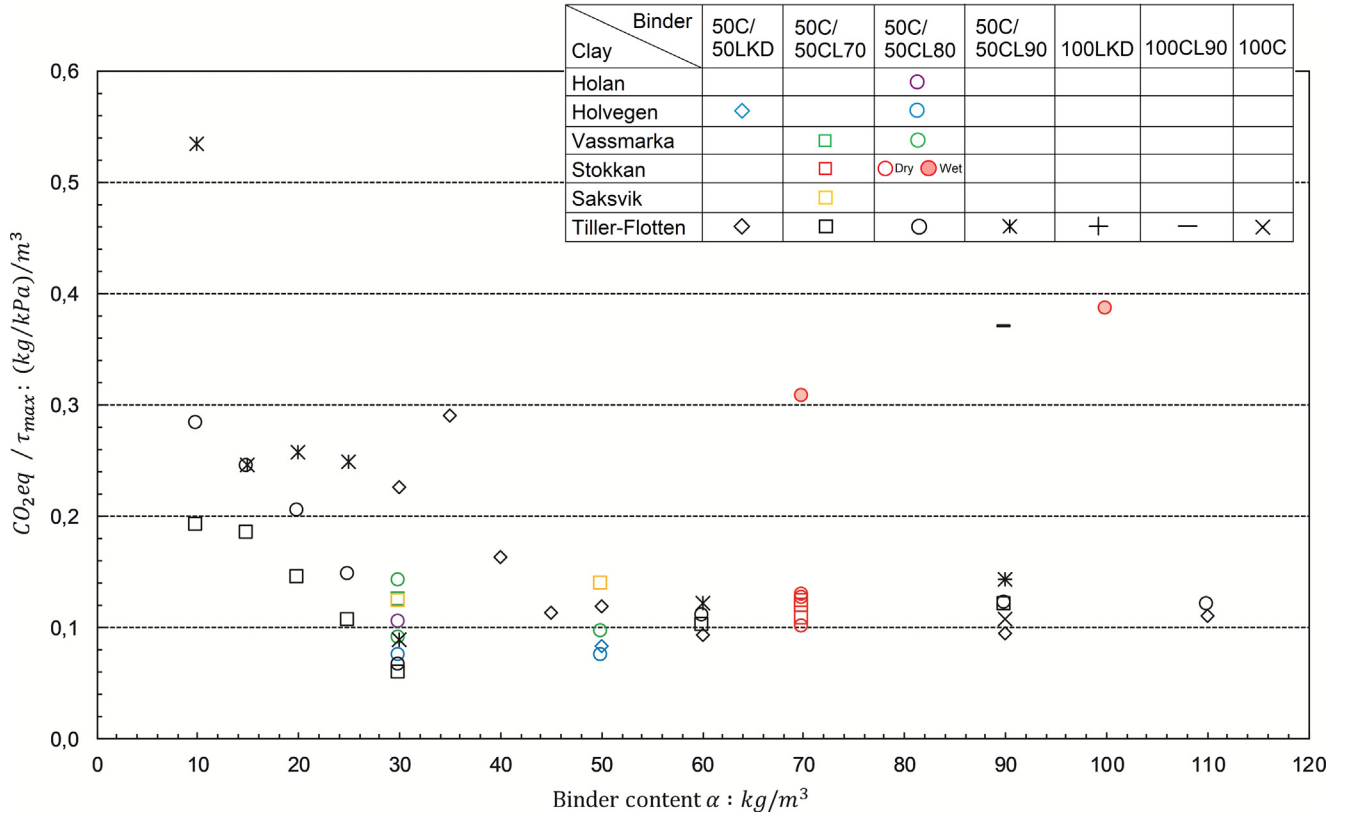
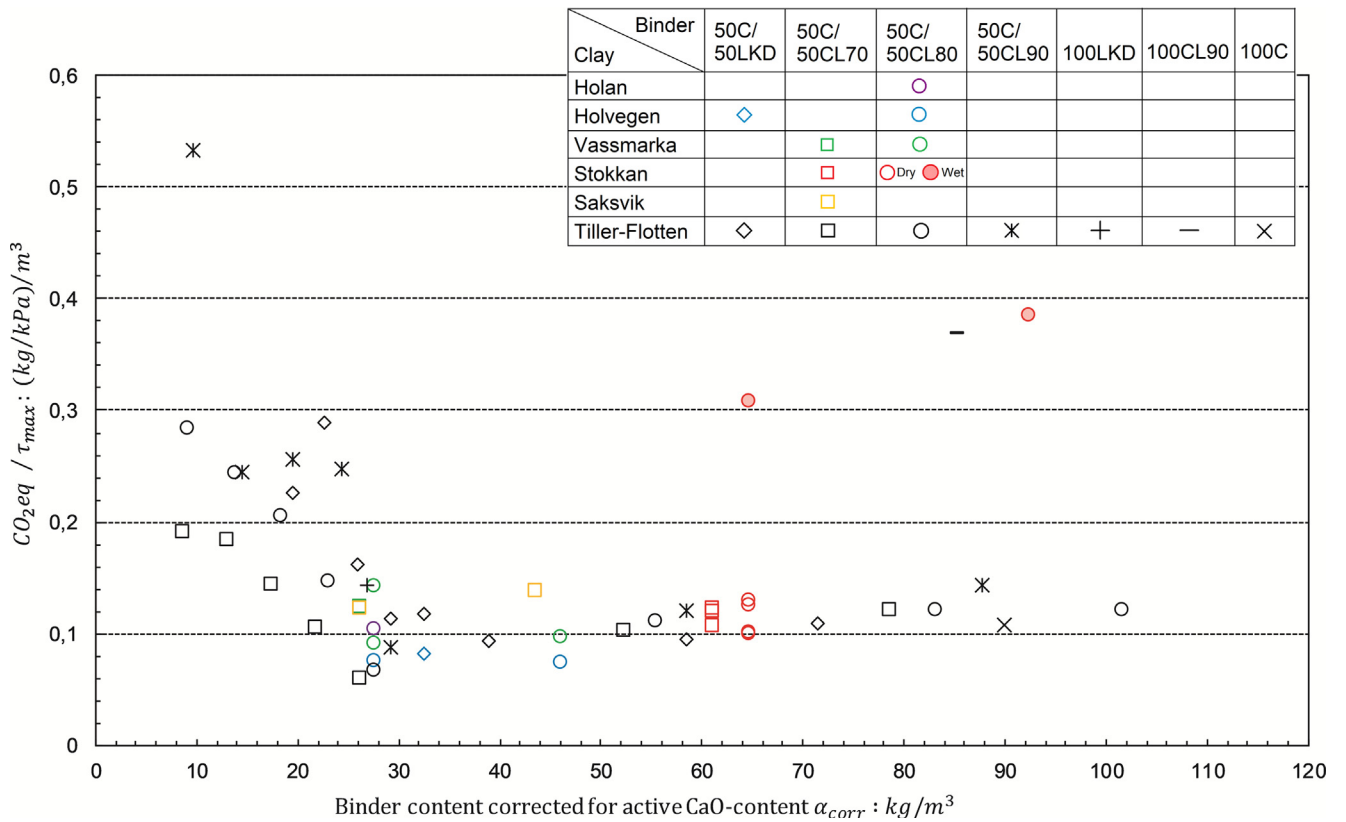Fig. 10. Ratio of carbon dioxide emission CO_2-eq over strength (τ_{max}) vs. α

Fig. 11. Ratio of carbon dioxide emission CO_2-eq over strength (τ_{max}) vs. α_{corr}

of around 30–50 kg/m^3 should be used. This coincides with the lowest possible α with current DDM equipment (NGI, 2020).

6. Application of results

The results presented herein follow the same laboratory procedures, e.g. mixing, sample preparation, curing conditions, temperature and testing method. This significantly reduces uncertainties and has enabled a comparison between different Trondheim clays. However, this is not always possible in engineering practice. Furthermore, laboratory results are not directly applicable to field conditions.

Laboratory and field strengths vary and depend on e.g. mixing procedure, curing conditions and testing methods (e.g. Kitazume and Terashi, 2013; Larsson, 2003). However, variations in α and binder type should logically give equal variations in τ_{max} for both laboratory and field conditions. For example, if τ_{max} in laboratory tests is reduced as the binder type or content (α) is changed, it can be expected that a similar reduction of strength is observed in the field conditions. For these types of analyses, the concept of *wbr* is shown to be highly valuable, at least for large variations in w_n or α.

As typical design values of τ_{max} in Norway are around 100–200 kPa (SVV, 2014; NGF, 2012), these results indicate that the lowest α_{corr} should be minimum 30–40 kg/m^3 for Trondheim clays where the w_n typically is around 25–35%. This means $\alpha > 30$–40 kg/m^3 for binders 50C/50QL, but somewhat higher for binder 50C/50LKD which should be $\alpha > 40$–50 kg/m^3 (Figs. 5 and 6).

These are low α compared to those traditionally used in the Nordic countries and are challenging from a field installation point of view. Current equipment has limitations in binder delivery, i.e., the rate of flow per unit time, and the lowest possible α is thus dependent on the mixing energy which is needed or required (by guidelines or a set project requirements) to obtain sufficiently homogeneous DDM columns. Mixing energy vs. binder distribution and strength variation has been studied for a few Swedish soils by e.g., Larsson (2001, 2003), however, no detailed study on Trondheim clays have been made. Using typical mixing energy required by Norwegian guidelines for ground improvement with lime and cement (NGF, 2012), the lowest α that should be used in the field is around 30 kg/m^3. A few field applications have been done using $\alpha = 30$ kg/m^3, however, subsequent excavation, block sampling and examination of the DDM columns has shown considerably larger binder accumulations than using a higher α, e.g. 80 kg/m^3 (NGI, 2021). It is thought that this is caused by insufficient mixing. Further field testing and adjustments of execution procedures are thus required.

Tests with single binder 100QL and wet mixing method does not show the same strength development. The former is due to the slower reaction of QL compared to C. The reason why the wet method yields lower τ_{max} given the same *wbr* or *wbr$_{corr}$* is not fully understood. As mentioned previously, this contradict some Swedish findings, but still clearly indicates that the wet mixing method cannot be used in Trondheim clays without further laboratory tests and field trials.

Finally, it should be noted that the correction of active CaO-content presented herein is only applicable to lime-based binders. Comparisons of for example 50C/50QL and 50C/50CKD on the Tiller-Flotten clay have been made by e.g. Eidsmo (2019) showing similar results between the two binders. The correction is thus not applicable for cement-based by-products although K_{CaO} in CKD is similar to LKD. It might be that CKD contains amorphous compounds available for reactions with C.

7. Conclusions

The results presented herein comprehends stabilisation of Trondheim clays with a variety of cement and lime-based binders. Analyses of strength, pH, Atterberg limits, XRD, XRF and SEM have been made, in addition to analyses of the CO_2-eq emissions from binder production.

The main findings can be summarised as follows:

- Both plastic (w_P) and liquid (w_l) limits, and hence plastic index (I_p) increases upon stabilisation. The high increase in w_l is due to the geologically leached quick clay.
- pH decreases over time, due to pozzolanic reactions consuming OH^- ions.
- Results from XRD analyses indicate dissolution of fine-grained quartz particles, predominantly in the clay fraction, which is thought to be the main pozzolan in the clay-binder reaction.
- The binder content (α) and water-binder-ratio (*wbr*) can be corrected with respect to the active CaO-content (K_{CaO}) to take the binder type into account (giving α_{corr} and *wbr$_{corr}$*)
- τ_{max} vs. *wbr$_{corr}$* shows a noticeable consistent correlation for all Trondheim clays, and is considered to be a usable concept in engineering practice also for DDM.
- The application of the K_{CaO} correction for the relation CO_2-eq/kPa vs. α_{corr} indicate that the type of lime-based binder has little influence on the CO_2-eq emissions from DDM works for $\alpha > 30$–40 kg/m^3. In practice, it can be said that any difference is negligible since α needs to be increased to compensate for a binder containing a lower K_{CaO}. However, in the region of $\alpha \leq 30$ kg/m^3, the results indicate a slight tendency of low reactivity binders (those with low K_{CaO}, in particular for C/CL70 and C/CL80) giving lower CO_2-eq emissions than those binders with a higher content of K_{CaO} (as C/CL90), for the same clay type.
- The lowest binder content for practical purposes in typical engineering applications corresponds to α around 30–50 kg/m^3. This seems to be a common value for both laboratory and field applications for Trondheim clays.

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.

Acknowledgements

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