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ORIGINAL PAPER

Strength and Stiffness Properties of Laboratory-Improved Soft Swedish Clays

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Abstract
The dry deep mixing method using lime and cement-based binders is widely used in the Nordic countries to improve soft and sensitive clays. Increasing the usage of industrial by-products is needed to reduce climate impact, and this requires thorough knowledge on engineering properties using these binders. A lot of research has been done on this topic; however, tests are often performed on fabricated soils, and there is also a lack of studies on cement kiln dust in organic clays. This paper presents a large database of laboratory-improved soft inorganic and organic natural Swedish clays using quicklime, cement and cement kiln dust. It is shown that many properties and relationships between strength and stiffness, strength development over time and strain to failure are in practice similar for both quicklime and cement kiln dust when combined with cement, but that the strength depends both on the water-binder ratio and soil type. Further, it is shown that cement kiln dust performs well also in organic clay. The data also shows that the Youngs' modulus on average is around 100 times the unconfined compressive strength. For strength development over time, it is seen that the strength increases on average 60% from 7 days of curing to 28 days of curing. The correlations presented herein will serve as a useful guidance in engineering practice.

Keywords Database · Dry deep mixing · Cement · Quicklime · Cement kiln dust

List of symbols

A	Empirical constant in the Abrams formulation [–]
B	Empirical constant in the Abrams formulation [–]
C	Cement
CaO	Calcium oxide
CKD	Cement kiln dust
DDM	Dry deep mixing
QL	Quicklime
WDM	Wet deep mixing
E_{50}	Secant Youngs' modulus at 50% peak strength [kPa]
α	Binder content [kg/m^3]
a_w	Ratio of dry binder to dry soil mass, weight ratio [%]
$c_{u,rem}$	Remoulded shear strength of natural clay [%]
c_u	Undrained shear strength of natural clay [%]
ε_f	Strain at peak strength (failure) [%]
$q_{\mathrm{u}(x)}$	Unconfined compressive strength at x days of curing [kPa]
q_u	Unconfined compressive strength (at 28 days curing if not otherwise stated) [kPa]
w_L	Liquid limit [%]
w_N	Natural water content [%]
w_P	Plastic limit [%]
w_{stab}	Water content of stabilised clay [%]
γ_N	Natural unit weight [kN/m^3]
γ_{stab}	Unit weight of stabilised clay [kN/m^3]
wbr	Ratio of water to dry binder, weight ratio [–]

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Introduction

The dry deep mixing (DDM) method is used extensively in the Nordic countries to improve soft soils. The improvement enhances the strength and deformation properties, and DDM is thus used to improve stability conditions and to reduce long-term settlements. Examples of applications are foundation of embankments and light-weight structures, improvement of slope stability and excavation pits and reduction of vibrations from e.g. high-speed railways [1–3]. The DDM method is used to improve a wide range of soils, e.g. inorganic clays, organic clays and gyttja (i.e., organic content > 6%). Historically, binders, such as quicklime (QL) and cement (C) have been used in DDM. During the last 10 years or so, however, other binders such as industrial by-products are increasingly being used to reduce both material costs and carbon dioxide emissions, e.g. [4–8].

In the Nordic countries, replacing QL with the industrial by-product cement kiln dust (CKD) is today common, but the use in organic clays and gyttja is limited. In addition, the use of CKD is restricted by some clients. The replacement of a 50%/50% weight mixture with C reduces the carbon dioxide emissions, i.e. kg CO_2-eq per tonne of dry binder, by around 50–55% [9, 10]. Because there is a high availability of CKD as a by-product from cement production, it is important that the usage of CKD is increased to further reduce the carbon dioxide emissions from the DDM method.

Although the effectiveness of CKD on improved clay strength development have been thoroughly investigated by e.g. [11–17], there seems to be a very limited number of published studies, if any, on CKD in organic clays and gyttja, and in particular how the strength development differs to that in inorganic clay. In addition, published studies on the effectiveness of CKD are typically limited to a few types of soils, often fabricated, with a rather small variability.

A valuable contribution was made by Paniagua et al. [7] which presented a large database of improved natural Norwegian clays. The variety in for example binder content (α) and natural water content (w_N) was however rather small due to the typical usage engineering practice, and there were no organic clays or gyttja available. Although the clays in the Nordic countries are similar from a mineralogical perspective, they can vary considerably in their engineering properties, and hence the strength and stiffness gain upon improvement is not necessarily similar. There is thus a great need for further studies on the engineering properties of improved natural clays with a higher variability, e.g. a larger variation in both α and w_N, particularly for soft inorganic and organic clays improved with various binder types such as C, QL and CKD.

This paper presents a large database of improved soft natural clays from Eastern Sweden, mainly the Stockholm area. A total of 877 soil samples have been improved with a large variety of binder types and binder contents, having various curing times. The properties of the original soil vary widely from silty clays to organic clays, and the binders used have been a mixture of mainly C, QL and CKD. Samples have been tested with unconfined compression (UC) tests where an unconfined compressive strength (q_u) and secant Young's modulus (E_{50}) were interpreted and plotted against binder content (α), dry binder/soil ratio (a_w) and water-binder ratio (wbr). In addition, the strength development over time was studied by comparing UC test results on samples with varying curing times. Inorganic and organic clays have also been compared. In addition, strains at failure have been compared with natural clays.

Materials and methods

Database

The database consists of 877 data points, and its basic statistics is summarised in Table 1. It mainly consists of East Swedish soft inorganic and organic clays with w_N = 34–272% and natural unit weight (γ_N) = 10.9–18.7 kN/m^3. The most common values of w_N are between 45 and 70%. A histogram of w_N is presented in Fig. 1(a).

The soils have been improved with α varying between 70 kg/m^3 and 400 kg/m^3, giving wbr around 2–10 and a a_w varying between 6 and 44%. The most common α is between 70 and 120 kg/m^3 as seen in the histogram given in Fig. 1(b). Typically, a higher α is used in the organic clays having higher w_N, and thus the variation in wbr is relatively limited.

The improved clays have resulting q_u and E_{50} varying considerably between 34 kPa and 1,266 kPa and 1,500 kPa and 190,000 kPa, respectively (Table 1).

Soil and Binder Types

The Eastern Swedish clays tested herein are typically heterogeneous varved clays with variable unit weight (γ_N), w_N and Atterberg limits with depth. Silty and sandy layers are common. Soils that herein are denoted inorganic clays have organic contents varying up to 2%, and soils denoted organic clays have organic contents over 2%. Soils with an organic content > 6% are denoted as gyttja and are classified as 'OH' according to the unified soil classification system [18]. Further, organic clays are typically having $w_L \approx w_N$ higher than around 100%.

Table 1 Basic statistics of the database (n = 877)

Parameter	Min	Max
w_N[%]	34	272
γ_N[kN/m^3]	10.9	18.7
α[kg/m^3]	70	400
wbr[-]	2.1	10.3
a_w[%]	5.6	43.8
q_u[kPa]	34	1,266
E_{50}[kPa]	1,500	190,000

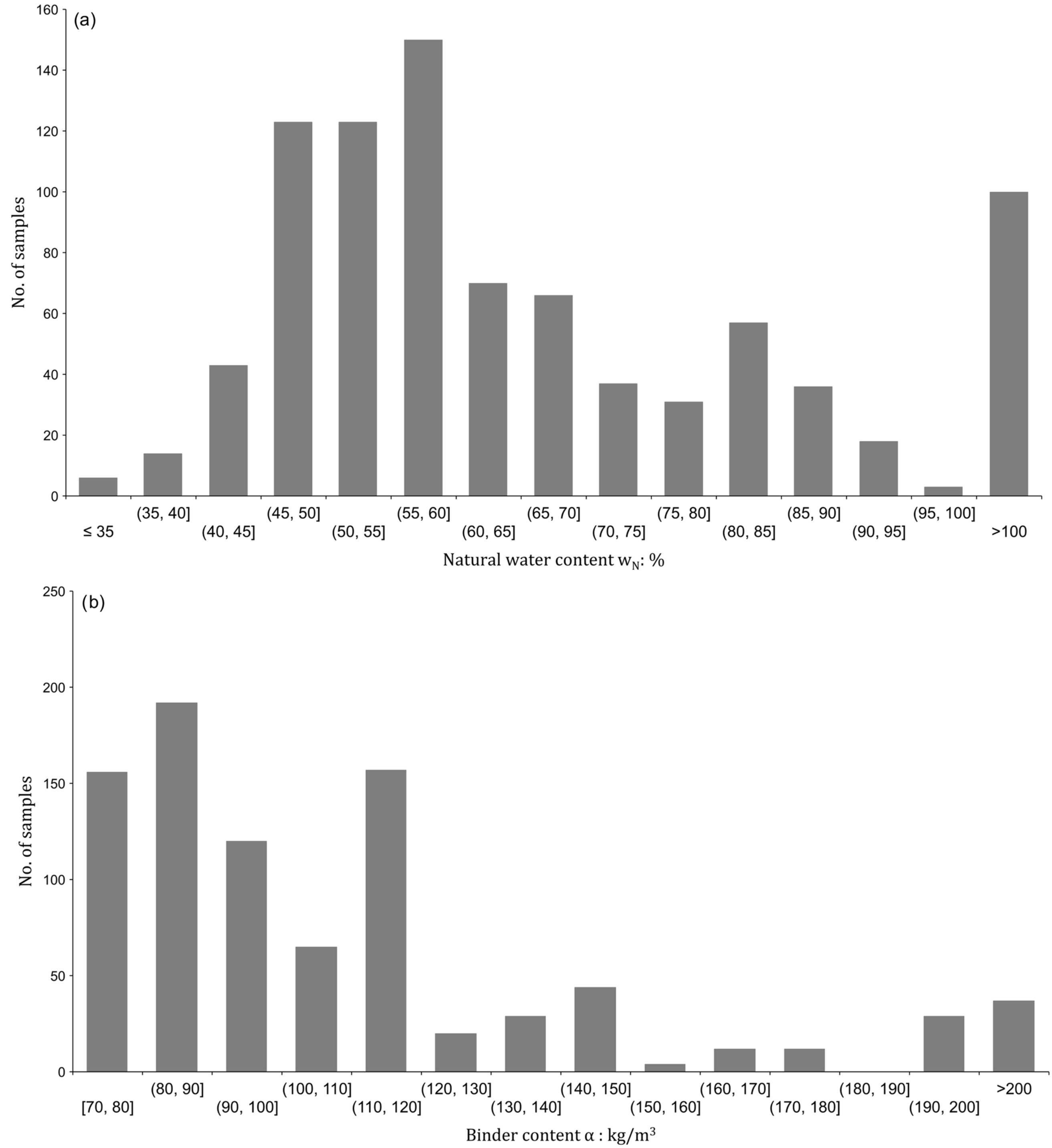

Fig. 1 Histograms of **a** w_N, and **b** α

The clay content for Eastern Swedish clays is typically 60–70%, except for silty clays, pH around 7.5–8.5 and a specific surface area (BET) of around 30,000 m^2/kg, although this can vary considerably. The chemical composition of a typical Eastern Swedish clay consists of around 45–55% SiO_2, 13–16% Al_2O_3, 1.5–2.5% MgO, 5–7% Fe_2O_3, 3–5% K_2O, and 1.5–3.0% CaO. The predominant clay mineral is illite followed by mainly chlorite and kaolinite.

In this paper, the results with different binder types and compositions are presented. The designation is based on the binder type and composition, where the composition is given in per cent of total dry weight of the total binder

Table 2 Sample denotation and frequency in database of the three major compositions

Designation	Binder composition	Frequency of total database %
50C/50QL	50% C and 50% QL	26
70C/30QL	70% C and 30% QL	23
50C/50CKD	50% C and 50% CKD	40

Table 3 Typical composition of the binders used (the CaO-total content consists of both active and non-active CaO) [19, 20]

Oxide	CEM II	QL	CKD
CaO total [%]	60.0	94.0	52.3
CaO active[a] [%]	~60	> 90	30–35
SiO_2 [%]	21.0	1.5	15.5
Al_2O_3 [%]	5.0	0.8	3.6
Fe_2O_3 [%]	2.3	0.4	2.1
MgO [%]	2.9	1.7	2.7
Alkali [%]	0.9	0.2	10.0

[a]The active CaO content, also referred to as free or available CaO content, is determined by dissolution of CaO in ethylene glycol and by titration with benzoic or hydrochloric acid[16]

content. Table 2 shows an overview of the three main binder compositions, i.e. 50C/50QL, 70C/30QL and 50C/50CKD, which together sum up to around 89% of the total number of samples in the database. The remaining binder compositions are 60C/40QL, 75C/25QL, 30C/70QL, 85C/15CKD, 70C/30CKD, 30C/70CKD, and 100C; however, these are not presented herein because of a limited number of samples available.

Table 3 presents typical chemical composition of the binders that have been used. The binders have been collected from the same supplier and manufacturing plant, giving very similar chemical compositions over time and thus allowing direct comparisons of all tests that are made. The C is a Portland-fly ash cement of the type CEM II/A-V 52.5 N according to EN 197–1. The QL is classified as CL 90 according to EN 495–1.

Laboratory Works

All laboratory works have been performed in a geotechnical laboratory in Stockholm, using the same preparation procedure for all samples. The sample preparation, mixing and moulding has been performed according to the Swedish guidelines which is a moulding technique with static compaction [21–23].

The intact natural soil samples were firstly mixed in a blender for about 3–5 min, the exact longevity depending on the remoulded shear strengths ($c_{u,rem}$) of the sample and how fast it is visually considered sufficiently homogeneous. The dry binder was weighted and pre-mixed in the correct ratio and thereby added to the remoulded clay and mixed for about 5 min until the mixture is visually considered sufficiently homogeneous.

From the mixed batch, individual specimens were then prepared by filling 50 mm cylindrical reinforced plastic tubes with the soil−binder mixture. Layers of around ≤ 30 mm were compacted using a static load of 80–100 kPa which was applied for 5 s, up to a total specimen height of around 130–150 mm. The moulding technique is further described in, e.g. Carlsten and Ekström [21] and Åhnberg and Andersson [24]. Most commonly, four replicate specimens were produced from the same batch. All tubes were sealed with a plastic layer and rubber lids at each end. The time from mixing of soil and binder to sealing of all the improved specimens was completed within around 30 min. Photographs of the moulding process are shown in Fig. 2.

All specimens were left to cure in a climate-controlled room with a relative humidity > 70% and a temperature of around 7–8 °C, following recommendation by e.g. Larsson [22]. Normally, two of the four individual specimens were tested after 7 days, and the other two after 28 days of curing.

Testing of the cured specimens first consisted of determination of γ_{stab} and w_{stab}. They were then carefully trimmed to a height to diameter ratio of around 1.8–2.0 and tested in UC tests. Very little time was used on preparing and trimming of the samples before testing, ensuring negligible drying effects and temperature changes. The UC tests were performed at a temperature around 7–8 °C using a strain rate of 1.5%/min, and failure was normally reached within a few minutes.

Results

Strength and Stiffness Properties

Values of q_u vs. α and vs. a_w for all specimens are shown in Figs. 3 and 4, respectively. The data points are divided into 7 days and 27–31 days of curing and into inorganic clay and organic clay and gyttja. There is naturally a large variation as the figures contain data from all types of soil and types of binder. Even though the scatter is very large, the strength development over time is however apparent, and there is also slight increase in q_u with increasing α and a_w.

Values of E_{50} vs. q_u are presented in Fig. 5(a) for inorganic clay and Fig. 5(b) for organic clays and gyttja. Here, only the three main binder compositions 50C/50QL, 50C/50CKD and 70C/30QL are plotted. Linear relationships are also plotted to fit average values together with interpreted upper and lower bounds. Linear regression gives the following relationship between E_{50} and q_u (Eqs. 1 and 2):

For inorganic clays

Fig. 2 Specimen preparation, **a** pre-mixed dry binder, **b** homogenising of mixture, **c** moulding in reinforced plastic cylinders, **d** sealed cylinders under curing

$$E_{50} \approx 105 \times q_u \quad (1)$$

For organic clays and gyttja

$$E_{50} \approx 95 \times q_u \quad (2)$$

The relationships are remarkably similar for the different binder compositions, i.e. 50C/50QL, 50C/50CKD and 70C/30QL. The relationships given in Eqs. 1 and 2 can thus be applied for all these three main binder compositions, and for both inorganic and organic clays and gyttja. The scatter is however relatively large with lower and upper bounds of around 50 and 180. This is relatively similar as Norwegian clays as reported by Paniagua et al. [7], as well as other international data on stabilised soils with similar q_u, e.g. [1, 25–27].

The differences between inorganic and organic clay and gyttja should be considered together with the typical high scatter and variability for the DDM method. The measured differences in strength or stiffness need to be considerable not to be hidden by the large variations and uncertainties. As an example, the difference in average values of E_{50}/q_u for inorganic clays and organic clays and gyttja are ~ 105 and ~ 95, respectively, could in practice be assumed equal. From the author's point of view, a relationship of $E_{50}/q_u \approx 100$ can for practical purposes be used for both types of soil as an average value. It is of course important to remember the scatter.

There is however a trend that the ratio E_{50}/q_u increases with increasing q_u. A best fit for all samples of both inorganic and organic clay and gyttja using a power function is given by Eq. 3.

$$E_{50} \approx 30 \times q_u^{1.22} \quad (3)$$

In the Swedish Transport Administration guideline, the relationship $E_{50} \approx 13 \times \left(q_u/2\right)^{1.6}$ for q_u up to a maximum of 280 kPa is given. This relationship seems realistic compared to the data presented herein, however, it seems that Eqs. 1 and 2 are equally representative considering the large scatter.

Strain at Failure

Figure 6(a) and (b) shows strains at failure (ε_f) for inorganic clay and organic clay and gyttja, respectively. There is a slight trend that ε_f increases as q_u decreases. The trend is similar when plotting ε_f vs. E_{50}, i.e. a stiffer sample typically result in a lower strain at failure.

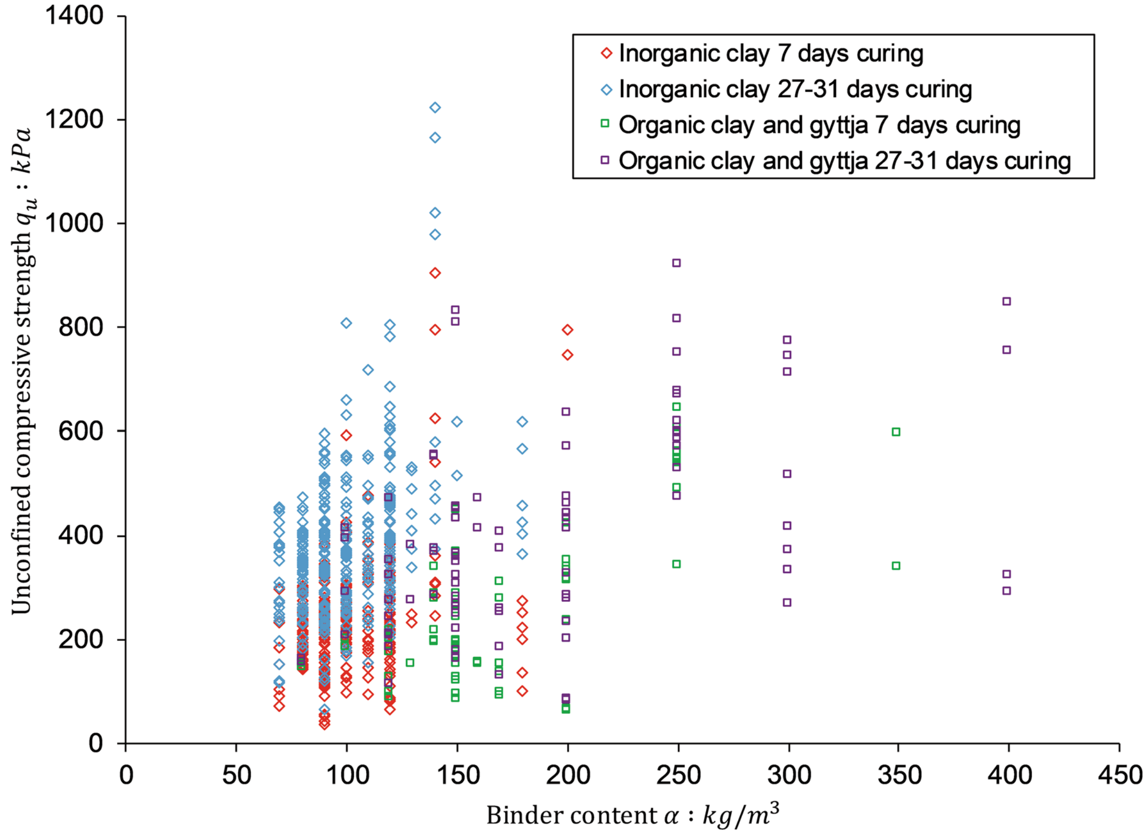

Fig. 3 Strength q_u vs. binder content α for all soil types, binder types and binder composition

The average ε_f for the inorganic clays are 2.2%, 1.8% and 2.0% for 50C/50QL, 50C/50CKD and 70C/30QL, respectively, and the average ε_f for the organic clays and gyttja are 2.9%, 2.1% and 2.4% for 50C/50QL, 50C/50CKD and 70C/30QL, respectively. The lowest ε_f is thus seen for inorganic clays, which is expected. Further, the lowest ε_f is seen for the binder 50C/50CKD for both types of soil. The values are similar to other studies [1, 7, 20, 25, 28].

For all specimens, the average strain at failure is 2.2%. For comparison, undrained triaxial compression tests on natural Eastern Swedish clays have shown the average strain at failure to be around 1.9% [29]. Similar values for natural clays are given by e.g. Karlsrud and Hernandez-Martinez [30] for Norwegian clays where strains at failure for high-quality block samples are on average around 1–2%. The strain at failure is thus rather similar for improved and natural clays, which contradicts other researchers' findings or postulates that strain at failure is considerably higher for natural clays than improved clays, e.g. [31]. Thus, in engineering design, it can be assumed that strain compatibility is obtained for active/compression loading and for improved clay with similar strength values. However, research by e.g. Ignat et al. [32] indicates that this might not be the case for passive/extension loading.

Strength Development Over Time

Figure 7(a) presents ratios of q_u after 7 days ($q_{u(7)}$) and 28 days ($q_{u(28)}$) of curing for inorganic clay. Figure 7(b) present the same ratio for organic clay and gyttja. The ratio $q_{u(28)}/q_{u(7)}$ is plotted vs. $q_{u(7)}$ since this was the only parameter that varies somewhat with $q_{u(28)}/q_{u(7)}$.

As can be seen for inorganic clays, there is a decrease in $q_{u(28)}/q_{u(7)}$ as values of $q_{u(7)}$ increases, i.e. the higher strength after 7 days of curing, the strength development continues at a slightly lower rate. The scatter is however very large. For lower strength specimens however, the continued strength development over time is larger. There are quite small differences between the different binders, even though it is normally assumed that 70C/30QL give a faster strength development than e.g. 50C/50QL due to its higher cement proportion. Hence, in engineering practice, this effect can be said is negligible when comparing strength after 7 and 28 days considering the overall scatter. On average, the ratio $q_{u(28)}/q_{u(7)}$ is 1.50, 1.62 and 1.72 for 50C/50QL, 50C/50CKD and 70C/30QL, respectively. For all inorganic clays, the average is $q_{u(28)}/q_{u(7)} \approx 1.59$.

The same tendencies and differences between different binders apply to organic clays and gyttja as seen in Fig. 7(b);

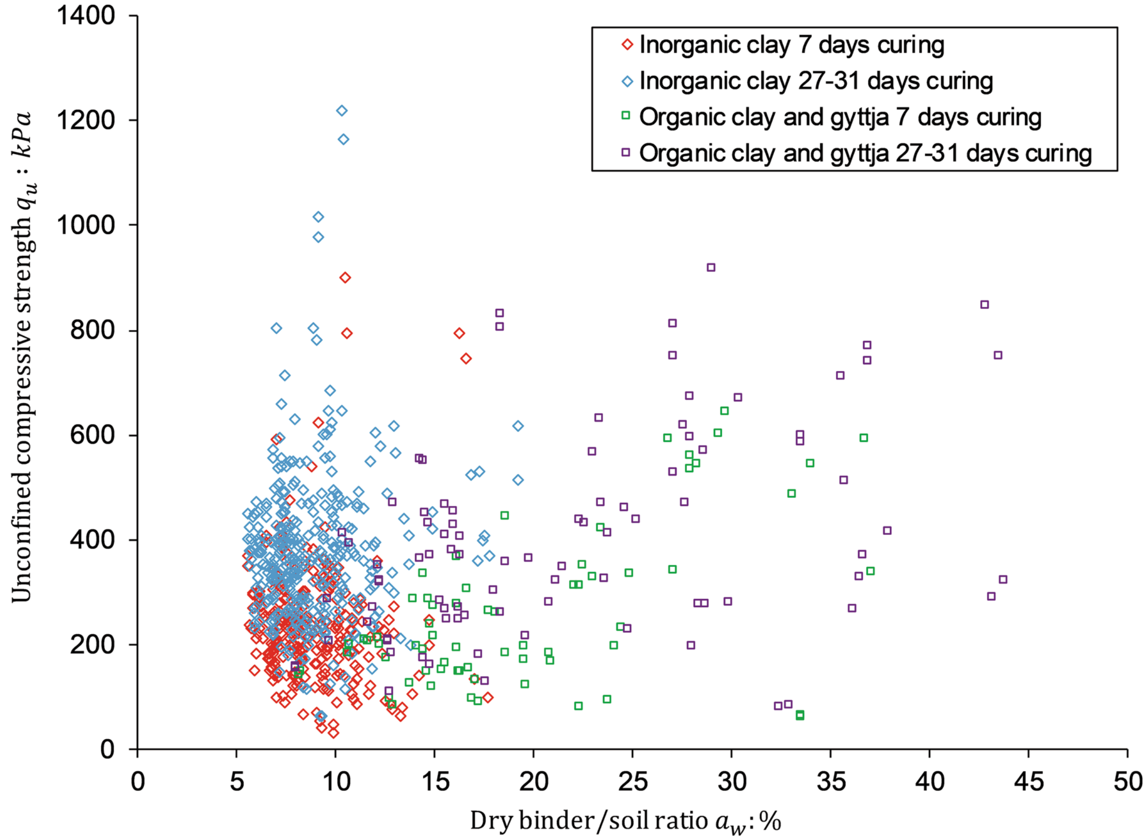

Fig. 4 Strength q_u vs. dry binder/soil ratio a_w for all soil types, binder types and binder composition

however, there are few data points and a considerable scatter. Here, the average $q_{u(28)}/q_{u(7)} \approx 1.65$.

Previous studies on strength development over time have shown similar results as that presented herein. Åhnberg [33] summarised several studies on improved Swedish clays by a logarithmic strength increase over time as $q_{u(t)}/q_{u(28)} = 0.3\ln(t)$. This gives $q_{u(28)}/q_{u(7)} \approx 1.71$. Japanese experiences on cement-improved clays are $q_{u(28)}/q_{u(7)} \approx 1.49 - 1.56$ [25]. Other researchers have shown ~ 1.92 on cement-improved Japanese soils [34], on average ~ 1.53 for cement-improved Finnish clays [35] and ~ 1.67 on Japanese and Thai clays [36]. The scatter is often large.

Water-Binder-Ratio vs. Strength

To account for the large difference in w_N seen in the presented database, the concept of *wbr* is used. The *wbr*, often used for WDM [1] and defined as the ratio of weight of water available for the binder reaction to the dry weight of binder. It has been shown to correlate well with the strength of improved soil, e.g. [17, 37–39]. A commonly used formulation is based on Abrams' law [40], originally developed for concrete technology (Eq. 4):

$$q_u = \frac{A}{B^{wbr}} \tag{4}$$

where A and B are empirical constants. These constants depend on several variables: type of soil (grain distribution, type of clay minerals, organic content), type of binder and composition, sample preparation, curing conditions (confining stress, temperature) and testing procedure (type of test, strain rate, sample size, height to diameter ratio, confining stress). It has been shown that the factor B is relatively constant, independent of types of soil, binder type and α, and is typically ~ 1.1–1.3, e.g. [36, 38, 41–43]. Also, Horpibulsuk et al. [36] showed that the factor B was constant over time, so that only the factor A was affected by curing time.

Values of *wbr* vs. q_u from the database presented herein are shown in Fig. 8(a) for inorganic clay. The data fits a relationship with B of ~ 1.24, similar to previous studies. The scatter in q_u is large but this seems only to affect the factor A. Again, no differences can be seen between the different binder compositions 50C/50QL, 50C/50CKD and 70C/30QL.

A similar plot for organic clays and gyttja is shown in Fig. 8(b). Although there are considerably fewer data points and the scatter is large, the data fits the same relationship,

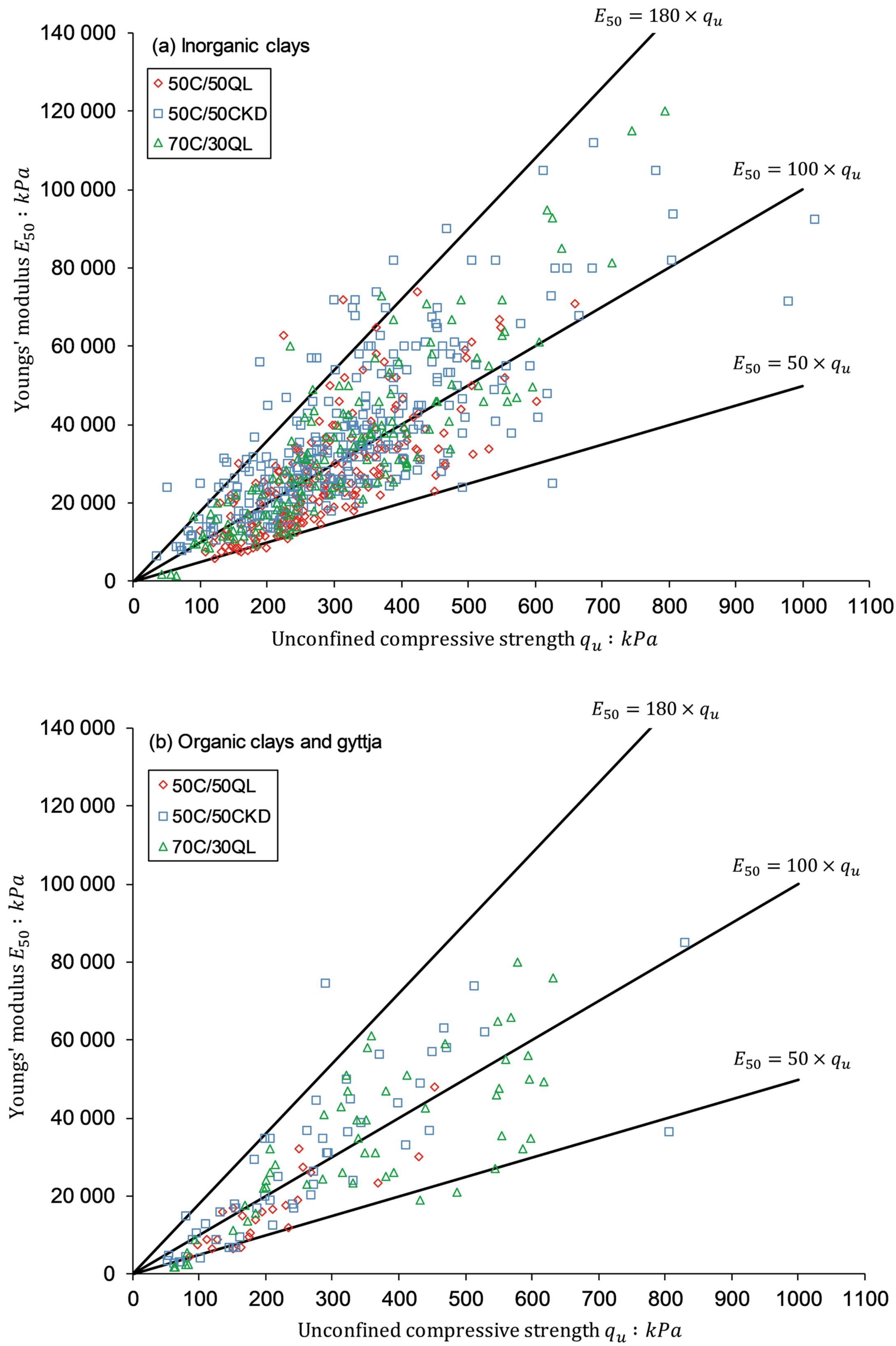

Fig. 5 Stiffness E_{50} vs. strength q_u for **a** inorganic clays, and **b** organic clay and gyttja (all curing times with varying binder types)

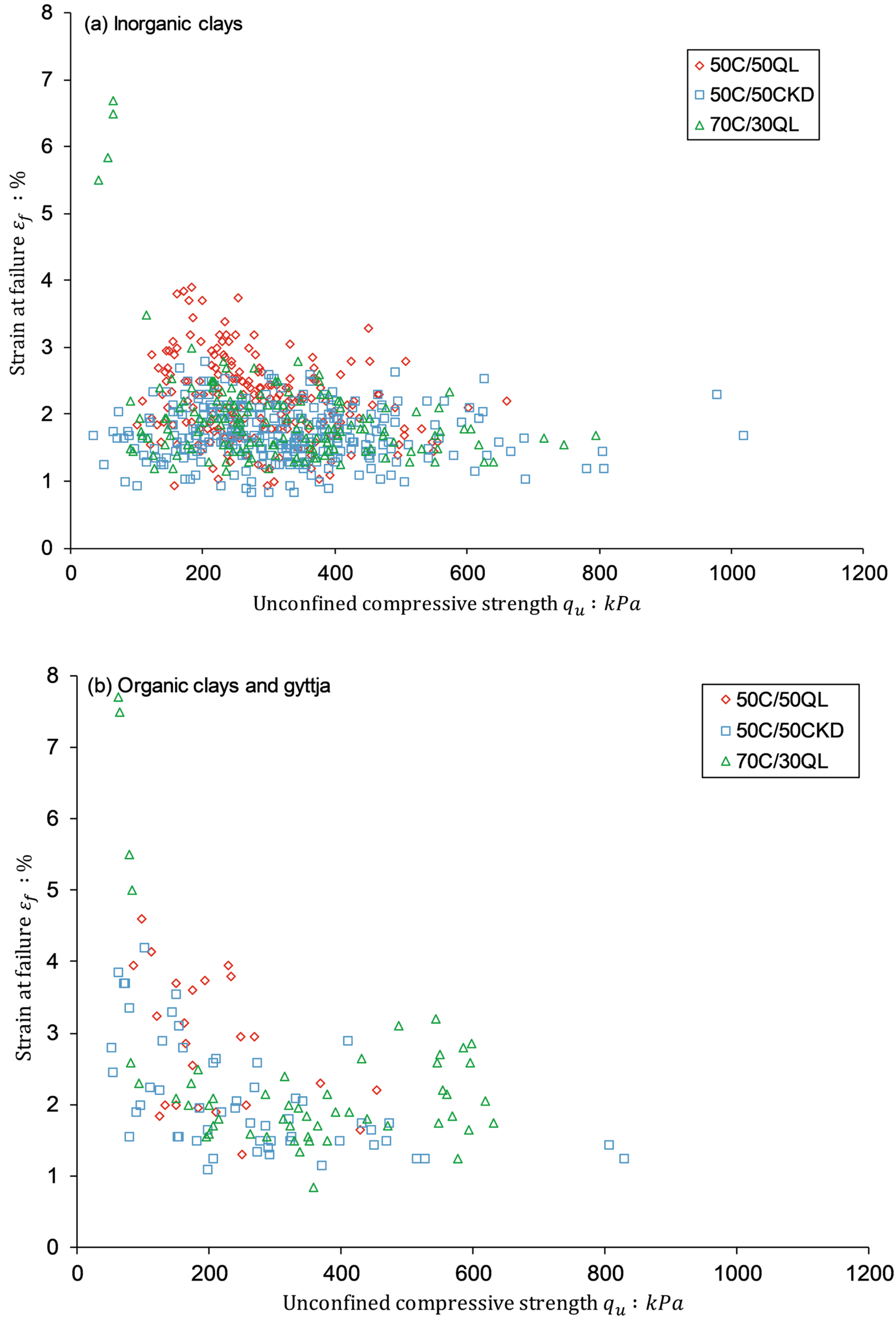

Fig. 6 Strength q_u vs. strain at failure (ε_f) for **a** inorganic clays, and **b** organic clays and gyttja (all curing times with varying binder types)

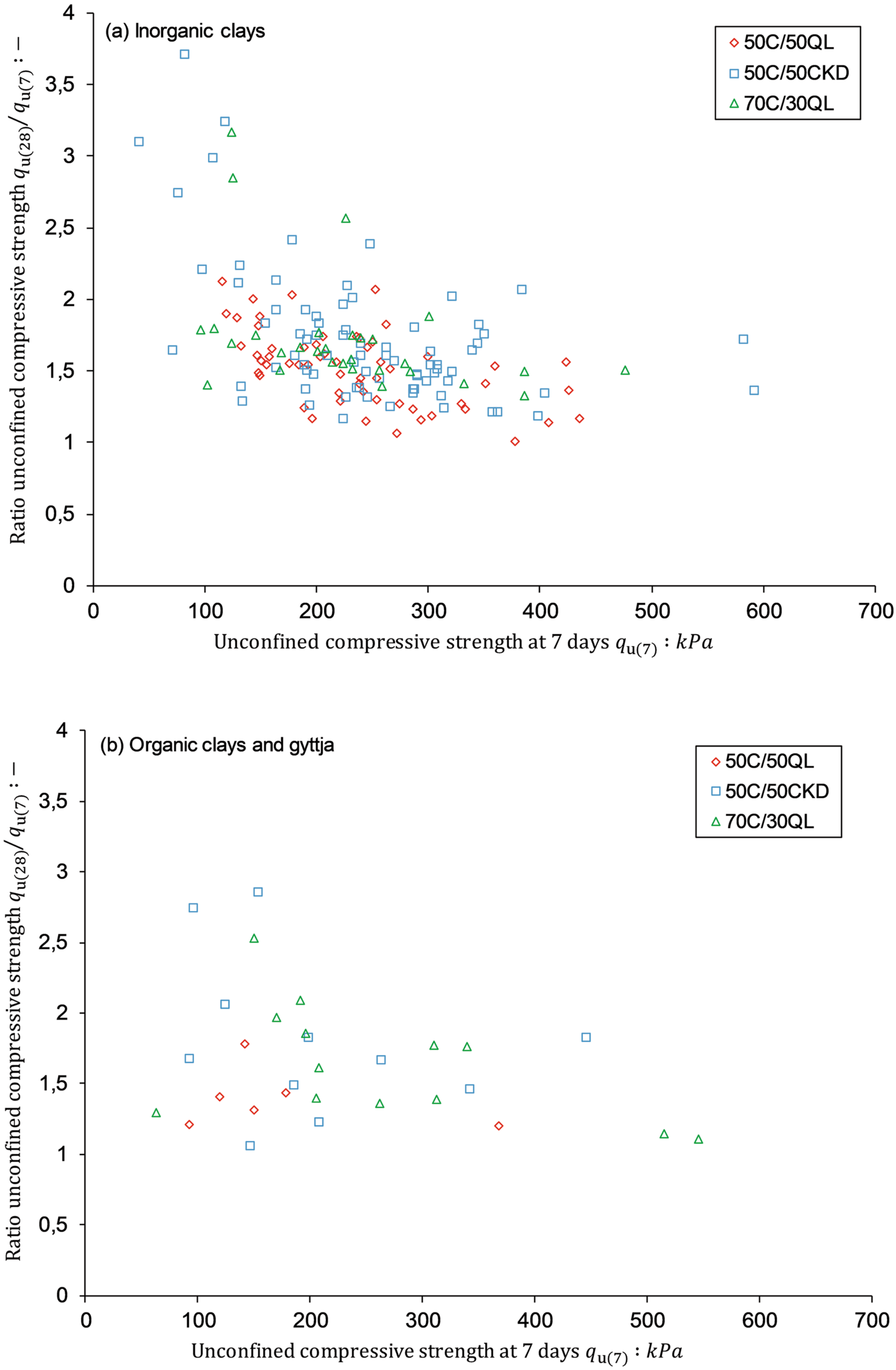

Fig. 7 Quotient $q_{u(28)}/q_{u(7)}$ vs. $q_{u(7)}$ for **a** inorganic clays, and **b** organic clays and gyttja (with varying binder types)

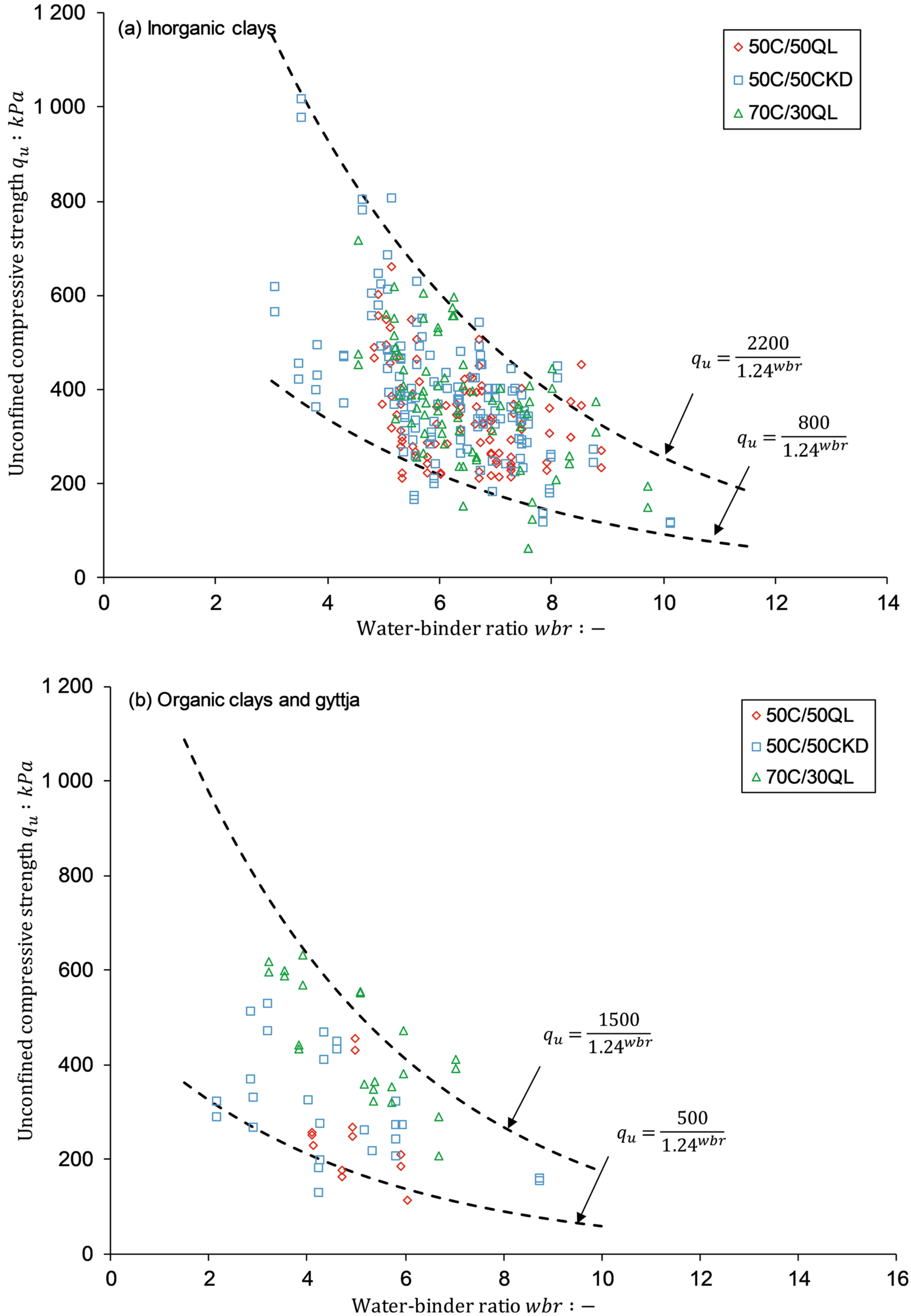

Fig. 8 Strength q_u vs. wbr for **a** inorganic clays, and **b** organic clays and gyttja (27–31 days of curing with varying binder types)

e.g. B of ~ 1.24. The plot shows that the concept of *wbr* vs. q_u can also be used for organic soils, as opposite to e.g. [44] which argued it cannot. For organic clays and gyttja, however, there are differences between the different binder types. 70C/30QL seems to yield a higher strength than both 50C/50CKD and 50C/50QL, in line with previous research which shows higher strength with increasing cement content for organic soils, e.g. [45, 46]. From Fig. 8(b) it can also be seen a slight tendency that 50C/50CKD perform better than 50C/50QL in these types of soil. Nonetheless, it seems that only the factor A is dependent on the variables mentioned above.

Comparing the inorganic clays, Fig. 8(a), to organic clay and gyttja, Fig. 8(b), it can be seen that the general strength development is higher for the inorganic clay than for the organic clay and gyttja, given the same *wbr*. This is expected from previous research on this type of clay, e.g. [20]. From the data presented herein, the factor A is around ~1.5 times higher for inorganic clays than for organic clays and gyttja, regardless of binder type. This will of course depend on the exact amount of organic content, but the factor ~1.5 times can serve as a useful general guideline for this type of clay.

Discussion

The effectiveness of the different binder types in the different soil types can illustratively be explained in terms of chemical reactions, and must normally take into account the active CaO content of the binder. The term 'active CaO' refers to the part of total CaO which is available for a binder reaction, and is not necessarily the same as the total CaO content, e.g. [43, 47].

Improvement of clays with QL, i.e. > 90% CaO, as a single binder is based on the reaction between active CaO and the soil containing water and soil particle. First, a reaction between the active CaO and water creates calcium hydroxide ($Ca(OH)_2$), which in turn reacts with dissolved soil particles, in particular silicates and aluminates. These reactions, termed pozzolanic reactions, results in cementitious calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H) which are the main contributors to improved clay strength. QL as a single binder, however, has been shown to be ineffective in Eastern Swedish clays, i.e. the type of clay presented herein [45, 48]. The reason is thought to be the slow pozzolanic reactions which take considerable time, most likely due to slow dissolvement of silicates and aluminates from the soil particles. Other clays can have other properties, and QL has for example shown to be effective in some soils, e.g. some Western Swedish clays [48] and some Norwegian clays [43].

Improvement with C as a single binder is essentially based on the same types of reactions, however, C already contains silicates available for reactions with its CaO (Table 3). The strength development is thus largely independent of the type of soil particles and their dissolvement. CKD contains a somewhat lesser amount of active CaO than C, however, it still contains silicates and some aluminates (Table 3). The CKD is thus also mostly independent of the soil particles. Notably, CKD has shown to be effective as a single binder in several types of soils, although it is still less effective than C as a single binder [11–13, 49].

In organic soils and gyttja, humic acids are known to react with $Ca(OH)_2$ and thus slows the soil−binder reaction, and a similar strength development as in inorganic clay is thus not expected. This is also demonstrated by several authors where an increase in organic content typically yield lower strength development than in inorganic soils, e.g. [45, 50, 51]. This is also the case for QL as a single binder, which has shown to be particularly poor in organic soils, e.g. [52, 53].

It can thus be hypothesised that replacing QL, an ineffective binder for the clay presented herein, with CKD should result in at least an equally strength development when used in a 50%/50% composition with C. This is also seen in the database, Figs. 6, 7, 8, where there is negligible difference in strength and stiffness properties between 50C/50QL and 50C/50CKD. In fact, 50C/50CKD perform even slightly better than 50C/50QL in some cases, e.g. strain at failure and strength in organic clays and gyttja. Increasing the proportion of C, however, resulted in a somewhat higher strength development.

Recently, Hov et al. [43] performed an analysis of a Norwegian clay improved using a binder with varying compositions of C, QL and lime kiln dust (LKD). The LKD is an industrial by-product of QL production and consist mainly of calcium carbonate ($CaCO_3$) and has thus no active CaO available to a binder−soil reaction. It was shown that when replacing QL with LKD, the strength was reduced, i.e. the factor A (Eq. 4) was lower. The total binder content was then corrected for the active CaO content, and a unique strength vs. *wbr* correlation was found. This could be done since LKD only acts as a filler, and replacing QL with LKD thus decreases both strength and carbon dioxide emissions. This is however only valid for lime-based binders. Herein, the cement-based binder CKD is used, and it is shown that the strength development is not affected by replacing QL with CKD, i.e. they give the same factor A (Eq. 4) as seen in Fig. 8(a) and (b). This is probably because CKD, in addition to the active CaO, also contains silicates and some aluminates available for reaction. Thus, even though the CKD contains a lower amount of active CaO than QL, this is compensated by the fact that QL alone is an ineffective binder in this type of clay, as previously mentioned [45, 48]. The carbon dioxide emission is however nonetheless reduced, meaning that CKD seemingly yields a higher strength gain per unit carbon dioxide emission than LKD. It has been shown that this applies to both inorganic clay and organic clay and gyttja.

In addition to CKD and LKD, there exists a large variety of other industrial by-products suitable for improvement of soft clays, e.g. fly ash, ground-granulated blast-furnace slag and phosphogypsum. How these compare to the data presented herein is not known; however, it is vital that detailed laboratory studies are performed to investigate their performance in the types of Swedish clays used in this study.

Another important factor to consider in engineering practice, besides the impact on carbon dioxide emissions, is the cost effectiveness of the different binders and industrial by-products. This has however turned out to be difficult to generalise as the cost is highly dependent on their availability and the geographical location, which also will affect the total costs of the soil improvement. These considerations are out of scope for this study and has thus not been analysed.

Conclusions

This paper presents a large database on lime-cement improved soft Swedish clays where strength and stiffness properties have been evaluated and analysed. The study has resulted in a valuable contribution to the effectiveness of various binders in various types of natural clays, both inorganic and organic, including gyttja. The use of *wbr*, typically used only for wet deep mixing (WDM), is shown to be a useful tool also for DDM applications. In addition, several useful correlations between key parameters are presented which will serve as useful guidance for DDM design purposes.

The following main conclusions are drawn:

- The relationship between the Youngs' modulus E_{50} and strength q_u showed little difference between different binder or soil types. On average, $E_{50} \approx 100 \times q_u$.
- Strains at failure (ε_f) increases with increasing organic content; however, there are no considerable differences for different binder types. On average, ε_f of improved clays is similar to natural clays, indicating strain compatibility for design purposes in active loading.
- Strength development from 7 to 28 days of curing ($q_{\mathrm{u}(28)}/q_{\mathrm{u}(7)}$) varies little with binder and soil type, however, the quotient increases somewhat with decreasing strength after 7 days of curing ($q_{u(7)}$). In practice, $q_{\mathrm{u}(28)}/q_{\mathrm{u}(7)} \approx 1.6$ is found to be a good approximation for most of the soils and binder types, although the scatter is very large.
- The concept of water−binder ratio (*wbr*) is considered applicable to DDM. It was found that Abrams' [40] formulation ($q_u = A/B^{wbr}$) can be used, and that the factor A depends on soil and binder type, binder content, etc. The factor B however appears to be constant and was shown to be around 1.24.

As a general conclusion, no significant difference on strength and stiffness properties can be seen between the three main binder types in the database, i.e. 50C/50QL, 50C/50CKD and 70C/30QL. It is hypothesised that replacing QL with CKD in a 50/50 mixtures with C does not affect strength development, since QL is known to be ineffective in the type of clay presented herein. This shows that the usage of industrial by-products, specifically cement kiln dust (CKD) in this case, can give equivalent engineering properties as traditional binders also in organic clays and gyttja, whilst importantly reducing carbon dioxide emissions.

Although the results from a specific database strictly only applies to the available dataset, i.e. lime-cement improved East Swedish soft clays prepared in laboratory, it is believed that the main findings and patterns are applicable to other similar types of soft clays as well. Specific testing should however always be performed before applying the findings to other types of clays.

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Declarations

Conflict of Interest The authors did not receive support from any organisation for the submitted work. The authors have no relevant financial or non-financial interests to disclose.

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