Transportation Geotechnics 42 (2023) 101090

Contents lists available at ScienceDirect

Transportation Geotechnics

journal homepage: www.elsevier.com/locate/trgeo

Investigating strength development over time of industrial by-products using the resonance column free-free technique

Solve Hov [a,*], Masaki Kitazume [b], David Gaharia [c], Kristina Borgström [d], Tony Forsberg [d]

[a] *Norwegian Geotechnical Institute, Geotechnics and Natural Hazards, Trondheim, Norway*
[b] *Kitazume Geotechnics, 2-43-2 Nakashirane, Asahi, Yokohama 241-0004, Japan*
[c] *LabMind AB, Geotechnical Laboratory, Fannys väg 3, 131 54 Nacka, Sweden*
[d] *GeoMind AB, Fannys väg 3, 131 54 Nacka, Sweden*

ARTICLE INFO

Keywords:
Soil improvement
Laboratory tests
Resonance column free-free test
Compressive strength
Strength development over time

ABSTRACT

Soil improvement using cementitious binders is used throughout the world to improve the strength and stiffness characteristics of soft soils. Strength verification is typically performed using unconfined compression tests; however, these are destructive and do not give detailed information on strength development over time. This note presents a laboratory investigation using the non-destructive resonant column free-free (RC-ff) technique to assess the primary wave velocity. This velocity is correlated to strength, and hence strength development over time can be investigated in detail using this simple and effective technique. Two soft clays, one inorganic and one organic, were improved with the industrial by-products cement kiln dust and ground-granulated blast-furnace slag in combination with cement. A semi-theoretical correlation between primary wave velocity and strength is proposed, and it is seen that this correlation is independent of these soil and binder types. This also applied to the seismic small-strain compressive modulus. The strength development up to 91 days of curing was investigated and it was seen that this highly depends on binder type, but to a lesser degree soil type. It is demonstrated that the RC-ff technique can be of great value both in engineering practice and research.

Introduction

The deep mixing (DM) method is used throughout the world to improve the strength and deformation characteristics of soft soils [1,2]. One of the most common applications is within the transportation sector where DM is used extensively to e.g., improve the stability and reduce settlements of railway and road embankments, and for foundations of bridges and other infrastructures. The method is performed by mechanically mixing either a water-cement slurry into the soil, referred to as the wet method, or mixing only a dry binder into the soil, referred to as the dry method. The traditional binders used to produce cementitious products in the natural soils are cement (C) and quicklime (QL), and the strength gain of improved soils using these binders have been shown to depend on e.g. soil type, binder type and quantity, degree of mixing, curing and testing conditions, etc. [1,3–5].

Many studies have been made to replace the traditional binders with industrial by-products in attempts to lower the carbon dioxide emissions of the DM method. Examples of these are ground-granulated blast-furnace slag (GGBS) [6–8], cement kiln dust (CKD) [4,9,10], and fly ash [11,12]. Unconfined compression (UC) tests are typically performed to investigate the strength gain after a curing period of 28 days, similar to normal practice in the concrete industry. However, it is also important to study the gradual strength development over time, both in practice where this can highly affect construction timelines and thus costs, and in research where this can give valuable insights into the soil-binder reactions and the cementation process. The strength development over time can in principle be obtained by UC tests on replicate specimens [13–20], but on the other hand, uncertainties of variability is introduced, in addition to time-consuming laboratory work.

Non-destructive geophysical testing techniques can be employed to measure compressive wave (V_p) or shear wave (V_s) velocities over time on the same specimen, eliminating any effects of variability of replicates [21,22]. These velocities are thereafter correlated to the unconfined compressive strength (UCS; q_u) which can be plotted against curing time. Most of these techniques, e.g., bender elements, are however time-consuming and pose challenges both in interpretation of wave arrival times and sufficient contact between a curing specimen and the piezoelectric elements.

A simpler and more effective non-destructive alternative is the

* Corresponding author.
E-mail address: solve.hov@ngi.no (S. Hov).

https://doi.org/10.1016/j.trgeo.2023.101090
Received 11 April 2023; Received in revised form 14 August 2023; Accepted 19 August 2023
Available online 20 August 2023

List of notations

α	Binder quantity [kg/m^3]
E_{50}	Secant Youngs' modulus to 50% peak strength [kPa or MPa]
V_p	Compression wave velocity (primary wave) [kPa]
f_P	Resonant frequency [1/s]
q_u	Unconfined compressive strength (UCS) [kPa]
w_N	Natural water content [%]
C	Cement
CKD	Cement kiln dust
DDM	Dry deep mixing
GGBS	Ground-granulated blast-furnace slag
WDM	Wet deep mixing
L	Specimen length [m]
wbr	Water to binder ratio, weight ratio [-]

Table 1
Basic properties of the two soils.

Parameter	Clay	Gyttja
Unit weight, kN/m^3	14.9	13.0
Water content, %	94–96	147–159
Liquid limit, %	~95	~150
Unimproved shear strength, kPa	10–15	4–8
Remoulded shear strength, kPa	~1	1.5–2
Organic content, %	~2	~8

Table 2
Chemical composition of the binders.

Oxide	CEM II	CKD	GGBS
CaO, %	60.0	52.3	36.0
SiO_2, %	21.0	15.5	36.0
Al_2O_3, %	5.0	3.6	10.0
Fe_2O_3, %	2.3	2.1	0.4
MgO, %	2.9	2.7	13.0
Alkali, %	0.9	10.0	1.0

resonance column free-free (RC-ff) technique, which can be used to assess V_p at various curing times on one specimen, and hence the strength development over time can be investigated. The applicability of this technique for soil improvement have been seen in several studies [23–27], however, none of these have studied the strength development over time and how this varies depending on soil and binder type, e.g., the effectiveness of different industrial by-products. One exception is the work by Lindh [28–30]; however, the strength difference over time for varying by-products was not studied.

This note presents a study on the strength development over time using the industrial by-products GGBS and CKD in combination with C. Two natural soft Swedish clays are improved; one inorganic clay simply referred to as 'clay', and one organic clay referred to as 'gyttja'. In addition to their natural state, water was added to some specimens to simulate the effect of change in water content when using the wet method as compared to the dry method. The RC-ff technique was performed on specimens at different curing times from 7 days of curing up to 91 days of curing. The V_p was used to assess the strength development over time, in addition to investigating the seismic small-strain compressive modulus E_{max}. UC tests were performed on specimens at 28 and 91 days of curing to establish a correlation between V_p and q_u, and to obtain the large-strain Youngs' modulus up to 50% peak strength (E_{50}).

The simplicity and effectiveness of the RC-ff technique is demonstrated, as well as how it can be used to study the stabilisation effect of industrial by-products in different soil types. It is seen that there is a clear difference in strength over time, which need to be considered in engineering practice. Further, a semi-theoretical correlation between q_u and V_p is proposed, and it is seen that this better fit the data than previously proposed pure empirical correlations. It is believed that the results presented herein is valuable to both practitioners and researchers of soil improvement.

Materials and methods

The soils used in this study were collected from a near-shore site in Stockholm, located in south-eastern Sweden. The water depth at the site is around 10 m, and the stratigraphy consists of around 5–6 m gyttja, an organic clay consisting of around 8% organic content and a natural water content (w_N) of around 150%. The gyttja is categorised as 'OH' according to the unified soil classification [31]. The gyttja is underlain by around 10–12 m 'inorganic' clay with around or less than 2% organic content and a w_N of around 95%, categorised as 'CH' [31]. Both have an intact undrained shear strength classified as extremely to very low according to EN ISO 14688–2. Basic properties of the soils are shown in Table 1. Two batches were made for each soil type from which soil samples was extracted to perform the laboratory mixing works.

The binders used for the improvement consisted of C and the industrial by-products CKD and GGBS. The C was a standard Portland cement CEM II [32] and the CKD a kiln dust from cement production, both obtained from the cement manufacturer Cementa Sweden. The GGBS, a by-product produced by iron blast furnaces in the iron manufacturing industry, was obtained from Thomas Concrete Group Sweden. Table 2 show the chemical composition of the binders. The binders were combined in three different compositions: 100% CEM II (designed 100C), 50% C and 50% CKD (designated 50C/50CKD) and 30%C and 70% GGBS (designated 30C/70GGBS). The binder quantity (α) was varied between 90 and 400 kg of dry binder per m^3 soil.

The mixing was performed by first homogenising the natural soil for around 3–5 min using a kitchen mixer with a K-type paddle assisted manually with a spatula when necessary, whereupon the dry binder was added. To simulate the effect of change in water content for the wet

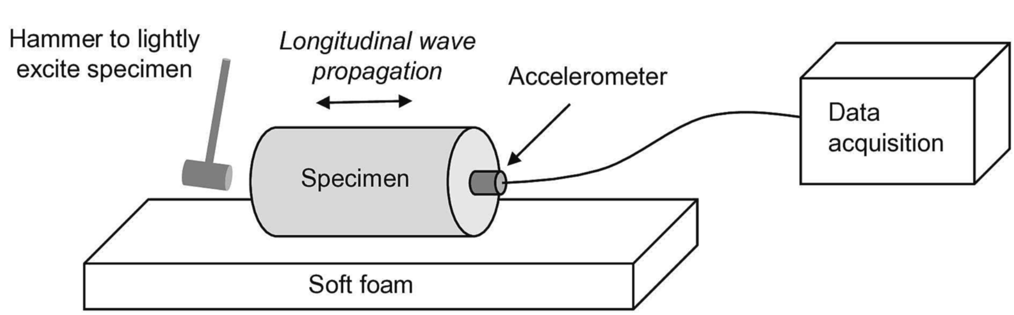

Fig. 1a. Illustration of the RC-ff method.

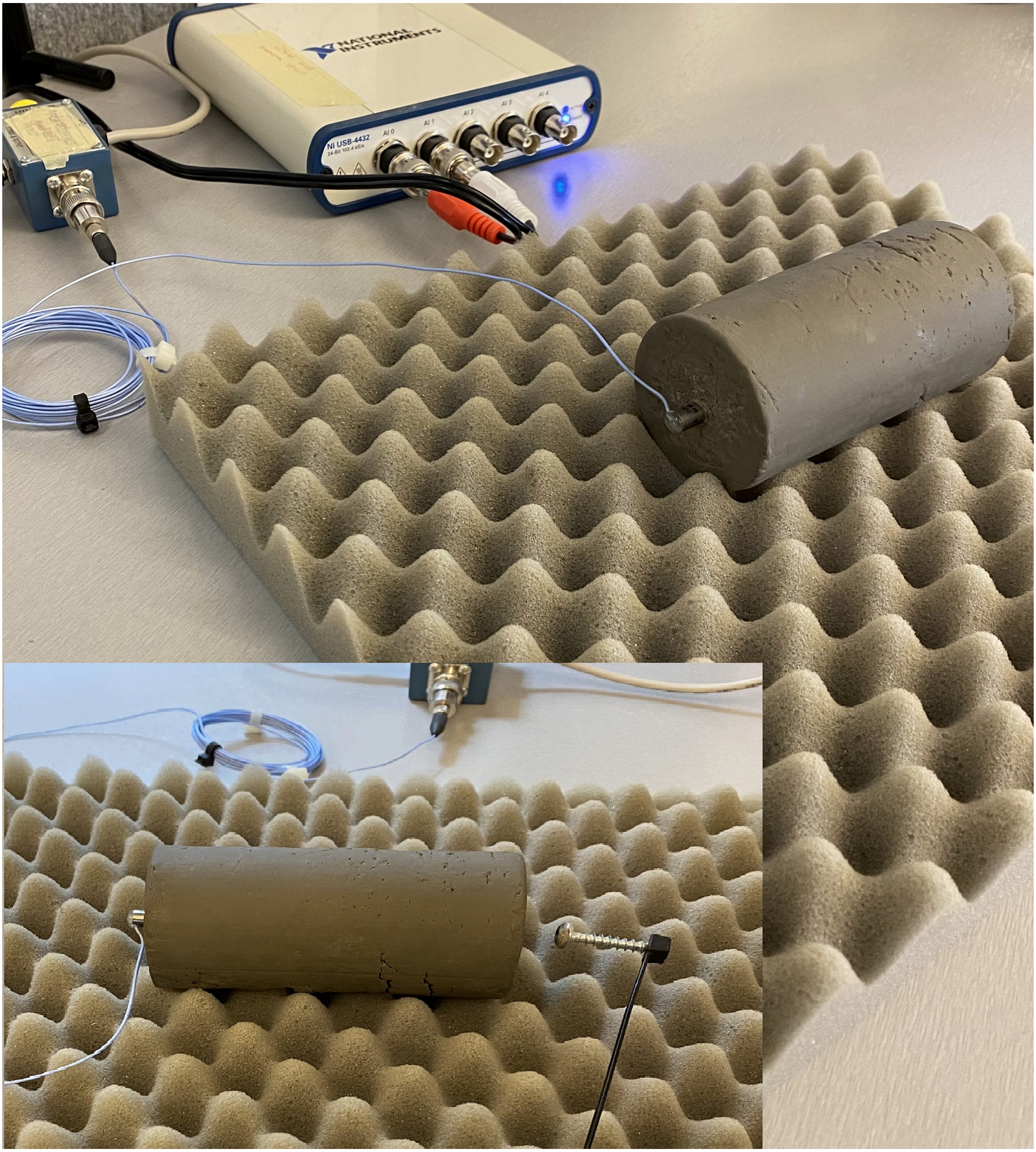

Fig. 1b. Photograph of the RC-ff method in use.

mixing method, water was added to a few specimens prior to the dry binder and homogenised with the soil, highlighted in figure legends by "-WC adj". The weight of water was 0.7–0.8 times the added dry binder quantity. The mixtures were then homogenised for around 5 min and subsequently moulded in plastic cylinders using the rodding technique [33]. The total time from start of mixing to completion of moulding was within 20–30 min. All specimens were cured for 3 days in the cylinders, after which they were carefully extracted and thereafter cured in watertight plastic bags to allow for RC-ff testing. All specimens had a diameter of 50 mm and a height of approximately 100 mm and were cured in room temperature. Three replicate specimens were made for each mixing combination, where two were cured for 28 days and then tested with the RC-ff test and UC tests. The final specimen was cured for 91 days and tested with the RC-ff technique at 7, 14, 28, 56 and 91 days, when a UC test also was performed.

RC-ff measurements are performed on improved cylindrical speci-

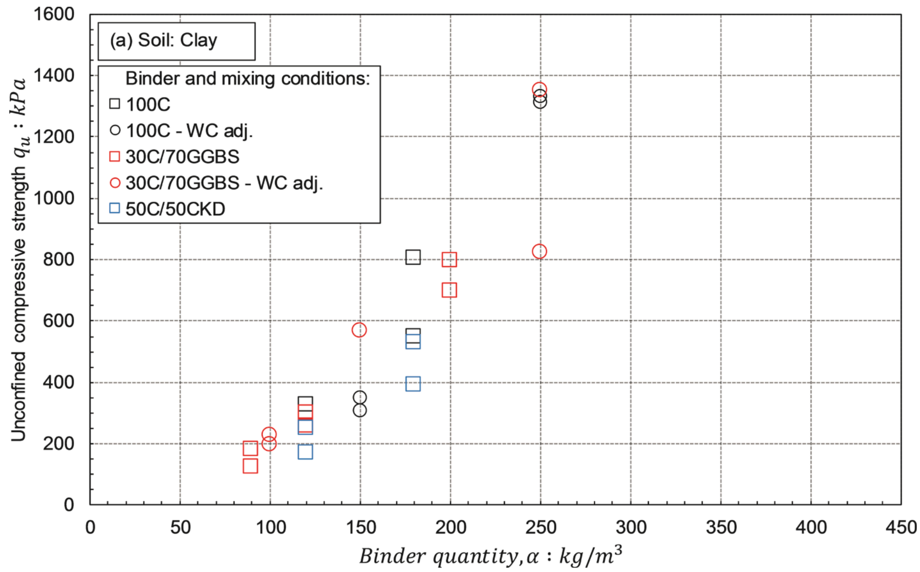

Fig. 2a. Binder quantity α vs. strength q_u for all clay specimens cured at 28 days (30C/70S = 30% cement / 70% slag, 100C = 100% cement, 50C/50CKD = 50% cement / 50% CKD).

mens lying on a soft foam. A light impact is executed at one end whilst measuring the amplitude at the other end using an accelerometer or a geophone. The impact creates longitudinally transmitted compression waves, also referred to as primary waves, and a natural resonant frequency is obtained as the specimen has free-free boundary conditions both in longitudinal and transversal direction. Using a fast-Fourier transform, the amplitudes are obtained in the frequency domain, and once the resonant frequencies are detected, the V_p can be calculated according to equation 1: $V_P = 2Lf_P$, where L is the specimen length and f_P is the resonant frequency [34]. A similar standardised test procedure also exists for concrete testing [35].

The RC-ff technique is illustrated and shown in Figs. 1a and 1b. In this study, a lightweight accelerometer 352B10 from PCB Electronics with 2–10,000 Hz frequency range and a National Instrument vibration device USB-4432 was used. It thus requires little equipment. The time for execution is short, typically a few minutes including specimen preparation. Very strong correlation between V_p and q_u have been shown [24,27], and the increase in V_p over time can thus be used to assess the strength (q_u) development over time. It should be noted that it is also possible to obtain the shear wave velocity by using the RC-ff method, however, this has not been done in this study.

Results and discussion

Figs. 2a and 2b plots strength gain (q_u) after 28 days of curing for clay and gyttja, respectively. A similar trend of q_u vs. α for all binder combinations in the clay was seen, although 50C/50CKD seemed to be in the lower range. For the gyttja, however, there were large differences

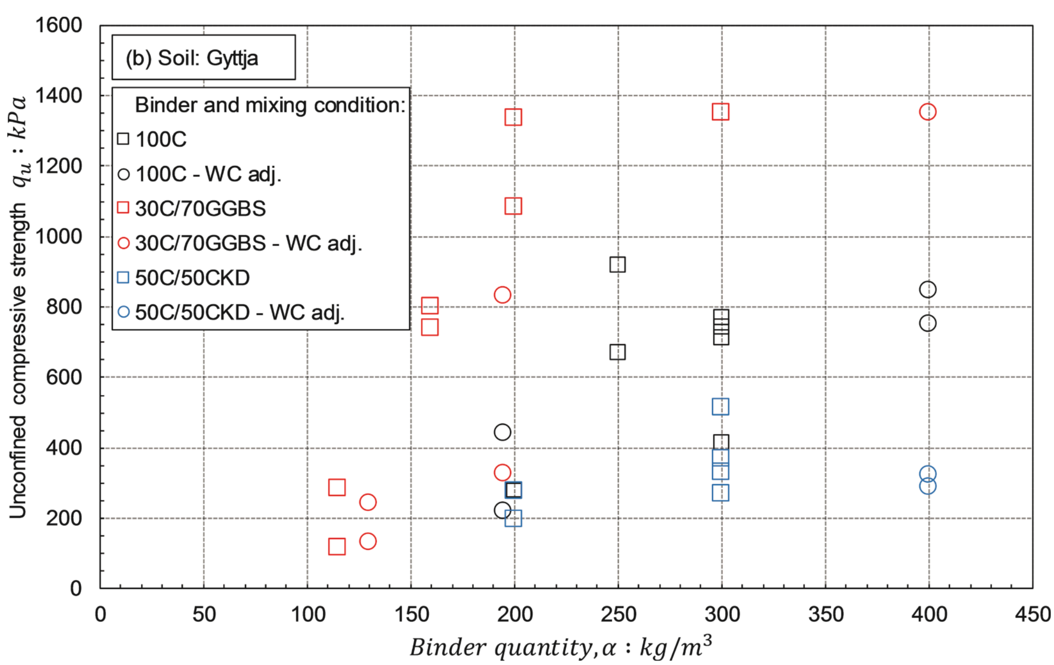

Fig. 2b. Binder quantity α vs. strength q_u for all gyttja specimens cured at 28 days (30C/70S = 30% cement / 70% slag, 100C = 100% cement, 50C/50CKD = 50% cement / 50% CKD).

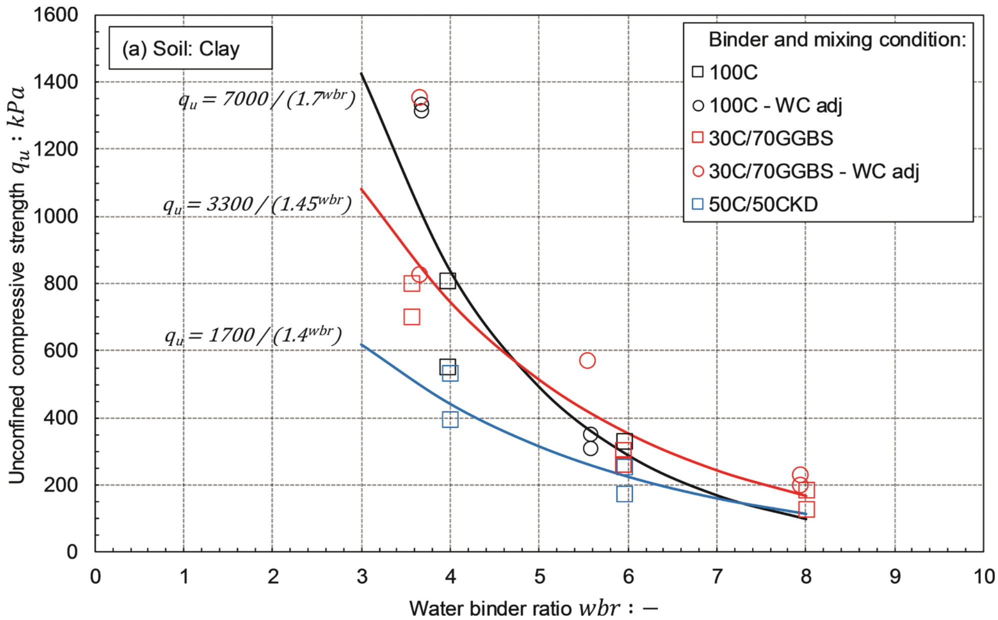

Fig. 3a. Water-binder ratio *wbr* vs. strength q_u for all clay specimens cured at 28 days (30C/70S = 30% cement / 70% slag, 100C = 100% cement, 50C/50CKD = 50% cement / 50% CKD).

between the binder combinations. It was seen that the 30C/70GGBS gave considerably higher q_u for a certain α. The strength gain can be explained using the water to binder ratio (*wbr*), defined as the ratio of total mass of water (originating from its natural content and any added water) and the dry mass of binder [1,13,20]. Results of q_u vs. *wbr* is therefore shown in Figs. 3a and b for clay and gyttja, respectively. An expected decrease in q_u was obtained with increasing *wbr*, irrespective of the type of soil and binder as also reported by e.g. [13,20,36–38]. For the clay, Fig. 3a, the binder 100C showed the largest strength and 50C/50CKD showed the lowest strength when the *wbr* was small, but the strength gain was almost in the same order irrespective of the binder type when the *wbr* became large. For gyttja, Fig. 3b, a similar phenomenon was observed; however, the 30C/70GGBS showed the largest strength gain almost throughout the whole *wbr* range. Further, there was no significant difference in strength gain as the water content was adjusted for either the clay or the gyttja, independent of the type of binder. There was a large scatter in the results; however, they nonetheless give clear indications of differences and similarities of type of method and type of binder.

Based on the RC-ff results, the small-strain seismic compression modulus (E_{max}) can be calculated according to elastic theory, equation 2:$E_{max} = \rho V_p^2$, where ρ is the bulk density. Fig. 4a plots results of q_u vs. E_{max} for all specimens. Here, E_{max} ranged between 600 and 1,300 times q_u where the average relationship was $E_{max} \approx 860 q_u$. In practice, the small-strain shear modulus (G_{max}) is more used for design, but since the Poisson's ratio (υ) for stabilised soils has been shown to vary between ~ 0.25 and ~ 0.45 [1,39], the G_{max} was calculated to range from ~ 300 to ~ 360 times q_u (equation 3: $G_{max} = E_{max}/2(1+\upsilon)$). This is in the range as reported by other researchers on C and QL improved clays, and shows that the correlations are valid also for industrial by-products and for

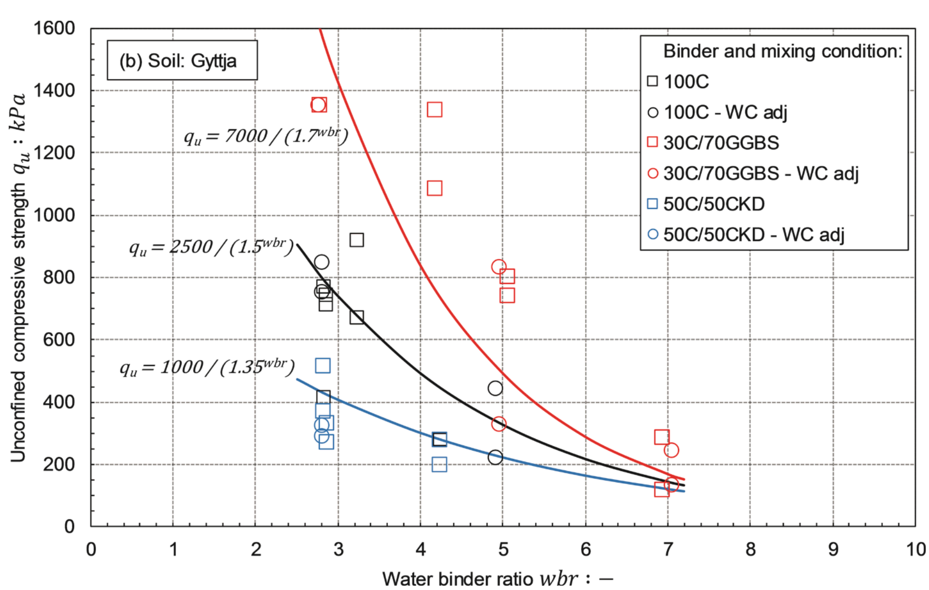

Fig. 3b. Water-binder ratio *wbr* vs. strength q_u for all gyttja specimens cured at 28 days (30C/70S = 30% cement / 70% slag, 100C = 100% cement, 50C/50CKD = 50% cement / 50% CKD).

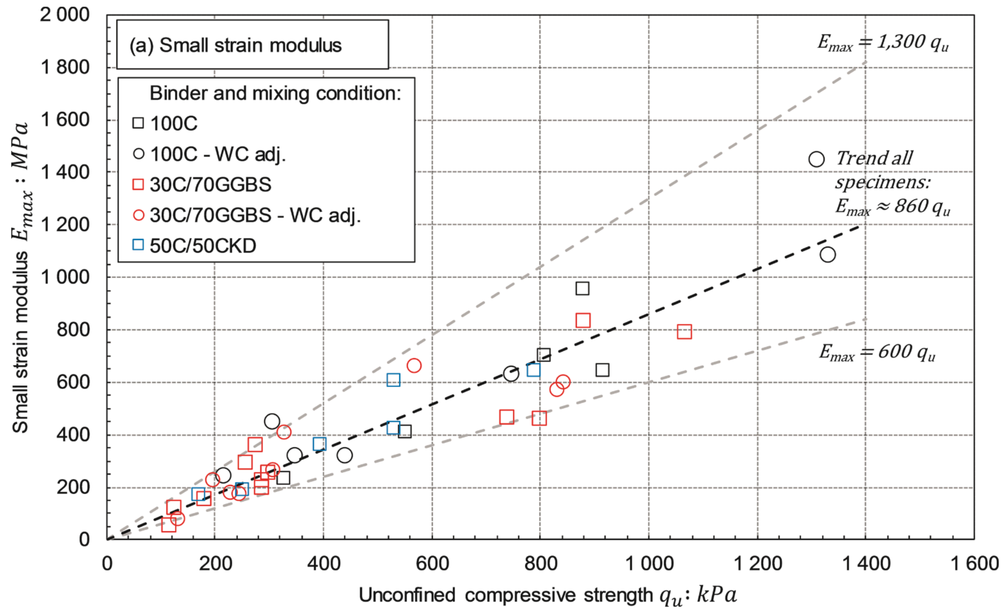

Fig. 4a. Strength q_u vs. small-strain modulus E_{max} for all specimens.

both inorganic and organic clays.

For comparison, Fig. 4b plots q_u vs. the large-strain modulus, i.e.,E_{50}. The type of soil gave slightly different linear trends where on average $E_{50} \approx 140 \times q_u$ was seen for the clay and $E_{50} \approx 110 \times q_u$ for the organic gyttja. These are similar values as seen previously on soft Swedish clays [4,14] where q_u typically is below 1,000 kPa, but lower than several other studies where the q_u typically is considerably higher than 1,000 kPa [40,41]. The ratio between the large and small strain moduli, E_{50} and E_{max} was on average around 6–8.

Fig. 5 shows results of V_p vs. q_u for all specimens tested at 28 and 91 days of curing. Previously proposed correlations between V_p and q_u found in literature are purely empirical; however, by a theoretical consideration, q_u should be squared of V_p (equation 2), assuming a linear correlation between q_u and E_{max} which is evident based on Fig. 4a. A strong correlation using this theoretical principle is seen which fit the data well, equation 4: $q_u \approx 0.0015 V_p^2$, where the factor 0.0015 was found to match the empirical data well. It was not dependent on soil or binder type, neither on any adjustment of water content. The correlation deviates somewhat from the previously empirical correlations seen for C and QL improved clays [27,28], however, it better fit the data and was valid over a large strength interval where q_u ranges from around 100 kPa to close to 1,400 kPa. The data shows that V_p from the RC-ff technique can be used to study the strength development over time with high confidence.

Based on this semi-theoretical correlation, Fig. 6 plots the strength development over time, calculated by equation 4, for the different binder combinations. It is seen that most specimens improved with 100C exhibited a very early strength increase, with one exception, whilst the 30C/70GGBS and 50C/50CKD had a slower strength development at early curing age. In fact, for the RC-ff technique, it is difficult to measure V_p for very soft specimens since they need to keep their shape without support (free-free boundary conditions), and hence some specimens

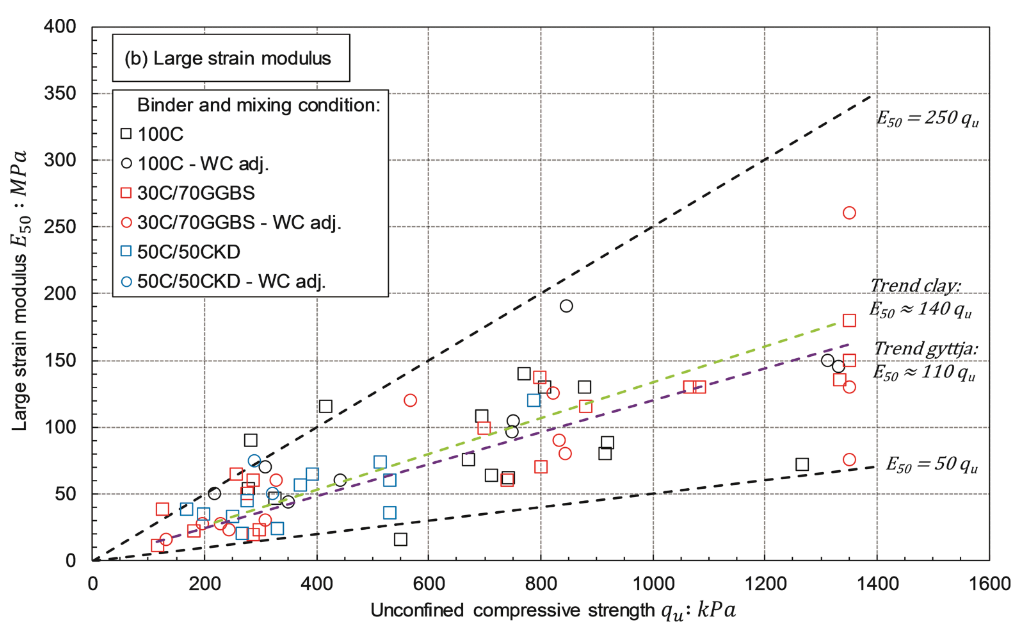

Fig. 4b. Strength q_u vs. large strain modulus E_{50} for all specimens.

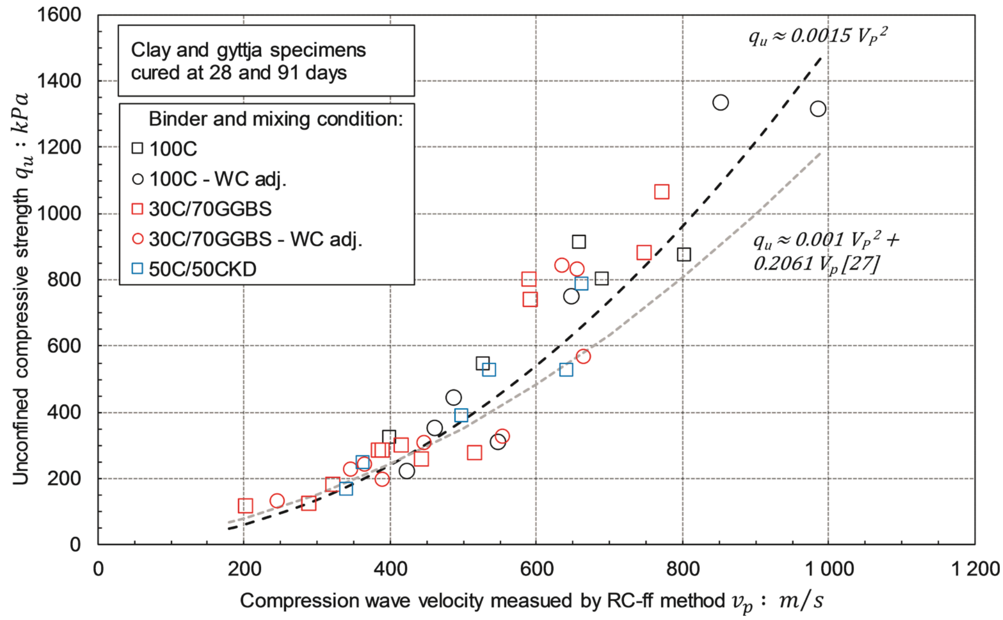

Fig. 5. Primary wave velocity V_p vs. strength q_u for specimens cured at 28 and 91 days.

could not be measured at very early curing age. The undrained shear strength immediately after mixing was however assessed using the Swedish fall cone method to around 1–6 kPa for all mixing combinations, a method also employed by other researchers at early curing age [21]. There were however no correlations between this immediate strength gain and strength after longer curing time.

Strength results over timer are in Fig. 7 normalised to the strength at 28 days of curing to better understand the differences. Most 100C specimens gained around 0.5–0.6 of the strength at 28 days of curing, i.e., the strength increase from 7 to 28 days of curing was 50–100%. From 28 to 91 days of curing however, the increase was only 0–30%. This is expected since the cement hydration reaction is fast, which also has been shown in other studies on soil improvement [4,13]. For 100C, the strength development in general follows the relationship $q_{u(t)} = 0.3\ln(t)q_{u(28)}$ proposed by Åhnberg [14].

The strength development in specimens improved with 30C/70GGBS were considerably slower. This is caused by the fact that there is a lower amount of cement hydration reactions products causing strength gain at early ages. Instead, reactions with GGBS are highly governed by slow pozzolanic reactions which typically occur after about 4 weeks. Up to 28 days of curing, the strength gain was nearly linear, where after it gradually decreased in rate. The increase from 28 to 91 days of curing was large, between 70% and 130%, illustrating the importance of taking this into consideration. Specimens improved with 50C/50CKD exhibited

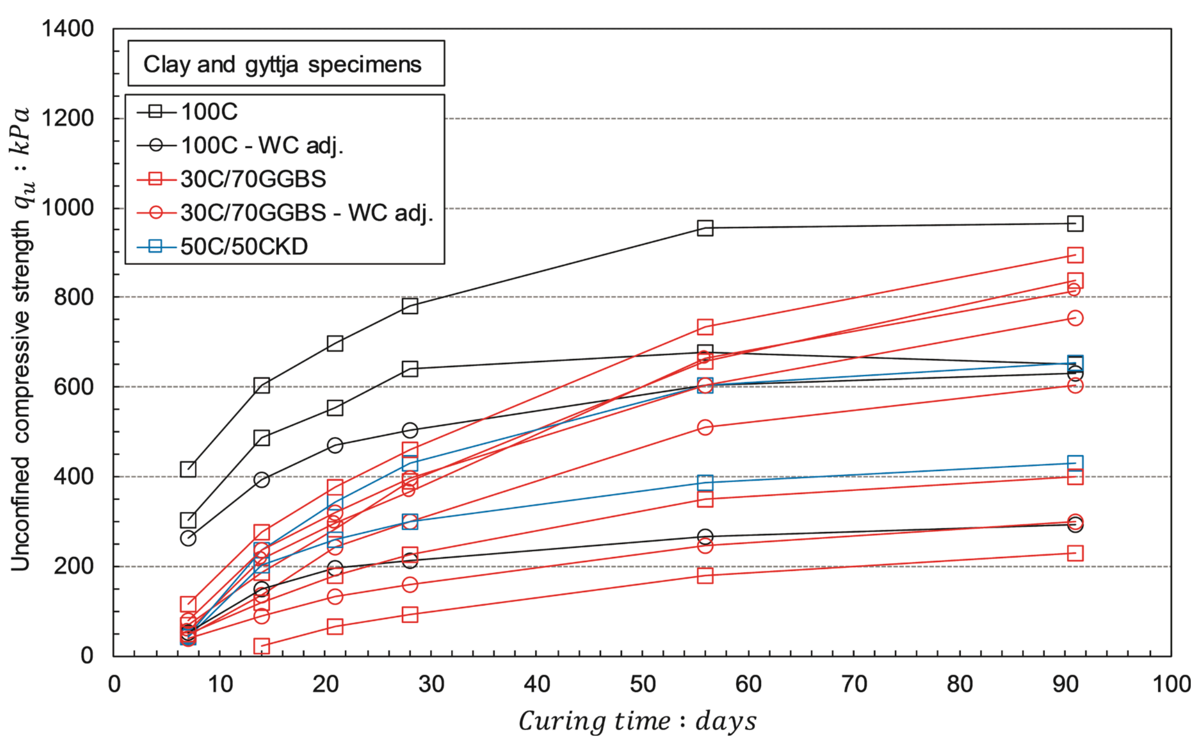

Fig. 6. Strength q_u vs. curing time. q_u is calculated by equation 4.

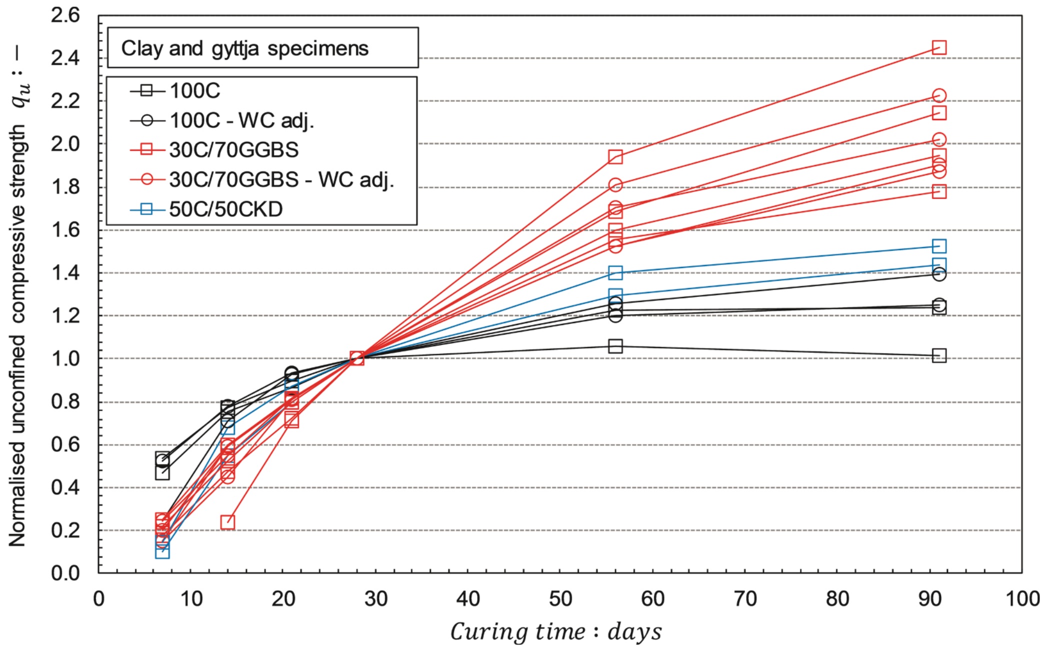

Fig. 7. Strength q_u normalised to strength at 28 days of curing vs. time.

a strength development in between these two extremes, which is reasonable since the proportion of C also is in between.

Concluding remarks

This paper presents a laboratory study comparing different binders using the RC-ff geophysical technique. It is demonstrated that the RC-ff is a simple and effective technique which require very little effort but give highly valuable information on for example strength development over time. This can be used in practice to assess the performance of different by-products and if and how this will affect construction timelines and costs. Notably, the RC-ff tests can be performed on both laboratory-prepared specimens or samples extracted from field, allowing practitioners to adjust execution or binder quantities in early stages of the quality control and assurance procedure. In fact, the strong correlation between V_p and q_u means that even the absolute strength value can be assessed with this non-destructive technique. In research, the value primarily lies in the complementary data one obtains to better assess soil-binder reactions and the cementation process.

The results presented herein can be summarised as follows:

- A semi-theoretical correlation ($q_u \approx 0.0015V_p^2$) is proposed and was found to be independent on type of soil or if the water content of the natural soil was adjusted. It was also independent of type of binder, in this case C and the industrial by-products CKD and GGBS.
- The small-strain compressive modulus E_{max} was shown to be on average around 860 times q_u, compared to E_{50} which was 110–140 times q_u. This is somewhat lower than many other studies but is believed to be caused by the lower q_u for the specimens tested herein.
- The type of binder highly affects strength development over time. Specimens improved with C followed a logarithmic strength increase, but specimens containing CKD and GGBS exhibited a slower strength development. For 30C/70GGBS, the increase from 28 to 91 days of curing was 70–130%, illustrating the importance of taking this into consideration in engineering practice as this can reduce total binder quantities considerably compared to normal testing procedures.

CRediT authorship contribution statement

Solve Hov: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft. **Masaki Kitazume:** Formal analysis, Writing – review & editing. **David Gaharia:** Resources, Investigation, Validation. **Kristina Borgström:** Supervision, Project administration. **Tony Forsberg:** Conceptualization, Methodology.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgements

The authors are grateful to Martin Holmén at the Swedish Geotechnical Institute who introduced the RC-ff technique to the geotechnical laboratory LabMind in Stockholm. The meticulous laboratory work of the co-workers at LabMind is also appreciated. The contribution by the anonymous reviewers giving constructive comments is also acknowledged.

References

[1] Kitazume M, Terashi M. The Deep Mixing Method. London: Taylor & Francis Group; 2013.
[2] S. Larsson, The Nordic dry deep mixing method - best practices and lessons learned, Proceedings of Deep Mixing '21, Deep Foundations Institute, 2021, p. 1219–1248.
[3] Paniagua P, Bache BK, Karlsrud K, Lund AK. Strength and stiffness of laboratory-mixed specimens of stabilised Norwegian clays. Proc. Inst. Civ. Eng.: Ground Improvement 2022;175:150–63. https://doi.org/10.1680/jgrim.19.00051.
[4] Hov S, Larsson S. Strength and Stiffness Properties of Laboratory-Improved Soft Swedish Clays. Int. J. Geosyn. Ground Eng. 2023;9(11). https://doi.org/10.1007/s40891-023-00432-3.
[5] Horpibulsuk S, Rachan R, Suddeepong A. State of the art in strength development of soil-cement columns. Proc. Inst. Civ. Eng.: Ground Improvement 2012;165(4):201–15. https://doi.org/10.1680/grim.11.00006.

[6] Xu B, Yi Y. Soft clay stabilization using ladle slag-ground granulated blastfurnace slag blend. Appl Clay Sci 2019;178:105–36. https://doi.org/10.1016/j.clay.2019.105136.
[7] Sharma AK, Sivapullaiah PV. Strength development in fly ash and slag mixtures with lime. Proc. Inst. Civ. Eng.: Ground Improvement 2016;169(3):194–205. https://doi.org/10.1680/jgrim.14.00024.
[8] Yi Y, Liska M, Jin F, Al-Tabbaa A. Mechanism of reactive magnesia – ground granulated blastfurnace slag (GGBS) soil stabilization. Can Geotech J 2016;53(5):773–82. https://doi.org/10.1139/cgj-2015-0183.
[9] Yoobanpot N, Jamsawang P, Horpibulsuk S. Strength behavior and microstructural characteristics of soft clay stabilized with cement kiln dust and fly ash residue. Appl Clay Sci 2017;141:146–56. https://doi.org/10.1016/j.clay.2017.02.028.
[10] Behnood A. Soil and clay stabilization with calcium- and non-calcium-based additives: A state-of-the-art review of challenges, approaches and techniques. Transp Geotech 2018;17:14–32. https://doi.org/10.1016/j.trgeo.2018.08.002.
[11] Mypati VNK, Saride S. Feasibility of Alkali-Activated Low-Calcium Fly Ash as a Binder for Deep Soil Mixing. J Mater Civ Eng 2022;34(1). https://doi.org/10.1061/(ASCE)MT.1943-5533.0004047.
[12] Sukmak P, Horpibulsuk S, Shen SL. Strength development in clay-fly ash geopolymer. Constr Build Mater 2013;40:566–74. https://doi.org/10.1016/j.conbuildmat.2012.11.015.
[13] Horpibulsuk S, Miura N, Nagaraj TS. Assessment of strength development in cement-admixed high water content clays with Abrams' law as a basis. Géotechnique 2003;53(4):439–44. https://doi.org/10.1680/geot.2003.53.4.439.
[14] Åhnberg H. Strength of stabilised soils - A laboratory study on clays and organic soils stabilised with different types of binder. PhD Thesis. Lund University; 2006.
[15] Di Sante M, Bernardo D, Bellezza I, Fratalocchi E, Mazzieri F. Linking small-strain stiffness to development of chemical reactions in lime-treated soils. Transp Geotech 2022;34:100742. https://doi.org/10.1016/j.trgeo.2022.100742.
[16] Sasanian S, Newson TA. Basic parameters governing the behaviour of cement-treated clays. Soils Found 2014;54(2):209–24. https://doi.org/10.1016/j.sandf.2014.02.011.
[17] Wang Y, Benahmed N, Cui YJ, Tang AM. A novel method for determining the small-strain shear modulus of soil using the bender elements technique. Can Geotech J 2017;54(2):280–9. https://doi.org/10.1139/cgj-2016-0341.
[18] Locat J, Berube MA, Choquette M. Laboratory investigations on the lime stabilization of sensitive clays: shear strength development. Can Geotech J 1990;27(3):294–304. https://doi.org/10.1139/t90-040.
[19] Kang G, Tsuchida T, Athapaththu AMRG. Strength mobilization of cement-treated dredged clay during the early stages of curing. Soils Found 2015;55(2):375–92. https://doi.org/10.1016/j.sandf.2015.02.012.
[20] Yamashita E, Cikmit A, Tsuchida T, Hashimoto R. Strength estimation of cement-treated marine clay with wide ranges of sand and initial water contents. Soils Found 2020;60(5):1065–83. https://doi.org/10.1016/j.sandf.2020.05.002.
[21] Seng S, Tanaka H. Properties of Cement-Treated Soils During Initial Curing Stages. Soils Found 2011;51(5):775–84. https://doi.org/10.3208/sandf.51.775.
[22] Kang GO, Tsuchida T, Kim YS. Strength and stiffness of cement-treated marine dredged clay at various curing stages. Constr Build Mater 2017;132:71–84. https://doi.org/10.1016/j.conbuildmat.2016.11.124.
[23] Lindh P, Lemenkova P. Shear bond and compressive strength of clay stabilised with lime/cement jet grouting and deep mixing: A case of Norvik. Nynäshamn Nonlinear Engineering 2022;11(1):693–710. https://doi.org/10.1515/nleng-2022-0269.
[24] Guimond-Barrett A, Nauleau E, le Kouby A, Pantet A, Reiffsteck P, Martineau F. Free-free resonance testing of in situ deep mixed soils. Geotech Test J 2013;36(2):283–91. https://doi.org/10.1520/GTJ20120058.
[25] Schaeffer K, Bearce R, Wang J. Dynamic Modulus and Damping Ratio Measurements from Free-Free Resonance and Fixed-Free Resonant Column Procedures. J Geotech Geoenviron Eng 2013;139(12):2145–55. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000945.
[26] Toohey NM, Mooney MA. Seismic modulus growth of lime-stabilised soil during curing. Géotechnique 2012;62(2):161–70. https://doi.org/10.1680/geot.9.P.122.
[27] Åhnberg H, Holmén M. Assessment of stabilised soil strength with geophysical methods. Proc. Inst. Civ. Eng.: Ground Improvement 2011;164(GI3):109–16. https://doi.org/10.1680/grim.2011.164.3.109.
[28] Lindh P, Lemenkova P. Resonant Frequency Ultrasonic P-Waves for Evaluating Uniaxial Compressive Strength of the Stabilized Slag-Cement Sediments. Nordic Concrete Research 2021;65(2):39–62. https://doi.org/10.2478/NCR-2021-0012.
[29] Lindh P. Alternative laboratory moulding of stabilised soil [In Swedish]. Linköping: Swedish Geotechnical Institute; 2017.
[30] Lindh P, Lemenkova P. Dynamics of Strength Gain in Sandy Soil Stabilised with Mixed Binders Evaluated by Elastic P-Waves during Compressive Loading. Materials 2022;15(21):7798. https://doi.org/10.3390/MA15217798.
[31] ASTM International, "ASTM D2487 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)." West Conshohocken, PA., 2020.
[32] European Committee for Standardization, "EN 197-1 Cement - Part I: Composition, specifications and conformity criteria for common cements." 2011.
[33] Kitazume M, Grisolia M, Leder E, Marzano IP, Correia AA, Oliveira PV, et al. Applicability of molding procedures in laboratory mix tests for quality control and assurance of the deep mixing method. Soils Found 2015;55(4):761–77. https://doi.org/10.1016/j.sandf.2015.06.009.
[34] Verástegui-Flores RD, Di Emidio G, Bezuijen A, Vanwalleghem J, Kersemans M. Evaluation of the free-free resonant frequency method to determine stiffness moduli of cement-treated soil. Soils Found 2015;55(5):943–50. https://doi.org/10.1016/j.sandf.2015.09.001.
[35] ASTM International. Standard Test Method for Fundamental Transverse, Longitudinal and Torsional Resonant Frequencies of Concrete Specimens. ASTM C215-19 2020. West Conshohocken, PA. https://doi.org/10.1520/C0215-19.
[36] Kitazume M, Satoh T. Development of a pneumatic flow mixing method and its application to Central Japan International Airport construction. Proceedings of Institution of Civil Engineers: Ground Improvement 2003;7(3):139–48. https://doi.org/10.1680/grim.2003.7.3.139.
[37] K. Yoneda Investigation of strength property of stabilized soil [In Japanese] Proceedings Geotechnical Forum 2011 Japan.
[38] Hov S, Paniagua P, Sætre C, Rueslåtten H, Størdal I, Mengede M, et al. Lime-cement stabilisation of Trondheim clays and its impact on carbon dioxide emissions. Soils Found 2022;62(3). https://doi.org/10.1016/j.sandf.2022.101162.
[39] H. Åhnberg, M. Holmén, Laboratory determination of small-strain moduli in stabilized soils, Proceedings International Symposium on Deformation Characteristics of Geomaterials 2018, vol. 1, p. 291–297, Amsterdam: IOS Press.
[40] A. Niina S. Saitoh R. Babasaki T. Miyata K. Tanaka Engineering properties of improved soil obtained by stabilizing alluvial clay from various regions with cement slurry [In Japanese] 1981 Japan.
[41] M. Terashi T. Okumura T. Mitsumoto Fundamental properties of lime-treated soils [In Japanese] 1977 Japan.