Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-541

ECSMGE 24
XVIII EUROPEAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Improving the remoulded shear strength of a quick clay using biochar

Améliorer la résistance au cisaillement remodelée d'une argile rapide à l'aide de biochar

E.W. Ånes*
Norwegian Geotechnical Institute (NGI), Oslo, Norway
Oslo Metropolitan University, Oslo, Norway

J.I. Loshelder
University of Arkansas, Fayetteville, Arkansas, USA

S. Hov, P. Paniagua
NGI & Norwegian University of Science and Technology (NTNU), Trondheim, Norway

S. Ritter
NGI & Oslo Metropolitan University, Oslo, Norway

**eivind.wiik.aanes@ngi.no*

ABSTRACT: In the pursuit of finding a less carbon-intensive binder alternative to cement, an ongoing research project in Norway is investigating the effect on properties of various soft soils when substituting parts of the cement with industrial by-products and biochars. This paper considers how three biochars influence the soil properties of a Norwegian quick clay when acting as the only binder. The practical application would first and foremost be to ease the handling and transportation of excavated quick clay by increasing its remoulded shear strength. The laboratory study determined that the biochar that yielded the lowest shear strength when added alongside cement had the distinctly largest positive influence when added alone. At a quantity of 100 kg/m^3, this particular biochar, made from calcinated sewer sludge, increased the fall cone shear strength of the remoulded clay from an average of 2.3 kPa to 85.0 kPa after 28 days of storage, and to above 100 kPa after 90 days. The follow-up unconfined compression tests only revealed shear strengths of 19.5-31.4 kPa, indicating serious method-dependency. Nevertheless, the calcinated sewer sludge biochar appears as a sustainable binder option to lime and cement when aiming at improving the shear strength of already excavated sensitive soils.

RÉSUMÉ: Dans la recherche d'une alternative de liant moins intensive en carbone que le ciment, un projet de recherche en cours en Norvège étudie l'effet sur les propriétés de divers sols souples lors du remplacement de parties du ciment par des sous-produits industriels et des biochars. Cet article examine comment trois biochars influencent les propriétés du sol d'une argile rapide norvégienne lorsqu'ils agissent comme seul liant. L'application pratique serait principalement de faciliter la manipulation et le transport de l'argile rapide excavée en augmentant sa résistance au cisaillement remaniée. L'étude en laboratoire a déterminé que le biochar qui a donné la plus faible résistance au cisaillement lorsqu'il était ajouté avec du ciment a eu l'influence positive la plus marquée lorsqu'il était ajouté seul. À une quantité de 100 kg/m^3, ce biochar particulier, issu de la calcination des boues d'égout, a augmenté la résistance au cisaillement du cône de chute de l'argile remaniée d'une moyenne de 2,3 kPa à 85,0 kPa après 28 jours de stockage, et à plus de 100 kPa après 90 jours. Les tests de compression non confinée de suivi n'ont révélé que des résistances au cisaillement de 19,5 à 31,4 kPa, indiquant une sérieuse dépendance à la méthode. Néanmoins, le biochar de boues d'égout calcinées apparaît comme une option de liant durable par rapport à la chaux et au ciment lorsqu'on vise à améliorer la résistance au cisaillement des sols sensibles déjà excavés.

Keywords: Quick clay; biochar; remoulded shear strength; fall cone test; unconfined compression test.

1 INTRODUCTION

Quick clays, recognized by their collapsible nature when disturbed or loaded beyond the yield strength, are found in urbanised areas in Scandinavia and Canada, as well as in parts of Russia. Groundworks in these areas typically require the soil to be stabilised, and often the dry deep mixing method is preferred. An ongoing research project in Norway investigates whether various industrial by-products and biochars may replace parts of the lime and cement to reduce the considerable CO_2 impact of the method. To be used in dry deep mixing, the alternative binders however should not degrade the engineering performance, and at the very least the resulting shear strength should surpass the in-situ undisturbed shear strength. In practice, this excludes several of the alternative binders and limits the amount of lime and cement that may be replaced. However, there are other uses that do not require the same engineering performance. In projects which include excavation of soil, the quick or soft clay above the final excavation level is sometimes mixed with a reduced binder (typically lime and cement) quantity to facilitate easier excavation and transport to a landfill. For these cases, the shear strength is only required to increase to a level where the soil becomes plastic rather than liquid, and easy and safe to handle and transport.

Biochars are materials made from heating organic masses in the absence of oxygen. Contrary to most industrial by-products proposed to be used as alternative binders, biochars sequester carbon that would otherwise have been emitted to the atmosphere. Thus, the use of biochars to stabilise soils can even have a carbon-negative footprint if enough of the cement and/or lime is replaced (Hov et al., 2023). This makes biochars especially interesting as alternative binders.

Findings from unconfined compression tests by Hov et al. (2023) and Ritter et al. (2023a) highlight that the effect of biochars on the strength and stiffness of soft soils depends heavily on the biochar and soil type, as well as on the added cement and biochar quantities (with both having an optimal amount).

Of the in total five tested biochars in the two studies, none were found to give more than a modest strength increase compared to when cement was added alone. Also, two of the biochars were found to have a negative influence. Hov et al. (2023) discussed that the water adsorption ability of the biochars is likely important to the stabilising effect when added alongside cement. While only one biochar was added without cement by Ritter et al. (2023a), none of the four biochars used by Hov et al. (2023) were added without cement. Thus, the knowledge of the individual effect of biochars on the properties of remoulded quick clays is limited.

The described research investigated how three of the biochars used along with cement by Hov et al. (2023) impacted the fall cone shear strength, $s_{u,FC}$, of the tested quick clay when added alone. The study was initiated as a cost- and material-effective way to provide a reference for the cement and biochar stabilised samples as well as to compare the individual effect of the different biochars.

2 METHODOLOGY

2.1 Materials

The soil used was a quick clay from the Norwegian GeoTest Site (NGTS) at Tiller-Flotten, Trondheim, in Norway. The clay from this site was well characterised by L'Heureux et al. (2019) and has previously been used for similar research (e.g. Hov et al., 2022, 2023; Paniagua et al., 2023; Ritter et al., 2022, 2023a). Tube samples from 14-18 m depth were mixed until visually homogenised. The quick clay from this depth has a clay content of around 50-60%, organic content < 1%, water content w = 40-45%, bulk density 18-18.5 kN/m^3, plasticity index I_P between 10-15%, liquidity index I_L around 1.5-2.0, undisturbed shear strength s_u (from unconfined compression and fall cone tests) approximately between 50 and 85 kPa, sensitivity $S_t >$ 30. A stiffness E_{50} of around 2.5 MPa has been measured for this clay (Ritter et al., 2023a).

All three biochars were produced at temperatures around 470-600 °C in a full-scale micro-wave-assisted pyrolysis (MAP) unit with a residence time of ~20 minutes (Hov et al. 2023). The three biochars (BC) originated from: BC1 - demolition wood such as wood panels, furniture etc., containing some metals and glue remains; BC2 - slightly decayed bottom sludge from municipal sewage with around 39wt.% of limestone, $CaCO_3$, added for hygenisation and workability before the sludge was used for biochar production; BC3 - sewage and food waste, with iron chloride ($FeCl_3$) added for flocculation. Before mixing, the biochars were sieved to grain sizes < 1 mm and oven-dried at 100 °C over night. Their respective specific surface areas (SSA) were measured to be 38.5, 54.8 and 51.3 m^2/g by adsorption of gas and calculated according to Brunauer-Emmet-Tellet theory (Hov et al., 2023). In terms of major elements present, determined by X-ray fluorescence, the most notable differences were high contents of CaO ($CaCO_3$) in BC2, and ferric oxide (Fe_2O_3) in BC3 (Hov et al., 2023).

2.2 Sample preparation and lab testing

For the main testing regime in which the shear strength was tested by the fall cone (FC) method, 29 samples were prepared. The quick clay and biochars were mixed by a Kenwood kitchen mixer according to standard Norwegian lime-cement stabilisation lab procedures (NGF, 2012). Seven mixtures were prepared: two of each biochar, with quantities of 50 and 100 kg/m^3, and one without binder. Following the mixing, around 150 g samples were prepared by pouring/scooping the mixtures into small aluminium containers (see Figure 1). The samples were then sealed and left for storage in room temperature (around

20 °C). For each of the biochar-stabilised mixes, four samples were prepared: three to be tested after 28 days of storage, and one to be tested after 90 days. The test regime consisted of calculating water content (NS-EN ISO 17892-1:2014, NS, 2014), performing fall cone shear strength tests in stored undisturbed and remoulded states (Norwegian correlation developed for testing natural soils, NS 8015:1988; NS, 1988), as well as determining the liquid (w_L) and plastic (w_P) limits (NS-EN ISO 17892-12:2018; NS, 2018). The Atterberg limits were only tested after 28 days of storage, on material from two of the prepared FC samples after FC testing.

Because the BC2 gave unexpectedly high fall cone strengths, three 10 cm unconfined compression (UC) samples were prepared with 100 kg/m^3 of BC2 to provide strength and stiffness values directly comparable to those from Hov et al. (2023). They were tested after 14, 28 and 90 days of curing at room temperature, using a strain rate of 3.8% of the height per minute (NS-EN ISO 17892-7:2017; NS, 2017).

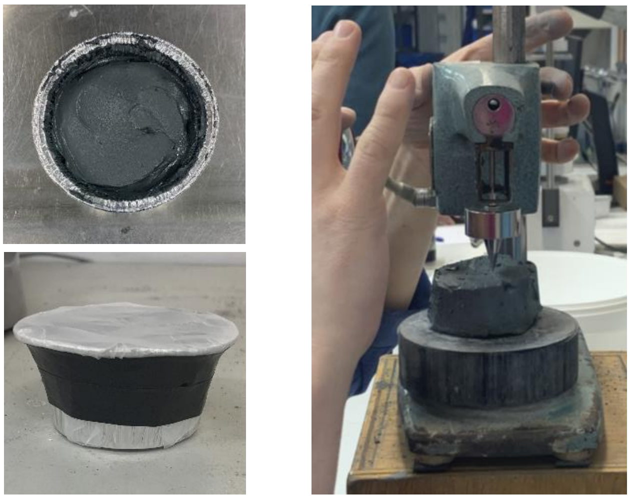

Figure 1. (Upper left) a prepared sample before storage, (lower left) a sealed, prepared sample, and (right) an extracted sample being tested in "undisturbed" state.

3 RESULTS AND DISCUSSION

Figure 2 presents the water contents and liquid and plastic limits. The FC samples with no added binder had a water content varying from 39.6% (1 day) to 37.5% (90 days), indicating that the latter sample might have experienced some drying. For the other samples, this trend was not observed, and the water contents varied insignificantly. The lower water contents when the biochars were added can be explained by the increased dry mass while keeping the amount of water constant. The higher water contents measured for the UC samples can likely be explained by less water being evaporated during mixing and storing.

Considering the Atterberg tests, BC2 had a considerably more prominent effect than BC1 and BC3, both in terms of increasing the liquid (w_L) and plastic (w_P) limits as well as the plasticity index. Although the BC1 and BC3 performed similar, BC1 was the least effective. Even when adding 100 kg/m^3 BC1, the samples still had a water content $w > w_L$.

Figure 3 presents key results from the fall cone (FC) and unconfined compression (UC) tests. Table 1 summarizes all shear strength test results. Every biochar increased the FC shear strengths compared to the non-stabilised remoulded samples. However, BC2 had a greater effect than BC1 and BC3, corresponding with the respective influences on the plasticity. The strength increase caused by BC2 began immediately upon mixing. While all biochars gave a larger strength increase at 100 kg/m^3 than at 50 kg/m^3, the effect was most pronounced for BC2 and BC3, where s_u more than doubled.

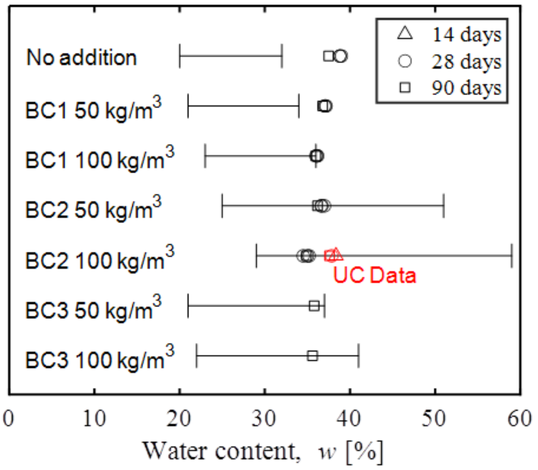

Figure 2. Measurements of w (symbols), and w_P and w_L.

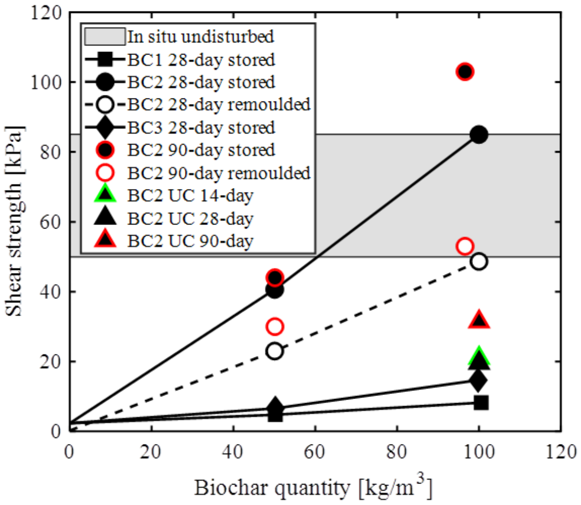

Figure 3. Key shear strength results.

Table 1. Fall cone and unconfined compression test results. Triplicate FC samples were tested after 28 days. All other shear strength results were from one sample/test. Shear strength from UC tests were derived as half the unconfined compression strength (UCS /2).

Binder	**Quantity**	**Fall cone (FC)**				**Unconfined compression (UC)**	
		Stored		**After remoulding**		**Stored**	
		s_u 28 / 90 days	**St. dev.** 28 days	s_u 28 / 90 days	**St. dev.** 28 days	***UCS/2*** 14 / 28 / 90 days	***E50*** 14 / 28 / 90 days
[-]	**[kg/m3]**	**[kPa]**				**[kPa]**	
None	-	2.3 / 3.3	0.12	0.2 / 0.6	0.05		
BC1	50	4.8 / 7.7	0.24	1.4 / 3.6	0.24		
	100	8.2 / 15	1.58	2.2 / 7.5	1.58		
BC2	50	40.7 / 44	1.70	23 / 30	1.70		
	100	85 / 103.0	2.83	48.7 / 53	2.83	21 / 19.5 / 31.4	220 / 450 / 1600
BC3	50	6.6 / 15	0.43	3.6 / 9	0.43		
	100	14.7 / 27	1.70	7.9 / 16	1.70		

The reasons why BC2 had a greater effect than the other two biochars have not yet been understood. Some aspects which may explain the observed differences will be discussed in the following.

3.1 Remoulding and time-dependency

Every FC sample experienced a decrease in shear strength upon remoulding. However, all stabilised samples retained a shear strength above the quick clay threshold of 0.5 kPa. As every sample was essentially remoulded upon storing, the reduction indicated a time-dependent strength increase during storing, even for the non-stabilised samples. This thixotropic tendency was also indicated by comparing FC and UC results after 28 and 90 days of storage. Only one sample from each series was tested after 90 days, but the fact that an increase was seen for all series, and that the loss of water content was negligible, strongly implies that there were active processes that increased the strength of the particle structures also after 28 days. How the binders themselves contributed to these processes are difficult to assess based on the results presented herein. It is nevertheless worth noting that percentagewise, both BC1 and BC3 provided a larger increase in stored shear strength from 28 to 90 days than BC2 (83 and 84% vs. 21% for the FC samples, respectively, and 61% for the UC samples). This could indicate that the processes providing the immediate (or short-term) and the time-dependent strength increase are not the same. Alternatively, the processes caused by additions of BC1 and BC3 may have initially been moving slower than when BC2 was added. The stabilising effects of BC2 are further discussed in Section 3.3.

3.2 Fall cone vs. unconfined compression tests

Studies have determined the correlation between unconfined compression tests and fall cone tests to be strongly soil dependent (e.g. Tanaka et al., 2012). From the results presented in this paper, it is also observed that the correlation is distant from 1:1. For example, the average $s_{u,FC}$ of the BC2 100 kg/m^3 samples after 28 days of storage was around 4×*UCS/2*. Part of the discrepancy is likely due to differences in sample preparation, sample size, and test method. Also, the fact that the framework for determining shear strength from fall cone tests was developed for natural soils, and not reconstituted ones, might be part of the explanation.

3.3 Biochar and cement vs. biochar

Not surprisingly, the biochar-stabilised samples exhibited much lower shear strengths than when 50 kg/m^3 of cement was included in the binder mixture (Hov et al., 2023, see Table 2). For BC2-stabilised samples after 28 days of storage, the addition of cement gave approximately a 20-fold increase of *UCS/2* compared to when only the biochar was used (396 kPa vs. around 20 kPa). The stiffness, E_{50}, of the BC2 samples was between 220 – 450 kPa, less than 1/50 of the BC2- and cement samples and less than the in-situ stiffness (2 500 kPa). After 90 days of storage, the *UCS/2* and E_{50} increased to 31.4 kPa and 1 600 kPa respectively which was still below the in-situ values.

Table 2. Extract of results from (Hov et al., 2023). Average shear strength and stiffness values from unconfined compression tests performed after 28 days of storage.

Cement	**Biochar**	***UCS/2*** **[kPa]**	E_{50} **[kPa]**
50 kg/m^3	-	460	118 000
50 kg/m^3	100 kg/m^3 BC1	396	102 000
50 kg/m^3	100 kg/m^3 BC2	166	25 000
50 kg/m^3	100 kg/m^3 BC3	217	41 000

Possibly the most surprising finding when comparing the two studies was that BC2 was the least effective biochar when used together with cement but the most effective one when added alone. It is unclear whether this is related to the biochar properties, such as water retention, or the constituents available for chemical reactions. Considering the latter, it may imply that the chemical compounds in BC2 are more active than those from the other biochars, and that the chemical compounds, or the chemical reactions which they are involved in, may obstruct the curing of the cement. However, Hov et al. (2023) discussed that the BC2 had no cementitous properties, as calcium is only present as calcite ($CaCO_3$) and not calcium oxide (CaO). Microstructural analyses, e.g. with a scanning electron microscope, could provide further insight into the mechanisms involved.

3.4 Implications for the use of the biochars

The calcinated sewer sludge biochar (BC2) notably increased the shear strength and plasticity of the remoulded Tiller-Flotten quick clay. As the strength increase began immediately after mixing in the lab, this biochar could be used as an alternative to lime and cement to stabilise already excavated soft and quick clays. Even at 50 kg/m^3 (or even lower), the instant improvement of the Tiller-Flotten clay would likely be enough to quickly make the clay safe and practical to handle and transport. While the other biochars could in theory also be used for this purpose, a larger quantity of biochar would be required. Further analyses should look at the economic implications due to the actual costs of biochar production.

Recently, the possibility to reuse excavated soils, instead of depositing them at landfills, has gained some attention. For example, an ongoing research project in Norway is investigating whether excavated lime and cement stabilised clays may be utilised as compacted clay liners at landfills (Ånes et al., 2024; Ritter et al., 2023b). In this regard, it could be interesting to explore how clays stabilised with biochars or other alternative binders compare to clays stabilised with lime and cement. If alternative binders are found to be better for this or other purposes, thus increasing the usability of the excavated mass, it could be an incentive for construction projects to rather use such binders to stabilise soft and quick clays after excavation.

4 CONCLUSION

All three biochars had a positive effect on the shear strength of the remoulded quick clay. Additions of 50 and 100 kg/m^3 of BC2 and BC3 stabilised the clay to above the quick clay threshold of $s_{u,\ remoulded} > 0.5$ kPa, as well as $w > w_L$. Samples with BC1 only surpassed the first criterion. BC2 had the distinctly most positive effect and increased the average fall cone shear strength after 28 days of storage from 2.3 kPa to 85 kPa, and *UCS/2* to around 20 kPa.

BC2 seems to be a viable climate-friendly alternative to lime and cement to improve the handling and transportation of quick and soft clays after excavation. The field performance including environmental and economic aspects of using BC2 as an alternative binder to improve remoulded quick clay should be studied further.

The reasons for the superior effects caused by BC2 compared to BC1 and BC3 have not yet been determined. Potential explanations could be a higher water retention capacity of BC2, or that BC2 contains constituents that react chemically when added to clay. However, from the performed chemical and mineralogical analyses by Hov et al. (2023), there are no obvious differences between BC2 and the other biochars to suggest this. Scanning electron microscope should be used to study the microstructure of stabilised samples to help expose the mechanisms.

ACKNOWLEDGEMENTS

This research was funded by Research Council of Norway, grant number 328767 "GOAL – Green soil stabilisation". The authors are especially grateful to Ingrid Peikli, Karl Sigmundstad Halse, and Maria Cansignia at the NGI geotechnical laboratory in Oslo for performing the laboratory tests.

REFERENCES

Ånes, E. W., Ritter, S., Pabst, T., Stridal, A. C., Nilsen, N. G., Hovland, K., & Okkenhaug, G. (2024). Utilisation of geological surplus masses in landfill cover: percolation results from pilot test. *Proceedings of the XVIII ECSMGE 2024*.

Hov, S., Paniagua, P., Sætre, C., Rueslåtten, H., Størdal, I., Mengede, M., & Mevik, C. (2022). Lime-cement stabilisation of Trondheim clays and its impact on carbon dioxide emissions. *Soils and Foundations*, *62*(3). https://doi.org/10.1016/j.sandf.2022.101162.

Hov, S., Paniagua, P., Ritter, S., Sætre, C., Long, M., & Cornelissen, G. (2023). Stabilisation Of Soft Clay, Quick Clay And Peat By Industrial By-Products And Biochars. *Applied Sciences*, *13(16)*.

L'Heureux, J.-S., Lindgård, A., & Emdal, A. (2019). The Tiller-Flotten research site: Geotechnical characterization of a very sensitive clay deposit. *AIMS Geosciences*, *5*(4), 831–867. https://doi.org/10.3934/geosci.2019.4.831.

NGF (Norwegian Geotechnical Society) (2012) Veiledning for grunnforsterkning med kalksementpeler. Guidelines for ground improvement with lime- and cement-piles (in Norwegian). Oslo, Norway.

NS (Standard Norge) (1988) 8015:1988 Geoteknisk prøving – Laboratoriemetoder – Bestemmelser av udrenert skjærstyrke ved konusprøving. Geotechnical testing – Laboratory methods – Determination of undrained shear strength by fall cone (in Norwegian). Standard Norge, Lysaker, Norway.

NS (2014) ISO 17892-1 Geotechnical investigation and testing – Laboratory testing of soil – Part 1: Determination of water content. Standard Norge, Lysaker, Norway.

NS (2017) ISO 17892-7 Geotechnical investigation and testing – Laboratory testing of soil – Part 7: Unconfined compression test. Standard Norge, Lysaker, Norway.

NS (2018) ISO 17892-12 Geotechnical investigation and testing – Laboratory testing of soil – Part 12: Determination of liquid and plastic limits. Standard Norge, Lysaker, Norway.

Paniagua, P., Ritter, S., Moseid, M., & Okkenhaug, G. (2023). Bioashes and Steel Slag as Alternative Binders in Ground Improvement of Quick Clays. *Proceedings Geo-Congress 2023*, 25–34. https://doi.org/doi.org/10.1061/9780784484661.003.

Ritter, S., Paniagua, P., Hansen, C. B., & Cornelissen, G. (2022). Biochar amendment for improved and more sustainable peat stabilisation. *Proceedings of the Institution of Civil Engineers: Ground Improvement*. https://doi.org/10.1680/jgrim.22.00023.

Ritter, S., Paniagua, P., & Cornelissen, G. (2023a). Biochar in Quick Clay Stabilization: Reducing Carbon Footprint and Improving Shear Strength. *Geo-Congress 2023*.

Ritter, S., Wiik Ånes, E., Hovland, K., Stridal, A. C., Hansen, H., Henriksen, T., & Okkenhaug, G. (2023b). Sustainable impermeable landfill barriers: The potential of using geological waste and surplus masses. *9th International Congress on Environmental Geotechnics (ICEG2023)*. https://doi.org/10.53243/ICEG2023-102.

Tanaka, H., Hirabayashi, H., Matsuoka, T., & Kaneko, H. (2012). Use of fall cone test as measurement of shear strength for soft clay materials. *Soils and Foundations*, *52*(4), 590–599. https://doi.org/10.1016/j.sandf.2012.07.002.