USING WOOD-BASED BY-PRODUCTS FOR IMPROVEMENT OF QUICK CLAYS

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KEYWORDS

Quick clays, bioashes, LCA, ground improvement, laboratory analyses

ABSTRACT

To improve the engineering performance of quick clays, the dry deep soil mixing method is applied using binders (lime, cement) which production is associated to large CO2-emissions. Therefore, there is a strong interest in finding alternative binders accompanied by integral analyses including the production, transport, installation, and performance of such materials during ground improvement works. This study focuses on a large laboratory study of mixing wood-based by-products, also called bioashes, in two forms: bottom-ash and fly-ash, each one combined with cement, into quick clay to investigate the strength and deformation properties of the improved quick clay, as well as the leaching of contaminants for its environmental characterization. The laboratory study is complemented with a Life Cycle Analysis (LCA) on the use of bioashes for quick clay stabilisation . These findings reveal that bioashes may provide sustainable alternatives to lime or cement in soil stabilisation of quick clays.

1. INTRODUCTION

Quick clays are clay types characterized by a collapsible grain structure and a very low remoulded shear strength. They are mainly found in Norway, Sweden, Canada, and Russia, and can cause large and destructive landslides. To improve the engineering performance of such clays, several ground improvement methods are usually applied. One of them is the in-situ deep soil mixing with binders such lime, cement, or a combination of these. However, cement and quick lime production are associated to large CO2-emissions, and therefore, there is a strong interest in finding alternative binders accompanied of

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integral analyses including the production, transport, installation, and performance of such materials during ground improvement works.

The possibility of adding by-products in combination with cement or/and lime to modify the engineering properties of clays has been studied before (Wu et al., 2021; Åhnberg, 2006) and some specific research has been focused on the use of wood-based ashes or bioashes (FHWA, 2003; Vegdirektoratet, 2007; Bujulu, 2008; Deb and Pal, 2012; Rangaswamy, 2016; Islam et al., 2018; Cheng et al., 2018; Hov et al. 2023). Still research is needed on specific by-products and its application to quick clay stabilisation .

Recently Paniagua et al. (2023) presented proof-of-concept results when mixing four types of wood-based ashes and cement with quick clay. It was shown that the strength and stiffness of the original material increased, and that the materials leached elements in quantities below or close to the leaching limits, after the European regulation, for being disposed on inert landfills. Paniagua et al. (2023) study focused on comparing the performance of the different wood-based by-products and therefore, just one dosage amount and one binder ratio were used.

The present study takes further Paniagua et al. (2023) conclusions and performs a larger laboratory study using wood-based by-products in two forms: bottom-ash and fly-ash, each one combined with cement, Multicem® or cement and lime into quick clay. Different binder ratios and dosages were combined to investigate the strength and deformation properties of the improved quick clay with time. In this paper, the focus is given to the strength development with time for the stabilized material. The study also includes a Life Cycle Assessment (LCA) on the use of bioashes for quick clay stabilisation .

2. MATERIALS AND METHODS

Tiller-Flotten quick clay

The Tiller-Flotten quick clay is a low plastic marine clay with a clay content (fraction < 2 μm) of ~50-75% (L'Heureux et al., 2019). At the depth where samples were taken (i.e., 7-19 m), the water content of the clay is 40-50% and the unit weight is ~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%). Unconfined compression tests on specimens taken from block samples give an undrained active shear strength of 50-70 kPa and an elasticity modulus (E50) of 2,5 MPa.

Wood-based by-products

The wood-based by-products (bioashes) come from the combustion centre of Bergene Holm at Brandval, Norway. The bioashes were tested in two forms: fly ash (FA) and bottom ash (BA). They come from the combustion of wood at 1000-1200°C (i.e., boiler temperature) with a type of fuel composed by approx. 40% dry wood chips and approx. 60% bark. XRF and XRD analyses on the ashes show the main presence (> 45%) of calcium oxide (CaO) in the form of portlandite (Ca(OH)2) for BA and calcite ($CaCO_3$) for FA.

Other binders: cement, lime and Multicem®

The wood-based binders were mixed with either cement (CEM), Multicem (MC), or cement and lime (B80), in different proportions. The cement used was a Portland limestone cement (CEM II/A-LL 42.5 R) produced in Skövde, Sweden. The Multicem (MC) used combined cement and Cement Kiln Dust (CKD), which is a by-product from cement production, in a 50/50 proportion. The lime (B80) used contained 80% quick lime and 20% lime kiln dust and it is commercialized as Terraplus B80 (B80).

Sample preparation & testing program

The laboratory analysis included geotechnical and environmental tests performed at NTNUs Geotechnical Laboratory. Before mixing, both ashes were dried in an oven set to 50°C for 24 hours to remove any excess water content. They were sieved to a grain size < 250 µm. Particles between 250 µm and 2 mm were grinded to powder in a mortar before being sieved again to sizes < 250 µm.

The wood-based ashes were combined with the other binders in different ratios and with different binder contents. The binder content was varied around 60 kg/m³ since this recently is a typical amount used in quick clay stabilisation (Hov et al. 2022). Table 1 presents an overview of the laboratory program followed for preparation of specimens with either BA or FA (named A as a general form). Three samples were made in each combination type.

Table 1 Laboratory program with curing time in [days]

Binder type	Binder ratio [%]	Total binder content [kg/m^3]		
		40	60	80
CEM	100	28	---	---
CEM/A	50/50	7,14,28	7,14,28	7,14,28
	35/65	28	---	7,14,28
	25/75	7,14,28	7,14,28	7,14,28
	15/85	7*,14*,28	7,14,28	7*,14*,28
MC/A	50/50	7,14,28	7,14,28	7,14,28
CEM/B80/A	25/25/50	7,14,28	7,14,28	7,14,28

*Just BA samples

The stabilized soil samples had a diameter of 50 mm and a height of 100 mm and were prepared according to the procedure outlined in NGF (2012). The procedure consists of mixing the remoulded natural clay and the dry binder mixture for 2–4 min and then dynamically compacting the specimens in layers of around 20 mm within plastic moulds. The specimens were cured at 20°C.

The samples were then tested in unconfined compression (UC) tests after the curing times described in Table 1. Measurements of water content and density for all stabilized samples cured for 28 days were done prior UC testing. The pH after 28 days of curing was also measured in some selected samples.

Life Cycle Assessment (LCA)

An environmental evaluation on the utilization of bioashes was carried out by an LCA. This methodology considers the life cycle of the product under analysis, the environmental impact, and challenges of the associated processes to the product under study and quantifies such environmental burdens to make comparisons between the systems under analysis (Bjørn et al. 2018). A complete description of the performed LCA analysis is presented in Jafarbiglookarami (2021). Here, a summary of this analysis is given.

To define the scope of the study, the whole process was divided into three sub-systems. The first two systems explain the processes leading to the production of ashes and cement. The third system describes the in-situ processes for applying deep mixing stabilisation over one cubic meter (1 m^3) of stabilized soil. A comparative and attributional type of LCA is done and it is meant to be a cradle-to-site (Song et al. 2020). The use, maintenance and disposal of the material are not included in the boundaries of the study. The transport sector between the installation site and the ash/cement production plants are also omitted in the studied boundaries since this can vary according to the project location. The service life for the mixed soil is also not included in the analysis as the operational lifetime may vary to a great extent, and no information is available in this context regarding the wood ash mixture.

The Life Cycle Inventory (LCI) includes:

- Binders LCI: the ashes are considered a by-product and therefore the environmental loads can be ignored since they are transferred to another sector. The cement is the only source of environmental burdens from the binders. According to the Environmental Product Declaration for the cement used this study emits 620 g CO2-equivalent.

- Deep mixing LCI: Fig. 1 presents the system boundaries defined for evaluating the environment footprint of the deep mixing method which includes mixing of binders, penetration of the mixing tool and injection of the binders while retracting the mixing tool. The mixing machine will require diesel to operate and it is influenced by the operation time of the machine and the ratio of binders to be injected in the soil (since this is influencing the mixing energy). In the analysis, it is assumed that the binders are delivered mixed. The diesel and cement are grouped as background processes (raw resources) and the mixing, penetration and injection are group as foreground processes.

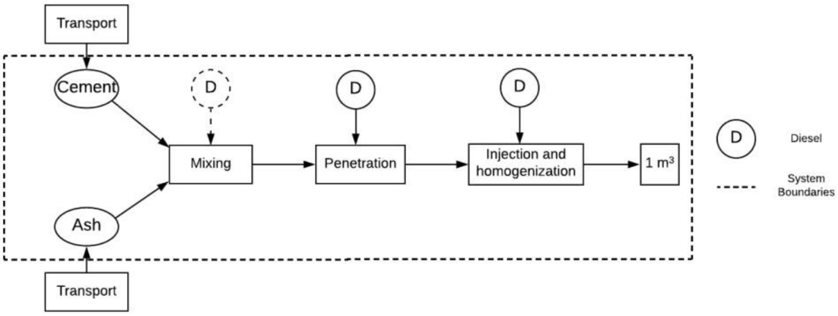

Figure 1. Proposed LCI for deep mixing. The process starts with mixing the binders in dry form, then penetration of the mixing tool, followed by injection (pumping) and homogenisation of the soil-binder mixture. The diesel needed for mixing the binder before injection in the soil is shown with a dashed line since it is neglected for simplicity. Taken from Jafarbiglookarami (2021).

The Life Cycle Impact Assessment (LCIA) framework used is the ReCiPe2016 (Huijbregts et al., 2017) which consists of different impact categories in human health, ecosystem, and resource extraction. More information is given in Jafarbiglookarami (2021). The selected impact categories include the ones listed in Table 2. Table 3 presents a summary of the assumptions made for LCA requirements.

Table 2 Selected impact categories for this study (Jafarbiglookarami, 2021).

Impact Category	**Abbreviation**	**Units**
Global warming	GWP100*	kg CO2-eq
Terrestrial acidification	TAP100	kg SO2-eq
Photochemical ozone formation (total)	POFP100	kg NOx-eq
Ozone depletion	ODP100	kg CFC11-eq
Freshwater eutrophication	FEP100	kg P-eq
Terrestrial ecotoxicity	TEP100	kg 1,4-DB
Human Toxicity (total)	HTP100	kg 1,4-DB

*100 for the Hierarchist value choice

Table 3 Assumptions made for LCA requirements (Jafarbiglookarami, 2021).

Diameter and Length (m)	0.8 m & 2 m, respectively
Time required for penetrating 2 meters (up and down)	0.8 min
Time required for injection and homogenization of 2 meters (i.e., compressor running time)	0.8 min
Penetration diesel consumption	30 L per hour
Compressor diesel consumption	5 L per hour

3. RESULTS AND DISCUSSION

Water content and density

The water content after 28 days of curing (Fig. 2) depend on the water content of the original clay. Since the clays were sampled from different depths and show different water contents in its natural state, it is convenient to express the results in terms of water content loss. The results show an increase in water content loss with an increase in binder content, no matter the ash type used. This is an expected observation since more soil water is used for binder hydration when more binder is added. On the other hand, when the ratio of ash to cement is higher (i.e., more ash is added respect to cement), the water content loss reduces. For the case of the ratio ash to MC or CEM/B80 no other differences in water content loss are observed.

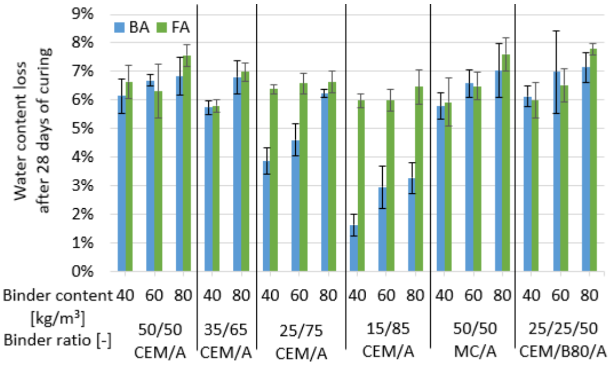

Figure 2. Water content loss after 28 days of curing.

The density of the specimens cured for 28 days is presented in Fig. 3. The density of the natural clay is also shown (grey shaded area). The measured values of the stabilized clay are slightly lower than the in-situ values as also presented by Paniagua et al. (2019).

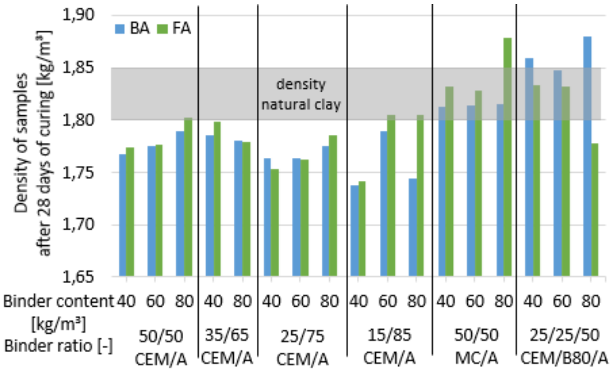

Figure 3. Density of samples after 28 days of curing.

pH results

Fig. 4 presents the pH values measured in some selected samples cured by 28 days and in the materials (clay, cement, and ashes) prior to being mixed (i.e. in a single state). The results show that samples mixed with CEM/BA binder have higher pH compared to CEM/FA specimens. Also, the CEM/A stabilized specimens show higher pH than the MC/A and CEM/B80/A specimens. The high pH of BA contributes to increasing the pH in the clay mixture for the pozzolanic reactions to occur. As discussed by Sargent (2015), an aqueous media with a pH > 10.5 is usually necessary for pozzolanic reactions. In this sense, a higher strength gain for the samples mixed with BA is expected.

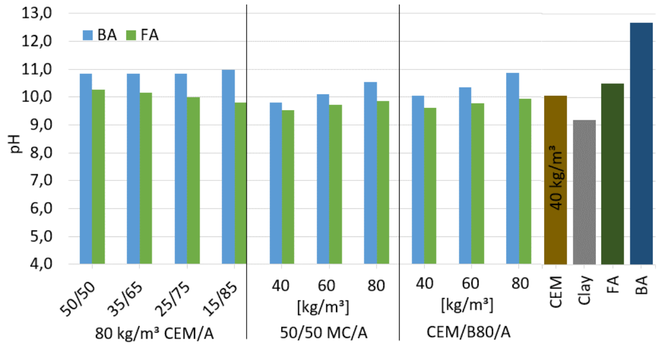

Figure 4. pH of stabilized samples at 28 days of curing

Strength results

Fig. 5 and Fig. 6 present the results of the maximum shear strength from UC tests measured at 28 days of curing and its variation with the amount of binder added to the mixtures. The results are presented in a form where the content of BA or FA, CEM, MC and B80 are separated to facilitate the discussion on the influence of adding the wood-based ashes for quick clay stabilisation .

Taking as a reference the sample stabilized just with 40 kg/m³ of CEM, one can observe that adding the same amount of BA gives an increase in strength. The strength also increases, but not as much as in the previous case, if the CEM content is then reduced to half and B80 is added instead in the same proportion as the CEM, keeping the ratio of CEM/B80 and BA equal.

Reducing the CEM content by approx. 25-30% from the 40 kg/m³ added to the reference sample and adding either BA in the same proportion of CEM (for a total binder content of 60 kg/m³) or in a ratio CEM/BA of 35/65 (for a total binder content of 80 kg/m³) gives stabilized clay samples with similar strength values and slightly below the strength reached for the sample stabilized with just CEM. A combination of 80 kg/m³ of MC/BA in a 50/50 ratio gives also similar strength results (one should remember that MC has 50% CEM in its composition, which then is also a reduction of the CEM used compared to the 40 kg/m³ sample).

Even though some of the results in Fig. 5 show a lower strength gain compared to the just CEM stabilized samples, the strength measured on these specimens are above the strength in UC test for the natural clay and might be enough depending on the required strength for the application of stabilized quick clay in practice. Looking at Fig. 6, the results indicate that the FA are not performing as well as the BA. The measured strength when combining CEM/FA in 50/50 proportion is slightly over the measured strength when just CEM was added. The incorporation of FA results in a relatively poor performance dependent on the cement content and the total binder content.

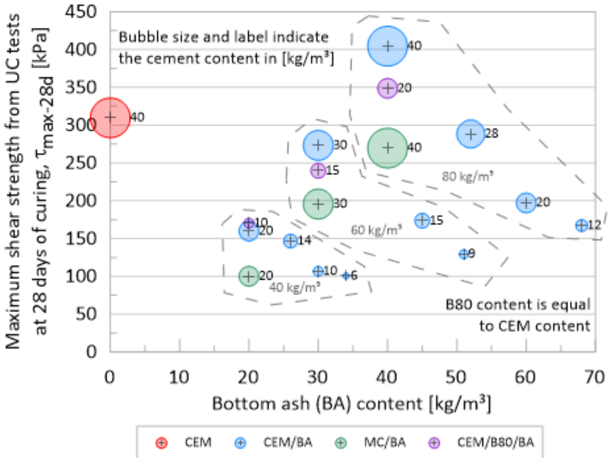

Figure 5. Variation of strength of stabilized clay samples, after 28 days of curing, with the content of BA, CEM and other binders.

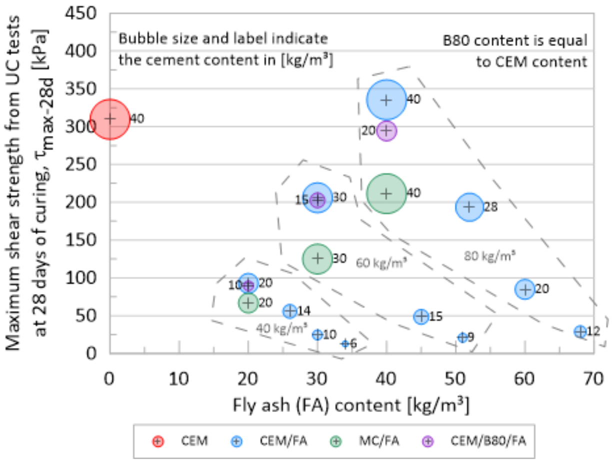

Figure 6. Variation of strength of stabilized clay samples, after 28 days of curing, with the content of FA, CEM and other binders.

The XRF and XRD analyses of ashes (Jafarbiglookarami, 2021) described that calcium oxide (CaO) is the dominating composition for both types of ashes in the form of Portlandite for BA and Calcite for FA. The BA contained higher silicium oxide (SiO_2) and aluminium oxide (Al_2O_3) (ca. 3%) higher than FA. This indicate that BA may have better pozzolanic properties than FA, however, the effect is very limited for both types of ashes. On the other hand, the flocculation phenomena can be enhanced by ions with higher electron charges, the data presented by Jafarbiglookarami (2021) indicate a higher concentration of phosphor, manganese, magnesium, and potassium in BA, which may indicate better exchange properties for BA. These results indicate that the FA have a more limited reactivity than BA and therefore can explain the lower strength values measured when the clay was stabilised with FA and CEM. Still, the initial cementing reactions are mainly related to the cement as expected and when BA was also added, BA might contribute to the pozzolanic reactions.

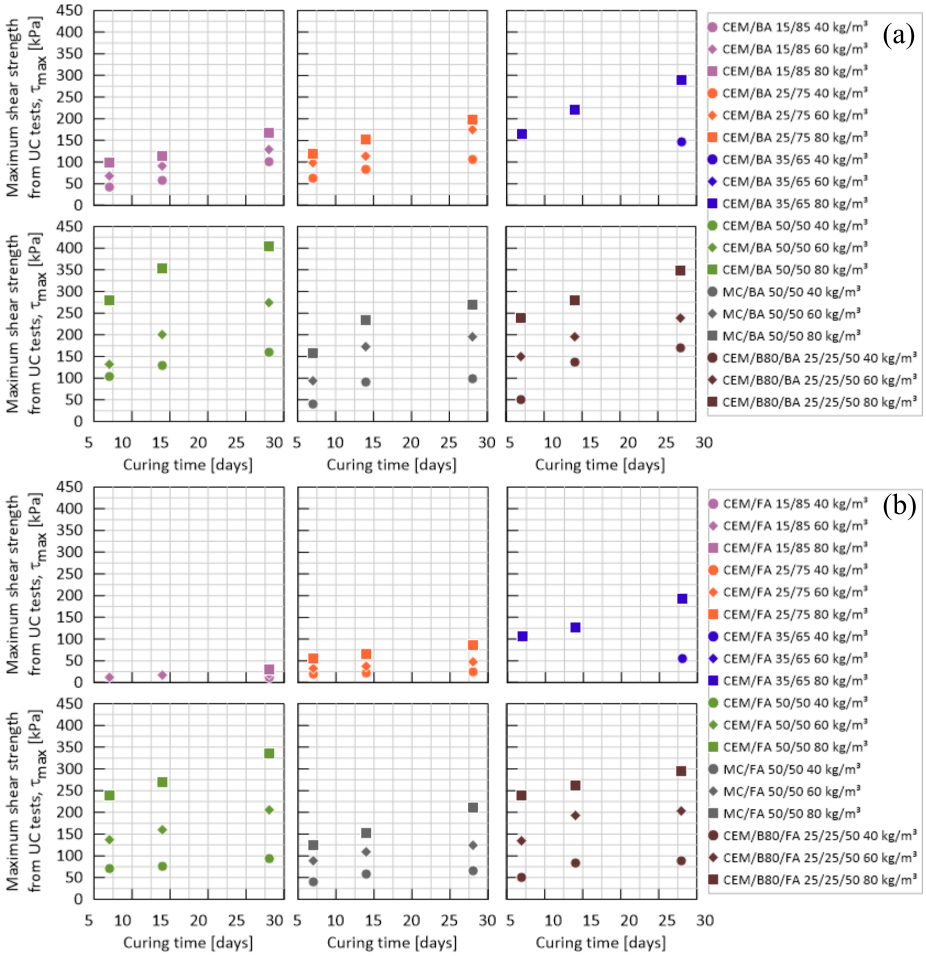

Figure 7. Variation of strength with curing time for different specimens stabilised with CEM and (a) BA or (b) FA in the proportions indicated.

Fig. 7 shows the strength increase in time for the stabilized clay samples, with the content of a) BA or b) FA, CEM and other binders. As expected, there is an increase in strength with curing time, however, this increase is faster for specimens stabilised with BA and CEM, compared to specimens stabilized with FA and CEM. The results also indicate the strong influence of the cement proportion when added in combination with FA: cement contents lower than 25% respect to the FA content give a limited strength gain with time and values below 100 kPa after 28 days of curing.

LCA results

The first assessment of the impact indicators was focused in the in-situ processes without considering the transport to make the results of this study no-case dependant. Then, the system under study just consumes cement and diesel and the results obtained indicated that the environmental impact indicators are proportional to the cement content, which then emphasises the importance in its reduction for deep mixing application. The authors strongly suggest revising Jafarbiglookarami (2021) for further details in this analysis.

Then, considering the low cement combinations into further analysis, the contribution of transport section becomes unneglectable due to its consumption of diesel. Therefore, the system boundaries were extended further from the ones presented in Fig. 1 and the results obtained from the LCA are presented in Fig. 8. It is observed that transport impact increases with distance.

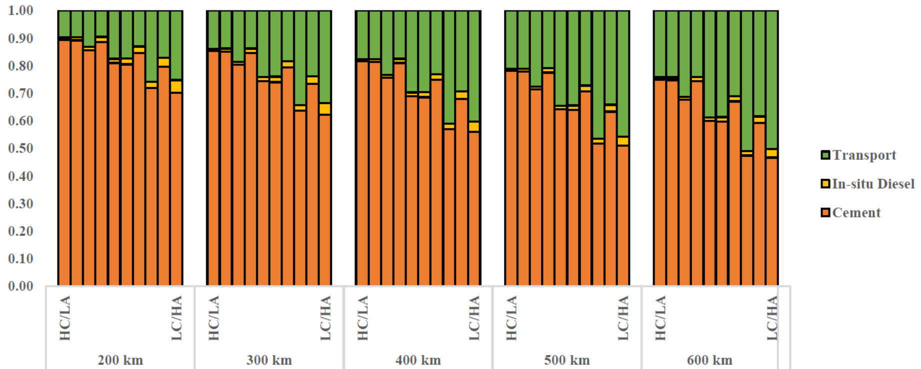

Figure 8. GWP contribution of transport, diesel and cement for the different distances between the ash source and project location (200 km to 600 km). HC denotes high cement content, LC denotes low cement content, HA denotes high ash content, and LA denotes low ash content. Taken from Jafarbiglookarami (2021).

Finally, to identify the binder combination giving the best performance in mechanical and sustainable terms, a minimum strength of 75 kPa was selected. With this classification, all combinations including BA and some of the combinations including FA were further utilised in the analysis (transport was not included in this analysis). Figure 9 presents the ratio between GWP100 and the maximum shear strength from UC tests at 28 days of curing per m of column installed (a column of 25 m was assumed in the analysis) vs the ash and cement content in selected mixtures. Then, the optimum combination in the case of mixtures including FA is the 80 kg/m^3 in a 50/50 proportion of FA since it is giving the lowest amount of kg-CO2 per kPa of strength and per m of column installed. In the case of the mixtures including BA, the combinations showing the lowest GWP impact are associated to strengths near the 100 kPa and include a relatively large proportion of BA respect to CEM. However, if higher strengths are required, the optimal binder content is calculated for 60 kg/m³ of CEM and BA in a proportion of 25/75. It should be mentioned that similar trends were observed for the other impact categories presented in Table 2, and these are detailed in Jafarbiglookarami (2021).

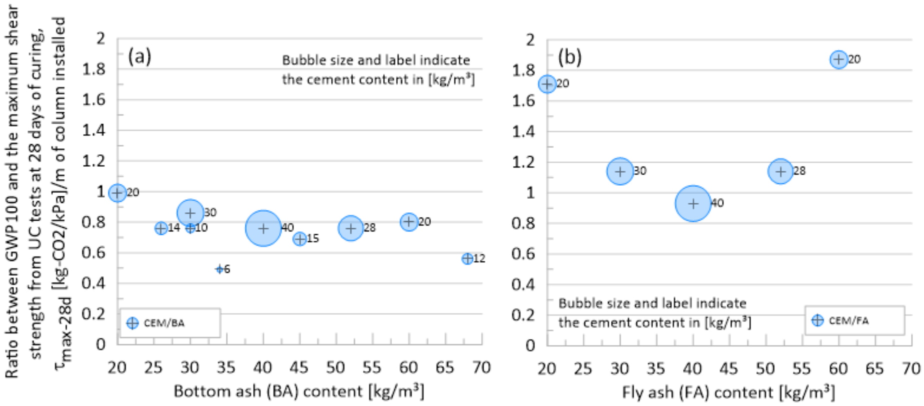

Figure 9. Ratio between GWP100 and the maximum shear strength from UC tests at 28 days of curing, per m of column installed vs the CEM and (a) BA and (b) FA content.

4. CONCLUSIONS

After combining bioashes with cement into quick clay, the strength and stiffness after 28 days of curing increased up to 5 times the values of the undisturbed clay. The increase of strength and stiffness with time was also measured, getting the largest strength gain for the samples improved with bottom ashes. Both types of ashes showed to be rich in calcium oxide and alkaline structures which indicated the positive contribution to the rate of chemical reactions to occur during quick clay stabilisation . The better reactivity for improving the strength was observed for the bottom ashes, however, due to the low particle size of the fly ashes, these could act as a non-reactive filler along with bottom ash, this requires further study.

The Life Cycle Analysis (LCA) on the use of bioashes for quick clay stabilisation revealed that the environmental costs relative to the obtained geomechanical response might sit in an acceptable range for bottom ashes and compares to traditional lime cement mixtures. The results indicate that the mixtures including BA and CEM performed better than the ones combining FA and CEM. However, in order to upscale the application of such wood based by-products; several barriers need to be overcome in particular regarding their physical characteristics that make them compatible to the current technology for deep dry mixing. In addition, the production of such materials in terms of amount and quality needs documentation and a further discussion: there is an inherent variability in the ashes due to the yearly variability of the raw materials. The quality documentation should be aborded from the mechanical effect (in terms of strength increase) and the environmental impact related to for example leaching of contaminants.

REFERENCES

[1] H. Åhnberg. Strength of Stabilized Soil-A Laboratory Study on Clays and Organic Soils Stabilized with different Types of Binder. PhD dissertation. Lund University, Sweden. 2006.

[2] B. Owsianiak et al. Main Characteristics of LCA. In Life Cycle Assessment: Theory and practice (pp. 9-16). Springer. 2018.

[3] P. Bujulu. Deep-mix Stabilization of Quick Clay: A Potential Area for Utilization of Wastepaper Sludge Ash. PhD thesis NTNU, Trondheim, Norway. 2008.

[4] Q. Cheng et al. Stress-dependent behaviour of marine clay admixed with fly-ash-blended cement. Int J of Pavement Research and Tech, 11 (6): 611-616. 2018.

[5] T. Deb & S.K. Pal. Correlations to assess compaction characteristics of local silty clay soil-fly ash mixes. Electronic J of Geotech Eng. 17:3479-3490. 2012.

[6] FHWA. Fly Ash Facts for Highway Engineers. American Coal Ash Association. Report FHWA-IF-03-019. 2003.

[7] S. Hov et al. Stabilisation of Soft Clay, Quick Clay and Peat by Industrial By-Products and Biochars. Applied Sciences, 13(16), 9048. 2023.

[8] S. Hov et al. Lime-cement stabilisation of Trondheim clays and its impact on carbon dioxide emissions. Soils and Foundations, 62(3), 101162. 2022.

[9] M. Huijbregts et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal of Life Cycle Assessment, 22(2), 138-147. 2017

[10] S. Islam et al. Strength development in clay soil stabilized with fly ash. Jordan Journal of Civil Engineering. 12(2):188-201. 2018

[11] Jafarbiglookarami. Alternative binders for improvement of soft soils – A geoenvironmental approach. MSc dissertation, NTNU. 2021.

[12] J-S. L'Heureux et al. The Tiller-Flotten research site: Geotechnical characterization of a very sensitive clay deposit. AIMS Geosciences, 5, 831-867. 2019.

[13] P. Paniagua et al. Strength and stiffness of laboratory-mixed specimens of stabilised Norwegian clays. Ground Improvement, 0(0), 1-14. 2019.

[14] P. Paniagua et al. Bioashes and steel slag as alternative binders in ground improvement of quick clays. In Proc Geo-Congress 2023, Los Angeles, CA, USA. 2023.

[15] P. Sargent. The development of alkali-activated mixtures for soil stabilisation. Handbook of Alkali-Activated Cements, Mortars and Concretes (555-604). Woodhead Publishing. 2015.

[16] X. Song et al. Life Cycle Assessment of Geotechnical Works in Building Construction: A Review and Recommendations. Sustainability, 12(20), 8442. 2020.

[17] J. Wu et al. A generic framework of unifying industrial by-products for soil stabilization. J. Cleaner Prod., 321. 2021.