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Challenges and opportunities of exploring biochar as a sustainable alternative for soil improvement

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ABSTRACT: One way to reduce carbon dioxide emissions in soil improvement is to replace traditional binders partially or completely with alternative options like biochar. Recent studies indicate that biochar can enhance the engineering properties of clays and peat, especially when used alongside traditional binders like cement. For instance, biochar has shown to increase the strength and stiffness of peat, potentially reducing the amount of cement required. Sustainability assessments suggest that biochar can achieve climate-neutral ground improvement. However, the current production cost of biochar outweighs its ground improvement benefits. There are also challenges in the practical conditions necessary for successful upscaling the use of biochar to field applications. The use of biochar in large-scale field projects remains limited, with most research conducted under controlled laboratory conditions. More work is needed to understand the long-term effects and economic feasibility of biochar in real-world scenarios. This paper discusses the challenges of integrating biochar into Deep Dry Mixing and in general, ground improvement practices. It addresses issues such as the variability in biochar properties, which can affect its performance as a stabilising or improvement agent, the logistics of large-scale biochar production and transportation, and practical execution aspects. Overall, while biochar shows significant potential for soil improvement, more extensive field trials and studies are necessary to fully understand its capabilities and optimise its practical applications.

KEYWORDS: biochar, ground improvement, sustainability.

1 INTRODUCTION

Ground improvement is critical for infrastructure development on weak soils. In the Nordics, one of the most popular methods for ground improvement is the dry deep mixing (DDM), which mechanically mixes dry binders and soil, aiming to increase the stability of slopes and excavation works (e.g. Karlsrud et al. 2015). Traditionally, the method utilises lime, cement, or a combination of both. The additives or binders react with water and soil, resulting in chemical reactions including flocculation, hydration, pozzolanic reactions and carbonation, and then improve the strength and deformation properties of the original soil material. This practice relies heavily on cement as the main binder, which contributes significantly to greenhouse gas emissions. For example, widely used Norwegian cement has a carbon footprint of approximately 625 kg carbon dioxide equivalents (CO_2-eq) per tonne cement. With the aim of finding less carbon-intensive binder alternatives to cement and lime, researchers in the recent years have shifted the focus to find and apply alternative binders, like industrial by-products and biochar, to partly or completely substitute cement in ground improvement. Biochar is a carbon-rich byproduct of biomass pyrolysis that has emerged as a promising alternative due to its potential to improve soil properties and sequester carbon. This paper presents the main findings from the Norwegian experience in investigating the feasibility of using biochar in geotechnical applications, discussing challenges and opportunities, and focusing on Norwegian soils and biochars.

2 WHAT IS BIOCHAR?

Biochar is a carbonaceous material ("engineered" charcoal), which can be made by incomplete combustion of organic waste. Norway generates large amounts of organic wastes, such as waste timber (shredded wood panels, furniture, spent pellets – 660,000 tonnes/y), garden waste (150,000 tonnes/y), forestry residues (3.7 mill tonnes/y), food/biological waste (340,000 tonnes/y) and sewage sludge (200,000 tonnes/y) (Miljøstatus, 2015). Biochar does not have cementitious properties (i.e. causing a pozzolanic reaction) but is characterised by a high porosity and surface area resulting in a change of the pore size distribution, a high water-holding capacity and improved soil aggregation (e.g. Pardo et al. 2018).

Another important aspect of biochar is that it contains as much as 80-90% carbon, and this carbon is stable for around 1,000 years (Lehmann 2007). Thus, the carbon in the original organic waste is stored, and biochar has been proposed by the Intergovernmental Panel on Climate Change (IPCC) as a carbon sequestration method (Cornelissen et al. 2018). In other words, biochar amendment to soils can reduce CO_2 emissions to the atmosphere and thus mitigate climate change: biochar sequesters approximately 2400 kg of CO_2-eq per tonne; thus, mixing in small amounts of biochar in construction materials (6.5% in concrete; 0.5% in asphalt) can make these materials climate-neutral.

3 BIOCHAR FOR GROUND IMPROVEMENT

While numerous researchers have studied the effects of biochar on agricultural properties of soils (e.g. Cornelissen et al. 2018) and its properties as contaminant sorbent (Ahmad et al. 2014), only a few studies on the impact of biochar on the mechanical properties of soils exist. Lau et al. (2023) showed the potential of biochar to partially replace cement when stabilising peat. Initial calculations show that replacing 20-25% of the cement by biochar will render the stabilisation carbon-neutral, without impacting its stabilizing properties (Lau et al. 2023), but at a 10-20% higher cost. Comparable works by Reddy et al. (2015) and Pardo et al. (2018) obtained similar beneficial mechanical behaviour when mixing biochar with silty clay or sand, respectively.

The effect of biochar on typical Norwegian soils, such as quick clay and peat, has been investigated in the last five years (Ritter et al. 2022, Ritter et al. 2023, Hov et al. 2023, Ånes et al. 2024). The studies have involved either peat, soft clay or quick clay as the main soil types to improve properties, cement of the type CEM I or CEM II, and several types of biochar. The different types of biochar were made from either clean wood and leaves, demolition wood, bottom sludge from municipal sewage, sewage and food waste or garden waste. The studies mostly focused on laboratory scale experiments where the biochar was added at varying dosages in combination with varying dosages of cement. Tests carried out allowed the measurement of remoulded shear strength, unconfined compression strength, water content and sustainability metrics (CO_2-equivalent emissions) as well as a complete characterisation of the biochars.

Ritter et al. (2022, 2023) studied the application of clean wood and leaves biochar to marine quick clay and peat. The biochar was also studied with the combination of cement (CEM II). The results (Figure 1, Figure 2 and Figure 3) showed that the used biochar has the potential to enhance the strength of quick clay (Figure 1) and cement-stabilised quick clay (Figure 2) and peat (Figure 3). Optimum quantities (i.e. given positive effects in enhancing strength and stiffness of the soil) of biochar were found to be in the range of 75 to 125 kg/m^3 for quick clay mixtures and exceeding 200 kg/m^3 for peat mixtures.

Hov et al. (2023) studied the effect of different biochars (BC1, BC2, BC3 and BC4, see Figure 4) when mixed with cement (CEM I) and three different types of soils. The same quick clay and peat as in Ritter et al. (2022, 2023) and a soft marine clay was used. The biochars were made from different source materials and the used quantities were in the optimum range as recommended by Ritter et al. (2022, 2023). BC1 originated from demolition wood, BC2 from municipal sewage with addition of limestone, BC3 from sewage and food waste and BC4 from garden waste. All the biochars were produced in a full-scale microwave assisted pyrolysis (MAP) unit with a residence time of ~20 min under a reactor temperature of 470–600 °C. Prior being mixed with the soils, all biochars were ground and sieved to a < 1 mm fraction and dried.

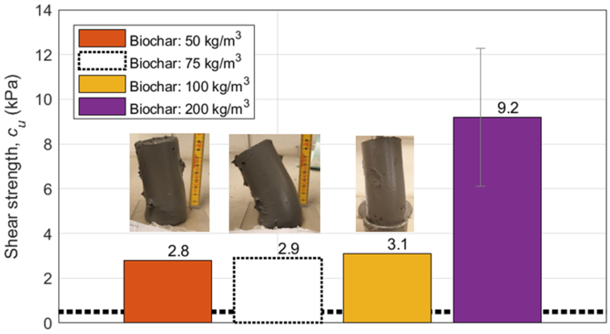

Figure 1. Increase in undrained shear strength, at 28 days of curing, after the same type of biochar was mixed in different quantities with quick clay. The dotted line indicates the remoulded shear strength threshold (i.e. 0.5 kPa) for the definition of quick clay in Norway (NVE, 2020). Vertical bars indicate standard errors of the means (n = 3). The figure has been modified from Ritter et al. (2023).

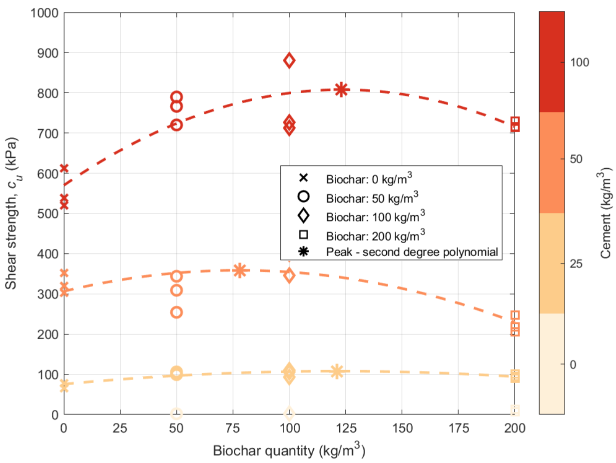

Figure 2. Variation in undrained shear strength (28 days of curing) of biochar mixed in different quantities with quick clay. Taken from Ritter et al. (2023).

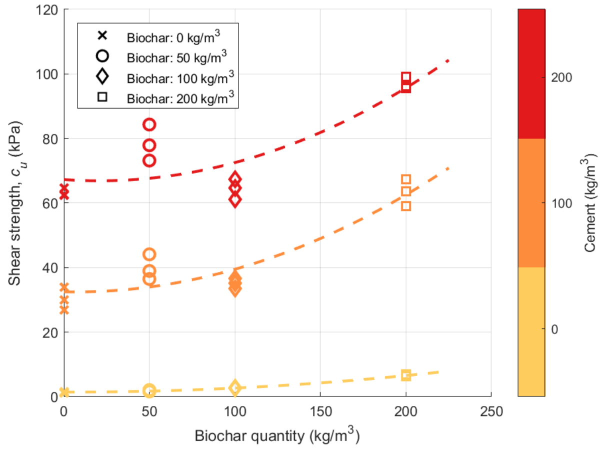

Figure 3. Undrained shear strength (28 days of curing) of biochar mixed in different quantities with peat. Taken from Ritter et al. (2022).

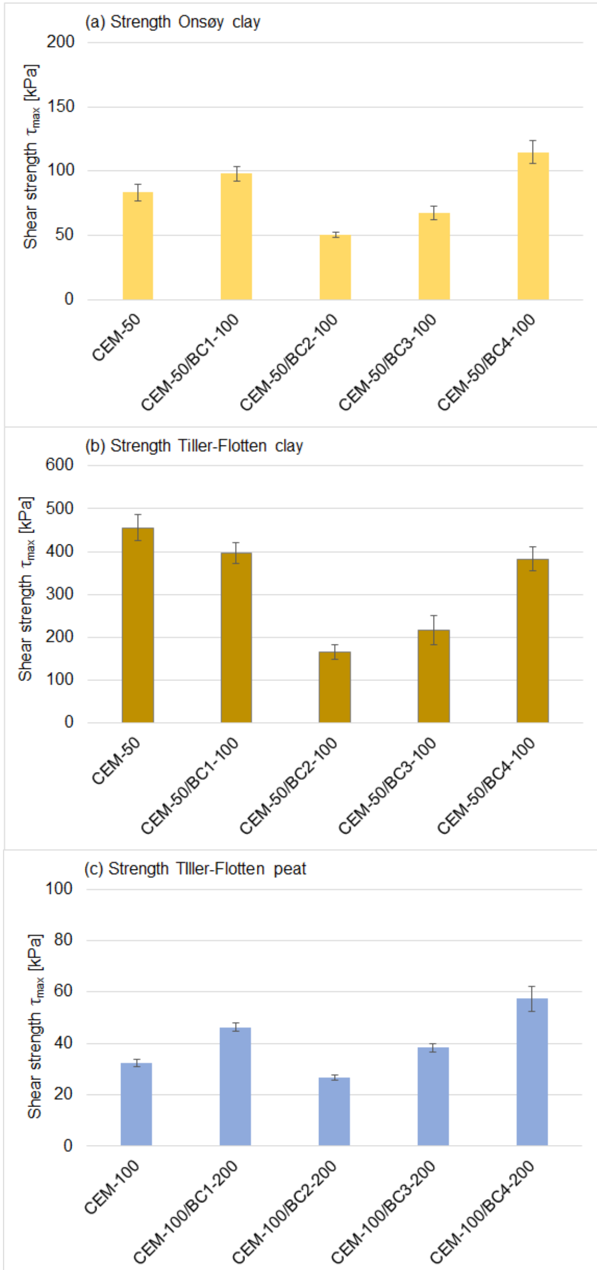

Figure 4. Undrained shear strength, at 28 days of curing, after different biochars were mixed in different quantities with (a) soft clay, (b) quick clay and (c) peat. Modified from Hov et al. (2023).

Different responses were observed for the different soils (Figure 4), with the biochar performing better for peat than other industry by-products tested in the study. BC1 and BC4 increased strength and deformation properties on the soft clay with high water content (~73%). However, all biochars had negative effect on the quick clay with a relatively low water content (~42%). However, BC1 and BC4 had the least negative effect. Three biochars (BC1, BC3 and BC4) had a positive stabilisation effect on the peat. Lau et al. (2020) reported similar observations of an increase in strength of cement-stabilised peat and discussed the positive effect of biochar in improving cement hydration due to its high water-absorption capacity.

Ånes et al. (2024) presented a study of the application of three of the same biochar types tested by Hov et al. (2023), i.e. BC1, BC2 and BC3; in Tiller-Flotten quick clay (L'Heureux et al. 2019). The purpose was to investigate how these biochars influenced the soil properties when acting as the only binder aiming the ease of handling and transportation of excavated quick clay by increasing its remoulded shear strength. All three biochars had a positive effect on the shear strength of the remoulded quick clay (Figure 5). BC2, which is the biochar made of municipal waste with added limestone, had the distinctly most positive effect by increasing the strength after 28 days of storage. These results indicated that such material could act as a viable climate-friendly alternative to lime and cement to improve the handling and transportation of quick and soft clays after excavation. Even though the study remarks that the reasons of why one type of biochar performed better than the others are unknown, the authors discussed the possibility of the higher water retention capacity of BC2, or that BC2 contained constituents that react chemically when added to clay.

The investigations mentioned above shed light on the potential of biochar in replacing parts of the cement and executing soil improvement carbon negative. For example, for the case of the biochar used by Ritter et al. (2023), which was made from clean wood and leaves, the replacement of more than 27% of cement with this biochar can render the soil stabilisation process carbon-negative, as this biochar has a carbon footprint of –2315 kg CO_2-eq per tonne, compared to cement's 625 kg CO_2-eq per tonne (Ritter et al. 2023). However, the costs of biochar are currently greater than its benefits, reaching near more than three times the current costs of cement (Ritter et al. 2023).

3.1 *CHALLENGES*

The potential use of biochar for improving soft soil strength and deformation properties may be associated to certain challenges mainly related to the understanding of the mechanical processes acting when biochar is added to the soil and its stabilisation effect as well as the practical conditions that can guarantee a successful upscaling to field applications. In the context of economic viability, biochar is currently more expensive than cement which in a cost-benefit ratio is unfavourable without subsidies or carbon credits.

When it comes to production and processing, ground improvement projects typically require large quantities of binders, which is challenging when using biochar due to its low bulk density, demanding large biochar volumes. Consequently, large storage space might be required, and the binder delivery systems of standard drill rigs could reach their limits. Another challenge of using biochar in the field is that pre-processing of with grinding, sieving and drying is needed. These processes are energy-intensive and time-consuming, and until now there is no equipment that can handle such large quantities, in the range of tonnes, in a practical way. A further obstacle of using biochar for ground improvement is that the properties of the source materials change with time which may affect the biochar quality. However, this difficulty could be solved by predesigning the biochar according to the needs.

When integrating biochar into existing DDM practices, challenges that might arise are: the flowability along the pumping system, risk of clogging and separation due to pollutions causing more frequent cleaning and production delays, lower density of the binder requires more binder volume (see above) which is also associated to a reduction of the production rate, mixing with cement or other binders like lime can cause chemical reactions and heat development, among other aspects.

In general, biochar has been proven to improve difficult soils like soft clays and peat, albeit showing a performance variability. Its effectiveness depends on soil type and biochar source. Not all biochars perform equally, as presented in the literature; some may reduce stiffness or strength or both.

Finally, the research on the applicability of biochar for ground improvement is very recent and therefore its practical use has regulatory and standardization gaps. There is a lack of standardized guidelines for biochar use in geotechnical applications. This may be associated as well to the uncertainties related to the long-term performance and durability of the biochar improved soil. Additional research and upscale application of the materials may shed light on this aspect.

3.2 *OPPORTUNITIES*

The use of biochar as a binder for ground improvement sets on the table the discussion regarding which mechanisms are acting in the improvement of the soil materials. Biochar may improve strength and stiffness in soft soils like peat and quick clay. Current observations when applying biochar to quick clay indicate that the strength gained is attributed to densification and cementation (see Figure 6). However, for the peat, the improvement is linked to soil drying, densification, and cementation. Further exploration of these mechanisms opens an opportunity for other applications upon ground improvement.

Regarding the environmental sustainability, biochar has a negative carbon footprint, which then means that replacing certain amount of cement with biochar can make soil stabilisation carbon negative. However, biochar must only be added if it improves the mechanical properties and it should not be just added with the purpose of reducing the carbon footprint of the ground improvement works. In addition, biochar is already coming from various sources, e.g., garden waste, demolition wood, which can be tailored to different soil types, thereby giving biochar versatile material characteristics.

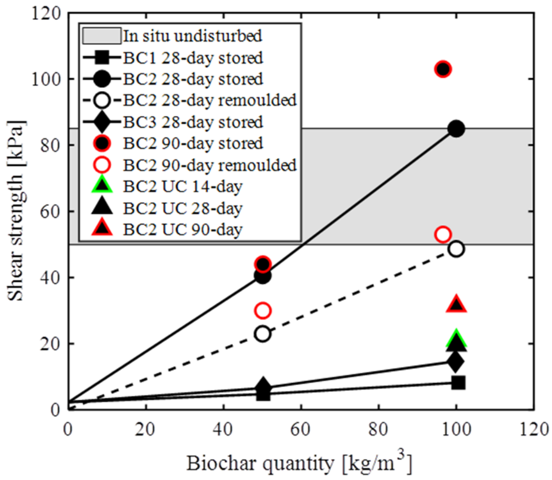

Figure 5. Undrained shear strength after the biochars were mixed in different quantities with the quick clay. Taken from Ånes et al. (2024).

Biochar supports waste valorisation and resource efficiency in the context of circular economy, since it utilises waste materials (e.g., sewage sludge, food waste) for high-value applications. There is a high innovation potential in the utilisation of biochar for ground improvement, for example, there is the possibility to engineer alternative binders by combining biochar with industrial by-products, and/or tailor the pyrolysis and preparation processes. These aspects open avenues for low-carbon infrastructure development. One good example is the study by Hanafi et al. (2024) where accelerated CO_2 curing was applied to biochar enhanced cementitious soft clay composites. In this study, the biochar facilitated uniform CO_2 diffusion in the clay matrix due to its honeycomb porous structure and hydrophilicity properties. In this way, internal curing was improved allowing the replacement of 50% of cement with biochar and reaching sufficient load-bearing capacity according to construction guidelines.

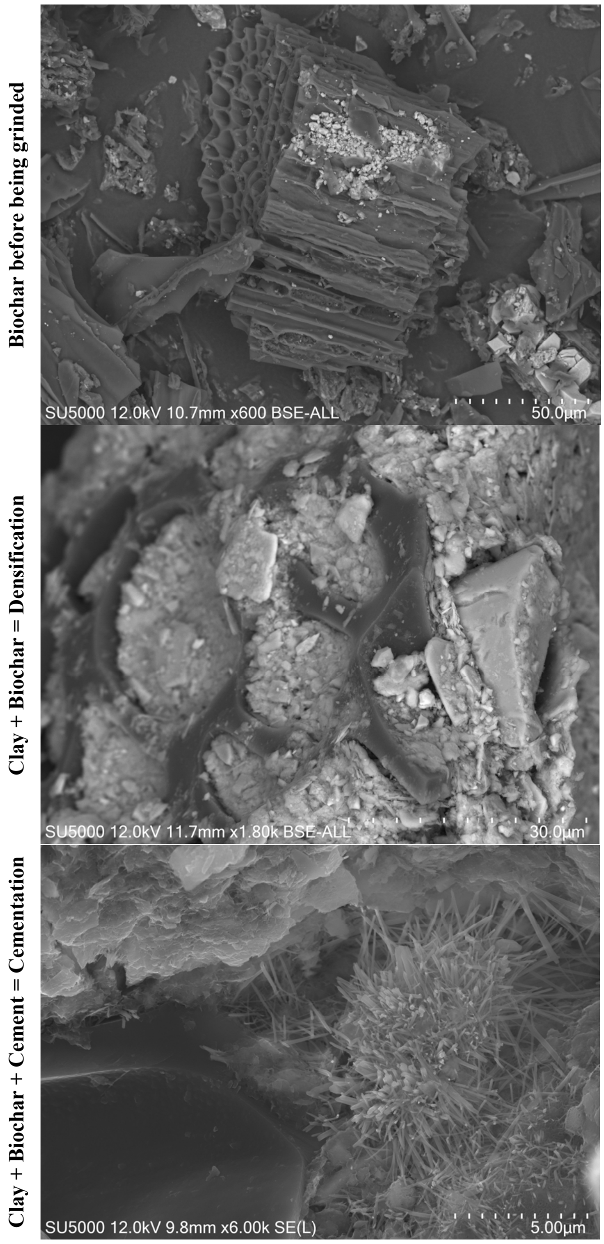

Figure 6. SEM micrographs of biochar, biochar mixed with clay and a clay-biochar-cement sample. The images show the honeycomb structure of biochar before and after the clay particles filled the cells helping with the densification process. Then, when adding the cement, the cementitious materials developed.

4 CONCLUSIONS

Biochar can enhance strength and stiffness in soft soils. It can partially replace cement and reduce carbon emissions. Its performance varies by soil and biochar type. It offers a promising trail when looking for sustainable soil improvement, with clear environmental and mechanical benefits. However, its widespread adoption centres on overcoming economic, technical and regulatory barriers. Continued research, pilot projects and policy support are essential to unlock its full potential. Practical and economic barriers must be addressed for field-scale adoption. Further work should be focused on further characterisation of biochar-soil interactions, development of engineered binders combining biochar and industrial by-products and field-scale trials to validate laboratory findings.

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