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Biochar amendment for improved and more sustainable peat stabilisation

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Carbon-intensive binders such as cement are traditionally employed to stabilise peat. Few studies have investigated alternative materials such as biochar to improve peat stability while simultaneously sequestering carbon dioxide. This study explored biochar produced through pyrolysis of clean wood and leaves to stabilise peat from Tiller-Flotten, Norway. Unconfined compressive strength, water content and pH measurements on biochar, Portland composite cement and peat compositions and a sustainability assessment were conducted. It was found that biochar amendment increased strength and stiffness of peat and cement-stabilised peat. Biochar showed the potential to reduce the cement amount when stabilising peat while retaining geotechnical properties. Peat stabilised with 200 kg/m^3 of biochar and 100 kg/m^3 of cement exhibited comparable strength (63.3 ± 4.2 kPa, *n* = 3) as samples with 200 kg/m^3 of cement (63.2 ± 1.3 kPa, *n* = 3), but with a negative carbon footprint. Adding biochar quantities greater than 27% of the cement quantities resulted in a climate-neutral stabilisation. At a carbon price of approximately €85/t, the biochar costs equalled the cement costs. The cement-only samples outperformed the ones with additional biochar in terms of shear strength/€, while future carbon prices increased the competitiveness of biochar amendments.

Keywords: geotechnical engineering/soil stabilisation/sustainability

Notation

c_u	undrained shear strength
E_{50}	secant modulus between 0 and 50% of the unconfined compressive strength
H	humification of peat
n	number of samples
v_s	shear wave velocity
w	water content
$\varepsilon_{a,f}$	axial strain at failure

1. Introduction

Peatlands can absorb and trap large amounts of carbon dioxide (CO_2) and thus play a pivotal role in mitigating climate change. However, damaging peatlands due to, for example, drainage can release the trapped carbon dioxide to the atmosphere. According to the International Union for Conservation of Nature, degradation of peatlands contributes to 5.6% of the human-induced carbon dioxide emissions (IUCN, 2017). Previous construction activities on peatlands often included removal of the peat due to its poor bearing capacity and high compressibility, which released significant amount of carbon dioxide. New regulations are reluctant to such construction methods that threaten peatlands (e.g. Miljødirektoratet, 2020).

Amending weak soils such as peat with chemical binders to improve its properties provides an alternative to peat removal. The so-called dry deep mixing (DDM) method, which mechanically mixes dry stabilising agents and soil, has been widely adopted to increase the stability of slopes and excavation works (e.g. Karlsrud *et al*., 2015). Traditionally, lime, cement or a combination of both is used. Treating soil with these binding agents results in chemical reactions including hydration, ion exchange, flocculation, pozzolanic reactions (converting silica-rich minerals with no or little cementing properties to calcium silicate) and carbonation (e.g. Åhnberg, 2006; Chew *et al*., 2004; Janz and Johansson, 2002; Lau, 2018). The production of cement and lime is, however, a carbon intensive activity. For example, widely used Portland-composite cement (CEM II) has a carbon footprint of approximately 625 kg carbon dioxide equivalents (CO_2-eq) per tonne cement (The Norwegian EPD Foundation, 2016). Consequently, these binders account for a substantial part of the carbon dioxide footprint of ground improvement works. There is, therefore, an urgent need to explore alternative, more environmentally friendly materials to improve the geotechnical properties of peat.

Biochar represents such an alternative material for soil stabilisation (GuhaRay *et al*., 2019; Lau, 2018; Lau *et al*., 2020; Pardo *et al*., 2018, 2019; Reddy *et al*., 2015; Vincevica-Gaile *et al*., 2021). It is a carbonaceous material (‘engineered’ charcoal), which can be made by incomplete combustion of organic waste. Biochar does not have high mineral content and thus limited cementitious properties (i.e. setting and hardening due to hydration when adding water) 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. Kelly *et al.*, 2017; Pardo *et al.*, 2018).

Another important aspect of biochar is its climate change mitigation potential. It contains as much as 80–90% carbon, and this carbon is stable for over 1000 years (Lehmann, 2007). Thus, 30–40% of the original carbon in the organic waste is stored, and biochar has consequently been proposed by the Intergovernmental Panel on Climate Change (IPCC, 2019) as an approved carbon sequestration method (Cornelissen *et al.*, 2018). Biochar sequesters over 2000 kg of CO_2-eq per tonne (Harvey *et al.*, 2012); thus, mixing small amounts of biochar in construction materials (around 6.5% in concrete, 0.5% in asphalt) can make these materials climate-neutral.

While numerous researchers have studied the effects of biochar on agricultural properties of soils (e.g. Cornelissen *et al.*, 2018; Kelly *et al.*, 2017) and its properties as contaminant sorbent (e.g. Hale *et al.*, 2016; Sørmo *et al.*, 2021), only a few investigations on the impact of biochar on geotechnical properties of soils exist. Several studies reported a strength increase when adding biochar to expansive clays (GuhaRay *et al.*, 2019; Lu *et al.*, 2014; Williams *et al.*, 2018; Zong *et al.*, 2014), silty clays (Reddy *et al.*, 2015; Sadasivam and Reddy, 2015) and sand (Pardo *et al.*, 2018, 2019). However, only one study on the effects of amending peat with biochar exists (Lau, 2018; Lau *et al.*, 2020).

Lau (2018) and Lau *et al.* (2020) reported that biochar from a hardwood timber feedstock increases the strength and stiffness of cement-stabilised peat, and that biochar should be considered as an alternative to utilising sand as a filler. Their study linked the increased strength observed in biochar samples to a more complete cement hydration. They proposed that more water is accessible in biochar-amended samples owing to high water-absorption capacity of biochar. In addition, previous research showed the potential of biochar to partially replace cement when stabilising peat: adding 400 kg/m^3 of a biochar in addition to 100 kg/m^3 of cement performed similar than using 200 kg/m^3 of cement only. They also found that biochar with a grain size smaller than 75 μm performed better than using coarser biochar, which is characterised by weak intact cells. Although these initial studies provided important insights into the impact of biochar on cement-stabilised peat, no single study exists on the effect of treating peat with solely biochar.

There has also been less discussion about the overall sustainability of stabilising peat with biochar including the mechanical performance and the economic and environmental impact. Our initial calculations show that replacing 20–25% of the cement by biochar would render the stabilisation carbon-neutral, without impacting its stabilising properties (Lau *et al.*, 2020), but at a 10–20% higher cost. While these initial investigations are encouraging, this is the first study to carry out a thorough quantification of the effect of biochar amendment on the carbon footprint and overall cost of cement-based peat stabilisation.

The general aim of this research was to answer the following question: Can biochar be used to improve both stability and sustainability of peat soils? The specific objectives were to evaluate the impact of different biochar dosages on the mechanical properties of stabilised peat and on the overall sustainability of the peat stabilisation works including carbon footprint and material costs. The main hypothesis was that biochar could reduce the carbon footprint of peat stabilisation works without compromising on mechanical properties.

2. Materials and methods

2.1 Materials used

2.1.1 Biochar

The biochar used in this research study was produced from a feedstock consisting of a mixture of clean wood and leaves from gardening waste (both hardwood and softwood). The biomass was pyrolysed in a Pyreg-500 pyrolysis unit with a residence time of 20 min and a continuously monitored temperature of 471–535°C (average 503°C). Arsenic (As), chromium (Cr) and polycyclic aromatic hydrocarbons (PAHs), as well as carbon monoxide and oxides of nitrogen (NO_x), were the most significant contaminants emitted during the pyrolysis process (numbers in Sørmo *et al.*, 2020). These contaminants need to be taken into account in overall emission budgets and life-cycle analysis when considering large-scale implementation of this technology. Important physical properties of the biochar include a bulk density of 0.229 g/cm^3 and a solid density of 1.58 g/cm^3, a surface area of 287 m^2/g according to BET-N2 and 12.6% porosity in the range 0.3–1.5 nm. The biochar consisted of 78.9% carbon, 3.5% calcium, 3.3% oxygen and 2.35% hydrogen. The hydrogen to carbon, H/C (molar) ratio was 0.35. It was alkaline with a pH value of 8.6. Further details about the feedstock composition, the pyrolysis unit, its operating principle and emissions and the biochar properties can be found in Sørmo *et al.* (2020) and in the supplementary material.

Before the biochar was mixed into the soil samples, it was dried at 40°C for 24 h to remove its initial 28% moisture. Then, it was crushed using a coffee grinder and sieved over a metal sieve to obtain biochar samples with a particle size smaller than 250 μm. The biochar has a particle-size distribution similar to a silty sand (see supplementary material).

2.1.2 Cement

A Portland-composite (standard cement FA, CEM II/B-M) according to NS-EN 197-1 produced by NORCEM in Kjøpsvik, Norway, was employed (The Norwegian EPD Foundation, 2016). A CEM II is characterised by less than 35% of additives such as fly ash, slag or limestone. The main components of the used cement are 72% clinker (CaO), 18% fly ash, 5.2% gypsum ($CaSO_4$), 4% limestone ($CaCO_3$) and 0.24% iron sulfate ($FeSO_4$) (The Norwegian EPD Foundation, 2016). At a curing period of 28 days, a compressive strength of 55 MPa was reported by the manufacturer (NORCEM, 2017). The adopted cement type is widely used globally in soil stabilisation projects.

2.1.3 Peat

The peat samples used in this study were obtained from the Tiller-Flotten Norwegian Geo-Test site (NGTS; L'Heureux *et al.*, 2019). This site is characterised by a peat layer over quick clay and has been extensively drained since the 1970s (NGI, 2019). The samples were taken at an Easting and Northing of 570 958 and 7 023 977 (UTM 32N) using a shovel and subsequently wrapped in plastic bags. The sampling depth was approximately 0.5–0.6 m.

The Tiller-Flotten peat was classified according to Von Post and Grandlund (1926), which is based on the following sub-categories (Figure 1): botanical composition, water content (w), content of fine, humification (H), coarse fibres and woody remnants. According to Von Post and Grandlund (1926), a peat can be classified between H_1, completely unhumified fibrous peat, and H_{10}, completely amorphous non-fibrous peat. At the sampling depth, the Tiller-Flotten peat was between H_2 to H_3 indicating an insignificant to very slight decomposition. Both fine and coarse fibre contents were in the low-to-medium range. The natural water content of the peat was approximately 1000% at the sampling depth. Shear wave velocities, v_s, in the range of 20–30 m/s were determined. The undrained shear strength, c_u; of the peat was derived using correlations in literature and direct simple shear tests. For the sampling depth, shear strength values in the range between 4 and 6 kPa were obtained. A more detailed description of the geotechnical properties of the peat used in this study and further Norwegian peats can be found elsewhere (NGI, 2019; Paniagua *et al.*, 2021).

2.2 Methods

2.2.1 Testing programme and sample preparation

Table 1 lists the different mixtures investigated in this study. A cement content of 100–300 kg/m^3 is generally required in practice to stabilise peat (NGF, 2012). In this study, the cement dosage added to the peat samples was varied between 0, 100 and 200 kg/m^3. Biochar amendments of 0, 50, 100 and 200 kg/m^3 were explored. The sample preparation followed the procedure described in NGF (2012). For each mixture, four samples with a diameter of 50 mm and a height of 100 mm were prepared. After mixing, the samples were cured at room temperature (~20°C) for 28 days (Bache *et al.*, 2022).

The water content, the pH and the mechanical properties of the biochar and/or cement-treated soil mixtures were quantified at different stages of the curing process (Table 2). To obtain the water content, the peat was oven dried with a temperature of 50°C

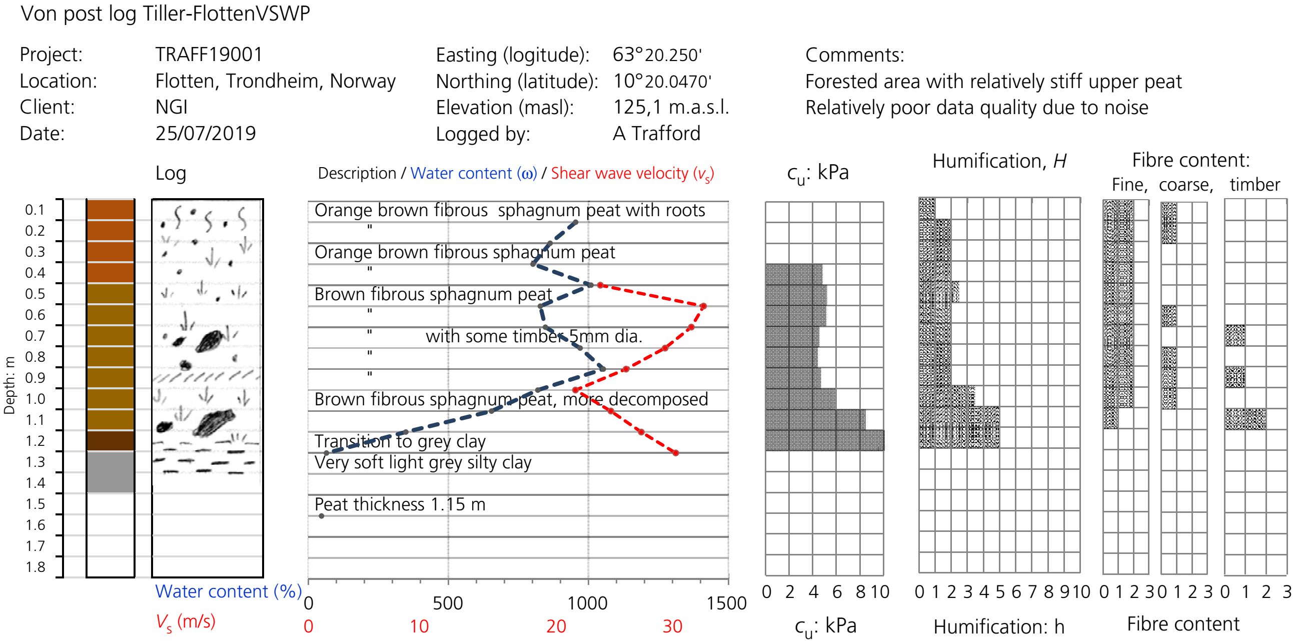


Figure 1. Tiller-Flotten peat Von Post log

Table 1. Biochar and/or cement-treated peat mixtures

Sample name	Soil	Cement dosage: kg/m^3	Biochar dosage: kg/m^3
Peat-0-0	Peat	0	0
Peat-0-50	Peat	0	50
Peat-0-100	Peat	0	100
Peat-0-200	Peat	0	200
Peat-100-0	Peat	100	0
Peat-100-50	Peat	100	50
Peat-100-100	Peat	100	100
Peat-100-200	Peat	100	200
Peat-200-0	Peat	200	0
Peat-200-50	Peat	200	50
Peat-200-100	Peat	200	100
Peat-200-200	Peat	200	200

Table 2. Experimental programme

Properties	Parameters	Laboratory testing method	Days after mixing
Water content	w	Water content analysis (NS-EN ISO 17892-1 : 2014 (NS, 2014))	0, 1, 28
pH	pH	pH analysis	0, 1, 2, 3, 7, 14, 21, 28
Mechanical properties	c_u, $\varepsilon_{a,f}$, E_{50}	UCS test	28

according to the standard NS-EN ISO 17892-1 : 2014 (NS, 2014). Unconfined compressive strength (UCS) tests were conducted on triplicate samples to quantify strength and stiffness and their standard deviations. Undrained shear strength values were derived by taking half of the UCS (i.e. peak of the UCS stress–strain curves). This procedure is a common approach and widely used in practice (e.g. NGF, 2012). However, one must keep in mind that c_u values obtained at different confinements (i.e. $\sigma_3 < 0$) will likely be different. The axial strain at failure, $\varepsilon_{a,f}$, was defined to be the strain value where a UCS stress–strain curve peaked. The stiffness was determined as the secant modulus, E_{50}, between 0 and 50% of the UCS, following the guidance in NGF (2012). The fourth sample was used for pH measurements. pH was measured by extracting the sample with a water solution (soil to water is 1 : 2.5), and after shaking for 2 h the pH was measured in the settling suspension (Houba *et al.*, 1989).

2.2.2 Sustainability assessment

A sustainability assessment was carried out to provide a more holistic assessment of the performance of biochar and/or cement-amended peat. This investigation related the obtained mechanical properties to the carbon footprint and costs of treating peat with biochar and/or cement. A cradle-to-gate analysis was carried out to assess the carbon dioxide emissions of the different mixtures when stabilising 1 m^3 of the Tiller-Flotten peat. This evaluation considered only the product stage of the cement and biochar production. It was therefore assumed that the transport distances of the different materials used for soil stabilisation (i.e. biochar and cement) were identical and that the soil stabilisation process, the use of the stabilised soil and its end of life were not significantly affected by using different stabilising materials and mixtures. The environmental product declaration (EPD) of the used cement was utilised to obtain the CO$_2$-eq of the product stage. The production of the used cement causes CO$_2$-eq emissions of 625 kg/t (The Norwegian EPD Foundation, 2016). Biochar sequesters carbon and thus has the potential to offset the caused carbon dioxide emissions. The used biochar contained 78.9% of carbon (Sørmo *et al.*, 2020) and was assumed to be 80% stable (Smebye *et al.*, 2017). These estimates resulted in a carbon offset of −2314.6 kg/t of biochar. Even though around 4 kg of carbon dioxide is released per kg biochar during pyrolysis (Sørmo *et al.*, 2020), it is important to realise that these emissions are accounted for in the overall C balance of the biochar generation process. The carbon dioxide released is around 50% of the carbon present in the feedstock (Sørmo *et al.*, 2020). However, this carbon has earlier been taken up by plants and trees, and can thus be considered to be climate neutral and does not contribute to the overall C balance of the process. The other half of the C in the feedstock is sequestered and removed from the C cycle by stable incorporation in the biochar. Thus, this part is carbon negative, and forms the overall carbon sink function of the biochar amendment. Emissions of the other GHG, methane, were very low (below detection) in the pyrolysis process (Sørmo *et al.*, 2020).

For the used cement, a cost of €105/t was determined following conversations with the cement producer. The biochar cost was assumed to be €350/t, which is within the range of 170–860 €/t typically found in literature (Thengane *et al.*, 2021). Carbon prices for the EU carbon quote market were taken as €69.40/t CO$_2$-eq for November 2021 (EU price 19.11.2021; Energi og Klima, 2021) and €90/t CO$_2$-eq as a realistic estimate for 2030 (Simon, 2021).

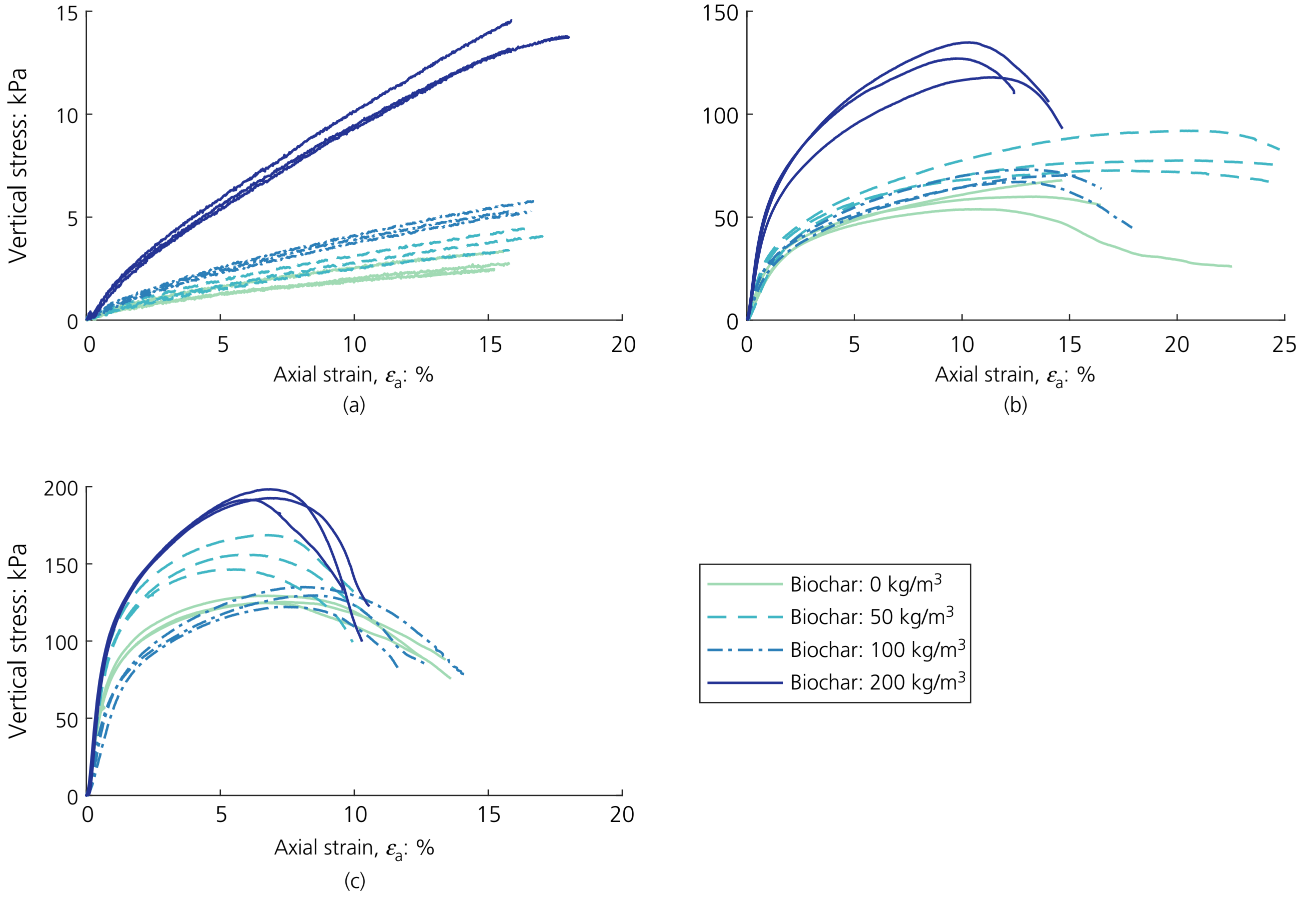
2.2.3 Data analysis

Changes in geotechnical properties of the peat, such as shear strength, stiffness, and axial strain at failure, due to biochar amendment were calculated using standard errors of the mean for each cement quantity. A Welch's unequal variances t-test (Welch, 1947) using $P = 0.05$ was applied to compare means. All data were analysed using Matlab© (network license number 62039).

3. Results

3.1 Shear strength

Figure 2 shows the vertical stress against axial strain curves for the different samples. The natural peat and the biochar-amended samples showed a typical strain hardening material behaviour (i.e. increase of material strength with strain). At the



(a)

(b)

(c)

Figure 2. Stress–strain curves of the Tiller-Flotten peat stabilised with different levels of cement and biochar after 28 days of curing. Note the different scales on the vertical axes. Cement quantity: (a) 0 kg/m^3, (b) 100 kg/m^3 (c) 200 kg/m^3

same axial strain, a notable increase in vertical stresses with the amount of added biochar is apparent from Figure 2(a). The cement-treated samples were characterised by a strain-softening material behaviour, which means that the material strength deteriorated with increasing strain after reaching a maximum stress. For mixtures with greater cement and biochar quantities, distinct stress peaks became evident.

The data from Figure 2 were utilised to derive undrained shear strength, c_u, values. As was mentioned above, distinct stress peaks were not obtained for samples with a strain-hardening response (i.e. strength increasing with strains, see Figure 2(a)). For this reason, it was defined to compute c_u at an axial strain of 15% as long as the maximum stress did not occur at a lower axial strain.

Figure 3 shows that amending the peat with solely biochar (i.e. 0 kg/m^3 of cement) resulted in higher c_u values compared to the natural peat. This increase of c_u was significant (Welch's unequal variances t-test; $P < 0.05$) for the peat samples treated with biochar levels of 100 and 200 kg/m^3. The c_u of

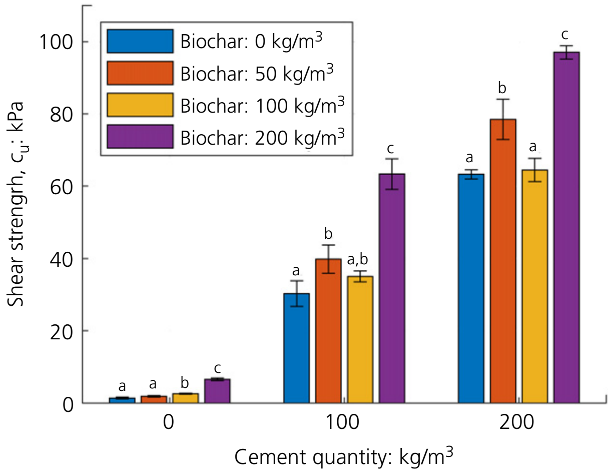


Figure 3. Shear strength of the Tiller-Flotten peat stabilised with different levels of cement and biochar after 28 days of curing. Vertical bars indicate standard errors of the means ($n = 3$). For each stabilised soil, bars with the same letter(s) within each cement quantity level are not significantly different according to Welch's t-test at $P < 0.05$. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

the peat amended with 200 kg/m^3 of biochar was found to be approximately 5 times greater than that of the natural peat.

A substantial increase in c_u on cement addition is apparent from Figure 3. Adding biochar generally caused a further increase of c_u. However, only adding biochar without cement resulted in significant, but not nearly strong enough increases in c_u (i.e. a c_u in the range of 50 kPa is often desired for rural roads, although the required c_u is strongly dependent on the type of road and type of peat). A significant change of c_u was obtained for the cement-stabilised samples when adding a biochar quantity of 50 and 200 kg/m^3, while the samples amended with 100 kg/m^3 cement did not exhibit a significant increase in shear strength on biochar amendment. This is a surprising result that may require further investigation or repetition. It is likely due to an anomaly, such as, the possibility of high degree of organic matter such as timber interfering with the cement reactions or causing hydrophobic behaviour of the peat (Valat *et al.*, 1991).

The most remarkable observation from Figure 3 is that the peat samples treated with 100 kg/m^3 of cement and 200 kg/m^3 of biochar expressed strength values (63.3 ± 4.2 kPa, $n = 3$) comparable to those of the peat samples amended with 200 kg/m^3 of cement (63.2 ± 1.3 kPa, $n = 3$). This finding implies that biochar can potentially replace some of the cement in peat stabilisation.

The relationship between c_u and the added biochar content is provided in Figure 4. Second-order polynomials were fitted to the samples with differing cement levels; a general trend of increasing c_u with biochar quantity is apparent. The data suggest that the optimum amount of biochar is likely to exceed the tested maximum of 200 kg/m^3.

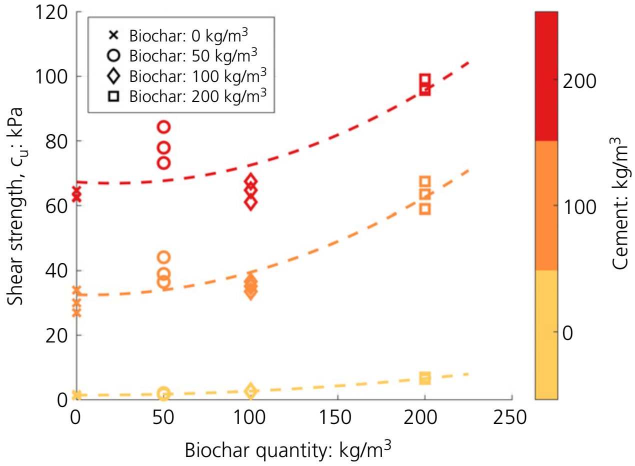


Figure 4. Variation of undrained shear strength, c_u, as a function of biochar dosage, at 0, 100 and 200 kg/m^3 cement. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

3.2 Axial strain at failure

The results of the axial strain at failure, $\varepsilon_{a,f}$, for the peat test series are presented in Figure 5. As was pointed out above, an axial strain threshold of 15% was defined for the mixtures characterised by a strain-hardening response. From Figure 5, it can be observed that the axial strain at failure was reduced with increasing cement dosage. This implies that the material behaviour shifts from strain hardening to strain softening. In other words, the cement level defines the ductility of the stabilised peat. Amending the peat with different levels of biochar had a minor impact on the axial strain at failure.

3.3 Stiffness

Figure 6 shows the relationship between the biochar quantity and the secant modulus E_{50} of the peat–cement mixtures. A clear trend of increasing E_{50} with both cement and biochar dosage is apparent. A significant stiffness increase ($P < 0.05$) was obtained for the different cement levels when amending the mixtures with 200 kg/m^3 of biochar.

The relationship between c_u and E_{50} is plotted in Figure 7. The E_{50} values fall into an envelope that is approximately bordered by $50c_u$ and $225c_u$ boundaries. A second-order polynomial was found to fit the data reasonably well. From this graph, one can also observe the advantageous performance of samples treated with 200 kg/m^3 of biochar.

3.4 Water content and pH value

The variation of the water content and pH of the peat samples after 28 days are shown in Figure 8, while their variation with curing time is presented in the supplementary information. An average water content of approximately 975% was measured for the natural peat along the curing period. Treating the peat with biochar, cement and a mixture of both caused a significant reduction of the water content. Amending the peat with

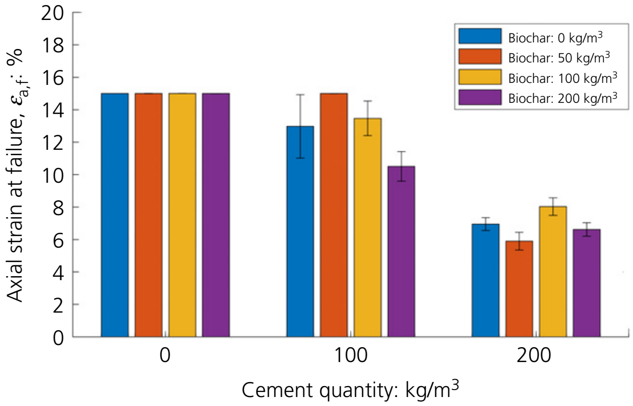
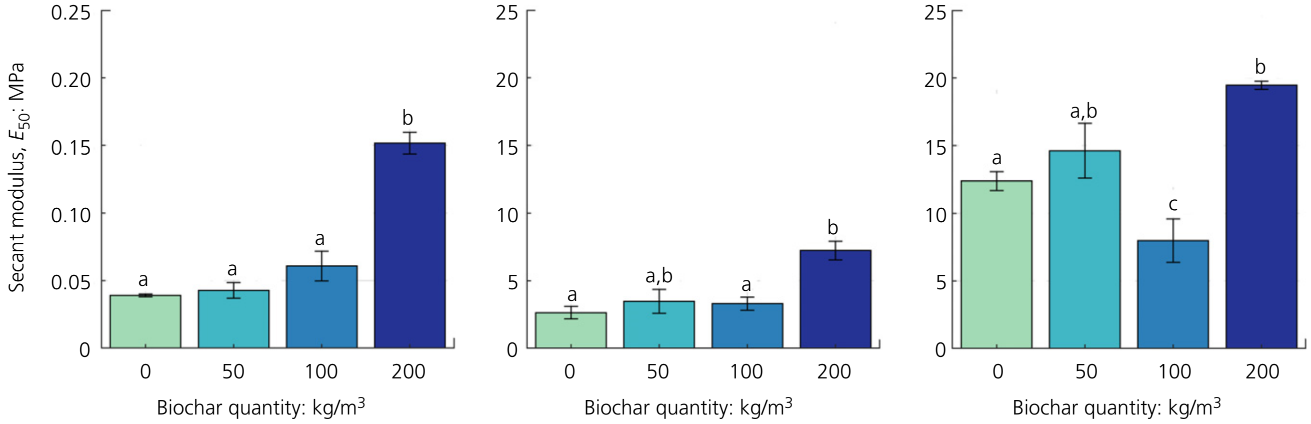


Figure 5. Axial strain at failure of the Tiller-Flotten peat stabilised with different levels of cement and biochar after 28 days of curing. Vertical bars indicate standard errors of the means ($n = 3$). For samples with strain-hardening response, the axial strain at failure was defined to be 15%. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)



(a) (b) (c)

Figure 6. E_{50} secant modulus of the Tiller-Flotten peat stabilised with different levels of cement and biochar after 28 days of curing. Vertical bars indicate standard errors of the means ($n = 3$). For each stabilised soil, bars with the same letter(s) within each cement quantity level are not significantly different according to Welch's t-test at $P < 0.05$. Note the different y-axis scales of the panels. Cement quantity: (a) 0 kg/m^3; (b) 100 kg/m^3; (c) 200 kg/m^3. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

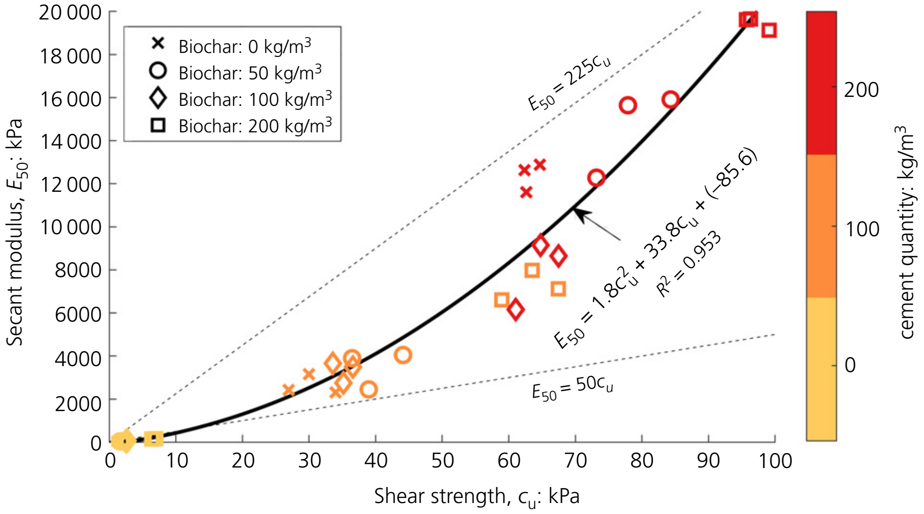


Figure 7. Relationship between E_{50} secant modulus and undrained shear strength, c_u, for the biochar-/cement-amended peat test series. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

100 kg/m^3 of biochar approximately halved the water content of the peat to 480% after 28 days. Cement showed a stronger effect on water content than biochar, with 100 kg/m^3 cement reducing the water content to approximately 400% without biochar and to approximately 200% with 200 kg/m^3 biochar.

Figure 8(b) compares the pH value for the peat samples. For the natural peat, a pH value of approximately 4.2 was measured. Amending the peat with biochar caused a notable pH increase. The peat sample treated with 200 kg/m^3 of biochar had a pH value slightly below 7. For the cement-treated peat, a fast increase of the pH to values between 11.25 and 12.75 was observed, which is within the expected range for cement hydration (i.e. pH = 11–13.5; Taylor, 1997). The highest pH values were measured for the 200 kg/m^3 cement samples. The supplementary information provides the pH variation with curing time.

4. Discussion

4.1 Biochar amendment of peat without cement

The current study found that peat treated with different biochar quantities experienced a substantial reduction in water content, while the pH value increased with the biochar content. These observations are encouraging considering that previous research stated an inverse relationship between the peat strength and the water content (e.g. Åhnberg *et al.*, 2003; Hernandez-Martinez, 2006). A distinct strain-hardening

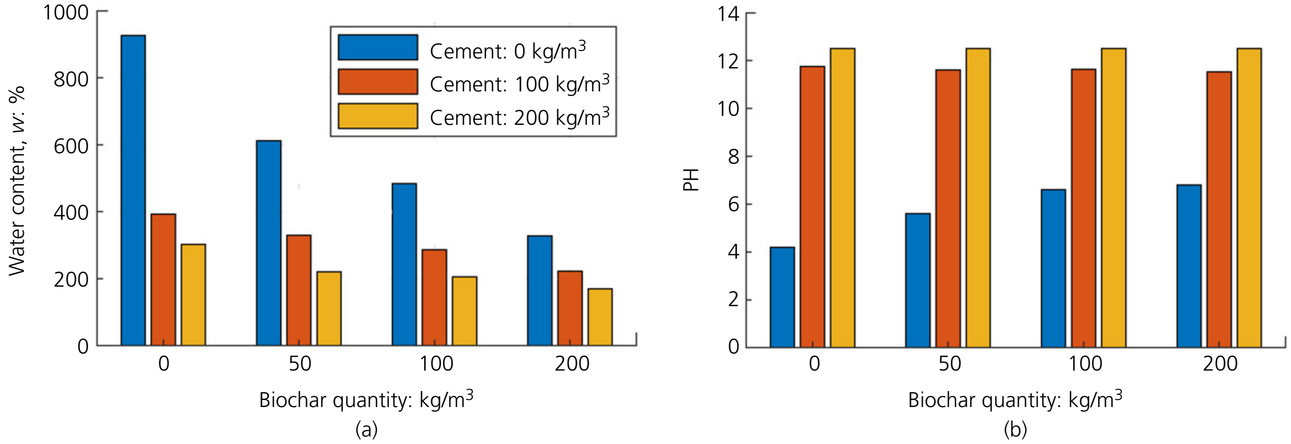


Figure 8. Change of (a) water content, *w* and (b) pH after 28 days of curing. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

behaviour was evident for the biochar-amended peat. The biochar amendment enhanced both the strength and stiffness of the peat. These results are likely directly related to the water adsorption causing soil drying and align with previous research that showed a strength increase with a drop in water content (e.g. Åhnberg *et al.*, 2003; Hernandez-Martinez, 2006). Peat samples treated with biochar quantities of 200 kg/m^3 showed the greatest strengths and stiffnesses. However, the increases were far lower than in the presence of cement and generally insufficient to meet typical requirements of rural road construction, which demand c_u in the range of 50 kPa and stiffness values in the range of 300–500c_u These results suggest that biochar amendment could have beneficial effects when adopting preloading or surcharging techniques to improve the strength and stiffness of peat which could be a topic for future studies.

4.2 Biochar amendment of cement-stabilised peat

The results of this study have demonstrated that biochar addition has a beneficial impact on the mechanical properties of cement-stabilised peat. Importantly, both the strength and stiffness of the stabilised peat increased with the added biochar quantity. The obtained data indicate that the optimum biochar quantity was probably greater than the maximum quantity tested in this study (i.e. 200 kg/m^3).

Strength properties which are often sufficient for rural road construction (i.e. $c_u = 50$ kPa) were obtained for the peat sample treated with 100 kg/m^3 of cement and 200 kg/m^3 of biochar (63.3 ± 4.2 kPa, $n = 3$). Likewise, all the peat samples treated with 200 kg/m^3 of cement and different biochar dosages exceeded this approximate strength threshold. The stiffness values of the cement and biochar-amended samples fell within the range of approximately 50–225c_u, which is below frequently demanded values for rural roads (i.e. 300–500c_u). Lau (2018) presented slightly greater stiffness results for biochar and cement-treated peat, which can likely be explained by using both higher biochar quantities and finer biochar.

The obtained results suggest that biochar can partially replace cement when stabilising peat. Especially, the peat sample treated with 100 kg/m^3 of cement and 200 kg/m^3 of biochar exhibited strength properties (63.3 ± 4.2 kPa, $n = 3$) almost identical to those of peat stabilised with 200 kg/m^3 of cement (63.2 ± 1.3 kPa, $n = 3$). Similar findings were presented by Lau (2018) and Lau *et al.* (2020), who showed that peat mixed with 100 kg/m^3 cement and 400 kg/m^3 hardwood timber biochar finer than 75 μm resulted in strength values comparable to those of samples stabilised with 200 kg/m^3 cement. The results on clean wood and leaves biochar with a grain size smaller than 250 μm provide further confidence that wood-derived biochar has the potential to partially replace cement and thus can be considered as an effective filler to improve the properties of cement-stabilised peat.

The observed trend of stiffness and strength increases when introducing biochar in peat stabilisation supports the hypothesis that the high-water adsorption of biochar results in more accessible water causing a higher degree of hydration (Lau, 2018; Lau *et al.*, 2020). This mechanism seems to be valid for wood-based biochar, but future study should focus on studying the role of different biochar types. Especially, the effect of different feedstocks and pyrolysis conditions on related biochar properties, such as, porosity and ash content, and their impact on peat stabilisation requires further investigation.

4.3 Sustainability of amending peat with biochar

To provide a holistic and practice-oriented assessment of the performance of biochar-amended cement-stabilised soils, the following sections discuss carbon dioxide emissions and material costs of the studied mixtures. Finally, the obtained strength properties of the biochar and/or cement-amended peat samples will be related to the material costs including carbon pricing.

4.3.1 Carbon dioxide emissions

Figure 9 shows the carbon footprint of the Tiller–Flotten peat samples stabilised with different biochar and/or cement levels.

The cement-stabilised samples caused significant carbon dioxide emissions. Stabilisation with 100 kg/m^3 of cement would cause emissions of approximately 62.5 kg CO_2-eq per m^3 of stabilised clay. As expected, the biochar amendment compensated the cement-related carbon dioxide emissions. For the considered cement and biochar with carbon dioxide emissions of 625 and −2314.6 kg/t, the addition of biochar quantities greater than 27% of the cement quantities rendered the soil stabilisation process to be carbon negative.

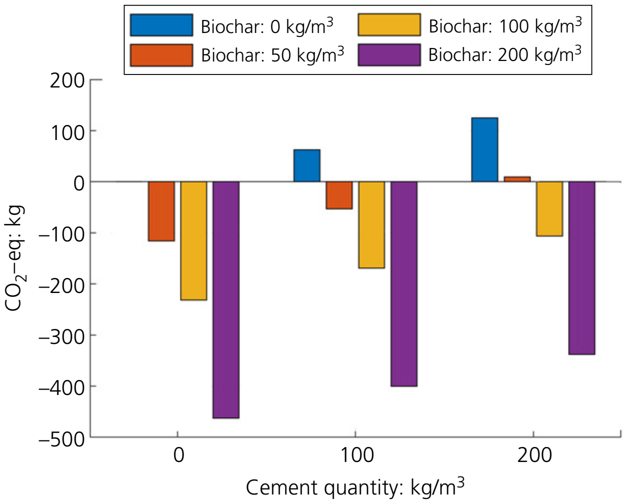


Figure 9. Greenhouse gas emissions (in CO_2-eq) from amending 1 m^3 of Tiller-Flotten peat with biochar and/or cement. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

4.3.2 Material costs

Figure 10 plots the material costs per m^3 of the stabilised Tiller-Flotten peat. Treating the peat with biochar considerably raised the costs (i.e. 1.8–7.7 times the costs of the cement-only-treated peat). Including a carbon price on cement and revenues from carbon offsetting on biochar (i.e. negative carbon footprint), considerably reduced the impact of biochar on the material costs (Figures 10(b) and 10(c)). A carbon price of €69.40/t (estimate for November 2021) raised the cement costs by 41% while lowering the biochar costs by 46%. Considering a carbon price of €90/t for 2030 (Figure 10(c)), the cement costs increased even further (54%), while the biochar costs reduced by 60%. In the future, the cost impact of using biochar for soil stabilisation will likely be further reduced due to an expected higher carbon price but also lower biochar production costs (not considered in Figure 10).

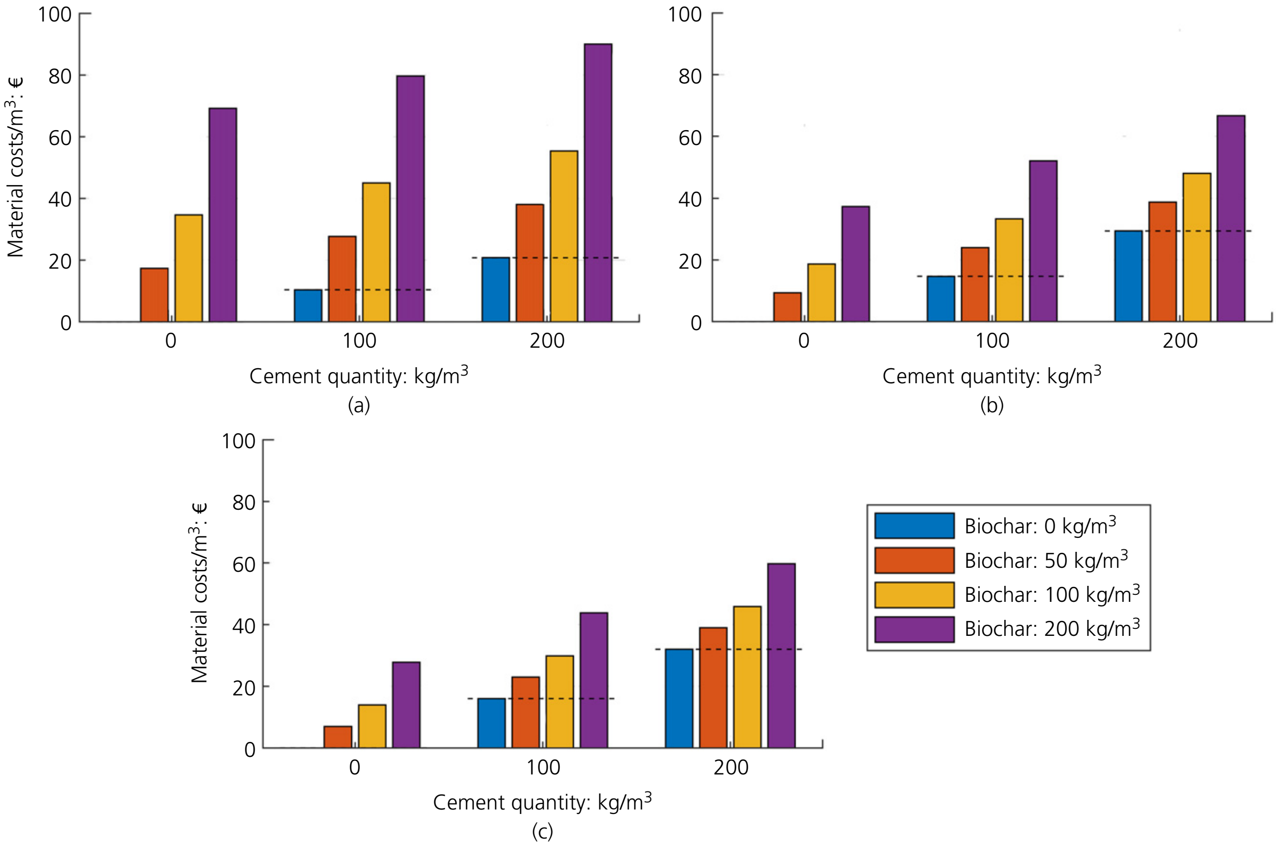


Figure 10. Material costs for 1 m^3 of biochar and/or cement-amended Tiller-Flotten peat. The dashed lines indicate the cement costs. Carbon price: (a) €0/t; (b) €69.40/t (Nov 2021); (c) €90/t (2030). A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

A carbon dioxide price of approximately €85/t was required for break-even when stabilising peat using equal biochar and cement quantities – that is, amending 100 kg/m^3 biochar to a peat stabilised with 100 kg/m^3 cement would not incur additional costs compared to 200 kg/m^3 cement if the carbon sequestration by biochar was awarded with carbon credits worth €85/t, with the same penalty for carbon dioxide emissions from cement use. This calculated break-even point is below typical estimates for 2030 (i.e. €90/t carbon dioxide; Simon, 2021).

4.3.3 Sustainability assessment

A sustainability assessment was carried out by merging the geotechnical, environmental and economic performance of the different mixtures (Table 1). The ratio between the shear strength, c_u, and the material cost including carbon pricing was adopted as an overall sustainability parameter. From Figure 11, it is evident that the cement-only-stabilised samples outperformed the ones with additional biochar amendment, especially at low carbon prices. The greatest benefits were observed for the peat improved with 100 and 200 kg/m^3 of cement (~3 kPa/€ when neglecting carbon costs; Figure 11(a)), while these cost–benefit ratios reduced when adding biochar (~0.8–2.0 kPa/€). As expected, even lower shear strength gains per € were obtained for biochar-only-amended peat (~0.1 kPa/€, Figure 11(a)). Figure 11 further indicates that higher carbon pricing would improve the competitiveness of biochar amendments.

5. Conclusion

This study has shown that biochar amendment can have beneficial effects on the geotechnical properties of peat. It was observed that biochar should be treated as a fill material with the potential of enhancing the mechanical properties of both natural and cement-stabilised peat. The biochar addition showed significant potential of partially replacing cement. Peat samples treated with 200 kg/m^3 of biochar and 100 kg/m^3 of cement had almost identical strength as samples treated with 200 kg/m^3 of cement, but at a strongly negative carbon footprint (i.e. net sequestration of carbon) instead of a significantly positive one. The obtained results suggest that biochar dosages exceeding 200 kg/m^3 will likely result in even more strongly positive effects on peat stability. Consequently, the main hypothesis of this research (i.e. that biochar could improve the carbon footprint of peat stabilisation works without compromising on mechanical properties) was not falsified.

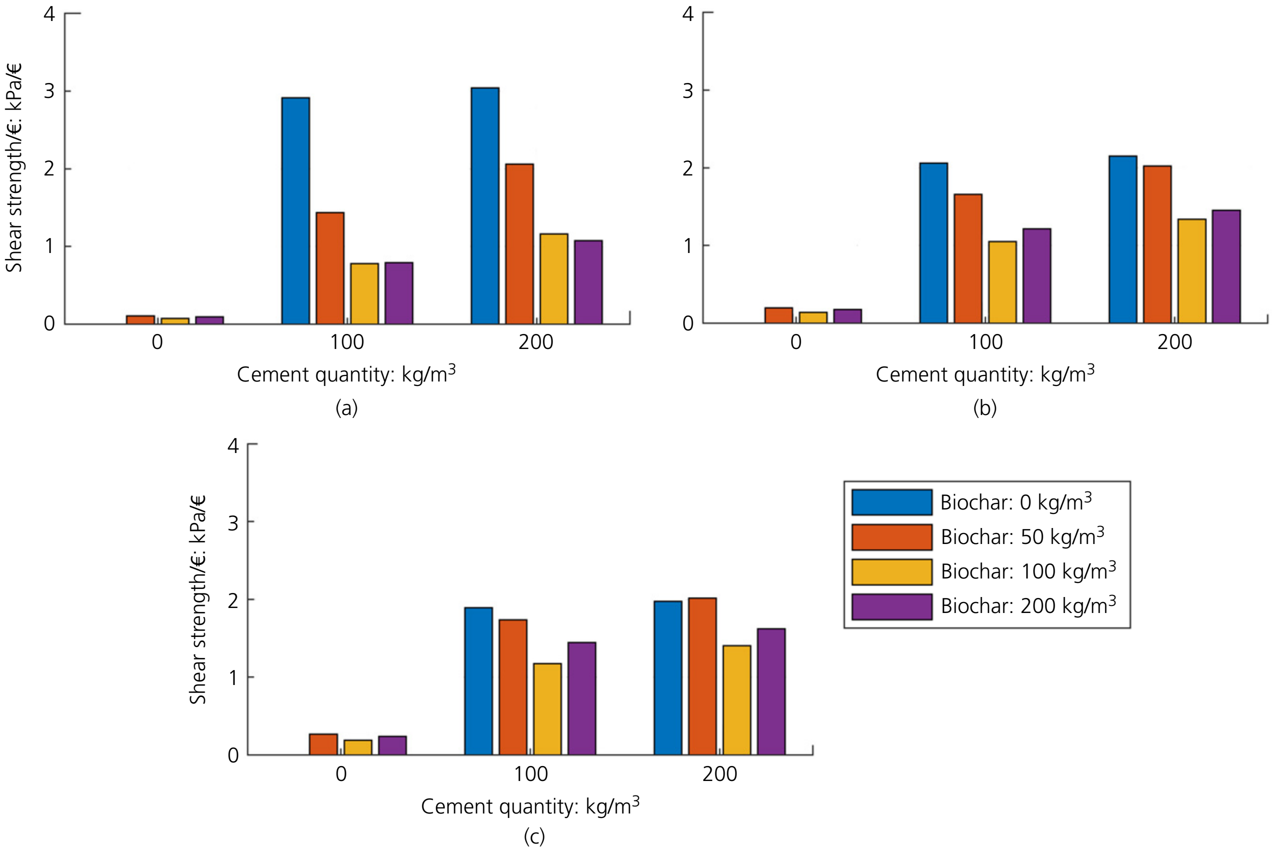


Figure 11. Sustainability analysis in terms of shear strength per € for the biochar and/or cement-amended Tiller-Flotten peat. Carbon price: (a) €0/t; (b) €69.40/t (Nov 2021); (c) €90/t (2030). A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

The current costs of biochar are, however, greater than its benefits. Future, higher carbon prices and cost reductions in biochar production would increase the competitiveness of biochar amendment for peat stabilisation. A break-even carbon price of approximately €85/t was calculated to make biochar addition for peat stabilisation economically competitive.

A natural progression of this study would be to understand the effect of varying biochar properties on peat including the impact of different feedstocks, such as, biochar from organic waste fractions or sludge-based biochar, and different pyrolysis conditions. Biochar optimised for soil stabilisation (e.g. with increased surface area and reduced particle sizes) may outperform the biochar dealt with in this study. Further research should also focus on exploring peat treated with biochar quantities greater than 200 kg/m^3. Another fruitful area of research would be to investigate the effect of biochar on other soil types such as sensitive clay and if biochar can be used to prevent clay from becoming 'quick'. Finally, this experimental study should be upscaled to investigate the performance of biochar amendment of peat at field scale.

Supplementary information

Supplementary information of this paper can be found online at https://www.icevirtuallibrary.com/doi/suppl/10.1680/jgrim.22.00023/suppl_file/jgrim.22.00023_Supplemental_Material.pdf.

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