REPORT

Biochar to stabilise unstable soft clay and peat soils

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Summary

Recently, there has been growing interest to reduce carbon dioxide (CO_2) emissions caused by ground improvement works. While most research aimed at optimising the content of typical binders such as lime and cement, there is a lack of studies that investigate alternative materials. Few studies have investigated the addition of materials such as biochar that can sequester CO_2 and thus mitigate climate change by rendering ground improvement carbon-neutral or even carbon-negative. Biochar is the product of incomplete combustion (pyrolysis) of organic feedstocks, such as waste timber, green waste, food waste, biogas digestate, and even sewage sludge. This contribution set out to study the effect of mixing biochar into quick clay, cement-stabilised quick clay, peat and cement-stabilised peat on geotechnical properties.

Biochar produced through pyrolysis of clean wood and leaves was crushed and sieved to particle sizes smaller than 250 μm. Quick clay and peat from the Tiller-Flotten Norwegian GeoTest Site (NGTS) in Norway and widely used CEM II cement was used. A series of laboratory tests including shrinkage limit tests, plasticity limit tests, pH measurements, unconfined compressive strength (UCS) tests and fall cone tests on different biochar, cement and soil compositions were carried out.

It was found that biochar has the potential to enhance the strength of quick clay and cement-stabilised quick clay. Quick clay amended with biochar showed a remoulded shear strength above the 0.5 kPa threshold characterising a quick clay. Adding biochar in the range of 75 to 125 kg/m^3 increased the shear strength of cement-stabilised quick clay. However, a stiffness reduction was observed when adding biochar to cement-stabilised quick clay, probably because of the brittle character of the larger biochar particles.

The investigation of the effect of biochar on peat has shown that the biochar amendment considerably reduced the peat water content which caused soil drying. Consequently, the biochar addition enhanced the shear strength and stiffness of both peat and cement-stabilised peat. Peat and cement treated peat samples amended with 200 kg/m^3 of biochar performed best; the trend of increasing strength and stiffness with increasing biochar quantities suggests that higher biochar quantities could be even more beneficial.

This research indicates that biochar should be treated as a fill material with the potential of enhancing the mechanical properties of both natural and cement-stabilised quick clay and peat. Particularly for peat, the biochar addition showed significant potential of partially replacing cement. Importantly, 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.

Carbon footprint and cost-benefit analyses confirmed that biochar addition can render soil stabilisation works carbon-negative, but the costs of biochar amendment are currently greater than its benefits as long as no carbon price is included. However,

considering future carbon costs up to 2,000 NOK/tonnes CO2, it was calculated that biochar addition for soil stabilisation would become economically competitive, especially when biochar prices drop, or if biochar from waste fractions such as sewage sludge is used. Finally, this report provides recommendations for further studies.

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Review and reference page

1 Introduction

Amending soft soil with chemical binders is widely carried out for ground improvement. In Norway, 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 flocculation, hydration, pozzolanic reactions and carbonation. Several works describe these chemical processes in detail (e.g. Chew et al. 2004; Janz and Johansen 2002; Åhnberg 2006; Lau 2019).

The production of cement and lime is, however, a carbon intensive activity. For example, widely used Norwegian cement has a carbon footprint of approximately 625 kg carbon dioxide equivalents (CO_2-eq) per tonne cement. Consequently, these binders account for a substantial part of the CO_2 footprint of ground improvement works. There is, therefore, an urgent need to explore alternative, more climate-friendly materials to improve the mechanical properties of soil. This requirement of studying alternative materials for soil stabilisation was also identified in The Norwegian Public Roads Administration (NPRA) report *"Klimatiltak ved bygging av ny veg"* as one of three most promising measures with a considerable potential to reduce CO_2 emissions (Statens vegvesen, 2020).

Biochar represents such an alternative material for soils stabilisation. It 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.

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. Recently, Lau et al. (2019) 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 stabilization carbon-neutral, without impacting its stabilizing properties (Lau et al. 2019), but at a 10-20% higher cost. Comparable works by Reddy et al. (2015) and Pardu et al. (2019) obtained similar beneficial mechanical behaviour when mixing biochar with silty clay or sand, respectively. However, the effect of biochar on typical Norwegian soils such as quick clay and peat has not yet been investigated.

The general aim of this research is to answer the following question: Can biochar be used to stabilize Norwegian soils and cement-stabilised Norwegian soils? The specific objectives are to evaluate (1) the optimal dosage of biochar to obtain the required mechanical properties of the stabilised peat and soft clay soils and (2) to investigate the impact of biochar on the overall sustainability of the soil stabilisation works including carbon footprint and material cost. The adopted research methodology is briefly described in the next section, followed by the interpretation of the experimental results and conclusions.

2 Research methodology

2.1 Materials

2.1.1 Biochar

The biochar used in this research was produced by Verora GmbH, Switzerland. It is produced from a feedstock consisting of a mixture of clean wood and leaves (Figure 1) from gardening waste (both hardwood and softwood). The biomass was pyrolyzed in a Pyreg-500 pyrolysis unit with a residence time of 20 min and a temperature of approximately 600°C. Further detail about the feedstock composition, the pyrolysis unit and operating principle can be found in Sørmo et al. (2020).

Figure 1 Biomass used to produce biochar. Source: Sørmo et al. (2020).

Table 1 lists the standard properties of the used biochar. Important physical properties of the biochar are 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-N_2 and a porosity of 12.6%. The biochar consists of 78.9% of carbon, 3.5% of calcium, 3.3% of oxygen and 2.35% of hydrogen. The H/C (molar) ratio is 0.35. It is alkaline with a pH value of 8.6. A moisture content of 28% was determined for the used biochar (Sørmo et al., 2020).

Table 1 Standard biochar properties according to the European Biochar Certificate (EBC) guidelines. From Sørmo et al. (2020).

Parameter	Unit	Clean wood and leave biochar	EBC Threshold values
Density (bulk)	kg/m^3	229	
Density (actual)	g/cm^3	1.58	
BET-N_2 surface (>1.5 nm)	m^2/g	287	
CO_2 surface (0.3-1.5 nm)	m^2/g	453	
Porosity (pores 0.3-1.5 nm)	%	12.6	
Ash (550 °C)	%	14.3	
Hydrogen	%	2.35	
Carbon	%	78.9	> 50
Nitrogen	%	1.15	
Oxygen	%	3.3	
Inorganic carbon	%	1.2	
Organic carbon	%	77.7	
H/C molar		0.35	< 0.6
$H/C_{organic}$		0.36	< 0.7
O/C molar		0.031	< 0.4
Total sulfur (S)	%	0.03	
pH ($CaCl_2$)		8.6	< 10
Conductivity	µS/cm	822	
Salt content	g/kg	5.55	
Phosphorus (P)	%	0.2	
Magnesium (Mg)	%	0.3	
Calcium (Ca)	%	3.5	
Potassium (P)	%	1.0	
Sodium (Na)	%	0.05	
Iron (Fe)	%	0.11	
Silicone (Si)	%	1.1	
TGA*	T (°C)*	320	

* TGA: thermogravimetric analysis. T is temperature where maximal weight loss is achieved – a way to determine maximum charring temperature.

Before the biochar was mixed into the soil samples, the biochar was dried at 40°C for 24 hours to remove moisture absorbed during storage. Then, it was crushed using a coffee grinder and sieved to obtain biochar samples with a particle size smaller than 250 µm. Figure 2 shows the particle size distribution of the processed biochar, which can be characterised as a fine sand.

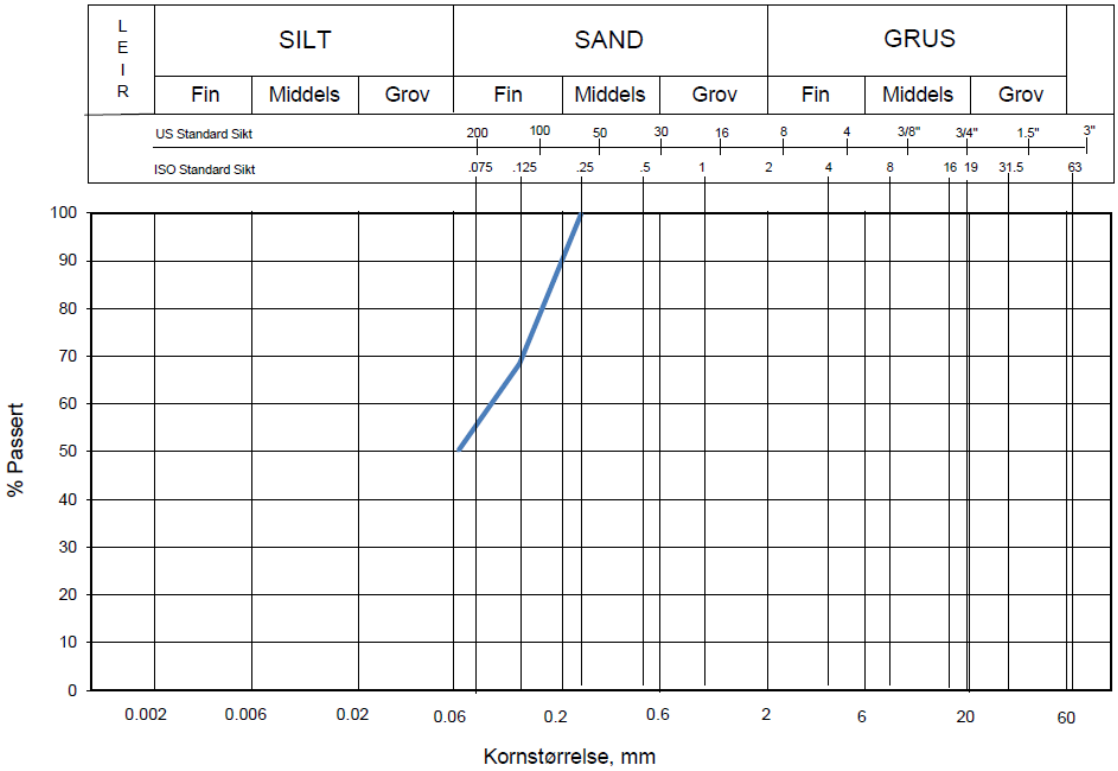


Figure 2 Particle size distribution of the processed biochar according to NS-EN 17892-4:2016.

2.1.2 Cement

A standard cement FA (CEM II/B-M) according to NS-EN 197-1 produced by NORCEM in Kjøpsvik, Norway is employed. 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 of 72% clinker, 18% fly ash, 5.2% gypsum, 4% limestone, 0.24% iron sulphate and 0.1% grinding aid (epd-norge.no, 2016). The adopted cement is widely used in soil stabilisation projects throughout Norway.

2.1.3 Clay

The clay used in this study was obtained from two block samples of the borehole TILB19 from the Norwegian GeoTest Site (STS) Tiller-Flotten, Trondheim. The clay from this research test site has been well characterised in previous studies (e.g. L'Heureux et al. 2019). The samples used in this research were derived at a depth between 9.30 to 10.05 m below the ground level. At this depth, the marine clay is part of the so-called Unit IIb, which has properties typical of a very sensitive quick clay (L'Heureux et al. 2019). Table 2 shows index properties of this Unit IIb as well as more specific data derived for the sampling depth.

Table 2 Basic index properties for the Unit IIB of the Tiller-Flotten clay and at the sampling depth of the used block samples. Properties were derived from L'Heureux et al. (2019) and additional laboratory tests.

Parameter	Unit	Tiller-Flotten clay Unit IIb	Sampling depth (9.30 to 10.05 m)
Particle density, G	g/cm^3	2.85	2.85
Water content, w	%	30 - 50	45±3
Bulk unit weight, γ_t	kN/m^3	18	18
Clay fines content	%	40 – 75	70
Plasticity index, I_P		8 - 15	15
Liquidity index, I_L		>1.6	2
Salt content, NaCl	g/l	2	2

The clay of Unit IIb has a low plasticity and a liquidity index above 1.6. For the block samples, a water content of 45±3% and a pH of 8.44 was measured. The grain size distribution indicates a clay content between 40 to 75% for Unit IIb. At the block sample depth, the clay content is approximately 70% and the silt content 30%. The high clay content is not typical for Norwegian marine clays, which generally have higher weight percentage of silt fractions compared to the clay fraction. According to investigations carried out in the NGTS project, the dominant mineralogical components in the clay fraction are biotite, illite/muscovite and chlorite. Notable quartz and plagioclase were found in the bulk fraction.

The engineering properties of the Unit IIb clay and at the sampling depth are summarised in Table 3. As expected, a wide range of undrained shear strength, c_u, values were obtained for the Unit IIb according to the adopted test method, the sample type and soil depth. For block samples obtained close to the sampling depth, a c_u between 50 to 75 kPa was determined. Drained shear strength properties were derived from CAUC triaxial tests of Unit IIb samples. Effective friction angle, φ', in the range of 29-32° and a cohesion intercept, c', of approximately 5 kPa were estimated. A more detailed description of the Tiller-Flotten clay is provided elsewhere (e.g. L'Heureux et al. 2019; NGI 2020)

Table 3 Engineering properties of the Tiller-Flotten clay Unit IIb and at the sampling depth. Data derived from L'Heureux et al. (2019).

Parameter	Unit	Tiller-Flotten clay Unit IIb	Block samples, sampling depth (9.3 to 10.05 m)
Overconsolidation ratio, OCR		2-3	2.5
Coefficient of earth pressure at rest, K_0		0.5-1.0	0.8
Undrained shear strength, c_u	kPa	12.5-75	50-75
Effective friction angle, φ’	°	29 -32	-
Cohesion intercept, c’	kPa	5	-

2.1.4 Peat

The peat samples used in this study were obtained from the Tiller-Flotten NGTS site (L'Heureux et al. 2019), which is the identical site as explored for the clay samples. This site is characterised by peat over quick clay and was extensively drained since the 1970s (NGI 2019). The samples were taken at an Easting and Northing of 570958 and 7023977 (UTM 32N) using a shovel and subsequently wrapped with plastic bags. The sampling depth was approximately 0.5-0.6 m.

Figure 3 summarises the von Post log of the Tiller-Flotten peat following the peat classification described in von Post and Granlund (1926) and presented in NGI (2019). This classification is based on the following sub-categories: botanical composition, water content (B), content of fine (F), humification (F), coarse fibres (R) and woody remnants (W). According to von Post and Granlund (1926), a peat can be classified between H1, completely unhumified fibrous peat, and H10, completely amorphous non-fibrous peat. At the sampling depth, the Tiller-Flotten peat is between H2 to H5 indicating an insignificant to moderate decomposition. A low to medium fine and coarse fibre content was obtained. The natural water content of the peat is approximately 1000% at the sampling depth. Shear wave velocities of approximately 20 m/s were found. The undrained shear strength 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 (e.g. Paniagua et al. 2020; NGI 2019).

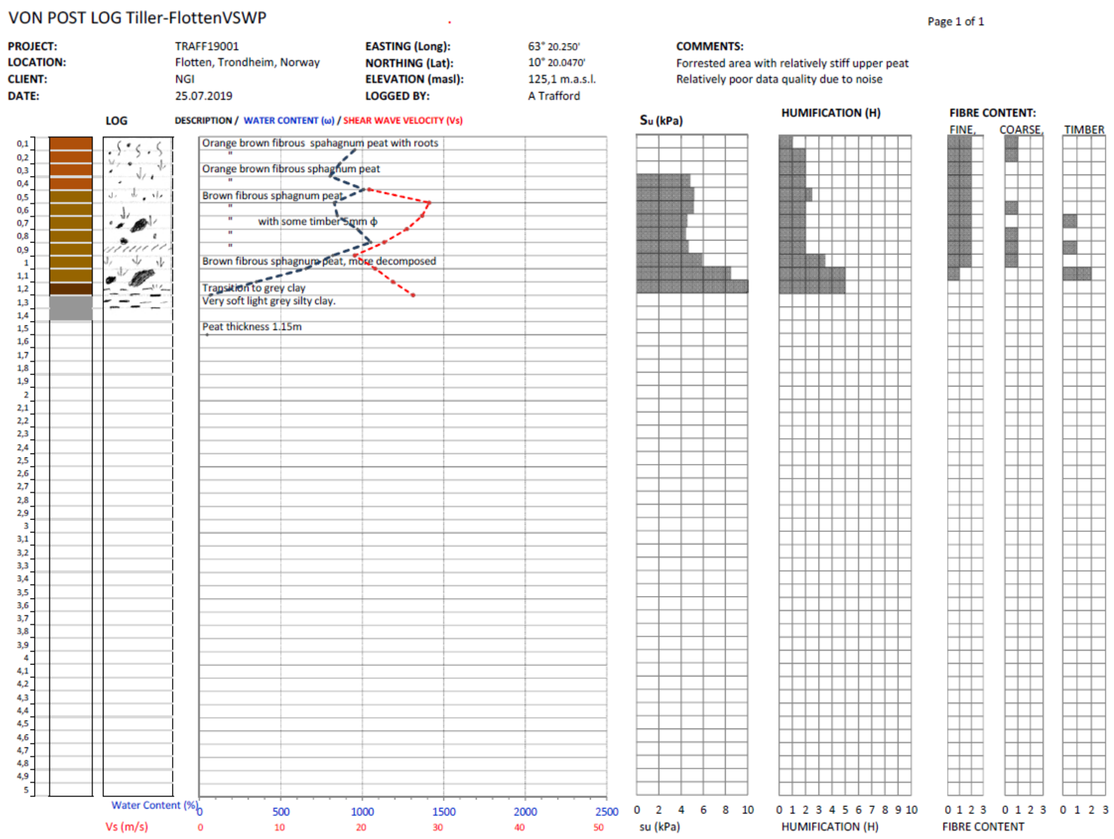


Figure 3 Tiller-Flotten peat von Post log. Source: NGI (2019).

2.2 Testing programme and sample preparation

An overview of the conducted laboratory experiments is given in Table 4. The state and index properties, the pH and mechanical properties of the biochar and/or cement treated soil samples were quantified at the NGI laboratory in Oslo. The microstructure and chemical composition of selected samples were investigated using a scanning electron microscope at the University of Oslo and XRD analysis performed by the Norwegian Geological Survey (NGU) in Trondheim. Further details about the SEM and XRD investigations is provided in the results section.

Table 4 Summary of performed laboratory tests.

Parameter	Abbreviation	Laboratory testing method	Days after mixing*
State and index properties	w_L, w_P, I_P	Atterberg limits (NS 8002, NS 8003)	0, 1
Water content	w	Water content analysis (NS-EN ISO 17892-1:2014)	0, 1, 28
pH	pH	pH analysis	0, 1, 2, 3, 7, 14, 21, 28
Mechanical properties	c_u	Unconfined compressive strength (UCS tests, Fall cone tests)	28
Microstructure		Scanning electron microscopy (SEM)	>28
Chemical composition		X-ray diffraction (XRD)	>28

*The tests after 0 days were carried directly after the sample preparation (i.e. mixing) was finalised.

Table 5 lists the different mixtures investigated in this study. Cement and/or biochar of different quantities per stabilised soil volume were added to the clay or peat following the sample preparation procedure according to NGF (2012). For each mixture, four samples with a diameter of 50 mm were prepared. Three samples were used to quantify the mechanical properties of the stabilised soil samples. The fourth sample was used for the pH measurements. After mixing, the samples were cured at room temperature (approximately 20°C) for 28 days.

For the clay samples, four different cement quantities per volume of soil stabilised soil were explored, including 0, 25, 50 and 100 kg/m^3. These binder content values are lower or within the range of typical values suggested for sensitive clay (i.e. 80-110 kg/m^3, NGF (2012)). The lower binder levels were studied because recent research showed shear strength values exceeding typical Norwegian design limits of 150-200 kPa with binder contents as low as 50 kg/m^3 (NGI, 2020). For each cement level, samples with biochar quantities between 0 and 200 kg/m^3 were prepared (Table 5).

A higher binder content is generally required to stabilise peat which is reflected in the peat mixtures (Table 5). NGF (2012) suggests a cement content in the range of 100-300 kg/m^3 for peat. In this study, the cement content added to the peat samples was varied between 0, 100 and 200 kg/m^3. Biochar contents of 0, 50, 100 and 200 kg/m3 were explored.

As a final part of this study a cost-benefit analysis was carried out. This investigation focuses on the carbon footprint and costs of treating soil with cement and/or biochar.

Table 5 Biochar and/or cement treated soil samples.

Sample Name	Soil	Cement content (kg/m^3)	Biochar content (kg/m^3)
Clay-0-50	Clay	0	50
Clay-0-75	Clay	0	75
Clay-0-100	Clay	0	100
Clay-0-200	Clay	0	200
Clay-25-0	Clay	25	0
Clay-25-50	Clay	25	50
Clay-25-100	Clay	25	100
Clay-25-200	Clay	25	200
Clay-50-0	Clay	50	0
Clay-50-50	Clay	50	50
Clay-50-100	Clay	50	100
Clay-50-200	Clay	50	200
Clay-100-0	Clay	100	0
Clay-100-50	Clay	100	50
Clay-100-100	Clay	100	100
Clay-100-200	Clay	100	200
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

3 Results and discussion

The results of this study are presented separately for the clay and peat test series. The findings of the clay tests are summarised in three phases. First, the effect of different combinations of cement and biochar quantities on soil state and index properties and the pH value are presented. Second, the results of unconfined compressive strength (UCS) and fall cone tests are discussed to show the mechanical behaviour of different mixtures. Third, SEM and XRD test results are explored to reveal the microstructure and chemical interaction between clay with cement and biochar. The peat test series focused only on the mechanical properties while SEM and XRD investigations were beyond the scope of this initial work. Finally, carbon budgets and results from a cost-benefit analysis are outlined to provide a more holistic view on using biochar to stabilise soils.

3.1 Performance of quick clay treated with biochar and/or cement

3.1.1 State and index properties and pH value

The change of the water content in the clay samples is shown in Figure 4. For all mixtures, the water content was below the average water content measured for the block samples (43.5%; based on two measurements of 42.8% and 44.2%). The results suggest that the water content further reduces with curing time. This finding was expected for the samples treated with cement and is a result of the hydration process consuming water. Interestingly, this trend can also be seen for the samples treated only with biochar. The biochar seems to consume some of the pore water causing a drying of the clay which may translate into a strength increase. The reason is probably that the narrow pores in the biochar absorb a lot of water.

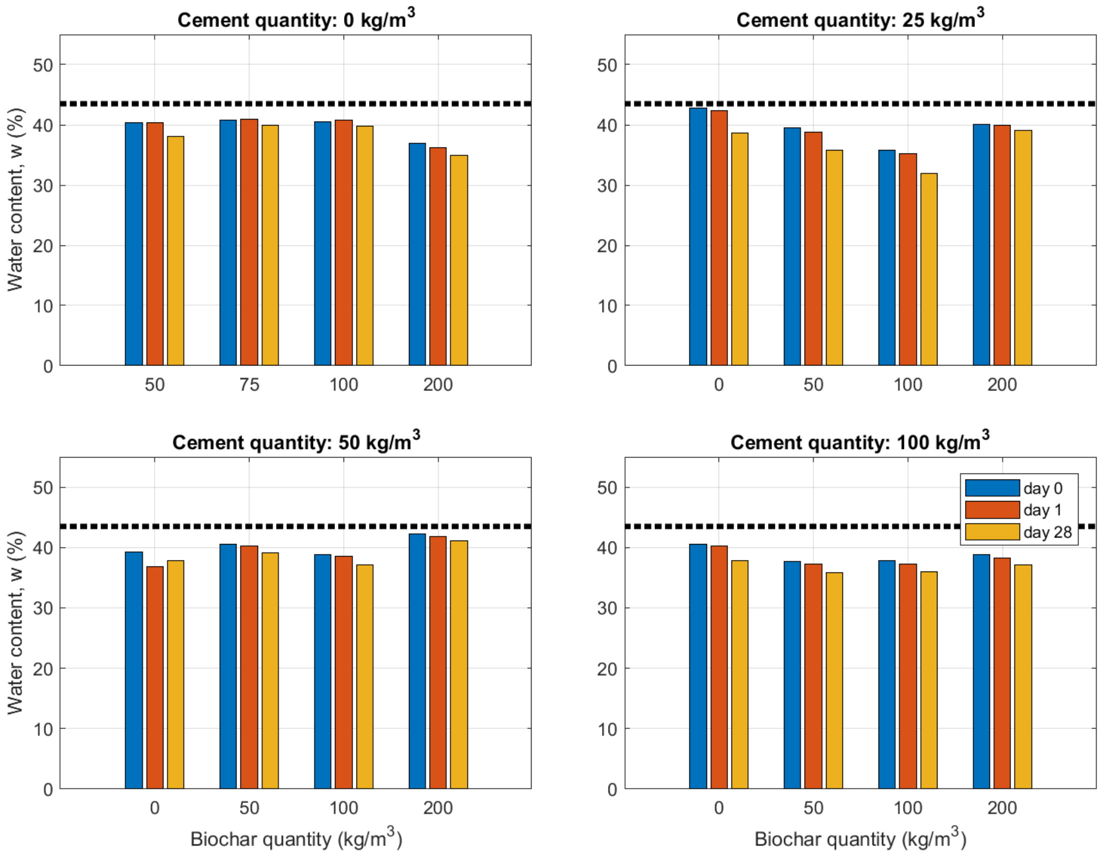


Figure 4 Change of water content (w) in the clay samples with curing. The average clay water content of 43.5% is indicated with the dashed line.

Figure 5 compares the liquid limit, w_L, of the clay mixtures after 0 and 1 day of curing to the in-situ liquid limit which is approximately 36% at the sampling depth. The liquid limit is defined as the water content where the soil starts to behave as a liquid, i.e., the water content separating the viscous liquid state and the plastic state of soil consistency. Amending the clay with only biochar caused a minor change of the liquid limit. By contrast, the liquid limit of the cement treated samples more than doubled directly after the mixing (i.e. day 0), because of the added strength of the cement. The liquid limit generally dropped with curing which is especially pronounced for the specimen with a cement quantity of 50 and 100 kg/m^3.

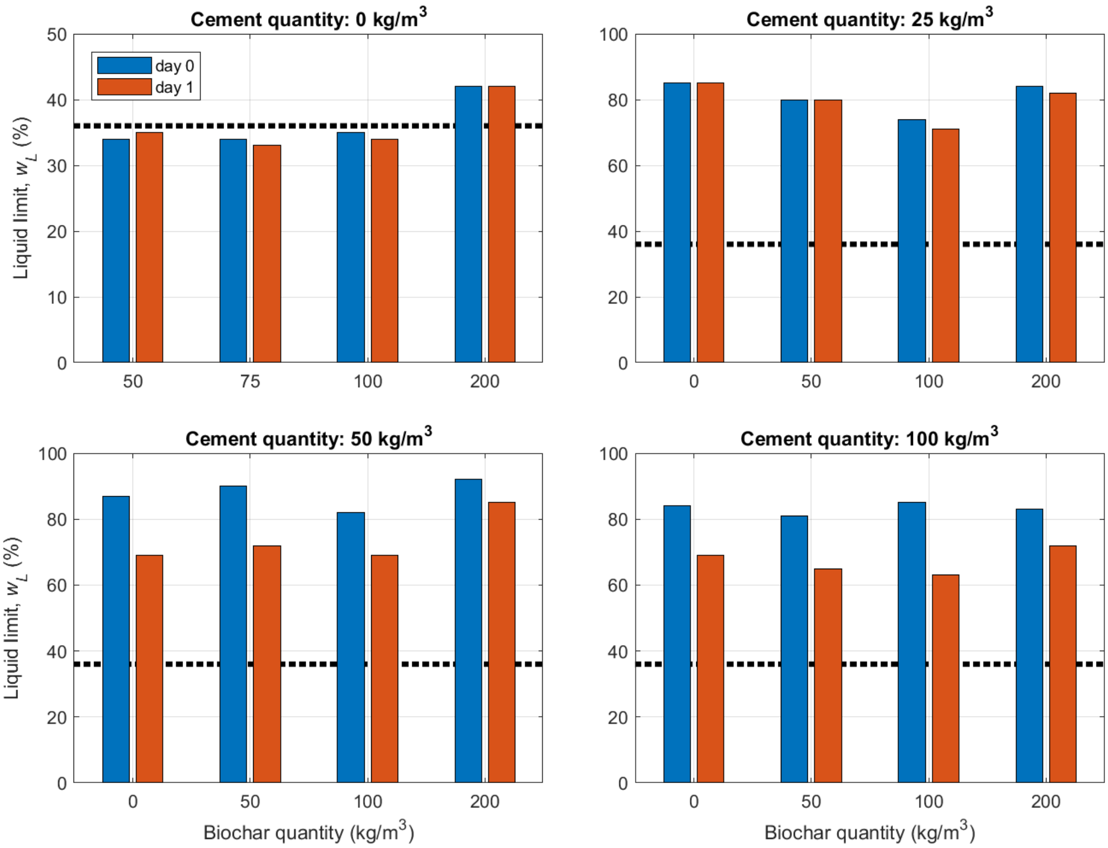


Figure 5 Liquid limit (w_L) at 0 and 1 days after mixing the clay samples. The dashed line indicates the in-situ liquid limit of the clay.

The plastic limit, which is the moisture content below which the soil is too dry to show plastic behaviour (i.e. can be rolled into < 3.2 mm thick threads), increased for all clay mixtures compared to the in-situ value for nonamended clay of approximately 21%, as can be seen from Figure 6. The plastic limit increased with both the biochar and cement quantity, probably because biochar absorbs water, and cement renders the soil less flexible and with less plastic behaviour. A minor increase was measured for the biochar treated samples, while the plastic limit of the cement treated samples doubled. Figure 6 indicates that the plastic limit increased from day 0 to day 1.

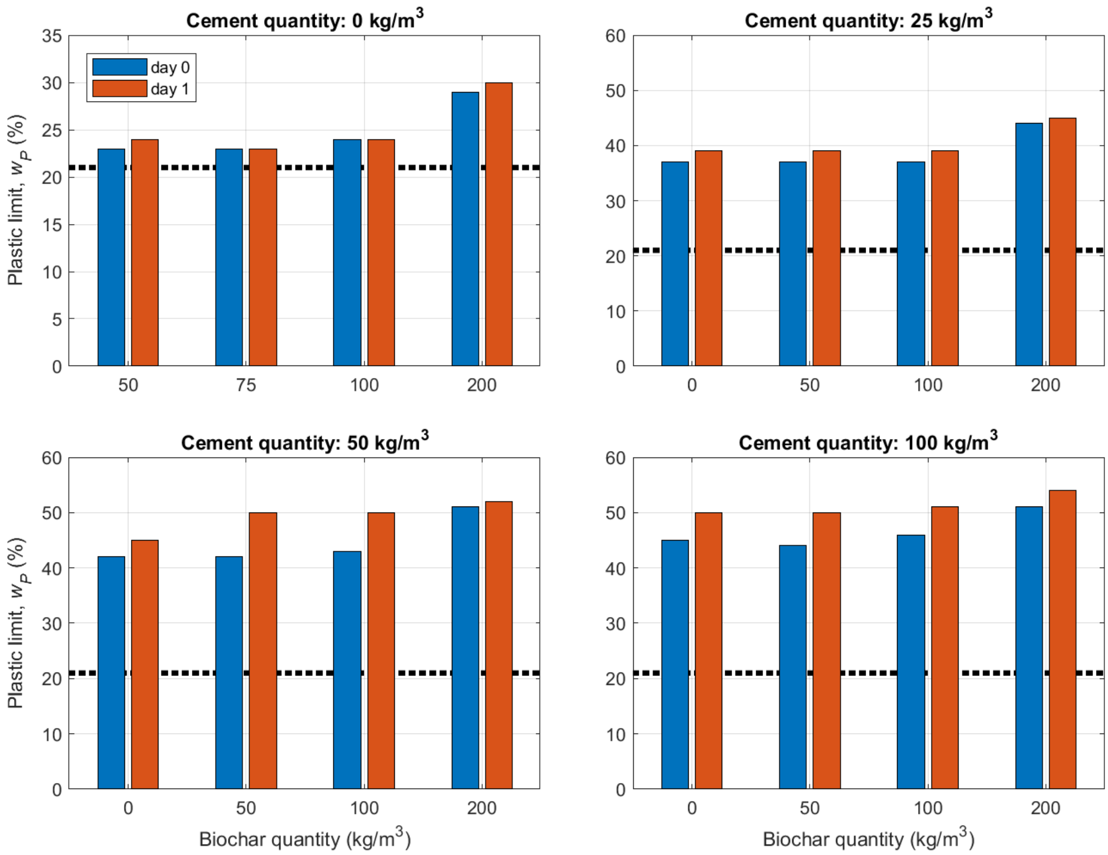


Figure 6 Plastic limit (w_P) at 0 and 1 days after mixing the clay samples. The dashed line indicates the in-situ plastic limit of the clay.

The effect of mixing the clay with biochar and/or cement on the soil plasticity is presented in Figure 7. The plasticity index, $I_P = w_L - w_P$, generally reduced when amending the clay with biochar (biochar making the soil less "clayey") but increased when treating the clay with cement (increasing the range of water contents where the soil shows plastic behaviour). From day 0 to day 1, the plasticity index generally reduced. A considerably reduction is apparent for the samples with a cement content of 50 and 100 kg/m^3 which is a result of the substantial reduction of the liquid limit with curing time.

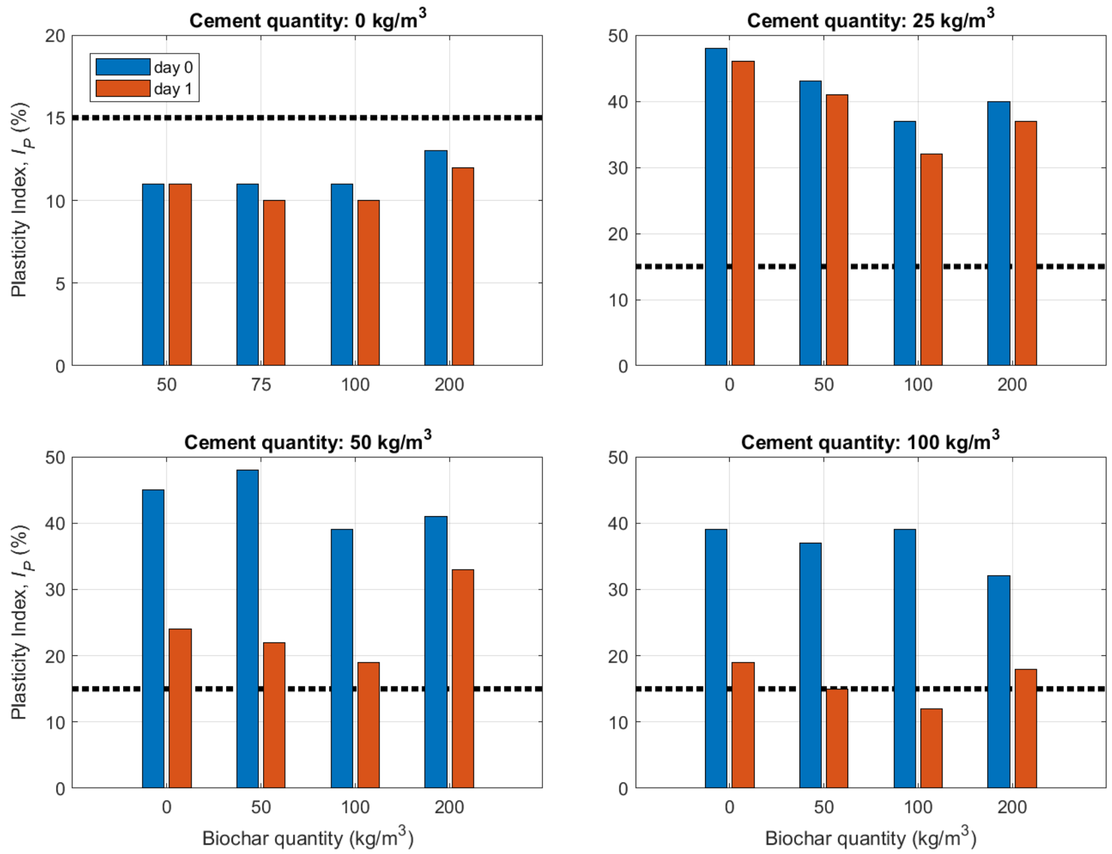


Figure 7 Plasticity index (I_P) at 0 and 1 days after mixing the clay samples. The dashed line indicates the in-situ plasticity index of the clay.

Figure 8 shows the change of the pH levels of the clay mixtures with curing time. Amending the clay with solely biochar caused a minor reduction of the clay pH value (i.e. 8.44). This can be explained by the lower pH value of the biochar which is approximately 8.1 (Eurofins, 2020). By contrast, amending the clay with cement immediately raised the pH values to values between 11.5 and 12.25. The highest pH level was measured for the samples with the highest cement quantity. The fast and substantial increase of the pH value for the cement treated samples is a typical result of the cement hydration process. As the curing continued, the pH value of the biochar-only amended samples was reduced slightly (approximately by 0.15). A more notable pH decrease with curing time of approximately 0.5 was observed for the cement amended clay.

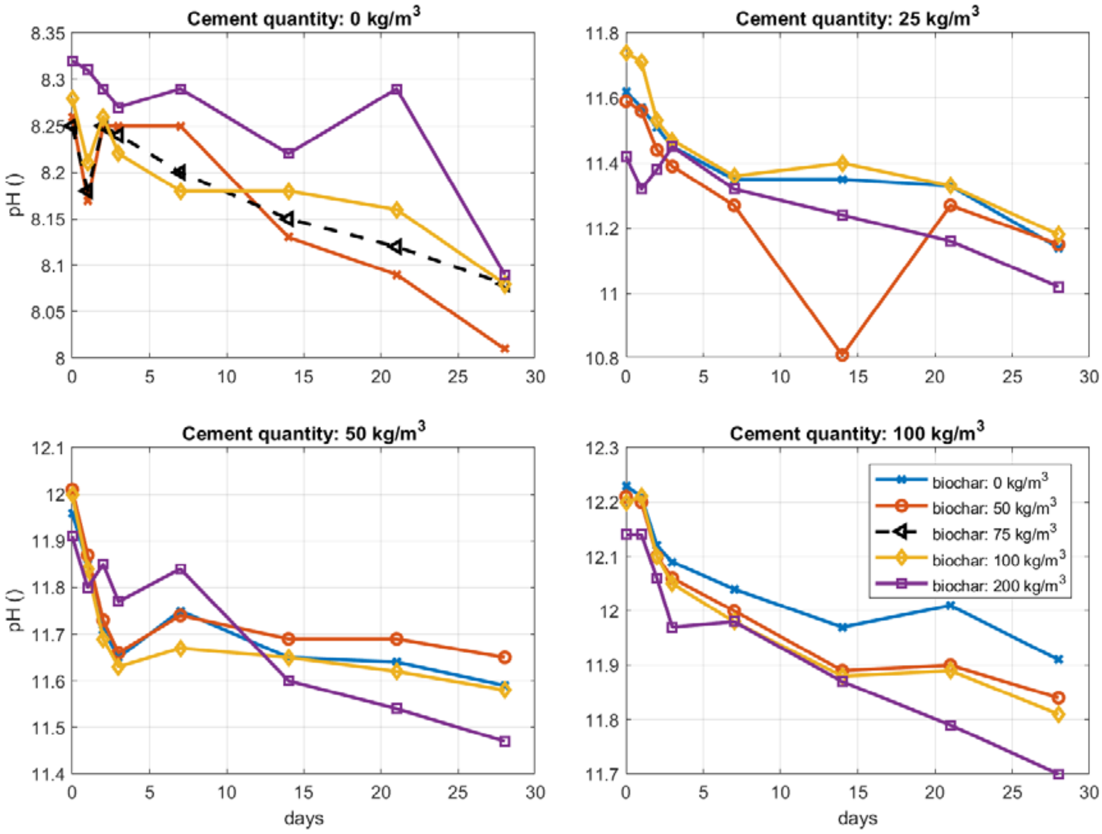


Figure 8 pH values with curing time for the clay samples. The dashed line indicates the in-situ plasticity index of the clay. The pH value of the clay and the biochar is 8.44 and 8.1, respectively. The pH measurements followed the procedure described by Houba et al. (1989).

3.1.2 Mechanical properties

To compare the difference in the mechanical behaviour of the different soil samples, unconfined compressive strength (UCS) and fall cone tests were performed. For each clay mixture, three samples were prepared and tested. Figure 9 shows vertical stress versus axial strain curves for the clay samples. A notably different stress-strain response is apparent for the different mixtures. The clay amended with biochar showed stress-strain curves typical for a strain hardening behaviour. By contrast, the cement-stabilised soils werre characterised by a strain softening response. Amending the cement-stabilised samples with biochar made the samples more ductile.

The clay samples treated with 50, 75 and 100 kg/m^3 of biochar did not develop sufficient strength to be tested in an UCS test. This can be seen in Figure 10 showing these biochar amended samples directly after removing from the mould. For these mixtures, fall cone tests were performed instead of the UCS tests.

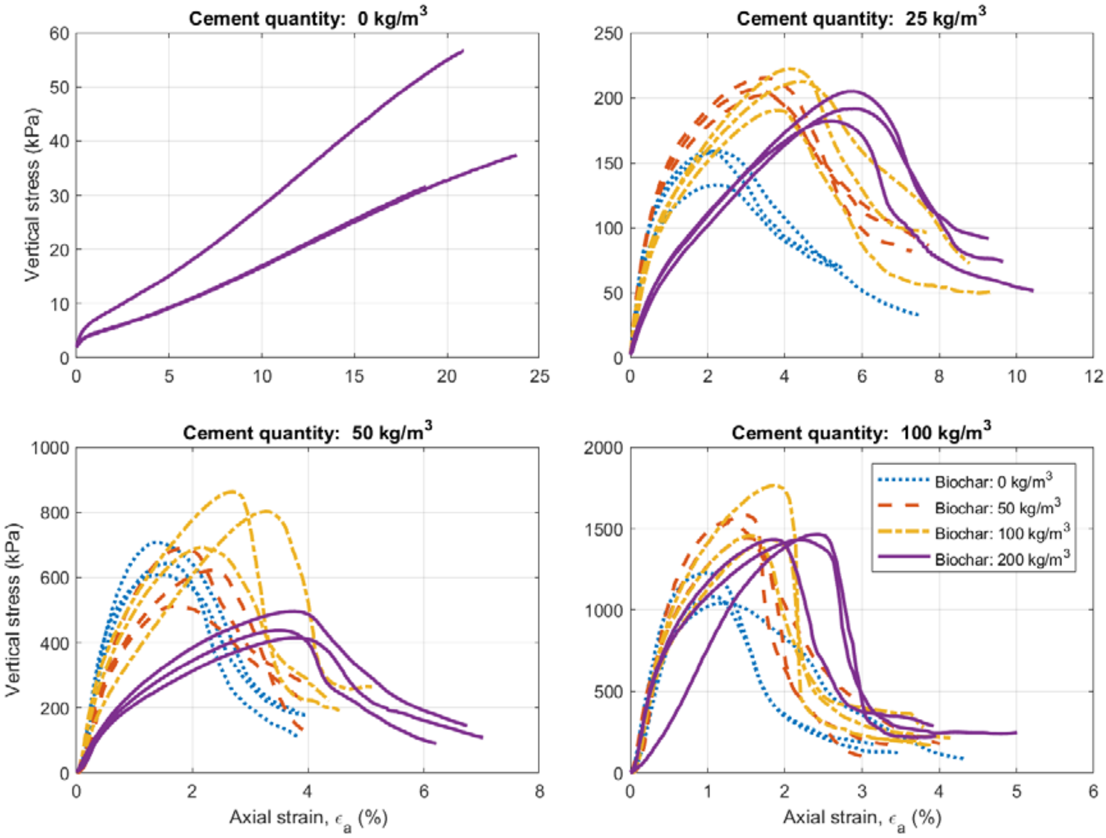


Figure 9 Stress-strain curves of the clay mixtures.

Figure 10 Clay samples treated with 50, 75 and 100 kg/m³ of biochar after 28 days of curing.

Shear strength

The stress-strain curves shown in Figure 9 were translated into shear strength, c_u, values by taking half of the unconfined compression strength. This procedure is a common approach in Norway and widely used in practice (NGF, 2012). However, one must keep in mind that c_u values obtained at different confinement (i.e. $\sigma_3 > 0$) will likely be different.

Figure 11 compares the shear strength results of the clay samples stabilised with different cement and/or biochar contents. Each bar represents the mean c_u value for the respective mixture, while the error bars indicate the standard deviation. As expected, this graph shows an increase of c_u with the cement content. Adding biochar generally further increased c_u compared to the reference mixtures (i.e. clay and cement only combinations). The increase of c_u with biochar addition is significant ($P < 0.05$) for the samples with cement content of 25 kg/m^3 and 100 kg/m^3. A significant difference was not observed for the samples with a cement level of 50 kg/m^3 and a biochar quantity smaller than 200 kg/m^3. For all investigated cement levels, the highest c_u values were observed for samples with 100 kg/m^3 of biochar. However, increasing the biochar level further to 200 kg/m^3 caused a reduction of c_u compared to the other biochar amended samples with equal cement quantity. This finding, while preliminary, may help to define the optimum biochar content.

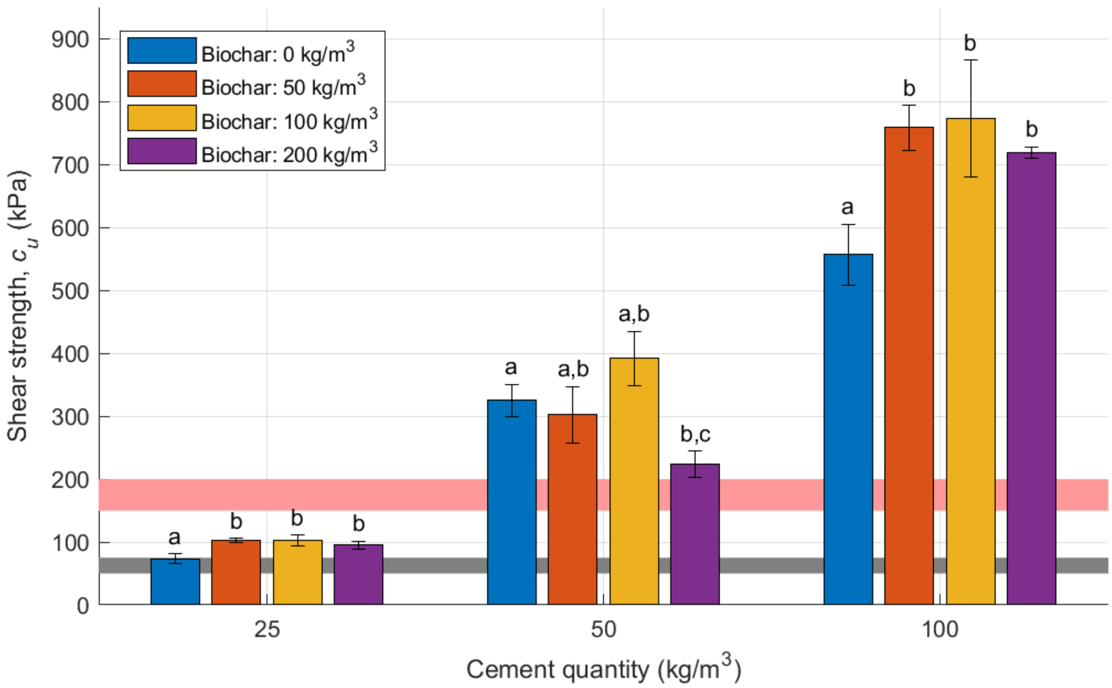


Figure 11 Shear strength of the Tiller-Flotten clay stabilised with different levels of cement and biochar after 28 days of curing. Vertical bars indicate standard errors of the means (n = 3). For each stabilised soil, bars with the same letter(s) within each cement quantity level are not significantly different according to Welch's t-test at P < 0.05. The horizontal red bar indicates a range of design strength limits (i.e. 150-200 kPa) typically used in Norway (Paniagua et al. 2019). The horizontal grey bar indicates the in-situ shear strength (i.e. 50-75 kPa).

From Figure 11, it is apparent that the entire cement and biochar treated samples resulted in c_u values greater than the in-situ values (i.e. 50-75 kPa). All the samples stabilised with a cement quantity of 50 and 100 kg/m^3 exceeded typical design strength limits (i.e. 150-200 kPa) widely adopted in projects in Norway (kPa (Karlsrud et al. 2015; Paniagua et al. 2019). The c_u values above 200 kPa for the entire test series with a cement quantity of only 50 kg/m^3 and a curing time of only 28 days are especially noticeable because the used cement level is below values typically used in practice (i.e. 80-110 kg/m^3).

The results of the clay samples stabilised with different levels of biochar (i.e. no cement) are presented in Figure 12. As mentioned before, the samples with a biochar addition of 50 kg/m^3, 75 kg/m^3 and 100 kg/m^3 developed a minor increase in strength. Fall cone tests were employed to determine their shear strength. UCS tests were conducted for the samples with a biochar content of 200 kg/m^3.

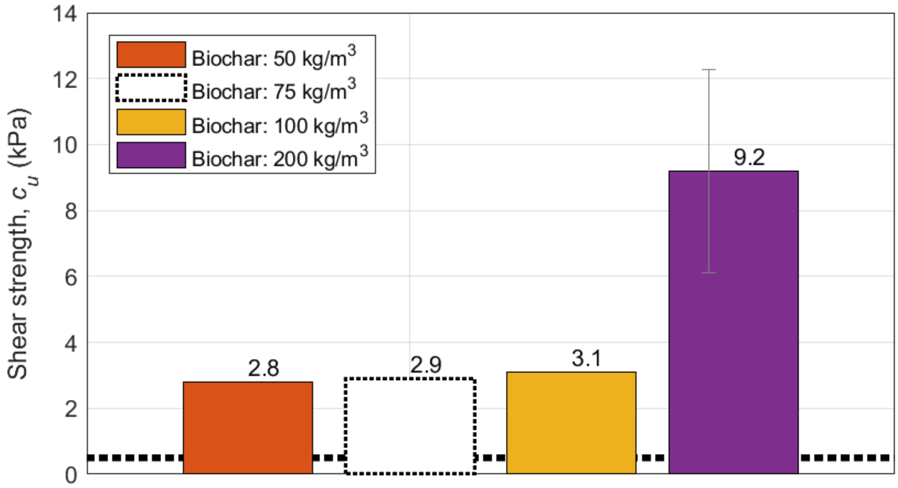


Figure 12 Shear strength of Tiller-Flotten clay stabilised with different levels of biochar (i.e. no cement). The numbers on top of the bars present the shear strength values for the different combinations. Vertical bars indicate standard errors of the means (n = 3). The samples with a biochar content <200 kg/m3 were tested with a fall cone according to NS 8015:1988. UCS tests were carried out on the samples with a biochar addition of 200 kg/m^3 and the c_u values were derived at 10% of axial strain.

A general pattern of increasing c_u with biochar content can be observed from Figure 12. This raise of c_u due to amending the clay with only biochar is particularly striking for a biochar content of 200 kg/m^3. For these samples a mean c_u of 9.2 kPa was obtained which is approximately 3 times higher compared to the samples with a lower biochar content. However, one should keep in mind that these c_u values were obtained at high axial strain values of 10% (Figure 9). Consequently, this strength value must be interpreted with caution.

The fall cone tests according to NS 8015:1988 were carried out on the stabilised samples (i.e. mixtures after 28 days of curing) but also on remoulded samples. Figure 13 compares these two values for the clay samples with biochar addition. The sensitivity, S_t, which is here defined as the ratio between stabilised and remoulded undrained shear strength is also shown. As expected, the measured remoulded shear strength, c_{ur}, is substantially lower compared to the stabilised undrained shear strength. Interestingly, the c_{ur} values for all samples are above 0.5 kPa, which is the threshold used in Norway to classify quick clay. The obtained sensitivity values are between 2 and 3 and thus notably lower than the threshold used to define "very sensitive" clay (S_t > 30, NGF (2011)). This finding can be explained by the low stabilised shear strength, which is substantially lower than the in-situ shear strength (i.e. 50-75 kPa, intact shear strength) and by utilising the remoulded shear strength of the biochar amended clay which is different to the remoulded shear strength of the in-situ clay. Consequently, one must be cautious when comparing the obtain sensitivity values with literature. Further work is required to reveal the impact of the biochar addition on the clay sensitivity, and if biochar addition can increase the remoulded shear strength above the quick clay threshold.

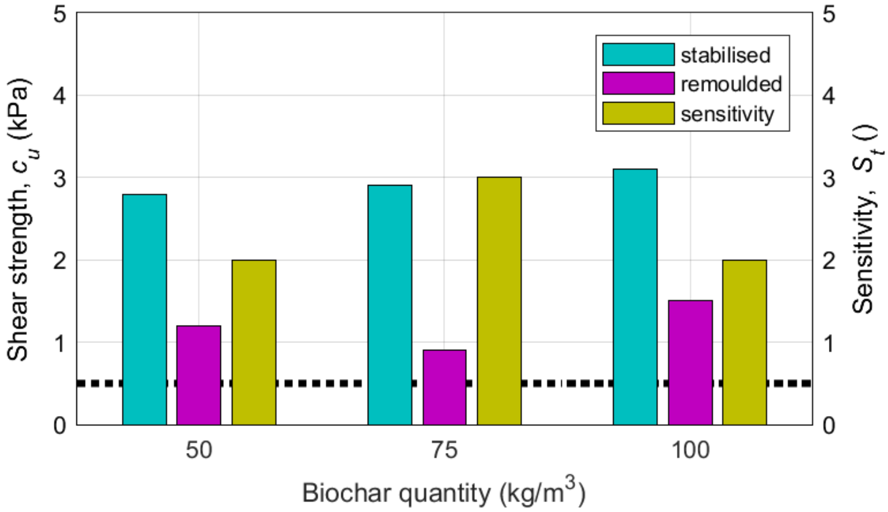


Figure 13 Stabilised, remoulded shear strength and sensitivity of biochar treated clay, without cement, according to NS 8015:1988. The dashed line indicates an undrained shear strenght of 0.5 kPa which is in Norway adopted as a quick clay threshold (i.e. remoulded undrained shear strength (c_{ur}) < 0.5 kPa).

Figure 14 shows the relationship between c_u and the biochar level of the Tiller-Flotten clay mixtures. A clear trend of increasing c_u with the biochar quantity was not observed. Second order polynomials were fitted to the clay samples with cement levels of 25, 50 and 100 kg/m^3. The peak values of the curves indicate a qualitative measure of the optimum biochar level resulting in the highest c_u for a given cement quantity. The data suggests that the optimum biochar quantity for cement-stabilised clay is between 75 to 125 kg/m^3.

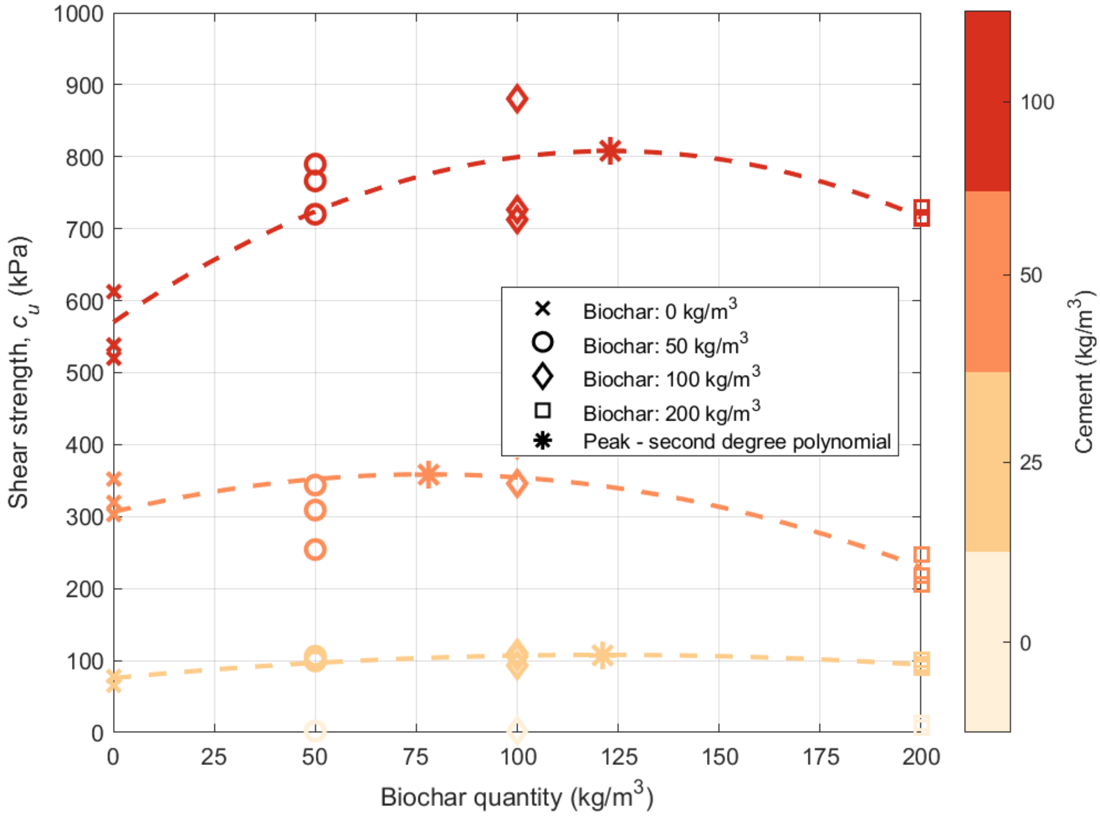


Figure 14 Variation of undrained shear strength, c_u, against biochar dosage, for the 4 different cement dosages (various colours).

The variation of c_u with cement quantity for the different biochar levels is shown in Figure 15. As expected, c_u increased with the cement quantity for all biochar levels. A linear regression line through the origin was fitted to the data of each biochar level. The highest slope for these best-fit lines was obtained for the samples with a biochar quantity of 100 kg/m^3 which supports the above identified range of optimum biochar quantity (75-125 kg/m^3) for the cement-stabilised clay.

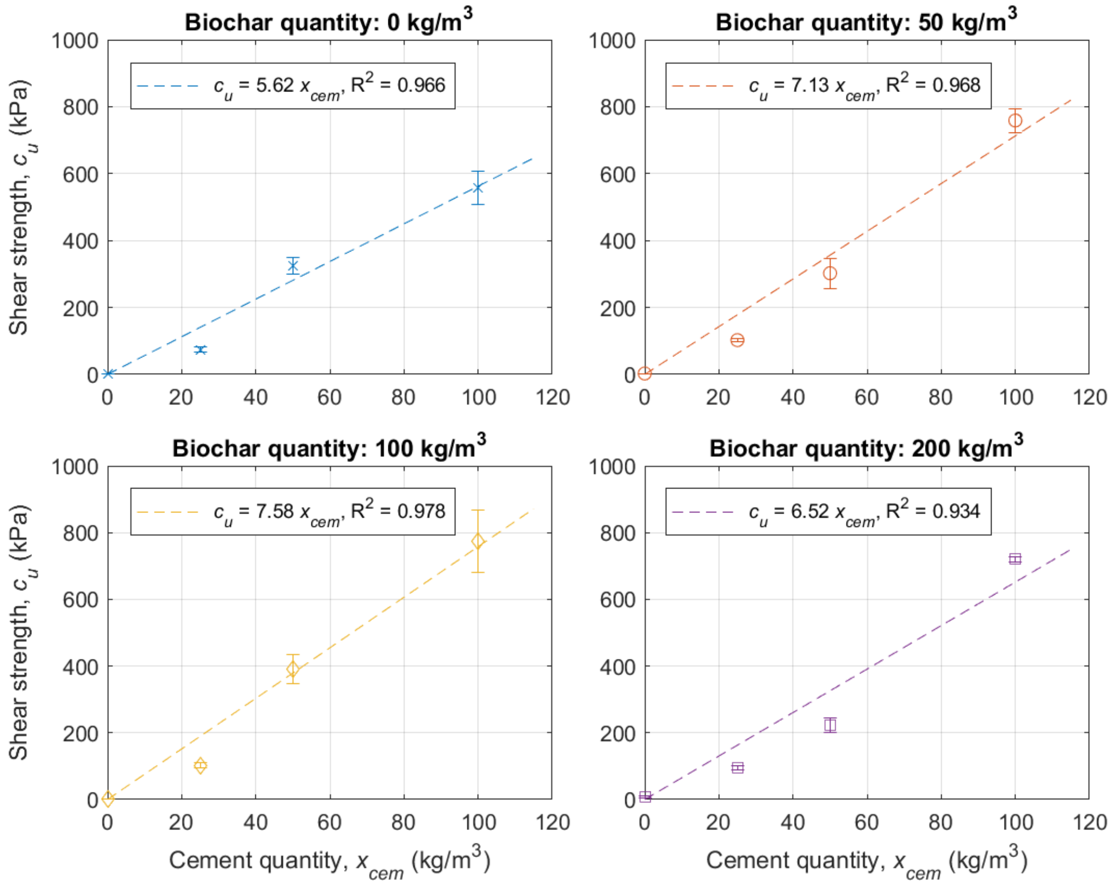


Figure 15 Variation of undrained shear strength, c_u, with cement quantity for the clay test series.

For lime and cement-stabilised soils, the total binder content, α, which is the sum of the lime and cement quantity, is frequently used to compare the performance of stabilised clays (e.g. Paniagua et al., 2019). Although it is not evident that biochar is a chemical binder with cementitious properties like cement or lime, the total binder content is in this work defined as the sum of the cement and biochar quantities added to the soil samples.

From Figure 16, a notable scatter between the total binder content and c_u is apparent. A clear trend between α and c_u was not obtained. This finding indicates that the biochar should not be considered as a binding agent like cement or lime. The biochar may be characterised as filler such as sand or gravel with beneficial properties to reduce the required binder content. Similar results were reported by Lau et al. (2020) for biochar and cement amended peat.

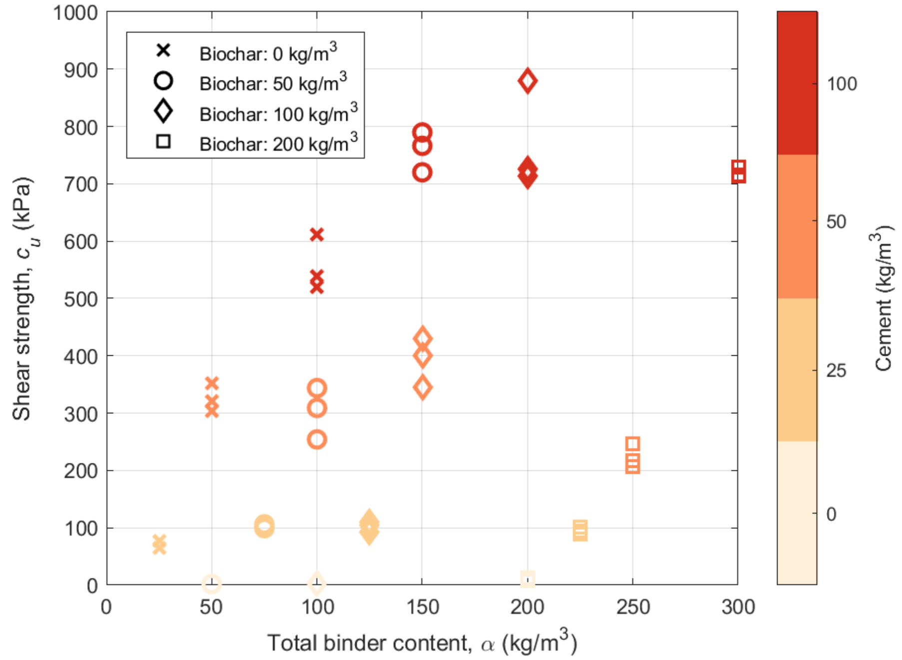


Figure 16 Variation of undrained shear strength, c_u, against total binder content, α.

Axial strain

Figure 17 shows the axial strain at failure, ε_{af}, which is a measure of how much the specimen is elongated to failure, for the clay samples treated with cement and/or biochar. The ε_{af} values of the clay notably increased when adding biochar compared to the reference mixtures with only cement addition. For example, adding 100 kg/m^3 of biochar approximately doubled the ε_{af} of the reference mixture. These observations show that adding biochar makes the stabilised soil significantly more ductile which is apparent in the stress-strain curves given in Figure 9. Increasing biochar dosages rendered more ductile clay/cement mixtures over the whole biochar dosage range (0-200 kg/m^3; Fig 17). One can follow that the biochar application for clay might be limited to certain geotechnical problems that are not controlled by deformation limits.

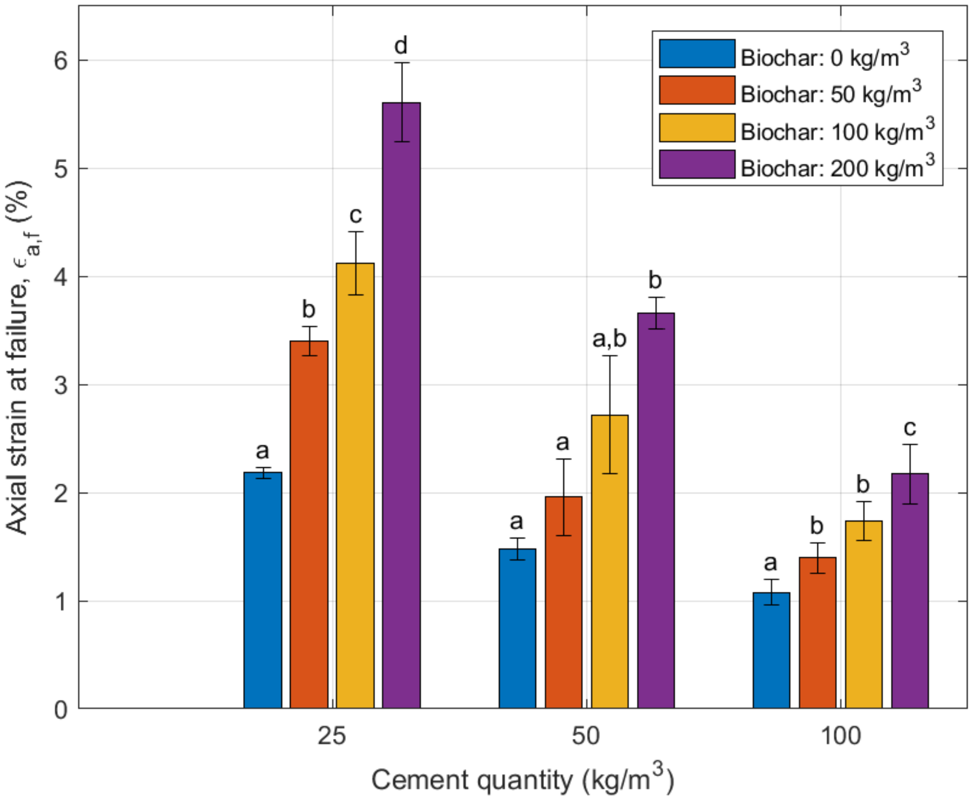


Figure 17 Axial strain at failure, a measure of ductile strength, of the Tiller-Flotten clay stabilised with different levels of cement and biochar after 28 days of curing. Vertical bars indicate standard errors of the means (n = 3). For each stabilised soil, bars with the same letter(s) within each cement quantity level are not significantly different according to Welch's t-test at P < 0.05.

Stiffness

The change of stiffness due to amending the Tiller-Flotten clay with different quantities of cement and/or biochar is shown in Figure 18. For all treated samples, the secant modulus, E_{50}, stiffness values exceeded the in-situ ones (i.e. E_{50} of approximately 2.5 MPa, obtained in UCS tests). The secant modulus, E_{50}, substantially increased with the cement content. Adding biochar, however, reduced the stiffness which is significant for the samples treated with 25 and 50 kg/m^3 of cement. A considerable scatter in E_{50} was apparent for the samples treated with 100 kg/m^3.

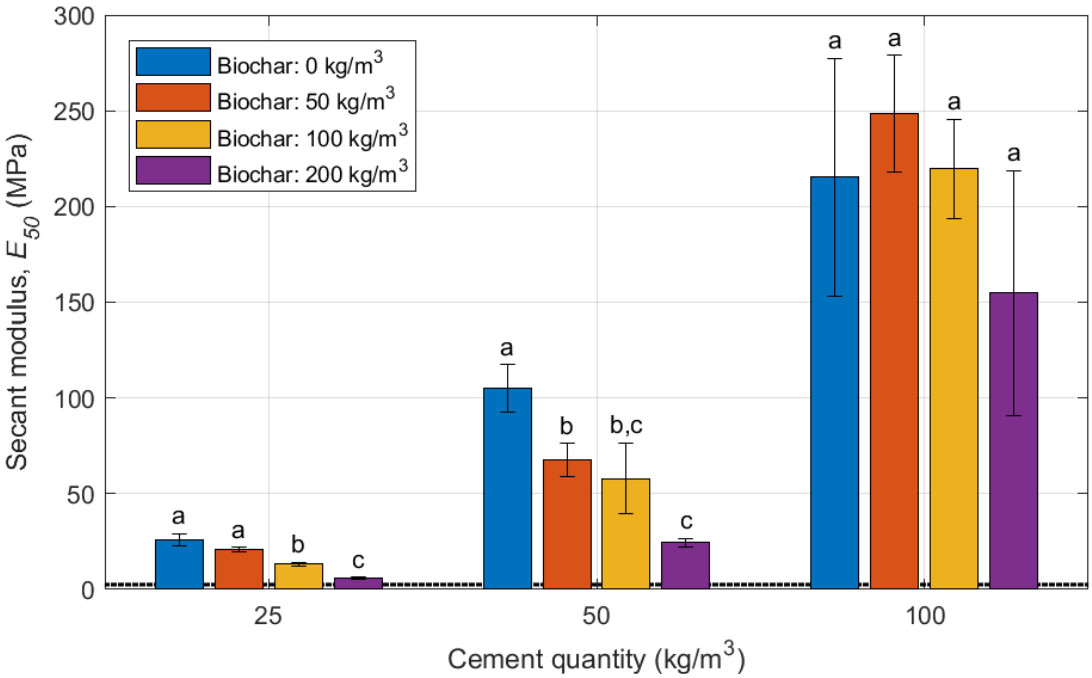


Figure 18 E_{50} secant modulus of the Tiller-Flotten clay stabilised with different levels of cement and biochar after 28 days of curing. Vertical bars indicate standard errors of the means (n = 3). For each stabilised soil, bars with the same letter(s) within each cement quantity level are not significantly different according to Welch's t-test at $P < 0.05$. The dashed line presents the in-situ E_{50} of approximately 2.5 MPa.

Figure 19 shows the derived E_{50} values as a function of shear strength. Both the E_{50} and c_u values notably increased with cement quantity. Amending the clay with biochar resulted in minor effects. The E_{50} data points generally fell within boundaries between $50c_u$ and $500c_u$. A best-fit line of $E_{50} = 278c_u$ was obtained with a coefficient of determination of 0.81 indicating a substantial scatter in the data.

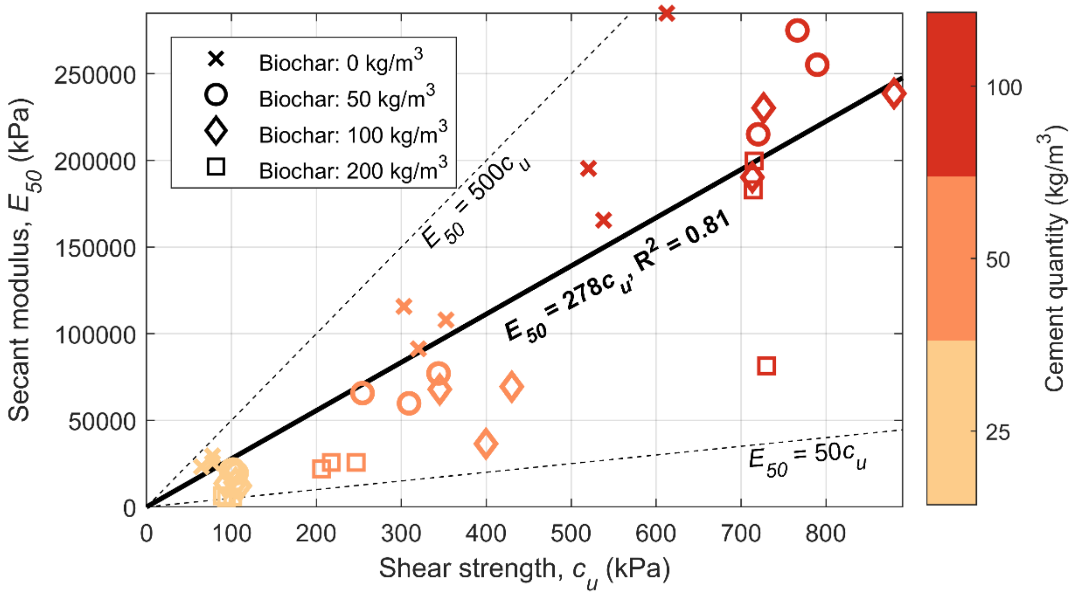


Figure 19 Variation of E_{50} with undrained shear strength, c_u, for the clay test series.

3.2 Microstructure investigation / Morphology

3.2.1 X-ray diffraction (XRD) analysis

The X-Ray Diffraction (XRD) analyses were performed with a Bruker D8 Advance with Cu X-ray tube and Lynxeye XE detector. Mineral identification was conducted with automatic or manual search for top positions in Bruker software Diffrac.EVA ver5.2. Both Crystallographic Open Database (COD) and PDF 4 Minerals from ICDD (International Centre for Diffraction Data) were used as databases. Mineral quantification was performed with Rietveld modelling and software TOPAS 5.0.

The XRD scans were performed with the following specifications: Co Kα, 35 kV/40 mA, scan 3-80°2θ; step size = 0.012 °2θ; time/step = 103 s; soller slits 4.0 ° variable divergence slit 10 mm; Ni-filter; knife edge; rotation 1/30. *GOF* (Goodness of fit) and R_{wp} (Weighted profile factor) indicate the reliability of the Rietveld modelling: *GOF* < 2.5 = very good modelling, *GOF* < 3 = reliable modelling. *Rwp* gives a numerically fit of the calculated pattern to the observed data.

Table 6 lists the samples investigated using XRD. In addition to the biochar and cement amended samples, the individual materials were also analysed.

Table 6 Samples investigated using X-ray diffraction (XRD) analysis: w_c = mass fraction of the cement and w_b = mass fraction of the biochar.

Sample ID	Details	Sample preparation	w_c (%)*	w_b (%)*
Biochar	Biochar grinded			
Cement	Hydrated cement (water/cement ratio of 0.5)	16.11.2020		
Clay	Clay			
Clay-0-200	Clay & biochar (200 kg/m^3)	20.10.2020	0	9.8
Clay-100-0	Clay & cement (100 kg/m^3)	26.05.2020	5.2	0
Clay-100-200	Clay & cement (100 kg/m^3) & biochar (200 kg/m^3)	13.10.2020	4.7	9.4

* The mass fraction is defined as the ratio of the mass of a substance of a mixture (i.e. cement or biochar) to the total mass of the mixture.

The results of the XRD analysis are shown in Table 7 and visualised in Figure 20. Calcite and quartz were found to be the main minerals of the tested biochar. The hydrated cement sample consisted mainly of calcium hydroxide (portlandite), calcium silicate (larnite), calcium aluminium sulfate (ettringite) and calcium carbonate (calcite). As mentioned before, the dominant minerals of the Tiller-Flotten clay are illite/muscovite, plagioclase, quartz, biotite and chlorite. The different clay samples stabilised with different combinations of biochar and/or clay resulted in an almost identical mineral composition. For the stabilised clay samples, the calcite component increased compared the clay. Typical cement hydration products such as portlandite, larnite and ettringite were not observed in the clay samples amended with biochar, cement or a combination of both. This result is surprising considering the clear evidence of their presence in SEM micrographs (see Section 3.2.2) but can likely be explained by a combination of their low crystallinity and diffuse reflections caused by amorphous materials such as biochar.

Table 7 X-ray diffraction (XRD) analysis results in terms of the mass fraction, *wt* (%), of the crystalline phase.

Sample	**Biochar**	**Cement**	**Clay**	**Clay-0-200**	**Clay-100-0**	**Clay-100-200**
Calcite	64	10	2	3	5	4
Ettringite		13				Traces
Portlandite		34				
Larnite		28				
Gorgeyite		7				
Anhydrite		5				
Quartz	36	3	16	15	14	14
Plagioclase			17	17	17	16
Illite/ muscovite			24	24	23	24
Biotite			14	14	14	16
Chlorite			14	14	13	13
Amphibole			9	9	10	9
Dolomite			2	2	2	2
Rutile			2	2	2	2
GOF	2,01	2,51	2,73	2,24	2,14	2,06
Rwp	4,81	9,56	7,07	5,68	5,72	5,30

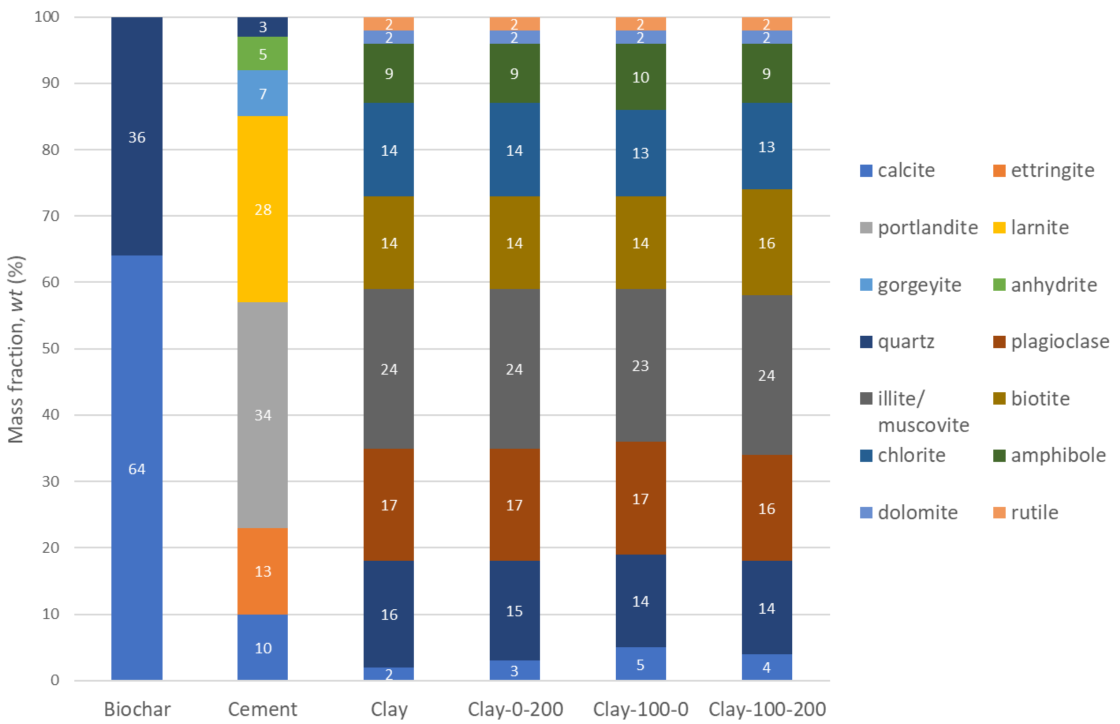
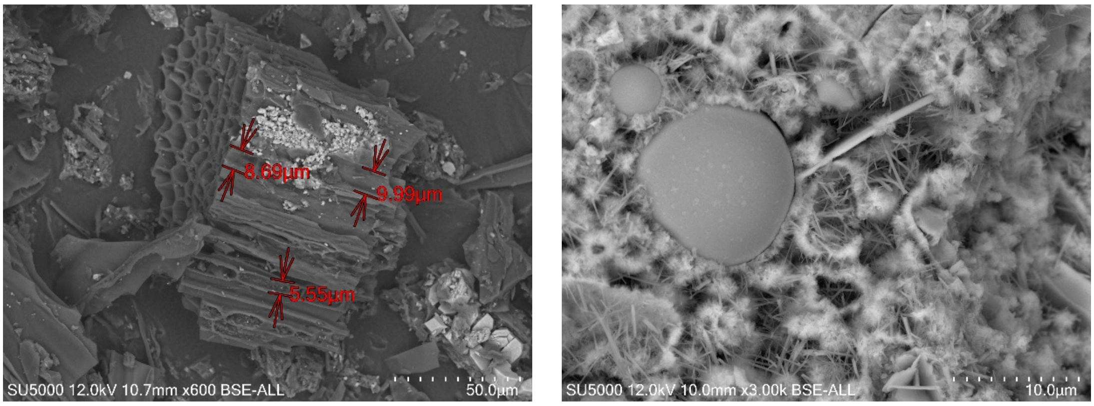


Figure 20 Results of the X-ray diffraction (XRD) analysis for the individual materials and selected clay mixtures.

3.2.2 Scanning electron microscopy (SEM)

The purpose of SEM imaging was to help understand the microstructure of the stabilised clay and observe effects of biochar addition. A Hitachi SU5000 FE-SEM (Schottky FEG) including low-vacuum mode and inlens SE-detector was used for imaging. EBSD (electron backscatter diffraction) were used for surface images using Bruker e-Flash HR EBSD system with Argus. EDS (Energy Dispersive X-Ray Spectroscopy) was used to give a semi quantitative chemical disposition within queried locations using Dual Bruker Quantax XFlash 30 EDS system.

Before imaging, the samples were dried at 60 degrees for 45 minutes, after which the samples were put on carbon tape. Figure 21 shows the SEM images of the stabilising materials (i.e. biochar and hydrated cement). The biochar fragments are characterised by a cellular structure (honeycomb structure) with a cell diameter below approximately 10 μm. The SEM micrographs of the grinded biochar show several intact cells, which were by Lau et al. (2020) identified as potential weak zones when exposed to external loads and may explain the reduction in shear strength, Fig. 11; and in stiffness, Fig. 18 of cement-stabilised samples amended with 200 kg/m^3 of biochar. Several of these biochar cells were filled with calcite ($CaCO_3$) as can be seen from Figure 21a and is also apparent in the XRD data. Small amounts of albite, apatite and minor iron contaminations (e.g. Fe, Cr, Ni, TiO2) were also identified in the EDS data.



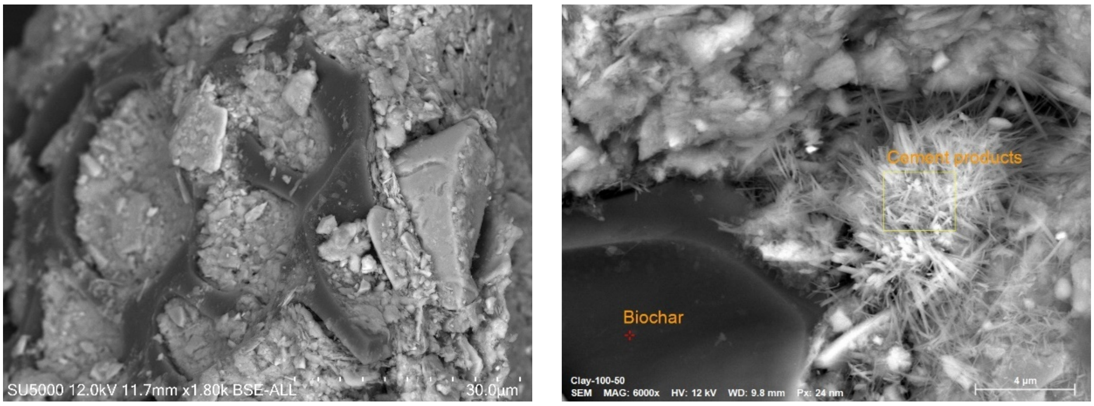
(a) Biochar (b) Cement

Figure 21 SEM images of (a) biochar and (b) hydrated cement after 10 days of curing.

Figure 21b shows a SEM micrograph for a cement sample after 10 days of curing. The needle-like morphology of Ettringite is clearly visible which is caused by the early hydration of gypsum (5.2% in the used CEM II, see Section 2.1.2). Sponge-like calcium silicate hydrates (C-S-H), which are a main early stage cement hydration product, are apparent in Figure 21b. The typical fly ash spheres were also easily observed in the SEM micrographs.

The interactions between the clay and the stabilising materials are visualised in Figure 22. From Figure 22a it is evident that the clay particles filled the intact biochar cells. Hydration (e.g. ettringite, C-S-H) or carbonation products, as identified by Lau et al.

(2020), were not visible in the biochar amended samples, in accordance with the XRD measurements.



(a) Clay-0-50 (b) Clay-100-50

Figure 22 SEM micrographs of (a) a biochar amended clay and (b) a clay-cement-biochar sample.

Figure 22b shows a SEM micrograph of a clay sample amended with cement and biochar. A biochar fragment and cement hydration products (predominantly Ettringite and C-S-H) are indicated and were also quantified in EDS spectra. The SEM image indicates that the cement hydration products are coating the clay and biochar surfaces. This indicates that typical hydration reactions occurred in the clay-cement-biochar samples which are the main contribution to soil stabilisation.

3.3 Performance of peat treated with biochar and/or cement

Having presented and discussed the results of the clay test series, this section addresses the effect of amending peat with biochar and/or cement. The peat is not a plastic material and thus Atterberg plastic limits were not obtained. The following section presents the change of the water content and the pH values with curing time, after which the mechanical properties of the biochar and/or cement treated samples are discussed.

3.3.1 Water content and pH value

The variation of the water content of the peat samples with curing time is shown in Figure 23. An average water content of approximately 975% was measured for the 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 100 kg/m^3 of biochar approximately halved the peat water content. For the cement treated samples, an even lower water content was determined. These observations are encouraging considering that previous research stated an inverse relationship between the peat strength and the water content (e.g. Hernandez-Martinez, 2006). The data also indicate a minor reduction of the water content with curing time.

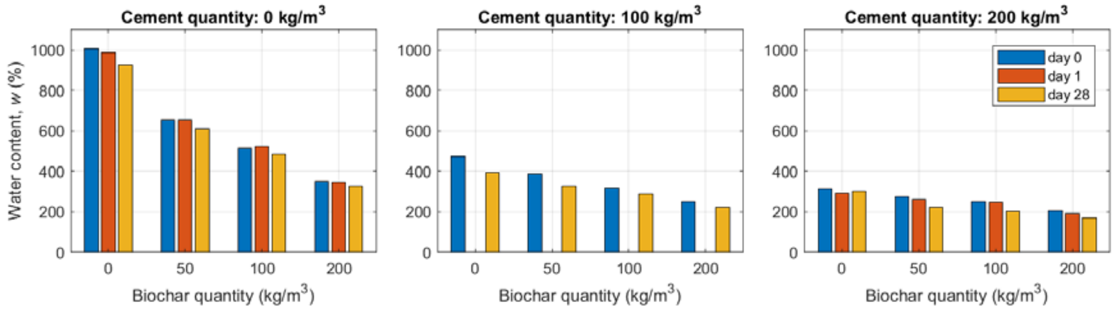


Figure 23 Change of water content (w) in peat samples with curing time. The water content at day 1 was not determined for the samples with a cement quantity of 100 kg/m³.

Figure 24 compares the pH value for the peat samples throughout the curing period. For the natural peat, a pH value of approximately 4.2 was measured. Amending the peat with biochar caused a rapid 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 were found 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. A notable change of the pH after day 3 was only apparent for the samples with a cement level of 100 kg/m^3.

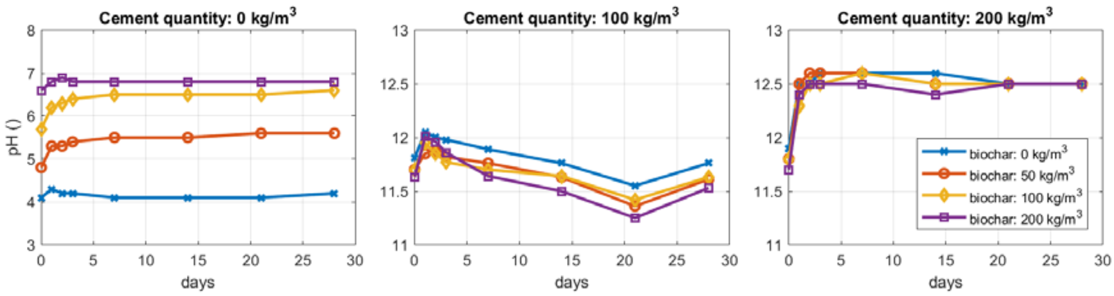


Figure 24 pH values with curing time for the peat samples. The pH measurements followed the procedure described by Houba et al. (1989).

3.3.2 Mechanical properties

Unconfined compressive strength (UCS) tests were performed to derive an insight into the mechanical properties of the stabilised peat samples. Figure 25 shows the vertical stress versus axial strain curves for the different samples. The natural peat and the biochar amended samples show a typical strain hardening material behaviour. For the same axial strain, a notable increase in vertical stresses with the amount of added biochar is apparent in Figure 25 (top, cement quantity: 0 kg/m^3). The cement treated samples are characterised by a strain softening material behaviour, which means that the material strength deteriorates with increasing strain. For mixtures with greater cement and biochar quantities, distinct stress peaks become evident.

Shear strength

The data given in Figure 25 was utilised to derive the undrained shear strength, c_u, of the different peat samples. As was mentioned above, distinct stress peaks were not obtained for samples with a strain hardening response (i.e. strength increase with strains, see top left of Figure 25). 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 26 shows that the peat samples amended with biochar resulted in higher c_u values compared to the natural peat. This increase of c_u is significant for the peat samples treated with biochar levels of 100 and 200 kg/m^3. The c_u of the peat amended with 200 kg/m^3 of biochar was found to be approximately 5 times greater than the natural peat.

A substantial increase of c_u when adding cement is apparent in Figure 26. Adding biochar generally caused a further increase of c_u. 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 did not result in a significant increase. This is a surprising result that may require further investigation or repetition. It is likely due to an anomaly or uncertainty in the data, since a mechanistic explanation for the absence of an effect for the intermediate biochar dosage is hard to envision.

What stands out from Figure 26 is that the peat samples treated with 100 kg/m^3 of cement and 200 kg/m^3 of biochar had comparable strength values than the peat sample amended with 200 kg/m^3 of cement. This finding implies that biochar can potentially replace some of the cement when stabilising peat. Similar findings were presented by Lau et al. (2020), who showed that biochar has the potential to partially replace cement when stabilising peat. More precisely, Lau et al. (2020) reported that peat mixed with 100 kg/m^3 cement and 400 kg/m^3 biochar resulted in comparable strength values than measured for samples stabilised with 200 kg/m^3 cement.

The relationship between c_u and the added biochar content is provided in Figure 27. Second order polynomials are fitted to the samples with differing cement levels; a general trend of increasing c_u with biochar quantity is apparent. The data suggests that the optimum amount of biochar is likely exceeding the tested maximum of 200 kg/m^3. This finding aligns with previous work by Lau et al. (2020) which showed that amending cement-stabilised peat with increasing dosages of biochar (up to 400 kg/m^3) caused shear strength increases.

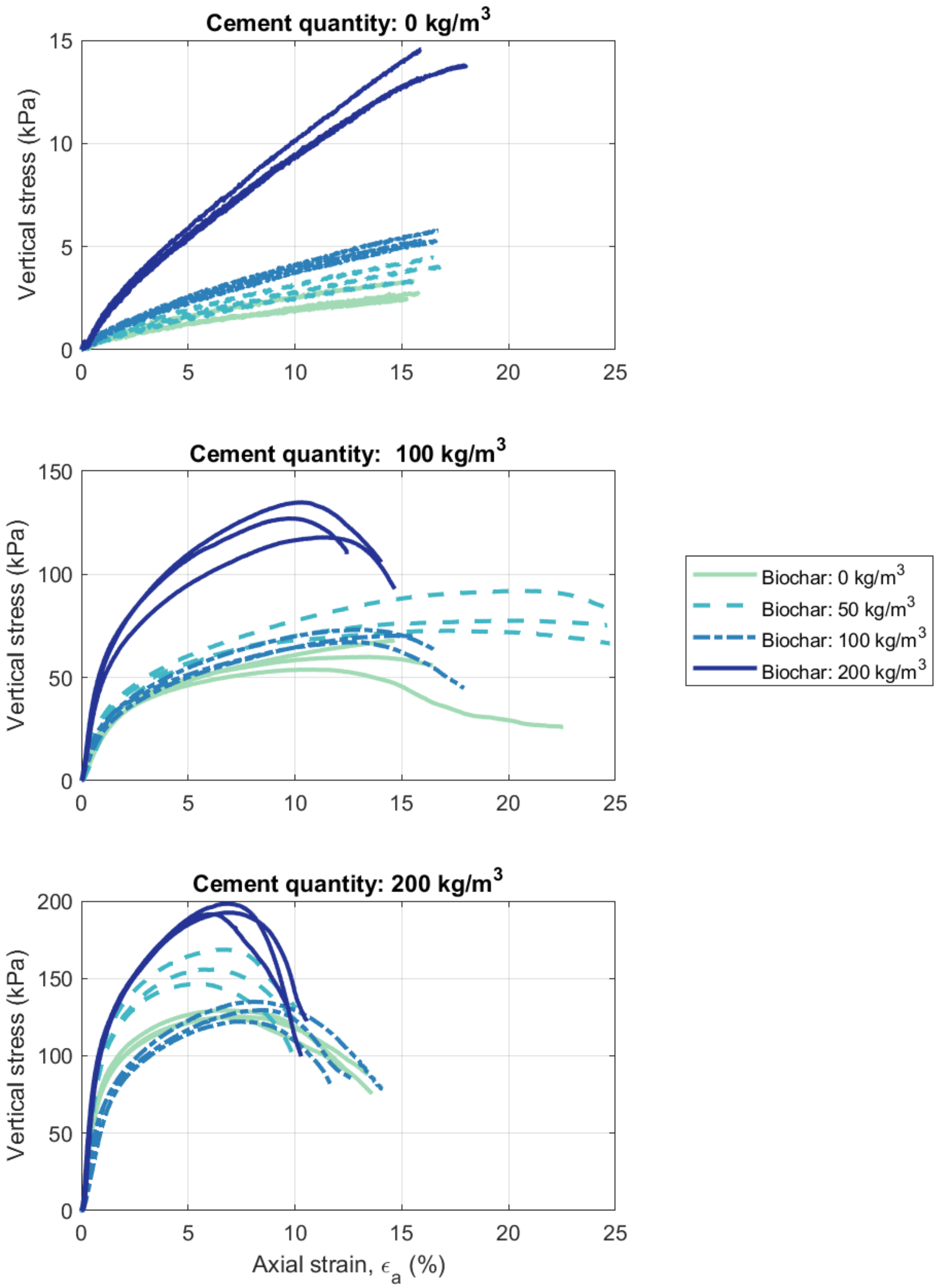


Figure 25 Stress-strain curves of the peat test series.

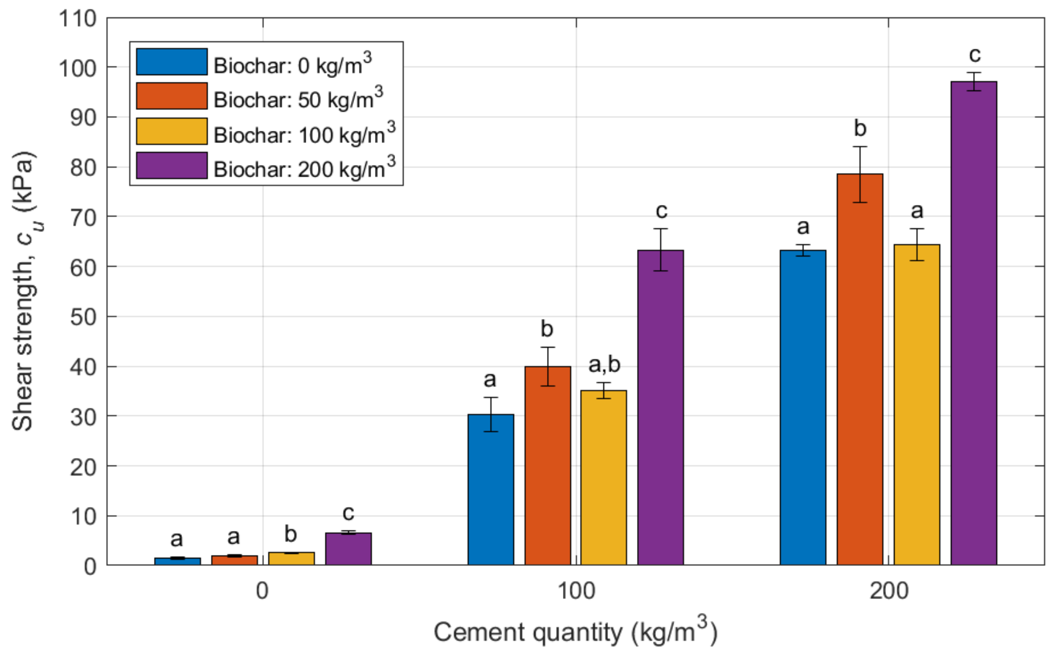


Figure 26 Shear strength of the Tiller-Flotten peat stabilised with different levels of cement and biochar after 28 days of curing. Vertical bars indicate standard errors of the means (n = 3). For each stabilised soil, bars with the same letter(s) within each cement quantity level are not significantly different according to Welch's t-test at P < 0.05.

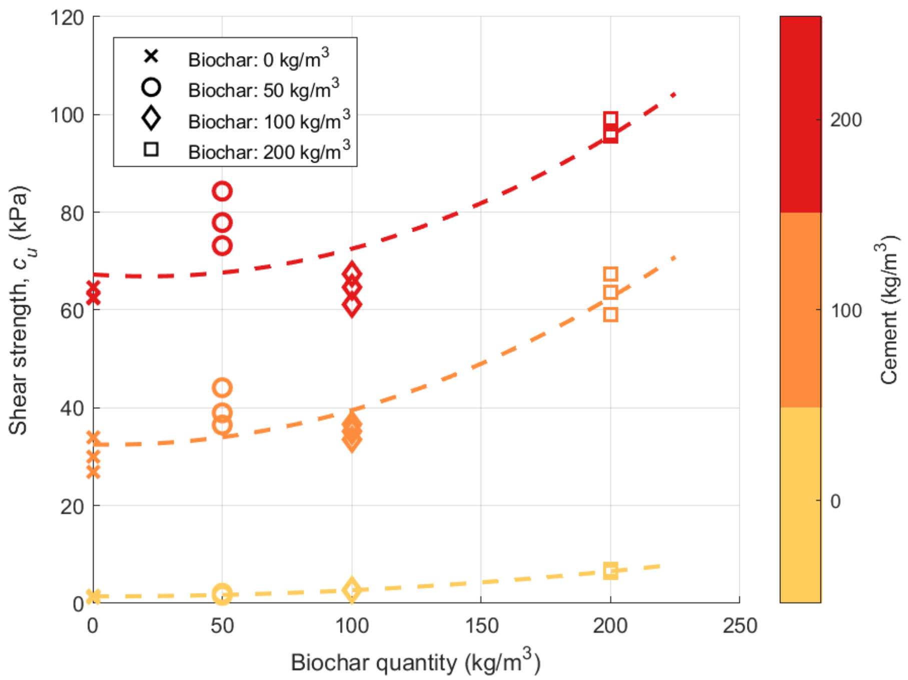


Figure 27 Variation of undrained shear strength, c_u, with biochar quantity.

Figure 28 illustrates the strength increase with cement content. The highest increase (derived from the slope of the curves) was found for the samples amended with 200 kg/m^3 of biochar. The linear polynomials fitted to the data points and the coefficients of determination suggest a linear relationship between the cement quantity and the shear strength of the stabilised peat samples. Further data is, however, required to provide more conclusive evidence.

The relationship between c_u and the total binder content (i.e. sum of cement and biochar quantities) is plotted in Figure 29. The c_u values generally increased with the total binder content, but a strong a strong influence of the used cement quantity is apparent. Linear polynomials were fitted to (a) the entire dataset and (b) the cement-stabilised samples. Although a notable scatter can be observed in this graph, these trendlines provide a first guidance for estimating the strength of peat amended with biochar and cement.

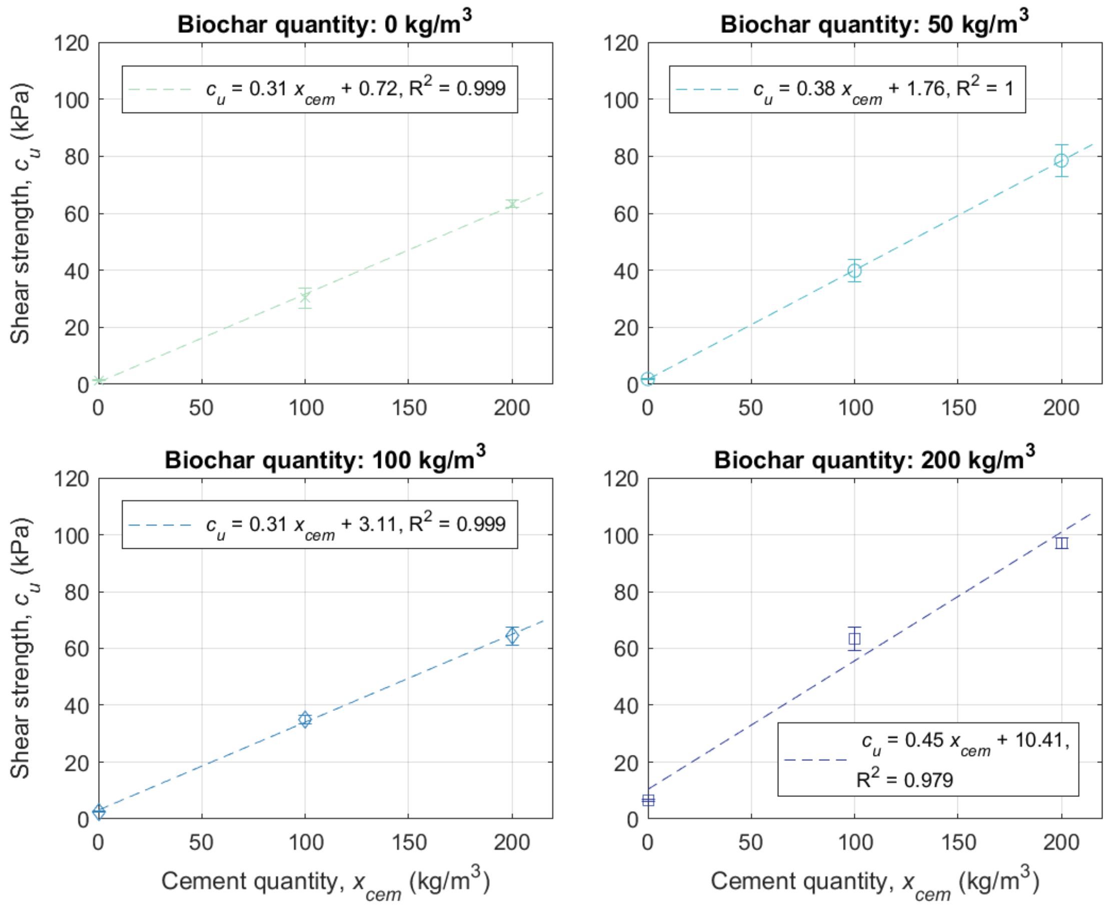


Figure 28 Variation of undrained shear strength, c_u, with cement quantity for the peat test series.

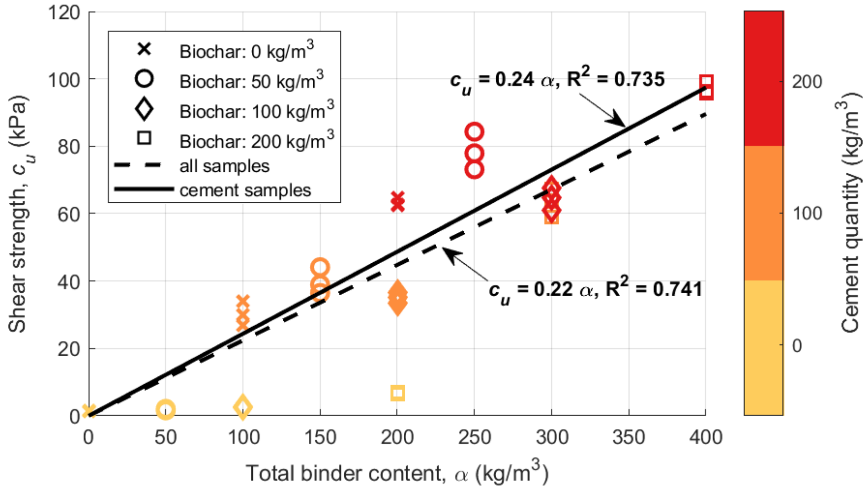


Figure 29 Variation of undrained shear strength, c_u, with total binder quantity, α, for the peat test series.

Axial strain

The results of the axial strain at failure, ε_{af}, for the peat test series are presented in Figure 30. As was pointed out above, an axial strain threshold of 15% was defined for the mixtures characterised by a strain hardening response. From Figure 30, it can be observed that the axial strain at failure was reduced with increasing cement quantity. 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.

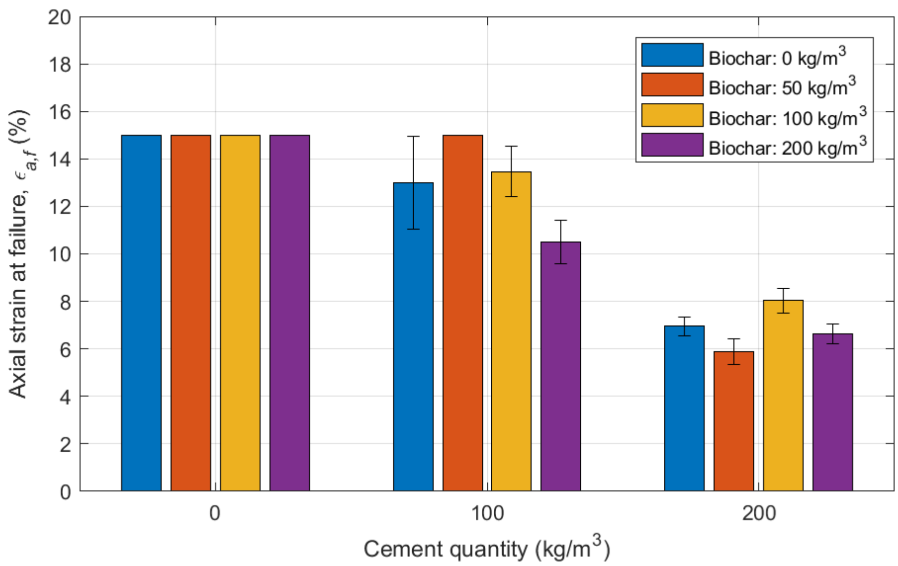


Figure 30 Axial strain at failure of the Tiller-Flotten peat stabilised with different levels of cement and biochar after 28 days of curing. Vertical bars indicate standard errors of the means (n = 3). For samples with strain hardening response, the axial strain at failure was defined to be 15%.

Stiffness

Figure 31 shows the relationship between the biochar quantity and the secant modulus E_{50} of the peat mixtures. A clear trend of increasing E_{50} with both cement and biochar quantity 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.

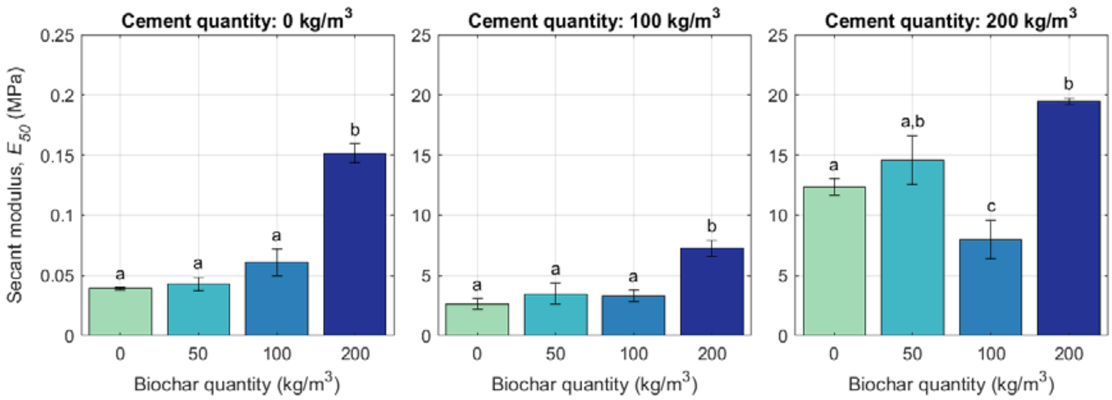


Figure 31 E_{50} secant modulus of the Tiller-Flotten peat stabilised with different levels of cement and biochar after 28 days of curing. Vertical bars indicate standard errors of the means (n = 3). For each stabilised soil, bars with the same letter(s) within each cement quantity level are not significantly different according to Welch's t-test at P < 0.05.

The relationship between c_u and E_{50} is plotted in Figure 32. The E_{50} values fall into an envelope that is approximately defined by $50c_u$ and $225c_u$ boundaries. A seconder order polynomial was found to reasonably well fit the data. From this graph, one can also observe the advantageous performance of samples treated with 200 kg/m^3 of biochar.

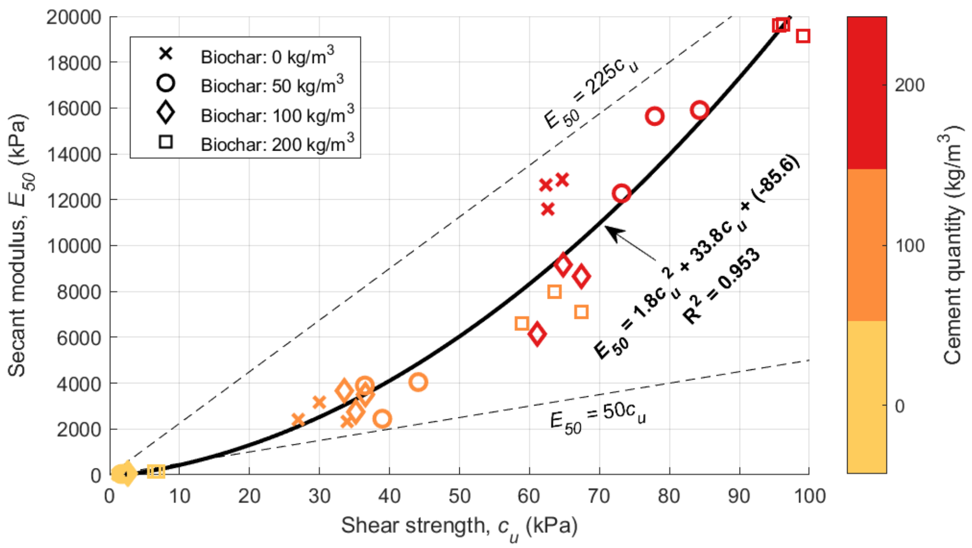


Figure 32 Variation of E_{50} with undrained shear strength (c_u) for the peat test series.

3.4 CO_2 emissions and cost-benefit analysis

To provide a more holistic assessment of the performance of biochar-amended cement-stabilized soils, the following sections present an estimate of the CO_2 emissions and a cost-benefit analysis. The focus of these sections is placed on the clay mixtures, but the obtained trends are also applicable for the peat samples.

3.4.1 CO_2 emissions

A so-called cradle-to-gate analysis was carried to assess the CO_2 emissions of the different mixtures when stabilising 1 m^3 of the Tiller-Flotten clay. This evaluation considered only the product stage of the cement and biochar production (Figure 33). It was therefore assumed that the transport distances of the different materials used for the soils stabilisation (i.e. biochar and cement) are identical and that the installation process of the soil stabilisation is not affected by using different stabilising materials.

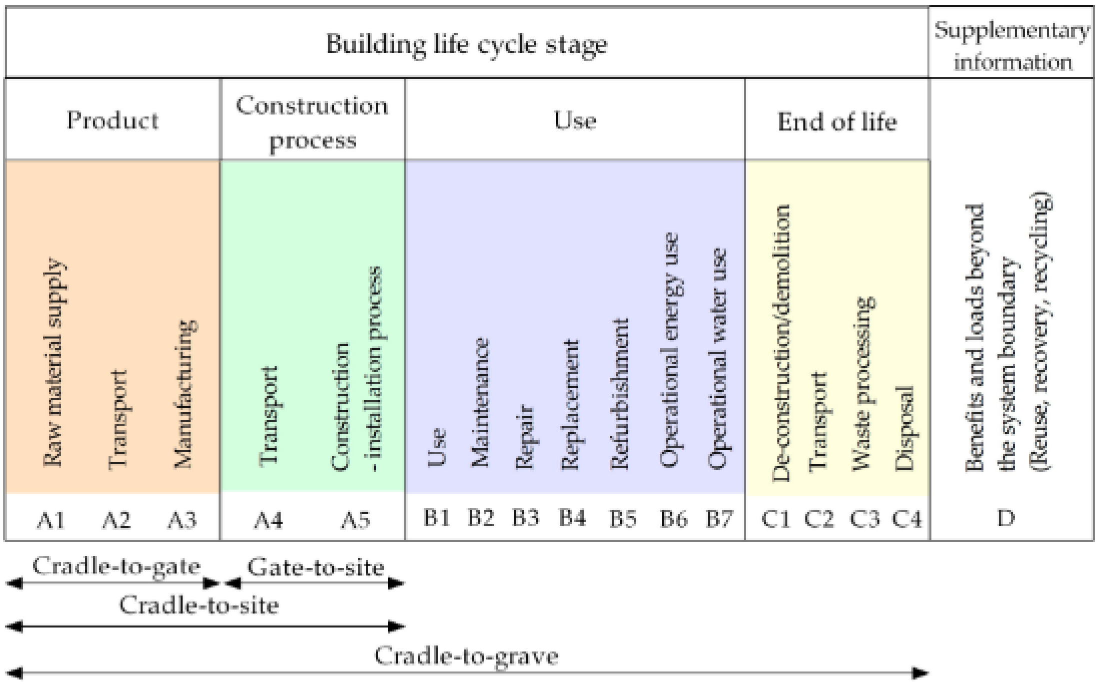


Figure 33 Life cycle assessment system boundaries related to the life cycle stages of a building Source: Song et al. (2020).

The environmental product declaration (EPD) of the used cement was utilised to obtain the carbon dioxide equivalent (CO_2-eq) of the product stage (A1-A3 in Figure 33). The production of the used cement causes a CO_2-eq of 625 kg/tonne (epd-norge.no, 2016). Biochar sequesters carbon and thus has the potential to offset the caused CO_2 emissions. The used biochar contains 78.9% of carbon (Sørmo et al. 2020) and is approximately 80% stable. A ratio of 3.667 was used to calculate carbon dioxide tonnes from one tonne of carbon. These estimates resulted in a carbon offset of -2,314.6 kg per tonne of biochar.

Figure 34 shows the computed carbon footprint of the Tiller-Flotten clay samples stabilised with different cement levels. The cement improved samples caused notable carbon 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 emissions. Adding biochar quantities greater than 30% of the cement quantities renders the soil stabilisation carbon neutral.

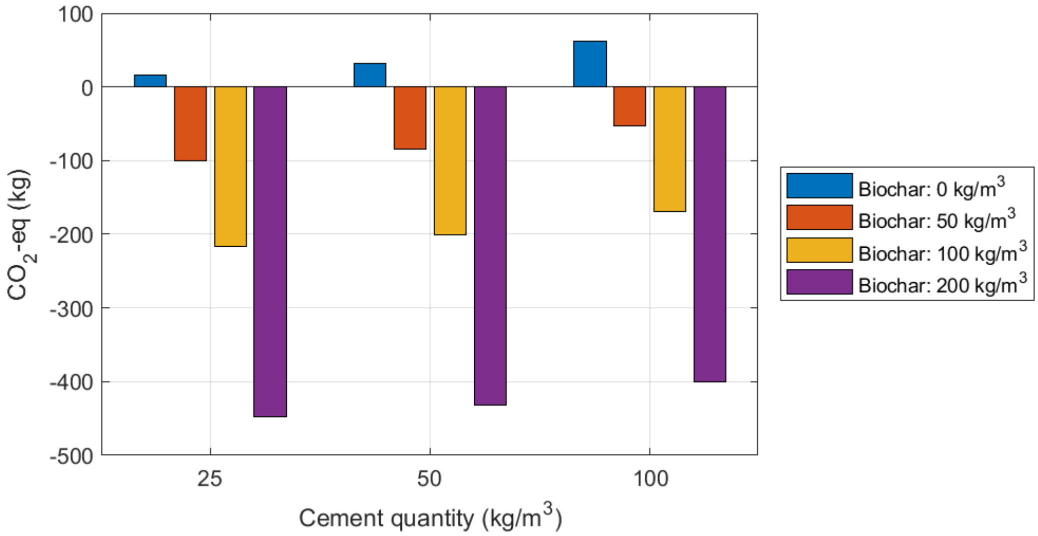


Figure 34 GHG emissions (in Carbon dioxide equivalent; CO_2-eq) from stabilisation by 1 m^3 of cement/biochar amended to Tiller-Flotten clay samples.

3.4.2 Cost-benefit analysis

The costs of the used materials for the soil stabilisation are evaluated next. For the used cement, a cost of 1,050 NOK/tonne was derived following conversations with the cement producer. The biochar cost was assumed to be 3,500 NOK/tonne which is within the range of 2,000 to 5,000 NOK/t typically found in literature. Carbon prices for February 2021 and 2030 were obtained from https://energiogklima.no/ and were estimated as 400 NOK and 850 NOK per tonne CO_2-eq, respectively.

Figure 35 plots the material costs per m^3 of the stabilised Tiller-Flotten clay. Treating the soil with biochar considerably raised the costs. Considering a carbon price and that a carbon offset (i.e. negative carbon footprint) will result in a revenue, reduces the impact of biochar on the material costs. In the future (2030 in Figure 35), 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 35).

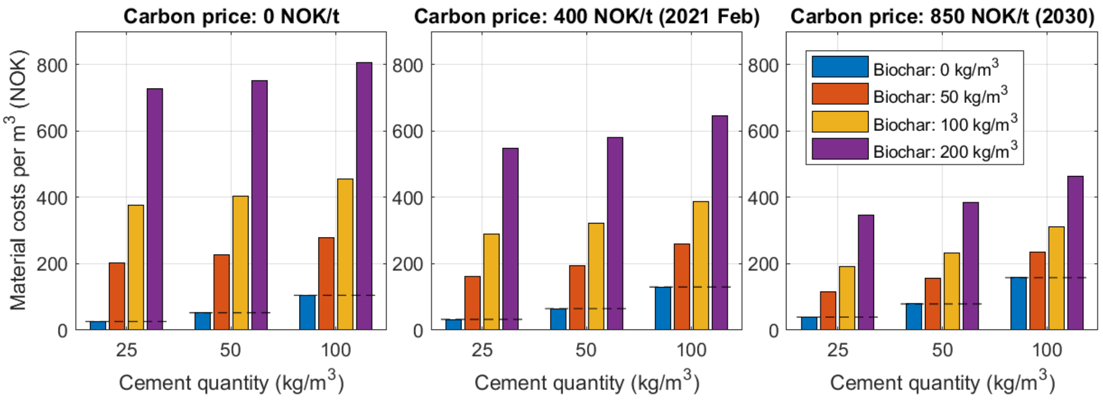


Figure 35 Material costs for 1 m³ of the cement-stabilised Tiller-Flotten clay. The dashed lines indicate the cement costs.

A cost-benefit evaluation was carried out to merge the geotechnical and economic performance of the different mixtures. The ratio between the shear strength, c_u, and the material cost was adopted as a cost-benefit parameter. Figure 36 shows the obtained results for the Tiller-Flotten clay. From this graph it is evident that the cement only stabilised samples outperformed the specimen with additional biochar amendment. The greatest benefit was observed for the clay improved with 50 kg/m^3 of cement, while the cost-benefit reduced with the biochar quantity. Figure 36 further indicates that potential costs related to CO_2 emissions improve the competitiveness of the biochar treated samples.

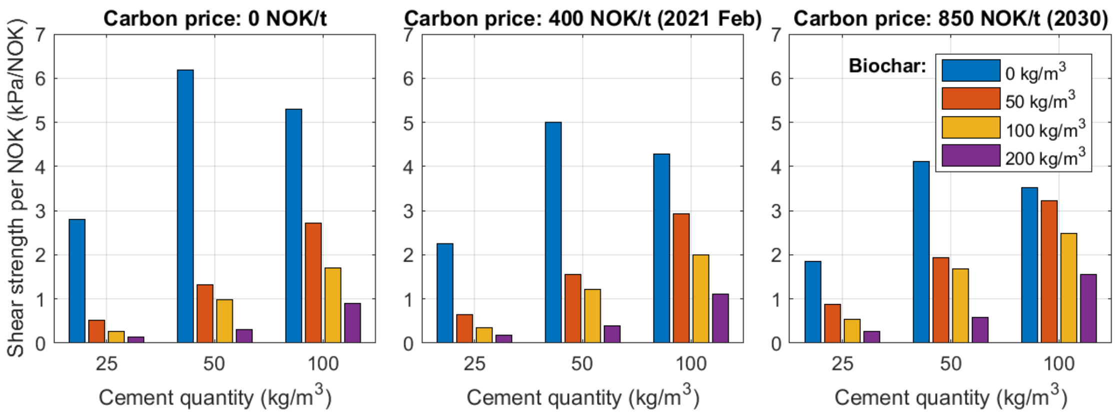


Figure 36 Cost-benefit analysis in terms of shear strength per NOK for the cement-stabilised Tiller-Flotten clay.

4 Conclusion

This research set out with the aim to investigate if biochar could provide a viable alternative to improve the sustainability of techniques to stabilize soft soils such as quick clay and peat. The adopted methodology to achieve this objective included an experimental investigation of quick clay and peat samples amended with biochar, cement and a combination of both. The following sections provide a summary of the main findings before recommendations for future work are provided.

4.1 Main findings

This study showed that biochar amendment can improve the mechanical properties of both natural and cement-stabilised quick clay and peat, while reducing its carbon footprint. Biochar can be treated as a beneficial fill material for soil stabilisation that may partially replace cement and renders ground improvement carbon-negative. More detailed findings are discussed in the following sections.

4.1.1 Treating quick clay with biochar

Adding biochar to natural quick clay caused a minor reduction of the water content, the pH value and the plasticity. The biochar amended quick clay samples were strain hardening and shear strengths between approximately 2 to 9 kPa were obtained for the studied biochar quantities. A direct relationship between the shear strength and the biochar quantity is evident. Remoulded shear strengths greater than the quick clay threshold of 0.5 kPa were obtained for samples treated with biochar quantities as low as 50 kg/m^3. This finding implies that biochar amendment may provide an effective mean to reduce the sensitivity of clays. The biochar amendment adsorbs some of the pore water of the clay, which causes a soil drying and a minor strength increase.

Biochar amendment enhanced the shear strength of cement-stabilised quick clay. An optimum biochar quantity in the range of 75 to 125 kg/m^3 was identified. The cement-stabilised quick clay samples treated with 200 kg/m^3 of biochar resulted in lower strength than samples with 100 kg/m^3. This can likely be explained by the intact cell structure of the biochar providing weak zones. Similar findings for the shear strength were presented by Lau et al. (2020) for biochar fragments greater than 75 µm. The cell structure of the biochar could provide a possible explanation of the observed stiffness reduction for the samples with biochar addition.

4.1.2 Treating peat with biochar

The peat treated with different biochar quantities experience a substantial reduction in water content, while the pH value increased with the biochar content. The biochar amendment substantially enhanced both the strength and stiffness of the peat. These results are likely directly related to the water adsorption and soil drying. Samples treated with biochar quantities of 200 kg/m^3 showed the greatest strength and stiffness. A distinct strain hardening behaviour was evident for the biochar amended peat.

This study has further shown that biochar addition had beneficial impact on the mechanical properties of cement-stabilised peat. Both the strength and stiffness of the stabilised peat increased with the added biochar quantity. The obtained data indicate that the optimum biochar quantity is greater than maximum quantity tested in this contribution (i.e. 200 kg/m^3). An interesting finding is that a peat sample treated with 100 kg/m^3 of cement and 200 kg/m^3 of biochar had almost identical strength properties than a peat stabilised with 200 kg/m^3 of cement. It can be followed that biochar has the capacity to replace parts of the cement when stabilising peat.

4.1.3 Cost-benefit of treating Norwegian soils with biochar

A first-pass cost-benefit analysis was carried out with focus on stabilising quick clay. First, the benefit of using biochar on the carbon emissions of soil stabilisation works was presented. Second, it was shown that using biochar substantially increases the costs of ground improvement works. Finally, a cost-benefit parameter in terms of shear strength per invested NOK was defined and determined for the different quick clay mixtures. This analysis found that the cement-stabilised quick clay outperforms the samples amended with also biochar. It was, however, also shown that the biochar addition becomes more competitive when considering future carbon costs.

4.2 Future research

This work has shown that biochar amendment can have beneficial effects on the geotechnical properties of Norwegian soils and cement-stabilised Norwegian soils. A natural progression of this work would be to further the understanding of the underlying mechanism. Future work should also study the effect of varying biochar properties on soil stabilisation including the impact of different feedstocks, pyrolysis conditions but also different particle size ranges of biochar. Biochar specifically designed for soil stabilisation may outperform the biochar studied in this work. Another fruitful area of research would be to further investigate the effect of biochar on the clay sensitivity an if biochar can be used to prevent clay from becoming "quick". Further research should also focus on exploring peat treated with biochar quantities greater than 200 kg/m^3. Finally, this experimental study should be upscaled to investigate the performance of biochar amend soil at full scale.

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