

EFFECT OF BIOCHAR ON THE GEOTECHNICAL PROPERTIES OF SATURATED SAND

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ABSTRACT

Biochar is a carbonaceous matter produced by heating any organic biomass in an oxygen-free environment through pyrolysis. Biochar has several properties that make it an environmentally friendly material. For instance, given its aromatic nature, biochar is highly recalcitrant, so it has great potential to sequester carbon and reduce greenhouse gas emissions. Additionally, due to its highly porous nature and a high specific surface area, biochar can be effectively used for the removal of contaminants from soil and groundwater. Since most of the research on biochar applications are about their use as a soil amendment, it is essential to assess its influence on soil properties from a geotechnical point of view. To date, little work has been done in this field. In this study, the effect of biochar addition at various amounts (3% and 5%) on the liquefaction resistance of loose saturated sand is investigated through simple shear tests. The results show that the addition of biochar increases the liquefaction resistance of sand by delaying the generation of excess pore water pressure and restraining shear strain development. In addition, the results for sand with 5% biochar are compared with those for sand with 5% fines content (silt), and the difference between them is considerable; implying that the mechanism by which biochar increases liquefaction resistance is different from just adding fines to the sand. The interaction between biochar and water is studied by rheological tests and ESEM analysis to provide an insight into the improvement mechanism. The results presented in this paper provide evidence that this material has the potential to be used for mitigation of soil liquefaction.

1 INTRODUCTION

Waste accumulation and greenhouse gas emissions are increasing every year. At the same time, it is essential to develop more sustainable alternatives to improve ground conditions. Biochar offers a solution to these problems. Biochar is the solid carbonaceous product of pyrolysis via the thermal degradation of organic biomass in the absence of, or under limited, oxygen conditions. Biochar has several features that make it a sustainable and environmentally friendly material. For instance: (1) it could be derived from wastes to reduce landfill wastes; (2) it is related with the production of bio-energy, because the main products of pyrolysis are syn-gas, and bio-oil (Bridgwater, 2004); (3) biochar is highly recalcitrant, which means the carbon stored inside the grains could remain stable under the ground for thousands of years with minimal degradation (Lehmann et al., 2006), and as a result, its potential to reduce anthropogenic carbon emissions and sequester greenhouse gases has been brought to the attention of many researchers (Winsley, 2007; Woolf et al., 2010); (4) biochar has a high specific surface area, so it has been used to remove organic and inorganic contaminants from soil and water (Chen et al., 2007; Park et al., 2011; Reddy et al., 2014; Sun et al., 2011); and (5) biochar's large specific surface area also helps the soil to retain minerals and promote vegetation growth, and hence it could be used to develop green slopes or green embankments. Therefore, biochar has the potential of simultaneously producing bio-energy and permanently sequestering carbon emission, while improving soil and water quality (Laird, 2008).

Regarding biochar mechanical properties, Byrne and Nagle (1997) produced monolithic carbonised wood to study the differences between the resulting biochar and the original wood. The authors measured a reduction in density of 82%, and a decrease in acoustic velocity in the axial direction, but an increase in the radial direction. They also measured 28% higher strength and a reduction of 37% in the stiffness compared to the virgin wood. Other studies have measured particle hardness by nanoindentation, and high variability of particle hardness and elastic moduli was found for different pyrolysis conditions. In general, higher temperature and a longer period of time inside the reactor produced a biochar with higher elastic modulus and hardness (Das et al., 2015a; Zickler et al., 2006).

From the geotechnical point of view, the effect of biochar on the geomechanical properties of soils has been hitherto neglected. Only a few researchers have performed monotonic direct shear tests on clays mixed with biochar, and the authors reported an increase in the shear strength of clays, with applications on expansive/shrinkable clays (Zong et al., 2014), and on slope landfill covers with silty clays where 10% biochar was added into the soil (Sadasivam and Reddy, 2015).

To date, research on the effect of biochar on the geomechanical properties of soil has been lacking, especially its influence on sand properties and the associated dynamic response. Therefore, the prospect of using this material for liquefaction mitigation might open a new direction on this topical subject area. Soil liquefaction is one of the major

causes of damage that occurs during earthquakes; it is a phenomenon in which the soil loses its strength and stiffness due to seismic shaking and, with the development of pore water pressure, cohesionless soils lose shear resistance and behave like a liquid, generating large deformations. It is possible that biochar could play a role in mitigating liquefaction by delaying the development of excess pore water pressure. While some traditional techniques for mitigating soil liquefaction have shown adequate performance during previous earthquakes, the liquefaction phenomenon is still occurring. Furthermore, more sustainable alternatives to tackle it are needed.

In this paper, the results of monotonic and cyclic simple shear tests conducted on sands treated with wood waste biochar are presented as evidence for the potential of this material as a sustainable alternative to improve soil conditions from a geotechnical point of view. The results of cyclic simple shear tests on specimens treated with 3% and 5% biochar by weight of sand were compared with untreated specimens as well as with those sand samples where 5% silt material was added. In an attempt to understand the mechanism behind the improvement, the interaction between biochar and water was studied in detail through rheological measurements and ESEM analysis.

2 METHODOLOGY AND MATERIALS

2.1 MATERIALS

The particle size distribution curves of the host sand, the biochar and the mixture with 3% and 5% of biochar by weight of sand are plotted in Figure 1. The curve for the non-plastic fines material (“Fines”) used to compare with biochar results is also included in the figure.

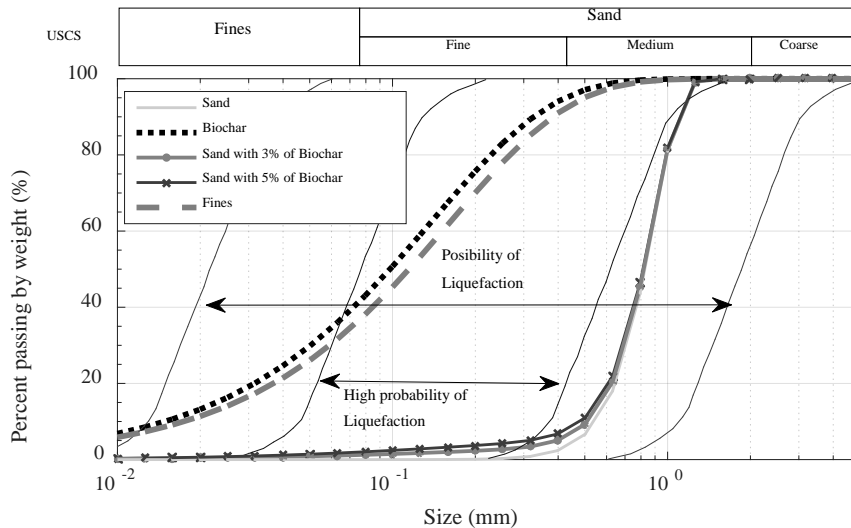


Figure 1. Grain size distribution curves with established boundaries of liquefaction, (Tsuchida, 1970)

2.1.1 Sand

The sand used in this study is a silica sand from Waikato River, in New Zealand. It has sub-angular particles (Fig. 2), with an average grain size of 0.81 mm. Given its poorly-graded size distribution ($C_u = 1.44$) and no fines content, this sand has a medium to a high probability to liquefy (Tsuchida, 1970). The specific gravity is $G_s = 2.65$, and its maximum and minimum void ratios are 0.854 and 0.629, respectively. In this paper, this material has been studied at a loose state, with a target initial relative density of $D_r = 29\%$ for all the tests. This was the relative density at which the selected sample preparation method (see section below) could be replicated systematically on pure sand specimens, with a variability of less than $\pm 2\%$.

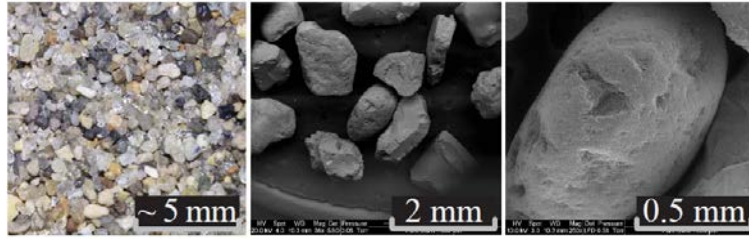


Figure 2. Sand grains

2.1.2 Biochar

The biochar used in this study has been produced by Alternative Energy Solution (Pukekohe, NZ) by fast pyrolysis, using pine bark with a residence time of 10 minutes at a temperature of 470°C. The particle hardness and elastic modulus have been reported elsewhere to be 0.4 GPa, and 5 GPa, respectively (Das et al., 2015b). Its particle size distribution is well graded (Figure 1, $C_u = 9.1$), the average particle size is $D_{50} = 150 \mu\text{m}$, and the measured specific gravity is $G_s = 1.43$. Close-up views of the biochar particles are shown in Figure 3. This material is very porous, and its specific surface area has been reported to be $0.98 \text{ m}^2/\text{g}$ (Das et al., 2015b).

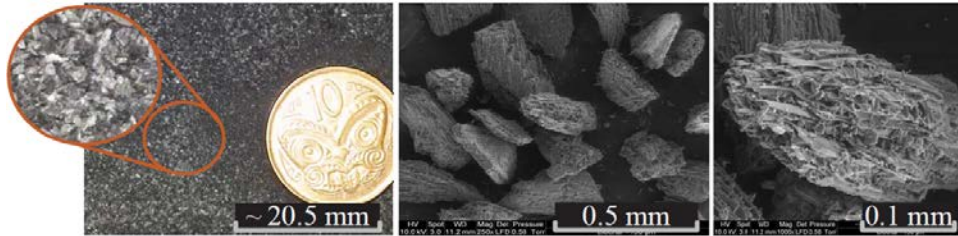


Figure 3. Biochar grains

2.2 SAMPLE PREPARATION METHOD

Sand was mixed in a dry state with biochar in a proportion of 3% and 5% by weight of sand, followed by the addition of de-aired demineralised water to the mixture to form a slurry. Cylindrical specimens of 63 mm diameter and 24 mm height were prepared by depositing the slurries into the mould to a target skeleton void ratio of 0.785 (corresponding to $D_r=29\%$). Since rheology and ESEM results showed that a period of about 10 hours was sufficient for the water to reach equilibrium with biochar particles, the samples were left to stabilise overnight under water. In this procedure, the sand skeleton is assumed to provide the shear resistance.

2.3 SIMPLE SHEAR TESTS PROCEDURE

The ShearTrac II-DSS direct simple shear apparatus was used to perform monotonic-drained and cyclic-undrained tests. In this equipment, the specimen was placed inside a stack of Teflon rings (Figure 4) that provided K_0 stress conditions, prevented lateral extension, and allowed horizontal shearing. The sample was initially consolidated at a defined vertical load, and then horizontally sheared either monotonically or cyclically, depending on the type of test being conducted.

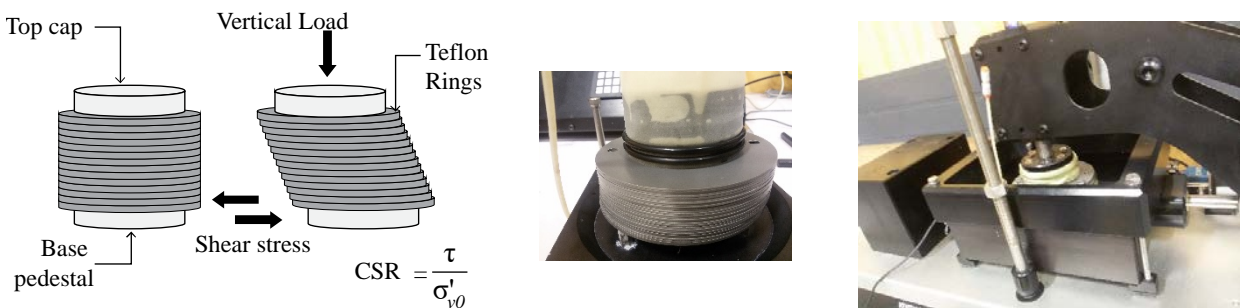


Figure 4. Simple shear apparatus

In this apparatus, full saturation of the specimens could not be confirmed; to ensure full saturation, the samples were prepared with enough de-aired water to have 100% degree of saturation (computed based on the specimen dimensions,

the amount of material and the specific gravity of the particles). In addition, the specimens were left to stabilise under water before testing.

The monotonic tests were conducted under drained conditions, keeping the effective stress constant and measuring changes in the height of the specimen. As the samples were restrained from lateral deformation, the vertical strain was equal to the volumetric strain. Drained simple shear tests (SSTd) were performed under vertical confinement of 50 kPa, 100 kPa, 150kPa, and 200 kPa.

Cyclic tests were performed in undrained condition by enforcing constant height of the specimen (constant volume). It has been shown that constant volume tests produce the same results as those under purely undrained condition, where pore pressure can be measured (Dyvik et al., 1987). Thus, the principle of effective stress was applied, and any change in the vertical stress was considered equivalent to an increase (or decrease) in pore water pressure. Undrained cyclic simple shear tests (CSSTu) were performed at an initial vertical confining pressure of 100 kPa, and sinusoidal shear stress was applied with amplitudes varying from 5 kPa to 28 kPa at a frequency of 0.56 Hz.

2.4 RHEOLOGY TEST PROCEDURE

The interaction between biochar and water was studied through rheological measurements. The suspension was prepared by mixing biochar with water in a concentration of 10.3% and 16.4% by mass, which were equivalent to a treatment of 3% and 5% by weight of sand, respectively, at a relative density of 29%. The suspensions were stirred for 10-20 minutes tested immediately, so the evolution of the structure between water and biochar could be measured as soon as possible. The rheology tests were performed on Physica UDS 200 rheometer using a cup-bob measurement device (Figure 5). This geometry reduces evaporation losses when the specimens are being sheared for a longer period of time.

Figure 5 shows a schematic graph of the tests performed in the rheometer. Time-sweep tests consisted of applying sinusoidal shear strain to the samples at constant low shear strain amplitude ($\gamma = 0.1\%$) at a frequency of 0.56 Hz (the same frequency used in CSSTu). As the only parameter that varies in this test is time, these tests are used to assess the effect of time on the mechanical properties of the mixture. Amplitude sweep tests were also performed, increasing the shear strain amplitude from 0.1% to 100% while keeping the frequency constant at 0.56 Hz. The response of the specimens was measured in terms of the shear stress induced during the test, as well as the computed shear modulus and damping.

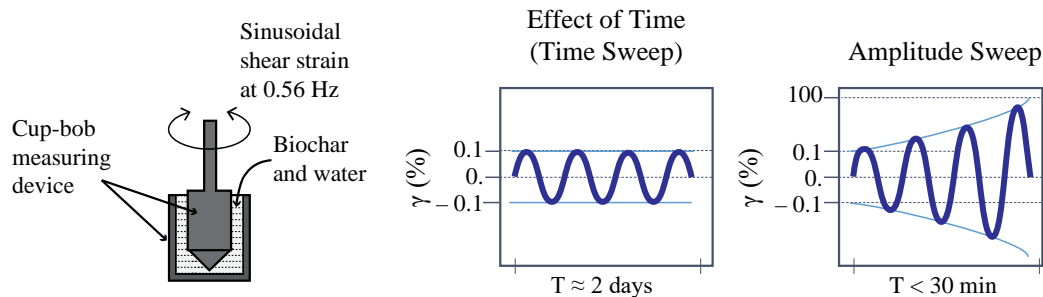


Figure 5. Rheology tests procedure

2.5 ESEM PROCEDURE

Environmental scanning electron microscope analyses were performed using FEI Quanta 200 field emission environmental SEM to study the interactions at a particle level between biochar and water. The ESEM device allows the study of wet samples at low vacuum pressure in the sample chamber (5.2-5.4 Torr). The colloidal suspensions were prepared in the same manner as the specimens for rheological measurements, that is, dry biochar was poured into the water in the same proportion as it would have been in a 5% treated sand by weight. Then, the mixture was stirred for 10-20 minutes until it reached a uniform appearance. Finally, the specimens were stored in an air-tight container and allowed to rest in these conditions for four different periods of time (Elapsed Time): $T < 1$ hour, $T \leq 10$ hours, $T \leq 1$ week, and $T \leq 1$ month. Elapsed time is the time when water and biochar are allowed to interact and stabilise. Following this, the samples were placed under the microscope, where an electron beam was directed into the surface of the specimen, and the interaction produced electronic signals that were received by detectors and converted the information into images.

3 RESULTS

3.1 MONOTONIC DRAINED TEST RESULTS

Figure 6 shows the results of drained monotonic simple shear tests performed on sand specimens treated with biochar. For pure sand specimens, the sample preparation method adopted in the experiments indicated satisfactory reproducibility of the results; the shear strength parameters obtained are as follows: cohesion, $c' = 0$ kPa and angle of internal friction $\phi' = 33^\circ$.

For biochar-treated specimens, more variability was obtained. In general, the static properties of treated sand seem not to vary much from the state without treatment (Fig 6). However, at lower confining pressure, specimens of sand mixed with biochar appear to develop higher resistance (Fig 6c). Regarding vertical (axial, ϵ_a) strain (Fig 6b), in general, specimens tested at higher confining pressure experienced less contractive behaviour. Furthermore, samples treated with biochar experienced less deformation than pure sand specimens. It is possible that biochar grains are restraining the sand grains from moving freely.

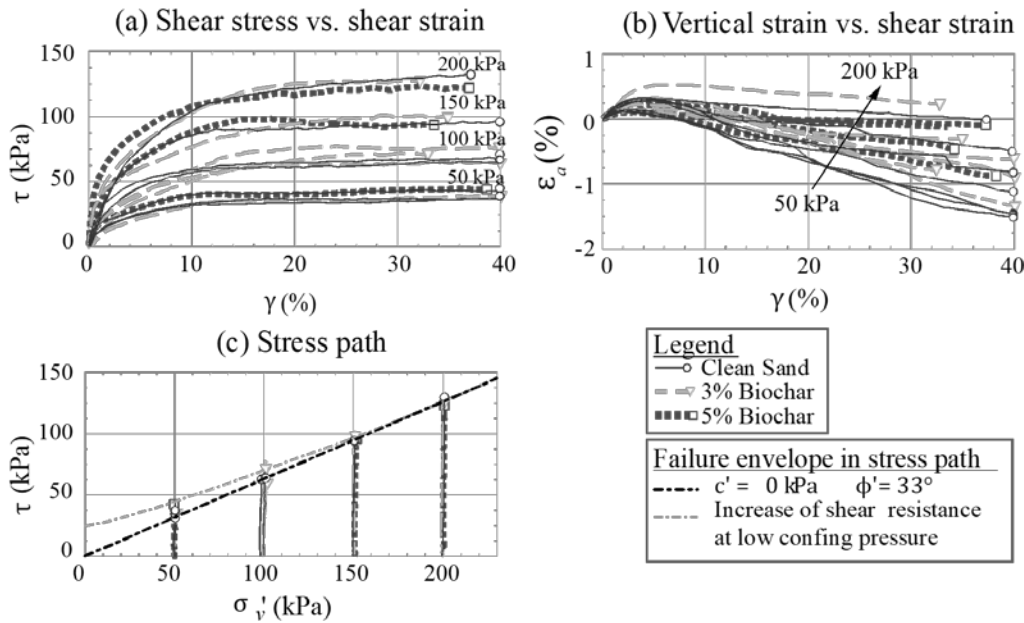


Figure 6. Results of monotonic drained simple shear tests

3.2 UNDRAINED CYCLIC SIMPLE SHEAR TEST RESULTS

Tests with 100 kPa vertical stress at different cyclic stress ratios (CSR, as defined in Equation 1) were performed on pure sand specimens and specimens treated with 3% and 5% biochar.

$$CSR = \frac{\tau}{\sigma'_{v0}} \quad (1)$$

with τ = shear stress, and σ'_{v0} = initial vertical stress. In general, biochar-treated sands showed a better cyclic response, i.e. higher liquefaction resistance than clean sand. Figure 7 displays the liquefaction resistance curves of the specimens. Liquefaction was defined in terms of the double amplitude shear strain criterion of $\gamma_{DA} = 7.5\%$. The tests that were stopped before the onset of liquefaction are plotted with arrow signs (indicating more cycles are required).

In Figure 7a, the relationship between the number of cycles to liquefaction, N , and the cyclic stress ratio (CSR) was represented by a power function (Equation 2). Thus, the relationship between $\log(CSR)$ vs $\log(N)$ was linear, with the slope b ranging from 0.15 to 0.17.

$$CSR = a \cdot N^{-b} \quad (2)$$

The tendency of biochar to increase the liquefaction resistance of the host sand is clearly observed in Figure 7. For specimens treated with 5% biochar, the number of cycles required to achieve liquefaction for a given CSR was more than six times (i.e. almost one order of magnitude). Figure 7 also shows representative test results for the case of $CSR \approx 0.18$ which were performed on specimens with different levels of treatment. There is a clear tendency for the biochar to delay the increase in the excess of pore water pressure and, more importantly, to reduce the double amplitude shear

strain (γ_{DA}) (Figure 7). Indeed, if the response of the three samples is compared during the 6th cycle, typically considered equivalent to an earthquake of magnitude 6 (Seed and Idriss, 1982; Youd et al., 2001), it can be observed from the graph of biochar content vs γ_{DA} at the 6th cycle that the accumulated shear strain (peak-to-peak) is reduced by more than four times with the addition of biochar.

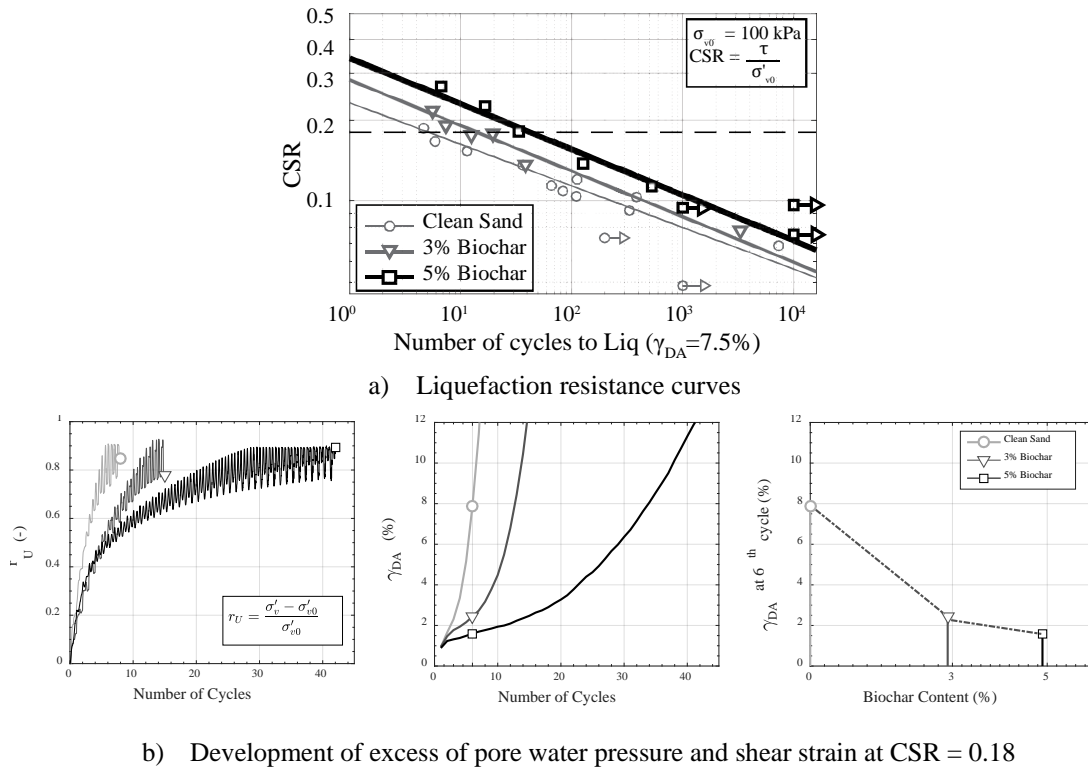


Figure 7. Cyclic simple shear test results on specimens treated with biochar

3.2.1 Comparison with 5% fines content with similar grain size distribution as biochar

A non-plastic silt was selected in order to compare the behaviour of sand with that mixed with biochar (also non-plastic). The material was sieved and forced to have a similar grain size distribution as the biochar used (Figure 1). The specimens with 5% fines content were prepared using the same preparation method as described in Section 2.2.

The results presented in Figure 8 indicate that the effect of adding 5% fines is negligible, as the liquefaction resistance is very similar to the case of pure sand. This is an indication that the improvement in the liquefaction resistance obtained by adding biochar does not have the same mechanism as that of just adding fines.

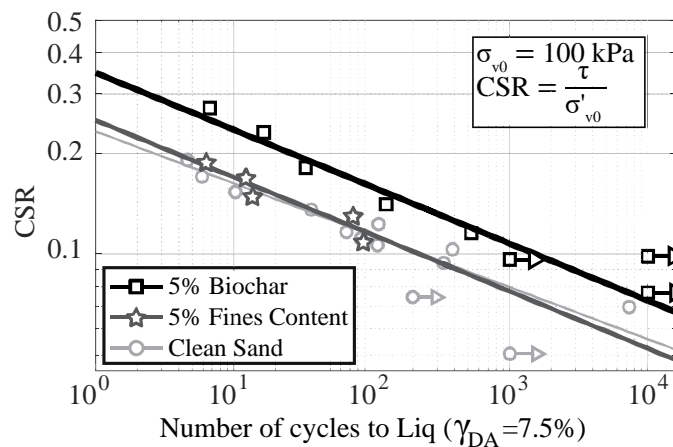


Figure 8. Comparison between the effect of biochar and other type of fines on the liquefaction resistance

3.3 INTERACTION WITH WATER THROUGH RHEOLOGY

The results of time-sweep tests are plotted in Figure 9a. Time sweep tests are useful to observe if there is any change in the stiffness of the biochar-water mixture with time. From the figure, there is an increase in shear modulus with time, which means that the interaction between water and biochar is developing with time. The shear modulus tends to stabilise, and about 10 hours are required to reach about 80% of the maximum shear modulus.

Amplitude sweep tests results are useful to observe how the stiffness of the mixture degrades with an increase in shear strain amplitude. Additionally, as the applied shear strain is not necessarily in the same phase as the shear stress measured (there is some delay), it is possible to compute the elastic shear modulus (shear strain and shear stress in the same phase), and the viscous shear modulus (shear strain and shear stress out of phase) (Figure 9b). When the viscous modulus is higher than the elastic modulus, it is considered that the sample behaves like a liquid (liquefied state). For specimen with a concentration of 10.3% biochar by weight of water (equivalent to a treatment of 3% biochar by weight of sand), liquefaction happens at a shear strain of 5.1%, which is one order of magnitude smaller than that with a concentration of 16.4% (5% biochar), which required 95% shear strain to have liquid-like behaviour. This is consistent with the result of CSSTu in Figure 7, where the improvement obtained with 3% biochar is considerably lower than the one measured with 5% biochar.

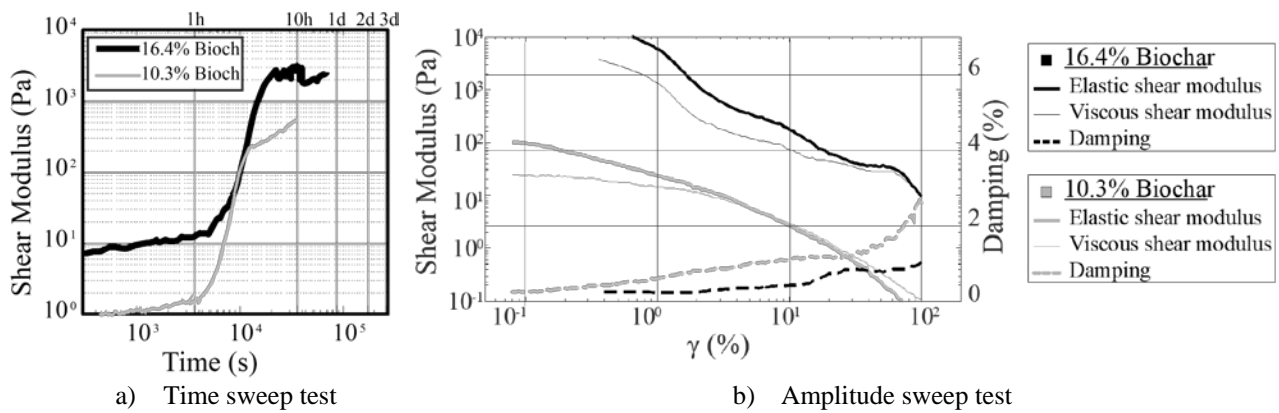


Figure 9. Rheology tests results

These results contribute to the hypothesis that the interaction between water and biochar influences the improved response of the sand specimens with biochar in the SSTd and CSSTu results.

3.4 INTERACTION WITH WATER THROUGH ESEM ANALYSIS

ESEM analyses were performed to show biochar-water interaction over different elapsed times after the preparation of the mixtures: $T < 1$ hour, $T \leq 10$ hours, $T \leq 1$ week, and $T \leq 1$ month, and the main outcomes are summarised in Figure 10. Figure 10a shows the state of the suspension with an elapsed time $T < 1$ hour, i.e. the suspension was just prepared before the images were taken; and Figure 10 b, c, and d show suspensions prepared 10 hours, 1 week and 1 month, respectively, before the images were taken.

When comparing the state of the suspensions at different elapsed times, it is observed in Figure 10a that when the elapsed time is less than 1 hour, the biochar edges are visibly dry, and the particles are just floating on top of the water. Thus, it is conceivable that at this stage, the biochar is not interacting yet with the water and may actually be repelling it (hydrophobic behaviour).

From Figure 10 b to d, a water film is observed to connect the biochar particles which, after one month, has a thicker texture, similar to a gel formation. It is important to mention that these images are merely descriptive, and other measurements, such as rheological measurements, are required. However, the observation from the images is consistent with the results from the rheology tests, where an increase of shear modulus was measured with time, e.g. after 10 hours, the specimens had developed nearly 80% of the shear modulus.

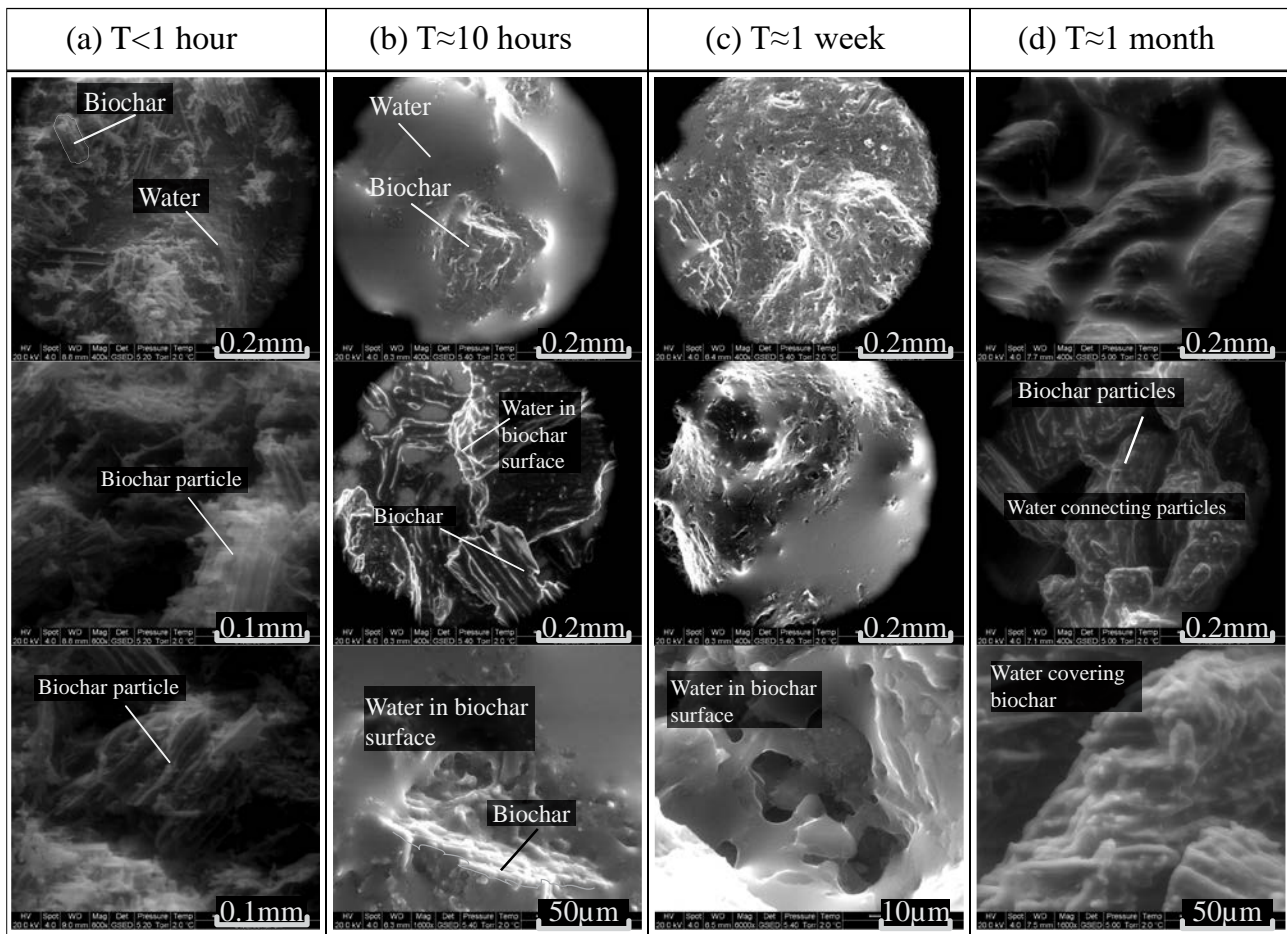


Figure 10. ESEM images of biochar in water at different elapsed times

4 DISCUSSION

In this paper, the effect of adding biochar in the loose saturated sand was investigated through simple shear apparatus, where monotonic drained and cyclic undrained tests were performed. In addition, the interaction between biochar and water was studied by rheological measurements and ESEM analysis.

The results from monotonic tests indicated that biochar did not have much effect on the drained shear strength, except at low confining pressure (less than 100 kPa), where it seems to provide apparent cohesion. In addition, the specimens treated with biochar experienced less volumetric deformation, indicating that biochar is restraining the free grain movement.

Regarding cyclic response, the specimens were tested at different cyclic stress ratios in a cyclic simple shear apparatus. It was found that biochar-treated samples had higher liquefaction resistance, i.e. required more cycles to reach a double amplitude shear strain of 7.5%, but also delayed development of excess of pore water pressure was measured. Comparing the level of deformation, for instance at the 6th cycle the double amplitude shear strain was reduced from 8% to 2% (Figure 7).

The cyclic results of biochar were compared with specimens with 5% fines content that had the same grain size distribution as biochar. However, these specimens performed very similar to the clean sand samples, which is in good agreement with what other authors have concluded (Chang, 1987; Law and Ling, 1992), i.e. adding 5% fines content does not influence the macro-response of the specimen and at least 10-20% fines content would be required to increase the liquefaction resistance. Therefore, the mechanism by which biochar would increase the liquefaction resistance is different compared to that of just adding fines to the sand matrix or a reduction in the void ratio. It is possible that the increase in excess pore water pressure would result in the opening of internal pores in the biochar by overcoming the capillary pressure. This, in turn, may have increased some pore volume within the biochar grains, which are initially inaccessible to water, and resulted in the delay in the development of excess pore water pressure.

Rheological measurements and ESEM analysis were performed to understand the interaction between biochar and water. Time sweep tests were conducted to measure any evolution in the structure of biochar-water mixture with time (Figure 9a), and an increase in shear modulus was measured which tended to stabilise with time, and, e.g. about 10 hours were required for the water-biochar mixture to reach 80% of the maximum shear modulus. As these tests were performed at constant shear strain amplitude, the increase in shear modulus directly correlates with an increase in shear resistance. On the other hand, the amplitude sweep tests (Figure 9b), showed that the suspensions were stable for a wide range of strain amplitudes. The point in which the elastic modulus becomes smaller than the viscous modulus was considered as the beginning of a liquid-like behaviour. The suspension equivalent to a treatment of 3% (i.e. concentration in water of 10.3%) reached liquid-like behaviour at a shear strain of 5.1%, while for the treatment of 5% this point was reached at 95% shear strain amplitude. According to these results, as soil liquefaction is defined as attainment of double amplitude shear strain of 7.5%, the biochar-water mixture would not behave like a liquid when the soil reaches liquefaction. This explains the increase in liquefaction resistance in Figure 7, where biochar is providing resistance before the specimens reached liquefaction.

ESEM analysis was performed to present a visual record of how the biochar-water mixture was changing with time. The images suggest that there is, indeed, a complex interaction between biochar and water that seems to develop with time, as measured in the time sweep tests (Figure 9a). Based on these results, it was decided, in the preparation method (Section 2.2) to leave the biochar-treated specimens to stabilise overnight before testing them.

5 CONCLUDING REMARKS

Biochar is an environmentally friendly material whose many applications required it to be buried in the ground. However, little research has been conducted on the influence this material has on the geotechnical properties of the host soil. This paper investigated the effect of biochar on the drained shear strength and cyclic undrained resistance of loose saturated sand and the interaction between biochar and water through rheological measurements. The results of this paper provided evidence that biochar could be used to mitigate soil liquefaction, adding a new possible use to this material that is currently being buried in the ground to help manage wastes, to reduce carbon emissions to the atmosphere, and to improve soil fertility.

The results from monotonic tests indicated that biochar did not have much effect on the drained shear strength, except at low confining pressure (less than 100 kPa), where it seems to provide apparent cohesion. On the other hand, under cyclic loading, biochar-treated specimens had higher liquefaction resistance than the pure sand samples. In addition, investigation of the interaction between biochar and water through rheological measurements showed the presence of a complex network between biochar and water. According to the time-sweep tests results, suspensions of biochar in water were capable of developing shear resistance with time.

It is believed that the mechanism of improvement in the shear strength and in the liquefaction resistance of the host sand with the addition of biochar is due to the interaction between the biochar particles and water, which helps to provide shear resistance, restraining the free grain movement and delaying the increase in excess pore water pressure.

It is important to note that the biochar properties are dependent on the original feedstock and pyrolysis conditions, i.e. different pyrolysis temperature and duration during the production would lead to different biochar with different physical, chemical and mechanical properties. Therefore, it is important to study other combination of pyrolysis conditions; the results presented in this paper are applicable exclusively to the biochar made from pine sawdust waste, pyrolysed at 470°C for 10 minutes.

While the target application of this material would be natural soils which already contain biochar, biochar could also be used as mixtures for backfills or in soil reclamation fills. Despite the possibility that additional compaction associated with some filling may induce crushing of the biochar, this would be beneficial because it would increase angularity of the particles and their surface areas; thus, the benefits from a geotechnical point of view would be higher. This material could be implemented in economically underdeveloped regions because it is a cheap material to obtain compared with other “engineered soils” (biochar is a by-product). Adding biochar to soil would not only increase its liquefaction resistance, but as it promotes vegetation growth, it could improve the aesthetics of the fill, and all the carbon stored inside would remain stable for thousands of years, avoiding carbon emissions.

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