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Experimental studies on the application of coir fiber for mitigating liquefaction in sands

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ABSTRACT

One of the major earthquake risks is sand liquefaction, which has caused numerous global losses. Grouting and densification are two common yet pricey liquefaction mitigation methods. Coir fiber is one of the most important by-products of the coconut business worldwide. The excellent tensile strength of coir fiber can be used to improve the resistance of sand to liquefaction. The effectiveness of coir fiber in liquefaction mitigation is experimentally investigated in this work. For this, a series of stress-controlled constant volume cyclic simple shear tests were run on sand specimens reinforced with various fiber contents of 0.25%, 0.5%, and 0.75%, and test results were compared. Test results showed that the liquefaction resistance improved as the fiber content increased. Liquefaction resistance increased to a maximum extent of 622% for sand reinforced with 0.75% coir fibers. Also, coir fibers were found to be beneficial in arresting the shear deformations in the specimen. Fiber contents beyond 0.75% are difficult to mix for practical purposes as they cause segregation and entanglement of the fibers.

Keywords: UN SDG 9, liquefaction, coir fiber, cyclic simple shear test, reinforced sand

1 INTRODUCTION

Flow failures, lateral spreading, loss of bearing capacity, and excessive settlements are serious threats to the soil structures that are posed by the liquefaction induced in loose saturated sands by seismic activities. The shear strength of the soil is lost completely due to the reduction in the effective stresses that hold the grain contacts with the accumulation of positive pore pressures. The compressible nature of the loose sands upon seismic shaking is the underlying cause for this (Seed & Lee, 1966; Castro, 1975; Ishihara et al., 1975). Research on the liquefaction response of sands gained momentum with the alarming levels of destruction caused during Alaska and Niigata earthquakes in 1964. Since then, much research has progressed in this field with contributions from several researchers across the globe. Effects of cyclic stress amplitude and frequency of seismic vibrations, relative density, fines content, and degree of saturation of soils are all studied extensively over the years (Lade & Yamamuro, 1997; Bouckovalas et al., 2003; Papadopoulou & Tika, 2008; Zhang et al., 2016; Zhu et al., 2021). Most recently, liquefaction response of sands is correlated to their morphological characteristics (Latha & Lakkimsetti, 2022).

Mitigating the liquefaction and its associated hazards is necessary to ensure the stability of the soil structures subjected to earthquakes. Liquefaction in sands can be avoided by: (a) prior compaction using vibrators which reduce their compressibility (Shahir et al., 2016), (b) installing earthquake drains in advance to diminish the pore pressures by enhancing their drainage conditions (Brennan & Madabhushi, 2006), (c) chemically cementing the grain contacts with the addition of binders which impart apparent cohesion to the grains (Rasouli et al., 2020), and (d) desaturating the sand (Okamura & Soga, 2006; He & Chu, 2014). These traditional methods are energy intensive, expensive, and leave a high carbon footprint on the environment.

Soils are weak in tension, which makes it easier for earthquakes to break their grain contacts by subjecting them to repetitive compressive and tensile stresses. High-tensile strength polymeric geosynthetics like geotextiles and geogrids established themselves as eco-friendly materials for providing sustainable solutions to various geotechnical problems (Krishnaswamy & Isaac, 1994). Inserting high tensile strength materials as an inclusion to them can impart additional confinement and apparent cohesion to the grain contacts, which help arrest the lateral movements of the particles when subjected to loads, thereby reducing their potential towards contraction and liquefaction. This ability of the high tensile strength materials makes them suitable as inclusions for liquefaction mitigation.

Several studies have utilized planar sheets of geosynthetics as inclusion for liquefaction mitigation in sands (Krishnaswamy & Isaac, 1994; Altun et al., 2008; Bahadori et al., 2020). Liquefaction response of soils at element level was researched through cyclic triaxial, cyclic torsional shear, and cyclic simple shear tests. Cyclic simple shear tests are considered to represent the field stress states during an earthquake more accurately than cyclic triaxial tests, due to their ability to allow the principal stress rotations (Ansell & Brown, 1978; Amer et al., 1987; Liu & Chen, 2022). Reinforcing soils with planar geosynthetics causes anisotropic improvement in the response because of the non-uniform distribution of reinforcement. Several studies showed that the random mixing of fibers provides a homogenous and isotropic enhancement in the response of reinforced sands (Latha & Murthy, 2007; Bao et al., 2020; Rasouli & Fatahi, 2022; Zhou et al., 2022; Jain et al., 2023). The advantages of adding high tensile strength polymeric fibers to the sands for improving their liquefaction response were studied by several researchers. It was demonstrated from these studies that increase in fiber length, and fiber content increase the liquefaction response of the sands (Maheshwari et al., 2012; Ye et al., 2017; Rasouli & Fatahi, 2022; Jain et al., 2023). Natural coir fiber is usually left as a by-product from many coconut and other related industries in many countries across the globe and is often discarded as waste and sometimes used in interior works of buildings and used as fuel for cooking purposes. Tensile strength of the coir fiber is in the range of 80 to 120 MPa, and hence coir fibers can be effectively utilized for reinforcing materials that are weak in tension (Rathod & Venkatarama Reddy, 2021). Studies on the coir fiber-reinforced concrete composites showed beneficial improvements in the performance of the composites (Rathod & Reddy, 2022). Coir fibers are biodegradable as their composition includes cellulose, lignin, and other organic compounds. However, several studies have shown that treating the coir fibers with alkaline compounds delay their degradation and increase their service life by many folds (Nam et al., 2011; Mittal & Chaudhary, 2019; Ahmad et al., 2022). Coir fibers have a low carbon footprint, and utilizing them for liquefaction mitigation in place of other energy-intensive methods holds a positive environmental impact. Hence, the objective of this study is to propose and verify the utilization of coir fibers as an alternative to the conventional techniques like compaction and chemical cementation that are being utilized for mitigating liquefaction in sands. For this purpose, a series of stress-controlled constant volume cyclic simple shear tests were performed on unreinforced and coir fiber-reinforced sands. Pore pressure response and shear strain accumulations in these materials are interpreted, and the beneficial effects of coir fiber as an environmentally friendly material to mitigate liquefaction in sands are discussed.

2 MATERIALS AND METHODOLOGY

2.1 Materials

Natural sand of a river origin is used in the current study. Figure 1 shows the grain size distribution of the sand along with a photograph of the sand particles. The sand is classified as poorly graded sand (SP) as per the Unified Soil Classification System (USCS), with a coefficient of uniformity (C_u) value of 3.4 and a coefficient of curvature (C_c) value of 1.088. For liquefaction testing, specific size fractions of sand particles ranging between 0.6 mm and 1.2 mm sizes scalped out from the sand sample were used. Specific gravity (G_s) was determined as per ASTM D854. The minimum and maximum void ratios (e_{min} and e_{max}) were determined as per ASTM D4253 and ASTM D4254, respectively. The morphological features of the sand particles, like Wadell's roundness (R) and sphericity (S) (Wadell, 1932, 1935), and Lees's angularity (A) (Lees, 1964), were determined using image analysis (Vangla et al., 2018). Physical properties of the sand, along with the computed morphological features, are listed in Table 1.

Table1. *Physical properties and morphological descriptors of the sand*

Material	Specific gravity (G_s)	Minimum void ratio (e_{min})	Maximum void ratio (e_{max})	Roundness (R)	Sphericity (S)	Angularity (A)
River sand	2.61	0.69	0.86	0.45	0.85	540

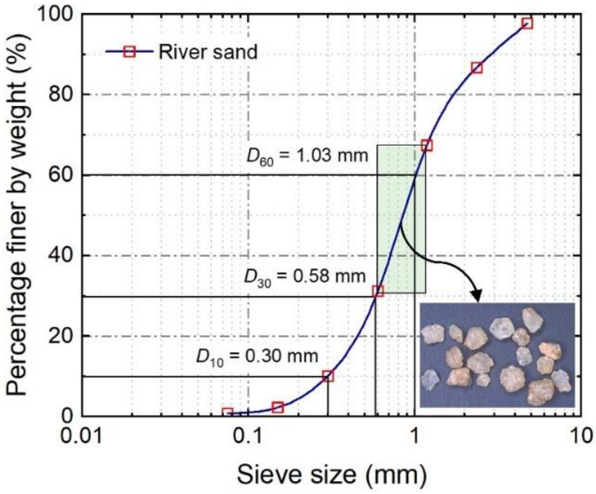

Figure 1. *Grain size distribution of the sand*

Natural coir fibers procured from a local supplier were used to reinforce the sand. The original length of the fibers varied from 25 to 250 mm with diameters in the range of 65 to 500 μm. The average tensile strength of the coir fiber was determined to be 102 MPa (with a standard deviation of 28.5 MPa) from 50 fiber tension tests carried out in a universal testing machine, as per ASTM D3822. These fibers were shredded such that the length of the fiber does not exceed the lowest dimension of the specimen. Figure 2 shows a photograph of the coir fibers used in the experiments.

Figure 2. *Photograph of the coir fibers used for reinforcing the sand*

2.2 Test procedure and specimen preparation

A Swedish geotechnical type of simple shear test setup (GCTS USA make) characterized by the specimen being confined with a stack of rigid Teflon-coated rings to impose at-rest (K_0) stress conditions on the lateral boundaries of the test specimen is used for the liquefaction testing. Specimens with a diameter of 100 mm and height of 40 mm were prepared for testing. This aspect ratio of the specimen with height to diameter ratio of 0.4 is within the permissible limits specified by the ASTM D8296-19 standard for simple shear testing. Liquefaction testing is performed under constant volume conditions where the specimen height is kept constant throughout the shearing using a mechanical clamp. In this way of testing, changes in the normal stress on the specimen are equivalent to pore pressures developed in case of undrained testing (Dyvik et al., 1987; Porcino et al., 2008). Figure 3 shows a photograph of the cyclic simple shear test setup used. It has a normal actuator and a shear actuator with 5 kN loading capacity each and ±25 mm stroke capacity. Both stress-controlled and strain-controlled tests can be performed.

All the specimens were prepared to a relative density of 30%. Pre-determined weight of sand needed to achieve this relative density was poured in and compacted using a lightweight tamping rod in 4 equal lifts, each of height 10 mm. For the fiber-reinforced test specimens, the fiber content was varied from 0.25 to 0.75% by weight of the sand in the specimen. Required quantity of coir fibers was weighed and thoroughly mixed with sand to ensure a homogeneous mixture. The mixture was split into 4 equal portions. Each portion was poured into the specimen mould and compacted to a height of 10 mm each. The photograph of a typical fiber-reinforced specimen prepared for a cyclic simple shear test is shown in Figure 4.

Figure 3. *Photograph of the cyclic simple shear test setup*

The prepared specimen was then mounted onto the sliding base of the test setup. The specimen was subjected to a normal stress of 150 kPa and left undisturbed until no change in the vertical linear variable differential transducer (LVDT) was noted. This represents the one-dimensional (K_0) consolidation of the specimen. Later, the specimen was subjected to stress-controlled constant volume cyclic shearing with a sine waveform of amplitude 26 kPa and frequency 0.2 Hz. The condition of pore pressure ratio (r_u) reaching a value of unity (i.e., to drop the initial normal stress of 150 kPa to zero) was considered as the indication of complete liquefaction of the specimen, and the number of cycles needed for the same was recorded.

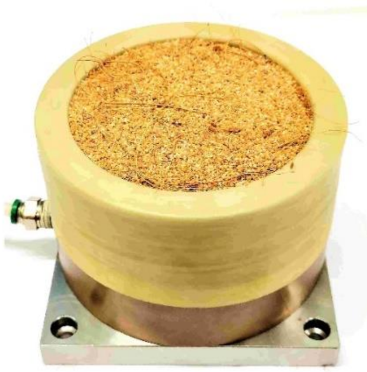

Figure 4. *Closeup view of the prepared fiber reinforced test specimen*

3 RESULTS AND DISCUSSION

Figure 5 shows the pore pressure response of the unreinforced and coir fiber-reinforced specimens with varying fiber contents of 0.25, 0.50, and 0.75% when subjected to a stress-controlled cyclic loading of amplitude 26 kPa and frequency 0.20 Hz. The value of the pore pressure ratio (r_u) reaching unity marks the onset of complete liquefaction in the test specimens. This criterion was adopted in several other studies on liquefaction testing (Rasouli & Fatahi, 2022; Zhou et al., 2022). It can be seen from Figure 5 that the unreinforced specimen liquefied in 9 cycles. Whereas sand reinforced with coir fibers liquefied in 26, 40, and 65 cycles, respectively, for fiber contents of 0.25, 0.50, and 0.75%. It is evident that coir fibers increased the liquefaction resistance of the sand. The improvement in the liquefaction resistance increased with the increase in fiber content. The percentage improvement in the liquefaction resistance of the sand with the addition of coir fibers in terms of the number of cycles is maximum for 0.75% fiber content with a value of 622%.

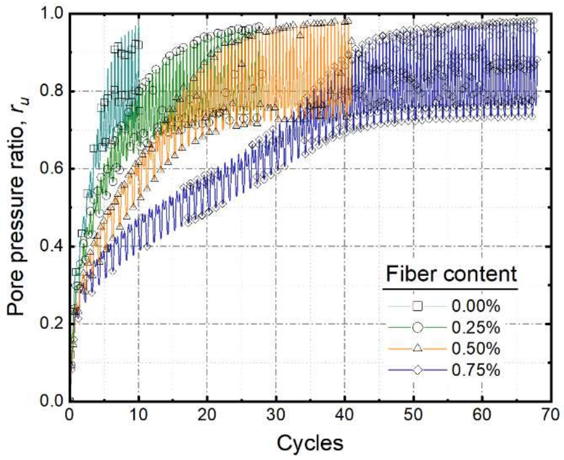

Figure 5. *Pore pressure response of the test specimens*

During liquefaction, shear strains increase drastically in the test specimens due to sudden loss in the shear strength. This sudden increase in the shear strains is responsible for lateral spreading and other associated failures of liquefaction, and it is essential to arrest these for ensuring the stability of soil structures. Figure 6 shows the shear strain accumulation in the unreinforced and reinforced test specimens. It is clearly seen that coir fibers were able to arrest the shear deformations in the specimen for a large number of cycles, while the shear deformations were large in the unreinforced specimen. A double amplitude shear strain of 7.5% is reached after 8 cycles in case of the unreinforced specimen, whereas it is reached after 21, 34, and 59 cycles, respectively, for 0.25, 0.50, and 0.75 % coir fiber reinforced specimens. With the increase in the fiber content, the shear strains were further arrested to a large number of cycles. Figures 5 and 6 collectively show the effectiveness of coir fibers in increasing the liquefaction resistance of the sands by several folds and also their ability to arrest the associated deformations for sustaining a large number of cyclic loads.

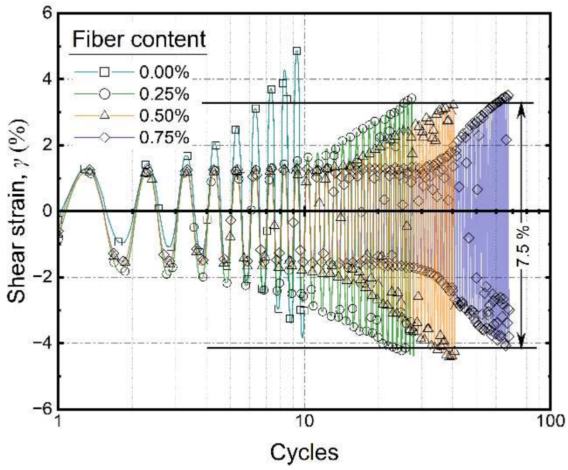

Figure 6. *Shear strains response of the test specimens*

Figure 7 compares the stress paths followed by the unreinforced and reinforced test specimens during the 9th cycle of the applied cyclic loading. It can be clearly seen that the normal effective stress dropped more rapidly in case of the unreinforced sand, and it almost reached a final value of zero. Coir fibers delayed the reduction in the normal effective stress. Figure 8 shows the stress-strain response (hysteresis loops) of the tested materials during the 9th cycle of the applied cyclic loading. Hysteresis loops widened more rapidly in unreinforced sand compared to coir fiber-reinforced sands.

This indicates that coir fiber addition retarded the shear modulus degradation of the sands when subjected to undrained cyclic loading. The addition of coir fibers increased the liquefaction resistance, arrested shear deformations, and improved the performance of sands when subjected to undrained cyclic loading. It is found that increase in coir fiber content enhanced the beneficial effects on the response of sands. However, mixing fiber contents beyond 0.75% to achieve a homogeneous mixture is difficult because of the segregation and entanglement of coir fibers. Hence the fiber content of 0.75% is optimal for achieving a homogenous mixture with significant improvement in the response of sands for undrained cyclic loading.

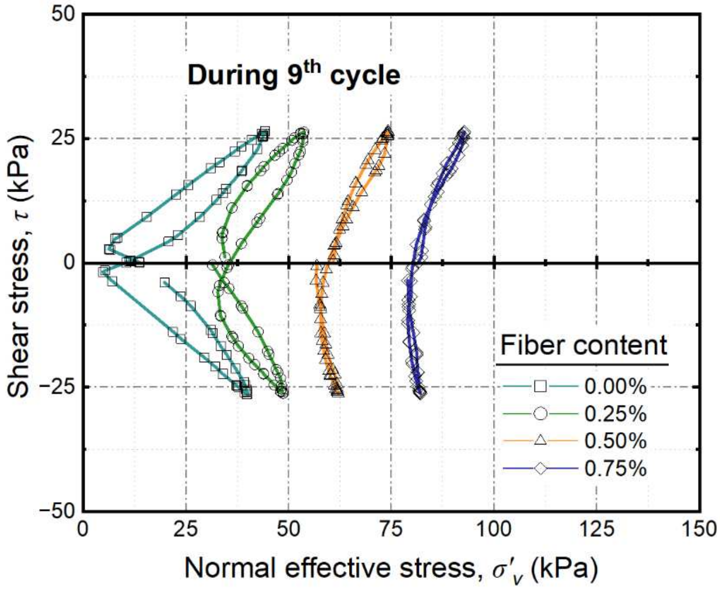

Figure 7. *Stress paths followed by the test specimens*

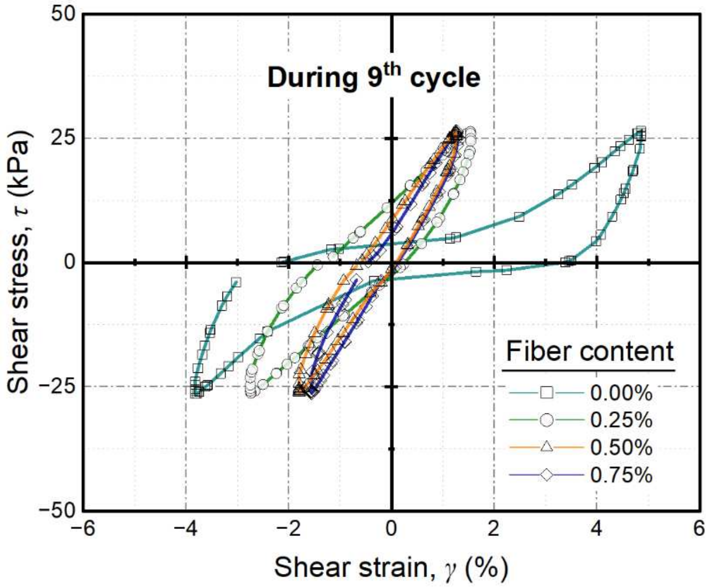

Figure 8. *Stress-strain response of the test specimens*

4 CONCLUSIONS

This study proposes and verifies the application of environmentally safe and eco-friendly natural coir fibers as a cheaper and sustainable alternative to conventional energy-intensive techniques that are being used for mitigating liquefaction in sands. A series of stress-controlled constant volume cyclic simple shear tests with an amplitude of 26 kPa and frequency of 0.20 Hz were performed on unreinforced, and coir fiber reinforced specimens with fiber contents of 0.25, 0.50, and 0.75% by weight of sand. Test results showed that coir fiber increased the liquefaction resistance of the sand. The liquefaction resistance increased further with the increase in fiber content. Unreinforced sand liquefied in 9 cycles. Whereas coir fiber-reinforced sand liquefied in 26, 40, and 65 cycles, respectively, for 0.25, 0.50, and 0.75% of coir fiber contents. A maximum of 622% improvement in the liquefaction resistance is obtained with the addition of 0.75% coir fibers to the sand. Also, coir fibers were found to arrest the shear deformations to a large number of cycles when compared to the unreinforced specimens. Test results suggest that coir fiber can be effectively used for mitigating liquefaction in sands. Adding coir fiber content of more than 0.75% and achieving a homogenous mixture is practically difficult as the segregation and entanglement of coir fibers occur beyond this fiber content. Hence 0.75% coir fiber content is optimal for all practical purposes to improve the response of sands subjected to undrained cyclic loads.

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