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Investigation of Sand-Tire Mixtures as Liquefaction Remedial Measure

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ABSTRACT: Previous large-scale earthquakes, such as 2010-2011 Canterbury earthquake sequence, have highlighted the impact of soil liquefaction in urban areas. To mitigate the damaging effect of liquefaction, ground improvement techniques, which involve reinforcing/improving the saturated sandy deposits, have been viable alternatives. For the purpose of better and more environmentally-friendly recycling methods, many researchers have examined the use of scrap tires as a new geomaterial. However, most results available in the literature have no information presented on the role of the size of the tire chips (or shreds) with respect to the undrained response of the composite soil. With the aim of providing alternative ground improvement method for the Christchurch rebuild, several series of undrained monotonic and cyclic triaxial tests were conducted on saturated specimens of sand-tire chips mixture. To achieve the best working performance under actual ground conditions, the tests were conducted on specimens prepared under a specified compaction energy and mix ratio between sand and tire chips by volume, but with different drying methods and tire chip sizes used. The results of both monotonic and cyclic tests showed that among the specimens investigated, large-sized tire chips which were oven-dried are the most effective, with higher undrained shear strength and liquefaction resistance.

1 INTRODUCTION

1.1 Background of worldwide scrap tires

The management of scrap tire has become a growing problem nowadays. Scrap tire is one of the main wastes, which is difficult to handle. Until early 1990s, the main treatment was through tire stockpiles on the field and this was used in many countries, resulting in many issues such public health, environment and pollution. In fact, because of the long-term durability of tires, it makes disposal almost impossible. Additionally, tires are thermal-set polymers, i.e. they cannot be melted or separated into their chemical components. In the late 1990s, however, many industries, such as chemistry, petroleum, and civil engineering among others, have started to reuse and recycle tire as a new resource, such as for oil, textiles, and filling materials (Clark et al. 1993).

Genan, the world largest tire recycling company, adopted the vision that "all scrap tyres in the world must be recycled in the environmentally and economically most beneficial way" (GBD 2012). Their research showed that the global number of cars would increase rapidly, accompanied by a large increase in the number of scrap tires. In general, about 13.5 million tonnes of scrap tires are being produced annually, with the United States producing 4.4 million tonnes, the European Union 5.7 million, and the rest of the world 5.7 million. Among the developing and developed countries, China and India have the largest demand for automobiles due to their current economic boom. Statistics indicate that in 2009, there were 187 million vehicles in China which produced more than 230 million scrap tires. Moreover, tire production took up to 70% of the total rubber consumption among hundreds of different rubber products in China (GRA 2014).

Based on the studies by the European Tire and Rubber Manufacture Association (ETRMA 2011), the recovery and reuse of scrap tires have been significantly improved in EU, although the annual cost for the scrap tire management was estimated to be in the order of 600 million Euro. In 2009, 18 of the 27

EU countries (plus Norway & Switzerland) recovered 90% or more of their annual used tire production. Moreover, 15 of these 18 countries recovered 100% while 6 countries attained between 80% and 90% recovery. Czech Republic was above 70% while 2 countries were still dependent on landfilling.

1.2 Ground improvement method

When an infrastructure is to be built at a certain location, the soil conditions under the ground are unknown until a site investigation is carried out. When the site investigation results indicate that the soil condition is not as strong as expected in terms of bearing strength, settlement or liquefaction resistance, engineers have to find the best solution to improve the ground condition. The conventional ground methods adopted in practice include preloading, vibro-compaction, stone columns, deep mixing and de-watering, to name a few. However, their effectiveness is reasonably good for a large-scale project, but the implementation cost of each method is enormously high. Additionally, these techniques can be directly applied to new projects, but hardly for sites with existing structures. Thus, a cost-effective ground improvement method is profoundly important for engineers to consider, preferably one which is applicable to both new design and existing structures.

Several researchers have shown that the mixture of sand and tire (either in chip, crumb or shred form) is a promising new ground improvement method. Studies on this composite material started in 1990s (Ahmed 1993) and the focus of research and application gradually shifted to the civil engineering industry in late 1990s (Edil & Bosscher 1994; Foose et al. 1996; Bosscher et al. 1997). More recently, researchers have introduced this technique as a liquefaction prevention method and results have shown that tire chips can suppress the generation of excess pore-water pressure when subjected to earthquake shaking (e.g. Uchimura et al. 2008; Kaneko et al. 2013; Neaz Sheikh et al. 2013); however, only a few relevant literatures are available and many of those studies are rather limited. There is no doubt that mixing tire chips to the sandy soil has the capability to reinforce the soil conditions, but the detailed application to practice has not been well guaranteed. Therefore, more detailed and specific verifications are essential before the technique is finally adopted in routine applications by the industry.

1.3 Objective of the study

The 2010-2011 Canterbury earthquake sequence (CES) had caused significant damage to the built environment due to the extensive liquefaction of the ground (e.g. Orense et al. 2011; 2012). With the aim of developing better and more environmentally-friendly recycling methods for tires and, at the same time, providing alternative ground improvement method necessary for the on-going Christchurch rebuild efforts, we investigated the undrained monotonic and cyclic behaviour of saturated Christchurch sands mixed with tire chips.

2 MATERIALS AND EXPERIMENTAL METHOD

2.1 Materials used

In this research, the test specimen was prepared using two types of materials: (1) clean sand (fines content $F_C < 6\%$) sourced from a site in Christchurch which liquefied following the CES; and (2) tire chips (TC). The tire chips were derived from used tires, with metals and fibres removed beforehand, and processed into smaller pieces. Two types of tire chips were used in the tests: one with maximum diameter of 1.18 mm (i.e. smaller particle size, referred to as TC_S); and another with maximum diameter of 3.25 mm (i.e. bigger particle size, referred to as TC_B). The density of the particles of tire chips is 1.15 g/cm^3, which is relatively light compared to conventional geomaterials. The mix ratio of sand to tire chips by volume was set at 6:4 because previous research (e.g. Hyodo et al. 2007; Okamoto et al. 2008) indicates that this is the optimal mix ratio where the effectiveness of tire chips becomes apparent. The grain size distribution curves and the relevant index properties of the materials used are shown in Figure 1 and Table 1, respectively. Note that the properties were not measured after the tire chips were oven-dried.

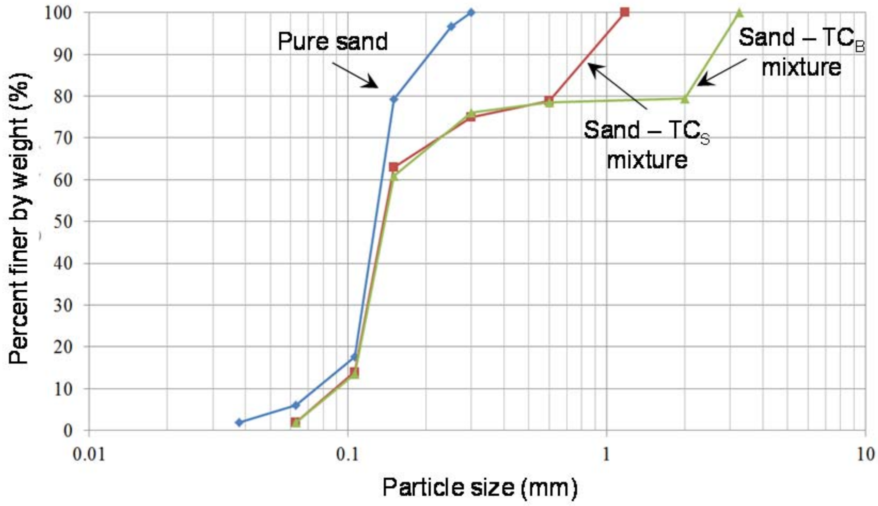

Figure 1. Particle size distribution curves for pure sand and sand-tire chips mixtures.

Table 1. Index properties of the materials used.

	Pure sand	Pure tire	TC$_B$ – sand mixture	TC$_S$ – sand mixture
G_s	2.67	1.15	2.06	2.06
e_{max}	1.08	1.51	0.71	0.91
e_{min}	0.67	1.22	0.38	0.45

2.2 Specimen preparation and experimental method

The tire chip-sand mixture specimens used for the undrained triaxial tests were prepared by moist tamping method. The tire chips were dried through two methods: exposing them to warm air to dry (called "air-dried") and, when re-using the samples after some tests, placing them in an oven with temperature set at 50^{O}C (called "oven-dried"). Note that the literature appears to suggest that the properties of tire chips will be changed at temperature above 40^{O}C; however, no clear evidence has been presented to support this. The dried tire chips and Christchurch sand were mixed at the prescribed mix ratio by volume. Water was added to the mixture to obtain a sample with initial water content w=20% after which the sample was thoroughly mixed again. Membrane was installed in the pedestal of the triaxial apparatus, and the mould 100 mm in diameter and 175 mm high was set up. The test specimen was prepared by placing the soil mixture inside the mould in five layers, with each layer compacted at a prescribed number of times by dropping an iron rammer from a prescribed height to control the compaction energy, E_C, which is given by the following expression.

$$E_C = \frac{W_R \cdot H \cdot N_L \cdot N_B}{V} \tag{1}$$

where W_R: the weight of rammer (kN); H: drop height (m); N_L: the number of layers; N_B: the number of drops per layer; V: the total volume of the specimen (m^3). In the experiments, the test specimens were prepared by adjusting H and N_B in order to obtain a compaction energy, E_C=26 kJ/m^3. This value of E_C was chosen such that the relative density of pure Christchurch sand specimen was approximately D_r=50%. Because water content has a large effect on the compaction characteristics of soils, a constant initial water content and compaction energy was adopted in the sample preparation.

To saturate the specimens of sand-tire chips mixtures, de-aired water was allowed to percolate after which a back pressure of 700 kPa was applied. This ensured that all specimens have B-value > 0.95. The saturated specimens prepared as outlined above were isotropically consolidated to a specific level of effective confining pressure, σ'_c, and undrained monotonic and cyclic tests were performed.

3 TEST RESULTS AND DISCUSSIONS

3.1 Monotonic tests

Firstly, the results of undrained monotonic triaxial tests on samples consisting of 60% sand and 40% TC_B (i.e. big-diameter tire chips) are discussed. Figure 2 shows the stress–strain relations and effective stress paths for pure sand and sand-tire chips mixture (both air-dried and oven-dried) under σ_c' =100kPa. In the figure, $p' = (\sigma_1' + 2\sigma_3')/3$ and $q = \sigma_1' - \sigma_3'$, where σ_1' and σ_3' are the vertical and lateral stresses, respectively. It is observed that under a constant deviator stress, q, the sand-tire chips mixture deform more than pure sand, as expected, with the air-dried mixture undergoing larger deformation. Moreover, the presence of tire chips in the sand results in marked decrease in undrained strength, with the air-dried TC_B-sand mixture having shear strength less than half of pure sand. While the pure sand specimen undergoes dilation from the start of shearing, the tire chip-sand mixture showed initial contraction (and pore water pressure development) followed by dilation, with the air-dried mixture showing larger contraction tendency. This is because of the elastic characteristics of the tire chips, which allowed for the compressive response of the mixture.

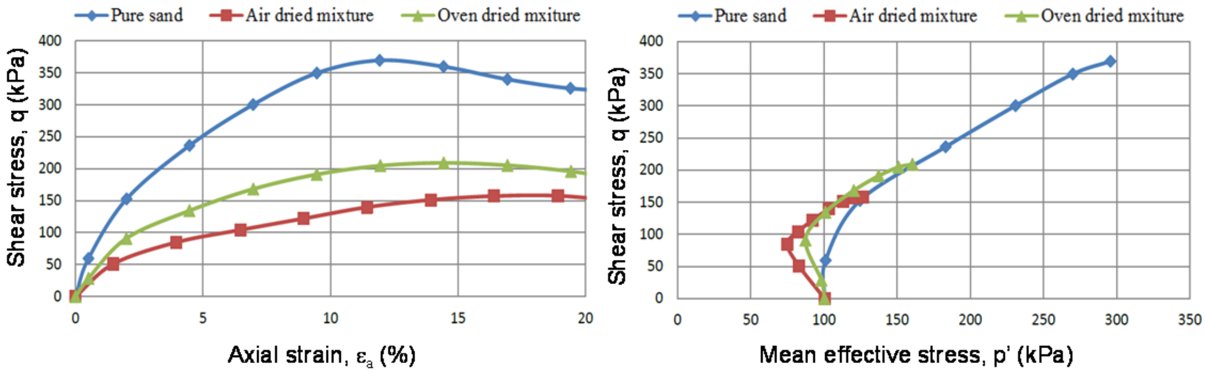

Figure 2. (a) Stress-strain relation; and (b) effective stress path for monotonic triaxial test under $\sigma_c' = 100$ kPa.

Comparing the peak friction angle, calculations indicate that both tire chip-sand mixtures have φ'_{peak}=33°, higher than that of pure sand (φ'_{peak}=31°), at least for the range of specimens tested. The introduction of tire chips into the sand matrix appears to increase the inter-granular friction between the particles, possibly because of the irregular surface texture of the tire chips.

3.2 Cyclic tests

Undrained cyclic triaxial tests were conducted on 5 different types of specimen: pure sand and sand-tire chips mixtures (both air-dried and oven-dried) using TC_S and TC_B tire chips. As mentioned earlier, all specimens were prepared under similar specific energy (E_C=26 kJ/m^3) and this is the key reference when comparing the test results. In the discussion below, the cyclic stress ratio is taken as CSR=$q/2\sigma_c'$.

Figure 3 compares the hysteresis loops and effective stress paths for pure sand and air-dried TC_S-sand mixture under CSR=0.16. It can be seen that under this level of applied shear stress, the development of axial strain and generation of excess pore water pressure are faster for the mixture. Note too that while the stress-strain relation for pure sand shows the “butterfly loop” typical of geomaterials, the relation for the mixture is more elliptical – an indicator of the visco-elastic contribution of the chips.

On the other hand, Figure 4 compares the hysteresis loops and effective stress paths for pure sand and oven-dried TC_S-sand mixture under CSR=0.20. For this level of CSR, the development of axial strain and generation of excess pore water pressure are faster for pure sand when compared to the mixture. While pure sand undergoes liquefaction (i.e., large deformation and high excess pore water pressure) in about three cycles, it took the mixture about 18 cycles to develop large axial strain with no total loss in effective stress, indicating that the oven-dried mixture is more resistant to liquefaction than pure sand, which in turn is stronger than the air-dried specimen (as discussed above). Again, the hysteresis loop for the tire chip-sand mixture shows more elliptical shape than that of pure sand.

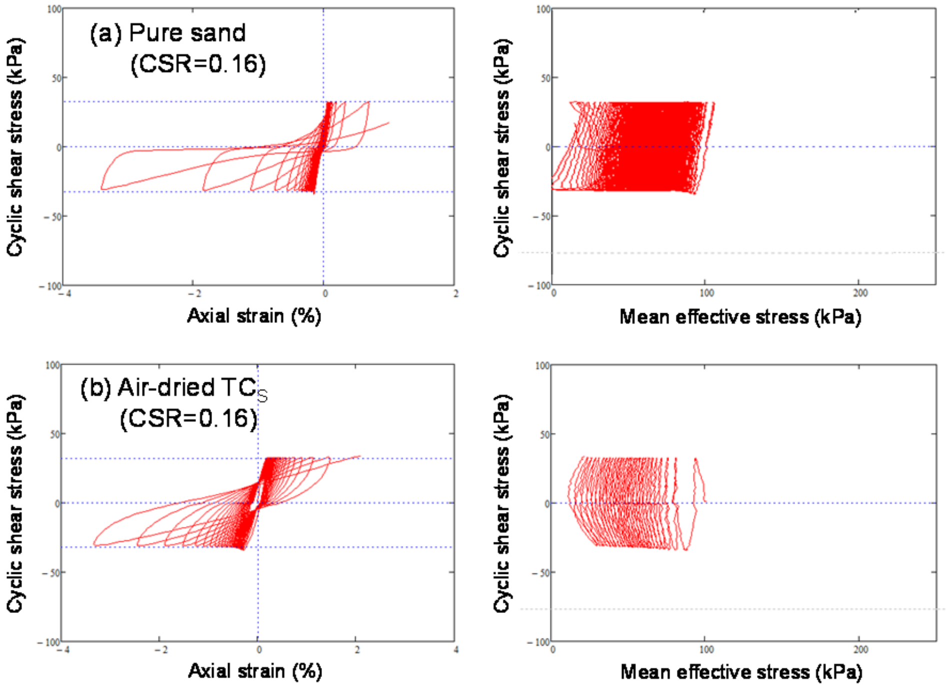

Figure 3. Stress-strain relation and effective stress path for: (a) pure sand; and (b) air-dried TC$_S$-sand mixture.

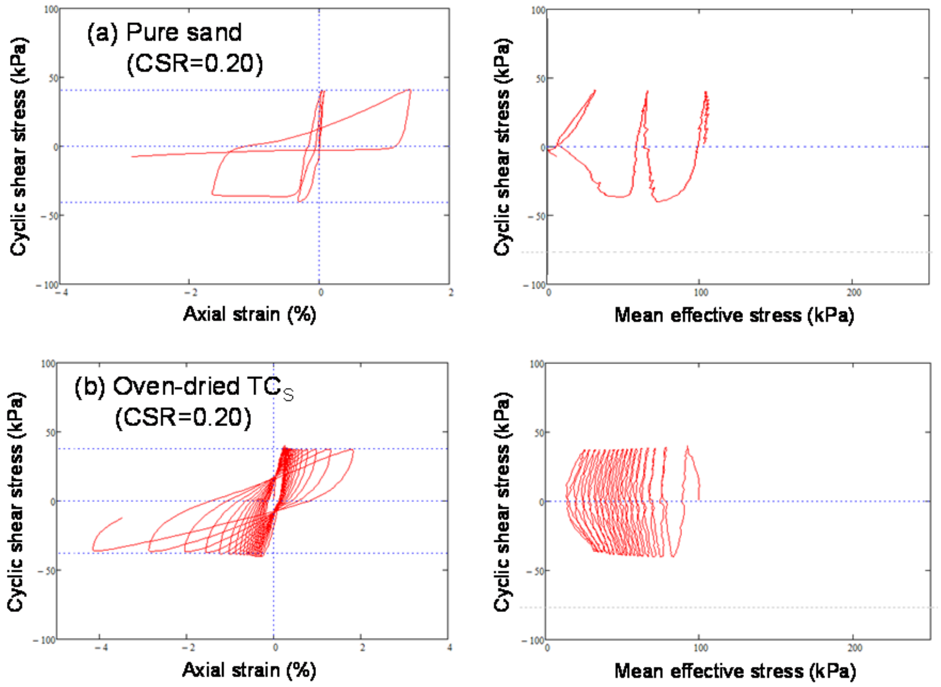

Figure 4. Stress-strain relation and effective stress path for: (a) pure sand; and (b) oven-dried TC$_S$-sand mixture.

The liquefaction resistance curves, defined in terms of the number of cycles required for the specimen to undergo double amplitude axial strain, ε_{DA}=5% for a given cyclic stress ratio, $CSR = q/2\sigma'_c$, for all the specimens tested are illustrated in Figure 5. Due to the limited number of samples, the curves for the sand-tire chip mixtures were assumed to be parallel to that of pure sand, although more tests are required to confirm this assumption.

As can be seen from the figure, the liquefaction behaviour of the sand-tire chip mixture is affected significantly by the drying method employed. In general, the liquefaction resistance curve obtained for the air-dried sand mixture plots lower than that of oven-dried sand mixtures. Moreover, sand specimens mixed with the bigger diameter tire chips (TC_B) appear to have higher liquefaction resistance than the ones with smaller diameter tire chips (TC_S).

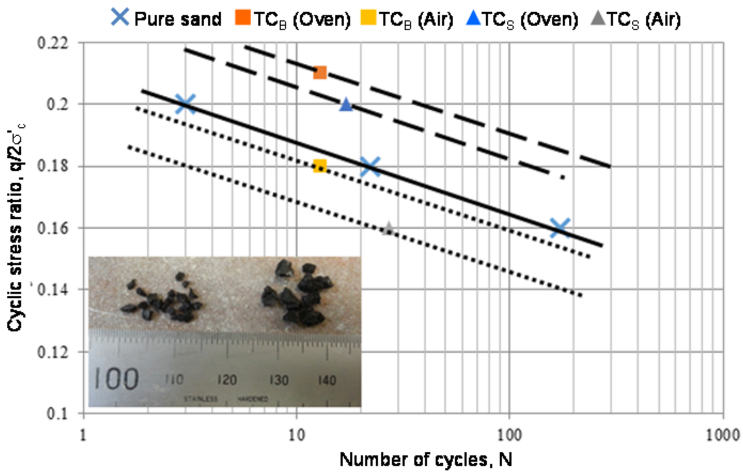

Figure 5. Liquefaction resistance curves corresponding to ε_{DA}=5% and $\sigma_c' = 100$ kPa.

3.3 **Discussion**

The tests discussed herein were performed on specimens prepared using a specified compaction energy, which was determined such that pure sand specimen would have initial relative density, D_r=50%. For example, the specimen of air-dried sand-TC_B mixture has D_r=38% while the oven-dried sand-TC_B mixture has D_r=62%. Therefore, air-dried sand-tire chip mixtures are relatively looser than pure sand and therefore they have lower liquefaction resistance. It can be said that considering the mix ratio investigated herein, the compaction energy delivered to the specimen was not transmitted well because the tire chips, being an elastic material, did not allow it to densify in the same way as pure sand. The presence of such elastic and highly deformable material within the soil matrix also affected the cyclic response, and large deformation, a manifestation of liquefaction, occurred earlier in the mixture as compared to pure sand.

An interesting artefact of the experimental results is the role of oven-drying in the liquefaction behaviour of sand-tire chips mixture. The high temperature (> 40°C) the tire chips were subjected to has changed their properties. Figures 6 and 7 illustrate the state of the mixture after air-drying and oven-drying, respectively. When water is poured into the air-dried sample (Figure 6), water infiltrates into the mixture easily; on the other hand, the oven-dried sample appears to be covered by a water-proofing material which did not allow water to infiltrate the mixture. When oven-dried to 50°C, oil began to ooze out of tire chips and, as drying continued with time, the oil covered both tire chips and sand particle surface, essentially converting them from initially hydrophilic (i.e. strong affinity to water) to hydrophobic (i.e. water-repelling). When mixing water with hydrophilic material, voids among the particles can lock the water firmly because of their capillarity property. However, for hydrophobic material, water can easily move in and out of the voids and therefore when subjected to the same compaction energy and water content, water in the oven-dried specimen can easily squeeze out, resulting in denser specimen.

Another observation is that for the same drying method, sand mixed with large diameter tire chips shows higher liquefaction resistance than the mixture with small chips. Figure 8 shows a schematic drawing of the failure within the matrix of the mixture created by shear force application. Unless the tire chip breaks, theoretical Path 1 crossing through the tire chip is unlikely to be triggered since Path 2 offers less resistance because tire chip has stronger breaking strength. Subsequently, the longer Path 2 that is reinforced by large tire chip size needs a larger force in order to overcome the resistance, resulting eventually in higher liquefaction resistance. Such longer path reflects the interlocking between tire chips and sand particles; the stronger interlocking is the main factor inducing higher liquefaction resistance for sands reinforced with big tire chips.

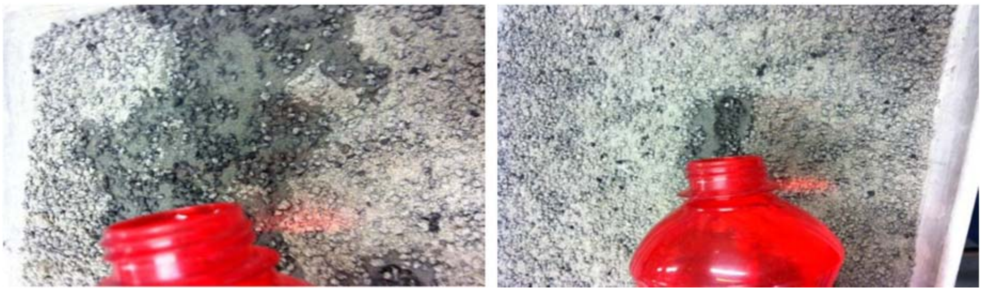

Figure 6. State of air-dried sample during the mixing process.

Figure 7. State of oven-dried sample during the mixing process.

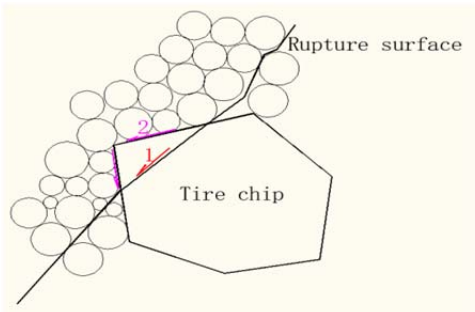

Figure 8. Illustration of interlocking mechanism.

Finally, as observed from the test results, air-drying the tire chips would not result in improvement of the liquefaction resistance of sandy soils, at least within the limits of the tests performed herein. The tire chips content adopted may not be sufficient enough to result in significant interlocking. Moreover, the tire chip sizes used in this research may not be large enough to influence the cyclic behaviour of the sand. More tests are required to investigate the role of tire chip size and mix proportion in affecting the shear and deformation characteristics of sand-tire chips mixture.

4 CONCLUSIONS

Monotonic and cyclic undrained triaxial tests were conducted to investigate the shear strength and liquefaction characteristics of sand-tire mixture under a specified mix ratio of 60% sand and 40% tire chips by volume and prepared under constant specific compaction energy 26 kJ/m^3. The following are the main conclusions of this study:

- Tire chips are elastic material and they absorb less energy during compaction. Therefore, under the same compaction energy, air-dried tire chip mixtures have lower relative density and consequently, less degree of interlocking than pure Christchurch sand. The addition of tire chips into the sand at the adopted condition did not result in improved strength; rather, the shear strength and liquefaction resistance generally decreased.

- The results from monotonic tests confirmed that the compressibility of the sand-tire mixture is much higher than that of the pure sand, although they have generally larger peak friction angles.
- The liquefaction resistance of pure sand is higher than that of the sand-tire mixture prepared using air-drying method, but lower than that prepared by oven-drying method. Additionally, the liquefaction resistance of the sand-tire mixture tend to increase with increase in the tire chip size, indicating that the size and the condition of the tire chips play significant role in the liquefaction behaviour of tire chips-sand mixture.

More tests, such as those which consider other mixing ratios and tire chip sizes (or the possibility of using tire shreds) need to be performed to further investigate the applicability of tire chips are liquefaction countermeasure.

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