

DYNAMIC BEHAVIOUR OF SHREDDED RUBBER SOIL MIXTURES

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ABSTRACT

Residential buildings in high population density areas are seismically vulnerable to the action of major seismic events. The high cost and technical difficulties related to the use of advanced seismic isolations systems precludes its installation to low-to-medium rise buildings in the developing world. The environmental issues attributed to the stockpiling of scrap tyres and its use as tyre derived fuel has led research to explore viable recycling solutions in civil engineering projects. Several authors have proposed a novel seismic isolation system by mixing recycled rubber tyres with sand particles. However, research to date has been mainly focused on the dynamic properties of this mixture in the low-to-medium strain range at a specific loading cycle. This paper has studied the dynamic properties in the medium-to-large shear strain amplitude (0.05%-1%) of shredded rubber-soil mixtures (ShRm). The influence of the rubber percentage, size ratio, shear strain amplitude and number of cycles have been evaluated. The shear modulus decreases at larger rubber percentages and strain amplitudes. The damping ratio has been found to increase by adding 10% rubber but it decays at greater rubber percentages. The results show that the dynamic properties of ShRm are affected by the number of cycles at the strain amplitude assessed in this paper. However, the addition of up to 30% of shredded rubber particles increase significantly the resilience of sand particles against cyclic loading leading to a reduction in the stiffness and damping degradation.

Keywords: Rubber-soil mixtures, Damping ratio, Shear modulus, Cyclic triaxial test, Large shear strains

1. INTRODUCTION

Since 1990, 17 major earthquakes ($M > 7.0$) occur every year and some 27,000 people die in seismic events annually (Spence, 2011). The majority of these casualties occur in high population density urban areas in the developing world mainly due to collapse of residential buildings which are seismically vulnerable. Since late 1960s, seismic isolation mechanisms have been developed for protecting structures against seismic motions. The use of rubber as base bearings is a commonly adopted solution due to its capacity to mitigate the impact of strong ground motions (Tsang, 2008). However, this sophisticated seismic isolation method is expensive and presents major technical difficulties related to the design and installation, precluding its installation to low-to-medium rise buildings in earthquake-prone developing countries (Tsang et al., 2012; Xiong & Li, 2013). Therefore, there is a need to develop low cost, easy deployment techniques for mitigation of earthquake damage in developing countries unable to afford the high cost of advanced base seismic isolations systems.

About 3.6million tonnes of scrap tyres are produced annually in Europe. Despite transport costs and environmental issues, there has been a gradual growth in the amount of tyres used in Europe in the last ten years reflecting the predisposition of the population to use the personal transport (ETRM, 2011). The actions taken under the legislation approved by the European Union (2006) have fostered a sustainable economy regarding the production of rubber tyres reaching a 96% of recovery rate in 2015.

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However, 50% of that recovery stems from using scrap tires as tire derived fuel (TDF) leading to the generation of additional dangerous products for human health, i.e. toxic gases which contain heavy metals, incineration ashes or carbon dioxide (ETRMA, 2015). Alternatively, there has been a growing interest in using recycled tyres as a geomaterial combined with construction materials including sand particles in civil engineering applications where significant amount of rubber can be used, i.e. lightweight construction material, backfill in retaining walls, and soil reinforcement (Lee et al., 1999; Youwai and Bergado, 2003). However, only 3.7% of the recovered tyres in Europe are currently being used in civil engineering projects (ETRMA, 2015). New markets are necessary to provide alternative routes for recovered tyres and thus diminish health risks attributed to the use of this material as a TDF. The use of scrap tyres combined with sand, referred to as rubber-soil mixtures (RSm), has been proposed for the mitigation of seismic disturbances in various investigations (Hazarika et al. 2008; Tsang, 2008; Kaneko et al., 2013a). Anastasiadis et al. (2012) and Senetakis et al. (2012) conducted more than one hundred experiments by using resonant column tests to evaluate the dynamic properties of RSm at a rubber range between 0% and 35% by mass. These investigations confirmed the results of previous research (Feng and Sutter, 2000; Senetakis et al., 2011) that RSm have a lower shear modulus and higher damping ratio than sand alone. However, most of these investigations are limited to the evaluation of the dynamic properties of RSm in the range of low to medium strain amplitude. On the other hand, Pistolas et al. (2017) evaluated the damping ratio of rubber-gravel and rubber-sand mixtures with cyclic triaxial equipment and it showed a reduction in the damping ratio with adding more than 20% rubber by mass at medium-to-large strains. Moreover, most contributions have only evaluated the dynamic properties of RSm at a specific loading cycle without considering the effect of the number of cycles on the dynamic behaviour of RSm. Major past earthquakes have reflected that the ground soil may be subjected to large shear strain amplitudes (i.e. $>0.05\%$) for a duration above ten seconds (Suetomi and Yoshida, 1998; Kumar and Krishna, 2013). Despite evidence suggesting that G and D are influenced by the number of cycles, only Mashiri et al. (2016) established that RSm exhibit stiffness and damping degradation when subjected to up to fifteen strain controlled cycles in the range of large deformations (i.e. 0.1-0.5%). Nevertheless, Mashiri et al. (2016) together with most of the previous investigations are fundamentally focused on assessing the dynamic behaviour of RSm using irregular scrap tyres (i.e., crumbs or chips) with a d_{R50}/d_{S50} ratio lower or higher than unity. Research needs to be conducted on RSm by including similar rubber and sand particles to understand the fundamental dynamic response of the mixture in the range of large deformations when subjected to longer periods of time in order to design resistant earthquake structures.

The objective of this paper is to evaluate the dynamic response experienced by RSM with the inclusion of refined rubber particles during strong earthquake events (i.e. peak shear strains above 0.05%). These samples consist of shredded rubber particles and stiff sand particles with a nearly similar grain size (i.e., $d_{R50}/d_{S50} \approx 1.5$) denoted as shredded rubber-soil mixtures (ShRm). This study seeks to determine the variation in the shear modulus and damping ratio of RSM in terms of rubber percentage by subjecting samples to strain controlled cyclic triaxial tests changing shear strain amplitude and number of cycles.

2. EXPERIMENTAL PROGRAMME

2.1 Materials

The material used in this study is a mixture of sand and reprocessed tyre rubber in granular form. The sand is coarse rounded to sub-rounded Leighton Buzzard sand. The average particle size is $d_{S50}=0.85$ mm and the coefficient of uniformity $C_u=1.27$. The specific gravity is $G_s=2.68$ determined by Cavallaro et al. (2001). The particle size distribution of Leighton Buzzard sand (LBS) is illustrated in Figure 1a. The granular rubber is obtained from car tyre sidewalls. Once all steel belts are removed, the rubber is devulcanised and subsequently mechanically shredded to the desired particle size range. The granular rubber has an average particle size $d_{R50}=1.3$ mm (Figure 1a) and it is classified as rubber fines according to ASTM 6270-12. These rubber fines exhibit the shape of small shreds particles (Figure 1b) thus these are going to be denoted shredded rubber (ShR) henceforth. The specific gravity of ShR is 1.12 as stated in previous investigations (Edil and Bosscher, 1994; Sheikh et al., 2012). Hence, shredded rubber sand mixtures (ShRm) used in this paper present a nearly similar size ratio with a $d_{R50}/d_{S50} = 1.53$. The initial

void ratio after consolidation exhibited by sand specimens is 0.62 whereas ShRm present a void ratio equal to 0.73. When expressed as an equivalent void ratio, based on the assumption that rubber grains possess very low shear stiffness (Feng and Sutter 2000, Anastasiadis et al., 2012, Pistolas et al., 2017), the void ratio increases with adding greater gravimetric proportions of rubber to the mixture obtaining 1.19, 1.79, 2.51 corresponding to 10%ShRm, 20%ShRm and 30%ShRm respectively.

2.2 Equipment

A pneumatic controlled cyclic triaxial (CT) testing apparatus manufactured by Wykeham Farrance was employed to conduct the experimental investigation and evaluate the dynamic properties of ShRm at large strains. The operational frequency range of the CT equipment is between 0.01Hz and 10Hz. The apparatus consists of a 50kN capacity loading frame with a pneumatic actuator that provides a double amplitude axial displacement of 25mm (+/- 12.5mm). A submersible load cell attached to a ram in order to measure static or dynamic loading. A linear variable differential transformer (LVDT) transducer is integrated in the actuator which is able to monitor precisely displacements of 0.001mm. In addition, three standard pressure transducers are contained in the equipment to measure the variation in cell pressure (CP), pore water pressure (PWP) and back pressure (BP).

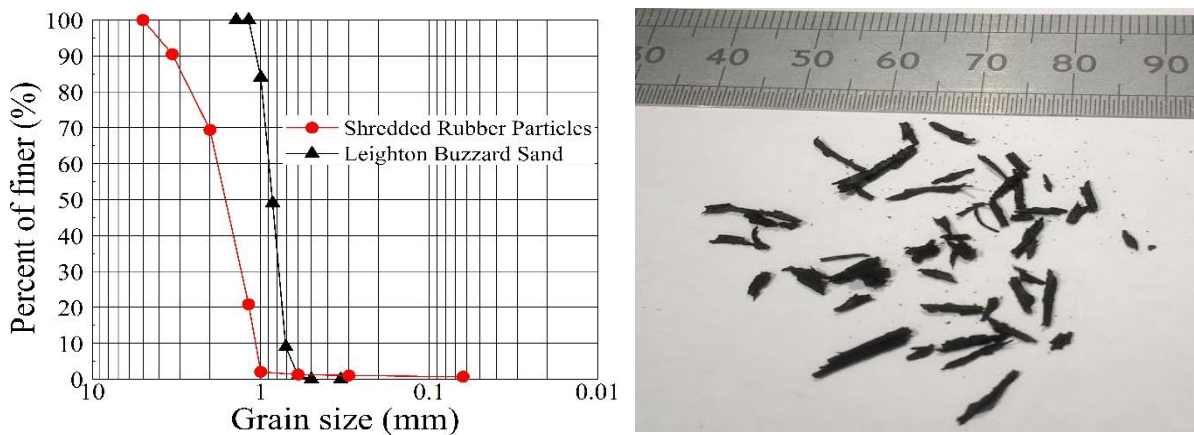


Figure 1. a) Sieve analysis of rubber particles and Leighton Buzzard sand b) Image of shredded rubber particles

2.3 Methods

All samples were formed in a cylindrical mould of 50mm diameter and 100mm height. Two sample preparation methods were employed for the construction of sand and ShRm specimens: dry pluviation and hand spooning respectively. Each specimen was prepared in four layers. Dry sand particles were poured through a cone funnel into the specimen mould to form sand specimens. Subsequently, sand particles and different inclusions of rubber, depending on the rubber percentage, were mixed together and carefully spooned into the cylindrical mould. To avoid segregation of RSM, a 2.5% moisture content was introduced to each specimen being mixed uniformly. A vacuum pressure of 10-15kPa was applied to support the specimens. The next step was to apply 20-25kPa of cell pressure. Then a water flow was introduced from the PWP valve, circulated through the sample and finally extracted using the BP valve. A combination of gradual increases in CP and BP were then performed to attain the saturation of the samples whilst maintaining a differential pressure of 15kPa. When Skempton pore-pressure parameter $B (= \Delta U / \Delta \sigma)$ reached a value over 95% the samples were considered to be saturated. After the saturation was completed, the samples were consolidated isotropically. The current programme is restricted to a single confining pressure at 100kPa.

2.4 Test programme

The experimental investigation consisted of 16 consolidated undrained cyclic tests on ShRm. Soil specimens were prepared under saturated conditions adding different amounts of ShR (0, 10, 20 and

30% by mass) to Leighton Buzzard sand and varying cyclic shear strain amplitudes (0.05, 0.1, 0.2 and 1%). Undrained cyclic tests were conducted at a constant confining pressure of 100kPa. In each test, 20 cycles with the same confining pressure and stress amplitude were applied on the sample under a strain controlled condition, denominated as strain controlled cycles (SCC), maintaining 1Hz of frequency.

3. RESULTS AND DISCUSSION

The dynamic properties of a soil (i.e. G and D) can be evaluated by considering a specific hysteresis loop out of all the cyclic loads applied to the material using the cyclic triaxial equipment. Shear modulus (G) represents the stiffness of the soil and damping ratio (D) is defined as the ratio between the energy dissipated in a loading cycle and the maximum elastic energy stored during the cycle. These two properties characterise the dynamic behaviour of soil materials. As reported by Kumar et al. (2017), different hysteresis loops have been used to determine the value of the dynamic properties ranging from the 1st to the 10th cycle (Nakhaei et al., 2012; Ehsani et al., 2015) based on the assumption that the hysteretic loop remains symmetrical up to the 10th cycle (Kokusho, 1980). With rubber inclusions, there appears to be a greater need to allow the loading platen to bend into the sample. Hence, the first loop is ignored in this study and instead the 2nd hysteretic loop has been chosen to evaluate G and D curves for ShRm. The variation in D and G have been assessed with modifying material aspects (sec 3.1 and 3.2) and test conditions (sec 3.3-3.5).

3.1 Effect of rubber inclusions on dynamic properties of ShRm

The effect of the rubber inclusions on the dynamic behaviour of ShRm when subjected to large strains is illustrated in Figs. 2a & 2b. Figure 2a shows the variation in the shear modulus and Fig. 2b depicts the damping ratio for ShRm at different shear strains (0.05, 0.1, 0.2 and 1%) when introducing various rubber percentages (0, 10, 20, 30%). Figure 2a shows that the shear modulus decreases with the addition of larger percentages of rubber at $\gamma=0.05$, 0.1 and 0.2%. The decay of G is most pronounced with the addition of 10%ShR and then the rate of reduction decreases with the inclusion of 20%ShR and 30%ShR. For $\gamma=0.2$ and 1%, it can be observed that the differences in G between 10%, 20% and 30%ShRm decrease significantly, compared to the values obtained at $\gamma=0.05\%$, exhibiting a nearly similar shear modulus at $\gamma=1\%$. Hence, stiffness in sand and 10%ShRm degrade with a higher rate than 20% and 30%ShRm leading to an state where 20%ShRm shows a higher value of G followed by 30%ShRm and 10%ShRm at $\gamma=1\%$. The common explanation for this behaviour is based on the argument that the addition of greater rubber inclusions reduces the degradation of the soil stiffness as a consequence of the high deformability conferred by rubber particles.

In terms of damping ratio, Figure 2b shows that 10% ShRm exhibits greater values than the rest of ShRm for all strain levels in addition to the substantial increase in D of sand particles when adding up to 30%ShR at $\gamma=0.05\%$. These results demonstrate the improvement in the damping capacity of sand with the inclusion of rubber particles mentioned in previous investigations (Nakhaei et al., 2012; Mashiri et al., 2016). This may be explained by the hypothesis that damping in rubber/soil mixtures is attributable to friction between particles contacts and the deformation of the particles. Due to the high stiffness of sand particles, the energy dissipation in sand particles is a result of frictional losses at the interparticle contacts whereas the energy dissipated in rubber particles is due to the deformation of highly elastic particles (Feng and Sutter, 2000). Nevertheless, it is found in Figure 2b that the addition of greater gravimetric proportions (i.e. 20% and 30%) causes a significant and progressive reduction in D at all strain levels presenting lower values than 10%ShRm. This may be attributed to the fact that damping obtained from the predominant friction between stiff particles (i.e. friction damping), added to the deformation of rubber particles found in 10%ShRm, contributes more to the overall damping than the damping originated through the particle sliding in sand specimens. On the other hand, the damping developed through the predominant deformation of elastic particles (i.e. deformation damping) in 20% and 30% ShRm present lower values than the overall damping friction found in sand specimens.

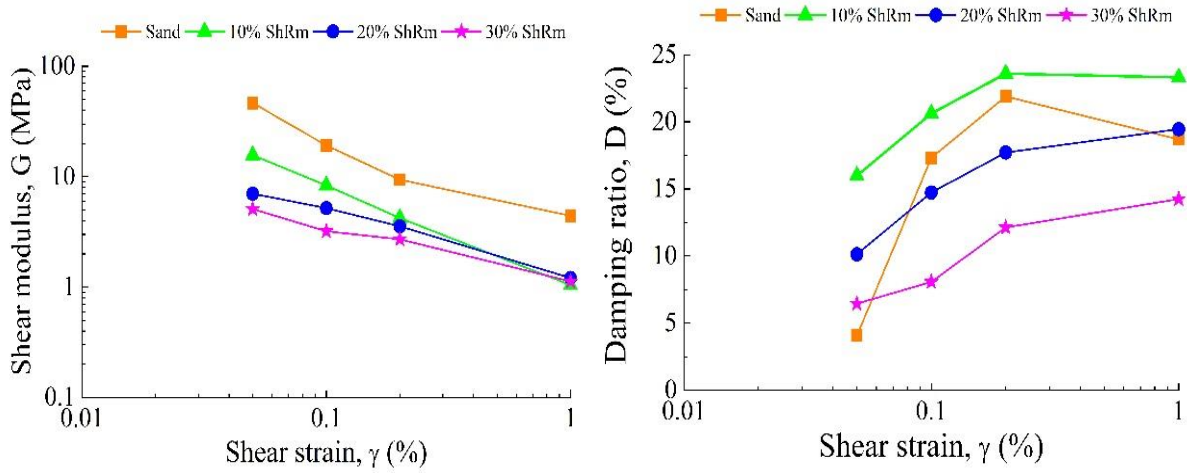


Figure 2. a) Shear modulus versus shear strain curve and b) Damping ratio versus shear strain curve

3.2 Effect of d_{R50}/d_{S50} ratio on dynamic properties of rubber-soil mixtures

Figure 3a shows the variation in G with shear strain shown by Mashiri et al. (2014). There are common features between the two investigations (Figure 2a & 3a) including rubber percentages introduced in the rubber-soil mixtures and shear strain amplitudes applied to the samples (i.e. $\gamma=0.1-0.5\%$). On the other hand, Mashiri et al. (2014) used big rectangular tyre chips as part of the mixture which presents a greater size than sand particles (i.e. $d_{R50}/d_{S50}>20$) differing notably from the nearly similar size ratio ($d_{R50}/d_{S50}\approx 1.5$) used in this investigation. It can be observed that the shear modulus decreases with the introduction of larger percentages of rubber and the difference in G between RSm drops steadily at large strains as stated for this investigation (section 3.1). On this occasion, the decay of the soil stiffness for all RSm reach an approximately similar value at $\gamma=0.4\%$, where 30%RSm exhibits a greater value than the lower rubber percentages, which contrasts with the results obtained in Figure 2a. However, the main difference between the two investigations is the higher soil stiffness exhibited by sand-tyre chip mixtures (STCh) evaluated by Mashiri et al. (2014) compared to all ShRm shown in Figure 2a at the strain range $\gamma=0.1-0.5\%$. The difference in the soil stiffness is more than double between both investigations at $\gamma=0.2\%$. For instance, 10% and 20% ShRm exhibits $G=4.2\text{MPa}$ and 3.6MPa in contrast to 10% and 20% STCh which shows $G=9\text{MPa}$ and 8.5MPa (Fig. 3a).

The gradual reduction in D with the addition of greater gravimetric proportions (i.e. 20% and 30%) shown in Figure 2b contrasts with the generalised improvement in the damping capacity of rubber-soil mixtures (RSm) for all rubber percentages reported by Mashiri et al. (2014) in Figure 3b. In this Figure, the damping ratio for different rubber percentages are depicted at a strain amplitude $\gamma=0.1-0.5\%$ and it can be observed that all RSm follow a similar trend with a positive evolution of D when adding larger rubber percentages. In addition, it is shown that the main improvement in D is achieved when introducing 10% rubber whereas the inclusion of larger percentages generates a marginal increase of the damping ratio showing slight differences in D between 10% and 30%RSm. However, it is found that the damping ratio exhibited by 10%ShRm in Figure 2b is much higher than all the rubber percentages presented in Figure 3b. These differences in the dynamic behaviour of the mixture can be mainly attributed to the number of contacts and the transition between the sand-like behaviour and the rubber-like behaviour which is in turn related to the size ratio and shape of rubber/sand particles evaluated as stated by Kim and Santamarina (2008) and Lee et al. (2010).

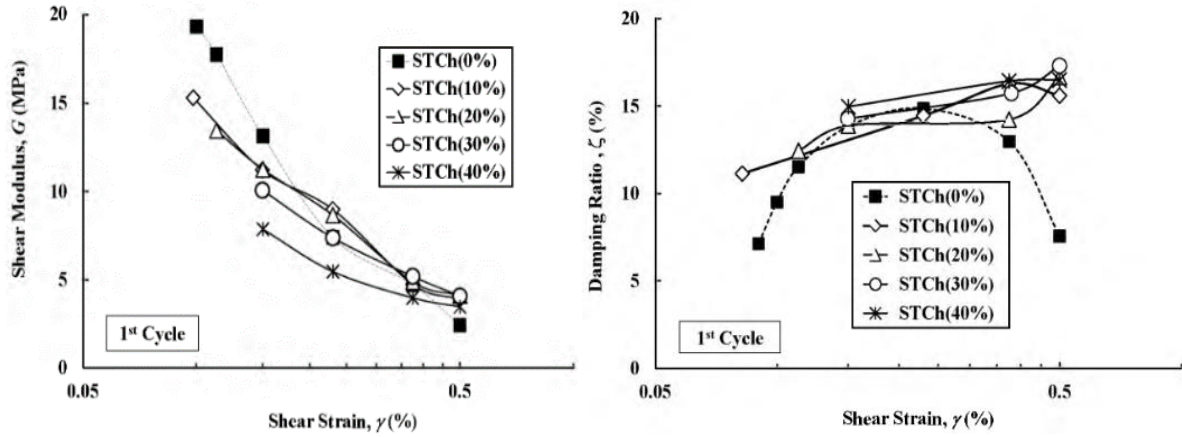


Figure 3. a) Shear modulus versus shear strain and b) Damping ratio versus shear strain (Mashiri et al., 2014)

3.3 Effect of shear strain on dynamic properties of ShRm

The effect of shear strain on the dynamic properties of RSm is also shown in Figs. 2a & 2b. Figure 2a shows that shear modulus decreases with the increase in the shear strain for all ShRm. This decay of G is more significant in sand particles passing from $G=48.5\text{MPa}$ at $\gamma=0.05\%$ to $G=4.8\text{MPa}$ at $\gamma=1\%$. On the other hand, the effect of the shear strain on the stiffness degradation of 30% RSm is lesser than on sand particles passing from $G=5.1\text{MPa}$ at $\gamma=0.05\%$ to $G=1.1\text{MPa}$ at $\gamma=1\%$. As previously mentioned, this can be explained based on the idea that the presence of greater rubber percentages confers the mixture a higher making it less susceptible to suffer stiffness degradation at shear strains $>0.05\%$.

Figure 2b depicts the increase in D of sand specimens under the action of larger strains until it reaches the maximum value at $\gamma=0.2\%$ and then drops at $\gamma=1\%$ as observed in previously published results (Kaneko et al., 2013b; and Mashiri et al., 2016). This marked reduction in D can be explained by loss of intergranular friction between sand particles as a result of the rapid accumulation of pore water pressure. In this Figure, it is observed a nearly similar progress in the development of damping properties at the different ShRm revealing a constant increase in D when subjecting ShRm to larger strains. This differs significantly from the irregular trend of D exhibited by sand particles where it is found that 20%ShRm presents a greater D than sand particles at $\gamma=1\%$ which can be due to the higher capacity of ShRm to withstand large deformations.

3.4 Effect number of cycles on dynamic properties of ShRm at selected shear strain amplitudes

The influence of the number of cycles (N) combined with the rubber percentage of the mixture in the shear modulus and damping ratio are presented in Figs 4a to 5b. Figs. 4a & 4b show the evolution of the shear modulus with N at $\gamma=0.1\%$ and 1% , respectively. It is found in Figure 4a that the shear modulus of all ShRm is not influenced by N and only sand is slightly affected by number of cycles, passing from $G=19.2\text{MPa}$ at $N=1$ to $G=14\text{MPa}$ at $N=20$. Hence, the results from this Figure reveal the shear modulus of both sand and mainly ShRm are relatively insensitive to the number of cycles at $\gamma=0.1\%$.

However, it can be observed in Figure 4b that the shear modulus of sand and 10%ShRm decreases significantly with N when subjected to strain controlled cycles at $\gamma=1\%$. In this occasion, sand suffers a shear failure after $N=13$ due to the combined effect of subjecting the sample to a very high strain for a certain amount of SCC. The rise in pore water pressure during undrained cyclic loading causes a reduction in the inter-particle contact which leads to the subsequent decrease in the effective stress resulting in the degradation of the soil strength (Kumar et al., 2017). Regarding 10% ShRm, there is an important stiffness degradation in the sample but the addition of this amount of rubber particles confers on the mixture a greater resilience against cyclic loading up to 20 cycles. This is more evident in 20% and 30%ShRm where the shear modulus remains nearly stable after 20 SCC at $\gamma=1\%$ which confirms the improvement in the resilience against cyclic loading when adding between 20% and 30% ShR.

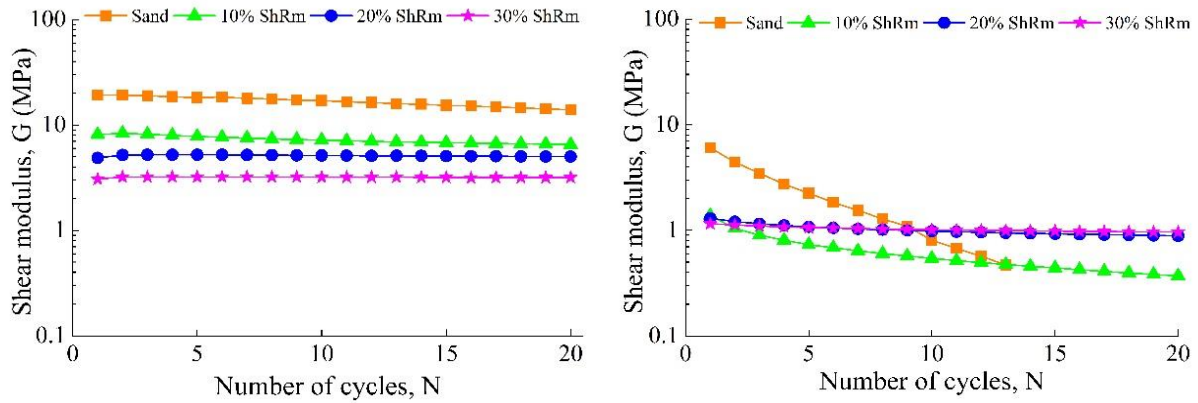


Figure 4. a) Shear modulus versus cycle number. $\gamma=0.1\%$ b) Shear modulus versus cycle number. $\gamma=1\%$

The damping ratio shows different behaviour in Figures 5a & 5b as a consequence of the effect of N and the amount of rubber on the damping ratio at $\gamma=0.1\%$ and 1% respectively. At $\gamma=0.1\%$, it can be observed that the damping ratio decreases gradually with the number of cycles regardless of the rubber percentage until $N=10$. The damping ratio for all ShRm continues decreasing with N after $N=10$, due to the particle rearrangement and the deformation of rubber particles, but the rate of degradation is observed to be lower between 10SCC and 20SCC. For instance, the damping ratio exhibited by 10%ShRm drops by 6% in the initial first cycles and after the rate of decrease decays significantly with a reduction of around 1% in the following ten cycles. On the other hand, the trend depicted by the sand specimen reveals that the damping ratio is slightly affected by N dropping only by 2% after 10SCC, mainly due to the rearrangement of sand particles, but then it starts to increase gradually until $N=20$. It can be observed that the sand specimen exhibits greater values of D than the rest of ShRm between $N=10$ and $N=20$. This is based on the argument that the low generation of pore water pressure is not affecting the sliding process of sand particles at this strain level ($\gamma=0.1\%$) and the particle rearrangement developed in the initial cycles is contributing to an improvement of the damping capacity. Consequently, the friction damping developed by sand particles is greater than the combination between the particle sliding and the rubber deformation developed by 10%, 20% and 30%ShRm after subjecting the specimens to 10SCC.

It is found in Figure 5b, when $\gamma=1\%$, that the damping ratio decreases progressively for all sand and ShRm until $N=20$. It can be observed that the rate of decrease is higher during the first ten cycles than in the following ten cycles as occurred in Figure 5a. However, the progressive decay of G and D exhibited by sand and ShRm specimens in this paper differ significantly from the assumption reported by Kokusho (1980) that the dynamic properties of soil materials are not affected by N after 10 cycles. This would suggest that the dynamic behaviour of soil materials remain influenced by N at a lower rate after 10 SCC when subjected to large amplitudes as shown by Mashiri et al. (2016). In this regard, it is remarkable the evolution in the damping ratio of sand specimen that decreases abruptly with N until reaching the shear failure at $N=13$. This is attributed to the rapid generation of pore water pressure and the loss of friction between sand particles as previously observed in Figure 4b. In contrast to the evolution in the degradation of the damping capacity for all ShRm shown at $\gamma=0.1\%$, the inclusion of greater rubber percentages diminishes the influence of the number of cycles on the decay of D at larger strain deformations (i.e. $\gamma=1\%$). Hence, it can be observed that the differences in the value of D between ShRm decreases with N as a consequence of the greater resilience exhibited by the mixtures when adding up to 20% and 30% shredded rubber particles. In this regard, it is found that the damping ratio exhibited by 10%ShRm drops by 10% after 20SCC whereas for 30%ShRm the value of D is slightly affected by N dropping by 3.5% at $N=20$. Despite the high D of the sand specimen at $N=1$, Figure 5b reveals the ability of ShRm to withstand large strain controlled deformations leading to a greater damping capacity than sand specimens after subjecting the sample to various SCC. Hence, the damping obtained through the combined interparticle friction, of both sand and rubber particles, and deformation of rubber particles in ShRm presents greater values than the damping developed from the predominant particle sliding in the sand specimen at $\gamma=1\%$ after 10 SCC. More experiments need to be conducted to

understand how the number of cycles affect the dynamic properties of RSm in the long-term in order to evaluate the increase in the endurance of sand samples with the addition of shredded rubber particles.

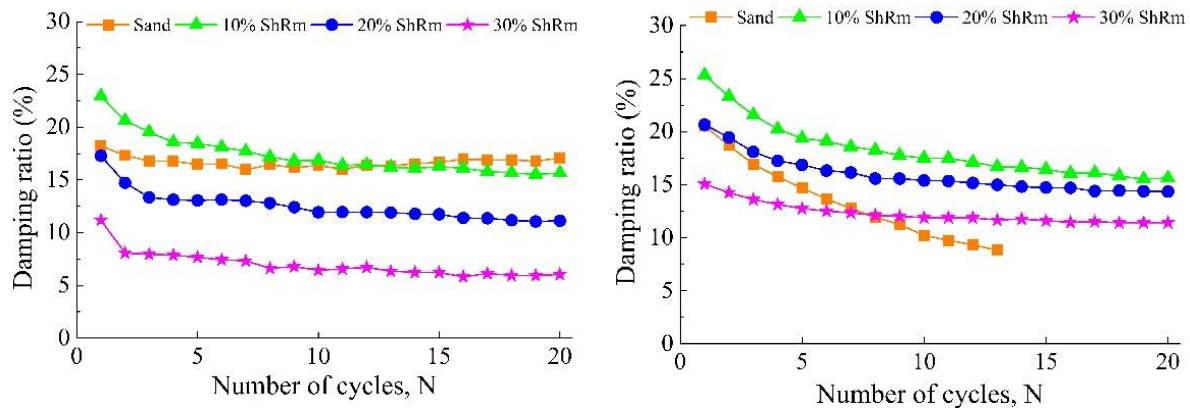


Figure 5. a) Damping ratio versus cycle number. $\gamma=0.1\%$ b) Damping ratio versus cycle number. $\gamma=1\%$

3.5 Effect of number of cycles on dynamic properties of ShRm at selected rubber contents

Figures 6a & 6b portray the influence of N and the shear strain on the shear modulus of sand and 20%ShRm. At an initial stage, the shear modulus decreases with the increase in the shear strain as previously stated (section 3.3). Figure 6a shows that the shear modulus remains constant at $\gamma=0.05\%$ and it is slightly affected by N at $\gamma=0.1\%$, however it suffers from a significant degradation at $\gamma=0.2\%$ and this is more severe at $\gamma=1\%$ where the sample fails after N=13. The gradual decay of G with N is attributed to the faster generation of pore water pressure that leads to a more rapid degradation of the soil stiffness when applying larger shear strains to sand specimens.

The stiffness degradation exhibited by sand specimens contrast considerably with the stability shown in Figure 6b by 20%ShRm. In this occasion, the shear modulus is not influenced by N after twenty cycles at $\gamma=0.05, 0.1$ and 0.2% and it decreases slightly at $\gamma=1\%$ passing from 1.3MPa in N=1 to 0.9MPa in N=20. The nearly constant shear modulus presented in Figure 6b by 20%ShRm after 20 SCC is different from the results reported by Mashiri et al. (2016) where the shear modulus of 20%RSm dropped by 5MPa in only 15 cycles at a lower shear strain amplitude (i.e. $\gamma=0.5\%$) and 69kPa confining pressure. This important decrease in the stiffness degradation with the use of shredded rubber particles may be attributed to the difference in the size ratio and shape between soft and stiff particles as discussed in section 3.2. Based on the results shown in Fig 6b, it can be established that the introduction of 20% ShR to sand particles with a nearly similar d_{R50}/d_{S50} leads to greater resilience of rubber-soil mixtures against cyclic deformations at large strain levels than the use of big tyre chips with a $d_{R50}/d_{S50} \gg 1$.

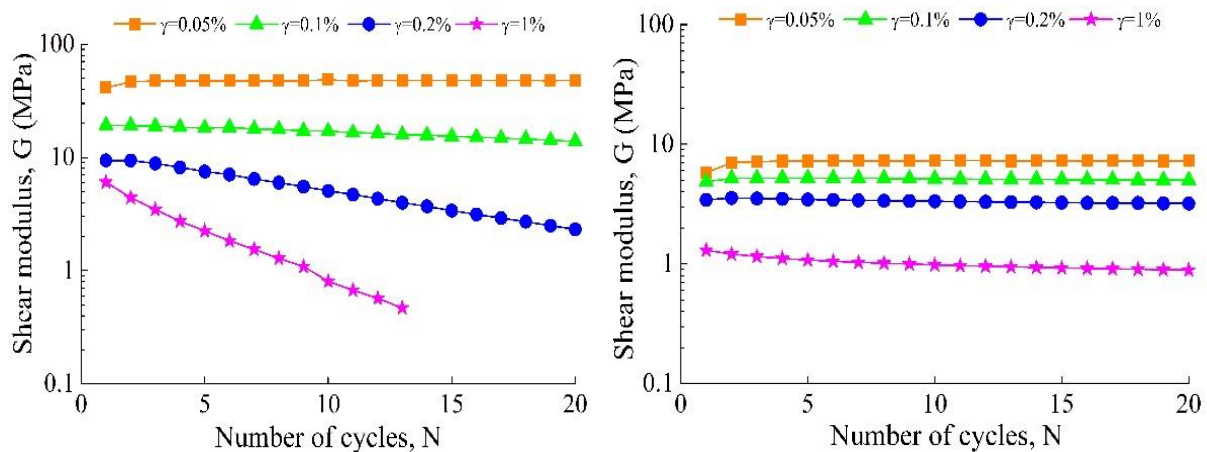


Figure 6. a) Shear modulus versus cycle number. Sand b) Shear modulus versus cycle number. 20%ShRm

The effect of N and the strain amplitude on the damping ratio of sand and 20%ShRm is illustrated in Figures 7a & 7b respectively. In sand specimen, the damping ratio remains nearly constant at $\gamma=0.05\text{-}0.1\%$ and it decreases with N at strains above 0.1% . On the other hand, it is found in Figure 7b that the damping ratio of 20%ShRm decreases with N for all strain amplitudes. In this regard, it is remarkable to observe that the damping degradation is more significant in 20%ShRm than in sand specimen up to 20 SCC at $\gamma=0.05\text{-}0.1\%$ whereas the opposite trend occurs at greater shear strains (i.e. $0.2\%\text{-}1\%$). This can be explained based on the argument that the deformation of rubber particles occurs since $N=1$ at $\gamma=0.05\text{-}0.1\%$ which is subsequently intensified by subjecting the mixture to a greater number of SCC, whereas the influence of N in the particle sliding of sand particles is marginal at these strain amplitudes. However, despite it can be observed that sand specimen exhibits a greater D than 20%ShRm at $\gamma=0.2\%$, the damping ratio decays more severely after 20SCC in sand specimens, as a result of the loss of friction between sand particles, than in 20%ShRm. This is more evident at $\gamma=1\%$ where it can be observed that damping ratio drops by 11.7% in sand specimen whereas the damping degradation is lower in 20%ShRm dropping by 6.3% after 20 cycles. This reveals the greater ability of ShRm when adding up to 20%ShR to withstand strain amplitudes $\gamma>0.1\%$ without suffering a significant damping degradation.

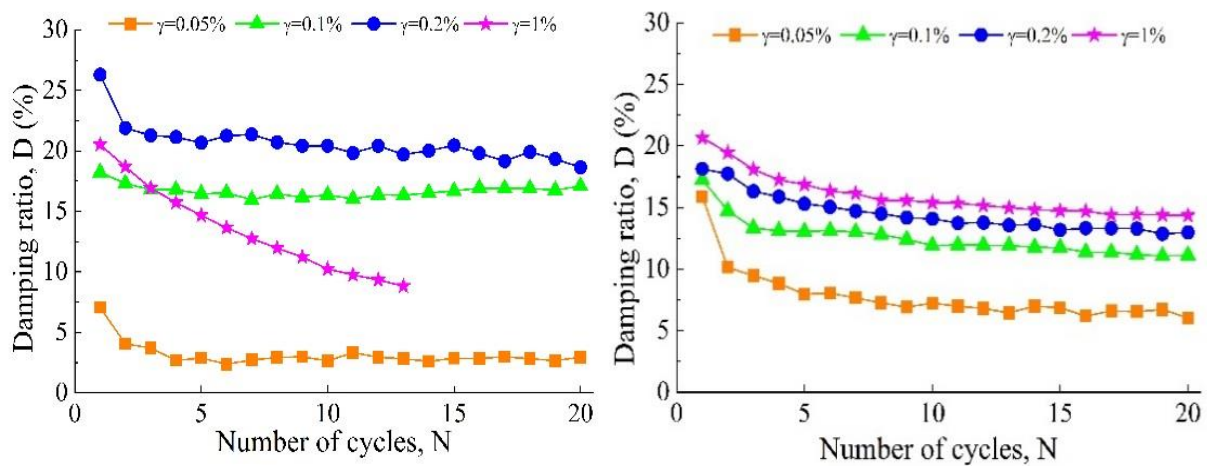


Figure 7. a) Damping ratio versus cycle number. Sand b) Damping ratio versus cycle number. 20%ShRm

4. CONCLUSIONS

In the present study the dynamic behaviour of shredded rubber soil mixtures (ShRm), characterised by the shear modulus and the damping ratio, has been assessed by means of cyclic triaxial experiments considering different rubber inclusions (0% , 10% , 20% and 30%), large strain amplitudes (0.05% , 0.1% , 0.2% and 1%) for a certain amount of strain controlled cycles (up to $N=20$).

It has been observed that the shear modulus of ShRm decreases with adding greater rubber inclusions and for larger shear strains but the differences in the soil stiffness between all ShRm decay at the shear strain range $\gamma=0.1\text{-}1\%$. Results from this investigation have shown that the addition of small shredded rubber particles with a nearly similar size ratio $d_{R50}/d_{S50}\approx 1.5$ result in lower shear modulus values for all rubber percentages than RSm reported in previous investigations (Mashiri et al., 2014). On the other hand, the influence of the number of cycles on the stiffness degradation of sand and ShRm increases with larger shear strain amplitudes and decreases notably with the introduction of greater rubber percentages. In this regard, the addition of between 20% and 30% shredded rubber particles with a nearly similar size ratio confers ShRm the ability to withstand up to twenty cycles at $\gamma=1\%$ without experiencing significant stiffness degradation. This differs from the rapid decrease in G observed in sand specimen which failed after 13 SCC and the lower stiffness degradation exhibited by 10% ShRm at $\gamma=1\%$. Consequently, the addition of up to 30% shredded rubber particles to sand particles with a $d_{R50}/d_{S50}\approx 1.5$ improve the resilience of sand particles against cyclic loading at large strains.

The damping ratio of ShRm is influenced by the percentage of rubber, size ratio between rubber and sand particles, number of cycles and shear strain amplitude. At $N=2$, it has been found that the damping ratio of sand specimens increases with the introduction of 10% ShR and decreases when adding between 20% and 30% ShR which is attributed to the shape of the rubber particles and the size ratio $d_{R50}/d_{S50} \approx 1.5$ presented in this paper. Moreover, the damping ratio of ShRm increases for larger strains in the range $\gamma=0.05-1\%$ whereas the sand reaches an optimum value at $\gamma=0.2\%$ and then it drops at $\gamma=1\%$. The number of cycles has different effect on the damping ratio of sand and ShRm depending on the amount of rubber and the strain amplitude. It has been observed that sand exhibits the highest damping ratio after 20SCC at $\gamma=0.1\%$ as a result of the higher degradation of the damping ratio experienced by ShRm. On the other hand, the addition of greater rubber inclusions leads to a notable decrease in the damping degradation of ShRm after 10SCC at $\gamma=1\%$, whereas the damping ratio of sand decreases rapidly in the initial cycles until it reaches the lowest damping ratio when it fails after 13 SCC. In this regard, the overall damping ratio of sand is higher than 20%ShRm after 20SCC in the range $\gamma=0.05-2\%$, however the damping ratio of 20%ShRm decreases with a lower rate than sand specimens at $\gamma>0.1\%$ due to the higher resilience exhibited by ShRm to cyclic loading at large deformations.

It has been found that the shear modulus and damping ratio of sand and ShRm are affected by the number of cycles more significantly in the initial ten cycles. However, the value of the dynamic properties exhibited sand and ShRm specimens decay steadily with N in the following next cycles. This result contrasts with previous assumptions which stated that the properties of soil materials remain constant beyond 10th cycle. Further investigation is necessary in this aspect to evaluate the long-term effect of N on the dynamic properties of ShRm when subjecting the material to large strain amplitudes.

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