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RECYCLED RUBBER DERIVATIVES FOR RESILIENT TRANSPORT CORRIDORS

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Abstract: The practical application of waste materials such as steel furnace slag (SFS) and coal wash (CW) is becoming more prevalent in many geotechnical projects. While the inclusion of rubber crumbs (RCs) from recycled tyres into mining waste mixtures of SFS and CW not only solves the problem of large stockpiles of waste tyres, it can also provide an energy-absorbing medium that will reduce vibration and track degradation. However, the high compressibility of rubber materials may subject track systems to increased deformation if they are included, which is why an engineering insight into the effect that rubber crumbs have on the cyclic deformation of SFS+CW+RC mixtures is imperative. In this study the influence of RC contents on the cyclic deformation, i.e. total and resilient deformation was investigated based on drained cyclic triaxial tests. The results reveal that with the inclusion of RC, the total axial strain increases, the volumetric strain becomes more contractive, and the resilient deformation and damping ratio of the SFS+CW+RC mixture increase while its resilient modulus and shear modulus decrease. By comparing with traditional subballast, the waste mixture with 10% RC was found to be the optimal waste matrix for subballast in view of controlling deformation while maintaining sufficient resilient modulus and stiffness.

1. INTRODUCTION

Coal mining and steel manufacturing are the two main industries in Australia, and although the country benefits economically, there are problems with the large stockpile of waste materials produced while they are being processed. These waste materials occupy large storage areas which create environmental issues such as air and water pollution. The problems caused by these waste materials become more severe because their production rate far exceeds the rate at which they are processed. Of these waste materials, coal wash and steel slag are the main waste products. In Europe, around 12 million tons of steel slag are produced annually, of which more than 35% is disposed (Motz & Geiseler, 2001), whereas in New South Wales (Australia) more than 2 million tons of coal wash (CW) is produced per year, which is about 25-40% of the total production of raw coal (Lu and Do, 1992; Rujikiatkamjorn et al., 2013). In the Wollongong region (Australia) alone, the production of SFS and CW can be more than 2mt per year (Chiaro et al., 2015). Moreover, the ever increasing stockpile of waste tyres is creating another critical environmental problem in both developed and developing countries due to the rapidly increasing number of vehicles. It is estimated that 13.5 million tons of scrap tyres (United States 4.4 million tons; European Union 3.4 million tons; and the rest of the world 5.7 million tons) are generated every year (Genan Business and Development A/S, 2012), while in Australia alone, more than 50 million tyre equivalent passenger units (EPU) of waste tyres are produced every year (Mountjoy et al., 2015). There is therefore an urgent to recycle these waste materials, and one efficient method is to utilise them in large civil engineering projects. The Environment Protection Authority of the state of New South Wales (NSW EPA, 2014) has approved the commercial use of these waste materials above and below the groundwater lever as no significant risk of environmental contamination would generated by those materials based on trace element concentration tests.

Although reusing these waste materials is environmental friendly and economical attractive, they cannot be used individually in civil engineering projects due to their adverse geotechnical characteristics such as the swelling potential of SFS, the particle degradation of CW, and the high deformation of rubber; this is why previous studies mixed them with other materials to reduce their detrimental effects. SFS is usually mixed with Class C fly ash, cement, asphalt or concrete to be used in landfill, unbound pavements, road construction, and the production of cement (Yildirim and Prezzi, 2015; Xue et al., 2006; Juan et al., 2011). Coal washery rejects have been used in civil engineering projects such as road embankments, reclamation fill, asphalt aggregates, concrete aggregates and subgrade fill (Indraratna et al., 1994; Malasavage et al., 2012; Heitor et al., 2016). Since rubber materials have good geotechnical properties such as low unit weight, high hydraulic conductivity, and high damping property (Senetakis et al., 2012; Zheng and Kevin, 2000), past studies blended rubber crumbs (RC) which are derived from waste tyres with soil and used it in road construction, ground erosion control, slope stabilisation, landfill construction, and seismic isolation foundations (Lee, et al., 1999; Li et al., 2016; Zheng and Kevin, 2000; Sheikh et al., 2013; Tsang et al., 2012). Moreover, to diminish the swelling potential of SFS and the collapse behaviour (particle degradation) of CW, past studies, i.e., Chiaro et al. (2013) and Tasalloti et al. (2015) mixed them together, and SFS+CW mixtures with a proper blending ratio has been successfully applied in port reclamation in Wollongong, Australia. Further, to extended the application of SFS+CW mixtures in dynamic loading projects, Indraratna et al. (2018) developed an energy absorbing layer for railway subballast by adding RC into the waste matrix.

Since excessive deformation will cause a hazardous impact to the foundation of a ballast railway track, there is some concern with using RC in a railway foundation, albeit it will increase the damping ratio and energy absorbing capacity of the waste matrix (Indraratna et al., 2018; Qi et al., 2018a). This paper will investigate the influence of RC content (R_b, %) on the deformation behaviour (i.e. total axial strain, total volumetric strain, and resilient strain) of SFS+CW+RC mixtures under cyclic loading. To achieve this goal a series of consolidated drained cyclic loading triaxial tests were carried out on SFS+CW+RC mixtures with SFS:CW=7:3, and $R_b = 0, 10, 20, 30, \text{and } 40\%$, and a comparison between the deformation of traditional subballast and the waste matrix will also be studied.

2. MATERIALS AND TEST PROGRAM

The source materials of SFS and CW are from ASMS (Australia Steel Milling Services) and Illawarra Coal Mining, respectively. The RC shredded from waste tyres used in this study is provided by Tyre Crumbs Australia, and three different sizes (0-2.3mm, 0.3-3mm, and 1-7 mm) were used. The particle size distribution (PSD) curves of SFS, CW, and RC are shown in Figure 1. The dry method was used to sieve SFS and RC, whereas the wet method was used for CW because some fine particles adhered to the larger particles. SFS and CW are classified as well-graded gravel with silty-sand (GW-GM), and well-graded sand with gravel (SW) (unified soil classification system), respectively, whereas RC is referred to as granulated rubber (ASTM D6270, 2008).

To prevent the influence of gradation, all the waste mixtures were mixed with the same PSD (the target PSD, Figure 1) chosen by Indraratna et al. (2018) on the basis of traditional subballast gradation in Australia. All the waste mixtures were blended by weight because by-weight percentage is more accurate during sample preparation (Edil and Bosscher, 1994; Zheng and Kiven, 2000). The blending ratio of SFS:CW was set as 7:3 because with this blending ratio the waste matrix would have less particle degradation and acceptable volumetric expansion while maintaining sufficient shear strength (Indraratna et al., 2018; Qi et al., 2018b; Qi et al. 2018c). The amount of RC in the matrix was not more than 40% to prevent the sample skeleton from being totally controlled by RC (Senetakis et al., 2012; Kim et al., 2008). The appearance of the SFS+CW+RC mixture with SFS:CW=7:3, and 10% RC is shown in Figure 1.

A series of stress-controlled drained cyclic triaxial tests were carried out on the waste matrix by following the procedure suggested by ASTM D5311/D5311M (2013). The specimen was 100 mm high and 50 mm in diameter and was compacted in three layers. All the specimens were prepared with the optimum moisture content and compacted to 95% of their maximum dry density. The effective confining pressure σ'_3 used for the cyclic loading triaxial tests were 10, 40, and 70 kPa. The maximum deviator stress q_{max} is determined by using the cyclic stress ratio ($CSR = q_{max}/2\sigma'_3$) CSR=0.8 and the effective confining pressure. All of the abovementioned conditions for specimens and triaxial tests were used to simulate the field conditions of railway subballast.

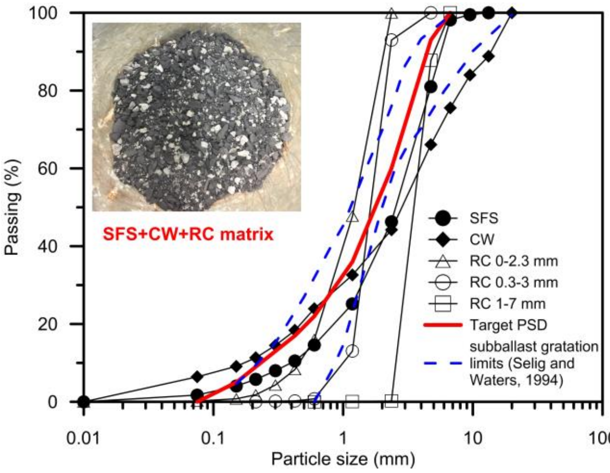

Figure 1 PSD of SFS, CW, RC, and the target PSD for the waste matrix

The cyclic loading triaxial tests were carried out in three stages; saturation, consolidation, and cyclic loading. The specimen was saturated using back pressure and this stage was completed when the Skempton's B value exceeded 0.98. After saturation, the consolidation stage continued using the desired effective confining pressure (i.e. $\sigma'_3 = 10, 40,$ or $70\ kPa$) until unnoticeable change in volumetric strain was observed. Cyclic loading was applied using the frequency f=5 Hz to simulate the quasi-static condition which is usually used in track design procedures; cyclic loading stage was continued for 50,000 cycles.

3. TEST RESULTS

3.1 Total Axial Strain and Volumetric Strain

The deformation of soil under cyclic loading can be characterised by permanent (plastic) strain and resilient (recoverable elastic) strain. The sum of permanent strain and resilient strain is the total strain. The definitions of total axial strain, permanent axial strain, and recoverable axial strain $\varepsilon_{1,rec}$ are shown in Figure 2. The permanent axial strain and resilient axial strain can both be reflected by the hysteretic cycles. Figure 3 (a-b) shows the hysteretic cycles of SFS+CW+RC mixtures with RC contents $R_b = 10\%$ and 30% tested under $\sigma'_3 = 70\ kPa$. Note that the permanent axial strain increases with the loading cycles but at a decreasing rate of accumulation, whereas the resilient axial strain decreases as the number of loading cycles increases and gradually stabilises after around 1000 cycles. Note that the maximum deviator stress increases within the first 1000 cycles because most of the densification occurs at the beginning of the test, and the desired maximum deviator stress is achieved after around 1000 cycles. Moreover, the permanent axial strain of the waste matrix with $R_b = 30\%$ is much greater than with $R_b = 10\%$ as more densification occurs when increasing RC content. The resilient strain also increases when R_b increases because as R_b increases the skeleton of the specimen gradually changes from SFS+CW to RC so the specimen behaves more like rubber and the strain will recover more during unloading.

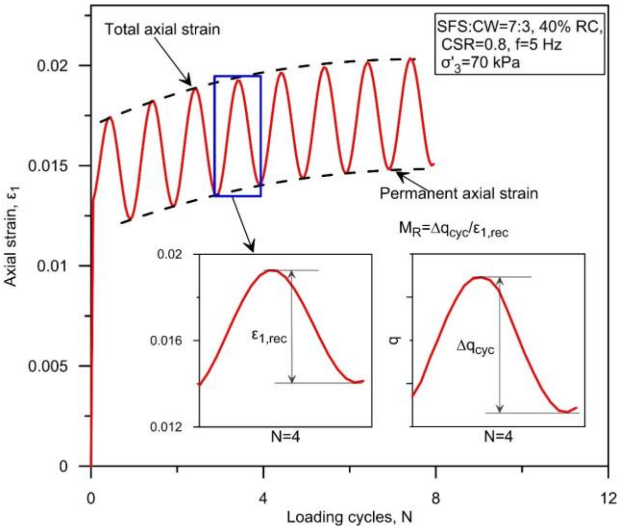

Figure 2 Definitions of total axial strain, permanent axial strain, recoverable axial strain and resilient modulus

The total axial strain and volumetric strain of SFS+CW+RC mixtures varying with the loading cycles are shown in Figure 4. It can be seen that under the same effective confining pressure, when R_b increases the axial strain increases and the volumetric strain becomes much more contractive. The axial strain and volumetric strain of the waste matrix with $R_b \leq 10\%$ stabilises at around 10,000 cycles, which achieves shakedown. Here, 'shakedown' is a physical phenomenon of granular materials under cyclic loading that can be achieved when the axial strain of the granular materials stabilises after a certain period of time, or certain number of loading cycles (Indraratna et al., 2011). For the waste matrix with $R_b \geq 20\%$ the axial strain continues to increase after 10,000 cycles, albeit this rate is marginal, and the volume of the specimens continues to compress to the end of the test.

The influence of effective confining pressure on the total axial strain and volumetric strain is shown in Figure 4 (c-d); note that for the same waste matrix, the axial strain and volumetric strain increase as σ'_3 increases. Under $\sigma'_3 = 10 - 70\ kPa$, the waste matrix with $R_b = 10\%$ is always contractive, and when $\sigma'_3 = 10\ kPa$, the volumetric strain is negligible.

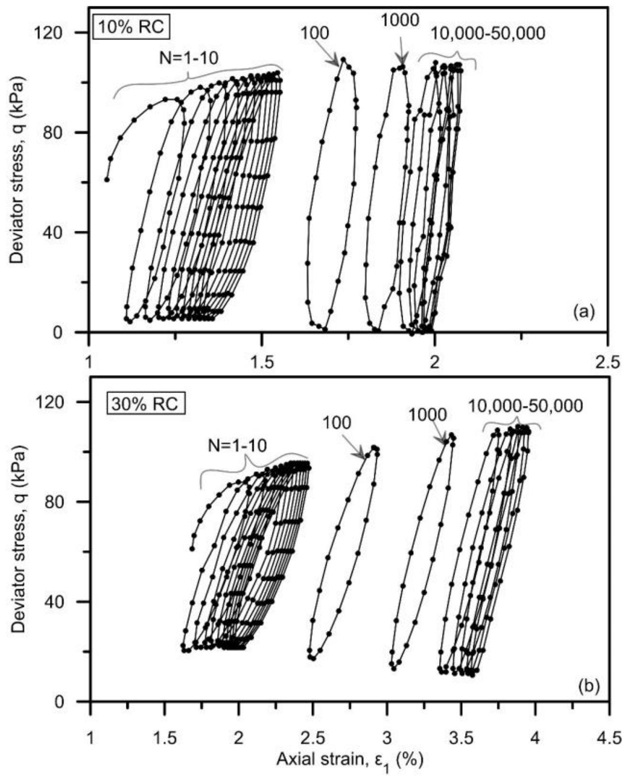

Figure 3 Hysteretic cycles of SFS+CW+RC mixtures tested with f=5 Hz and $\boldsymbol{\sigma'_3 = 70\ kPa}$

3.2 Resilient Modulus

The resilient axial strain (recoverable strain) can be evaluated by the resilient modulus M_R which is defined as (Figure 2):

$$M_R = \frac{\Delta q_{cyc}}{\varepsilon_{1,rec}} \quad (1)$$

where Δq_{cyc} is the difference between the maximum deviator stress and the minimum deviator stress; $\varepsilon_{1,rec}$ is the recoverable strain (elastic axial strain) during loading and unloading.

To eliminate any influence of the irregularity in loading that might have occurred in the initial stage, M_R was determined after 1000 cycles where the maximum deviator stress was stable and more than 90% of permanent axial strain was generated (Figure 3). This agrees with previous studies by Nazzal and Mohammad (2010) and Lackenby et al. (2007). Figure 5 shows how the resilient modulus of the SFS+CW+RC mixtures varies with the number of loading cycles. The magnitude of M_R increases slowly as the number of loading cycles increases, and then stabilises after 10,000 cycles (Figure 5a). Under the same effective confining pressure ($\sigma'_3 = 40\ kPa$) M_R decreases as RC is added, due to the larger recoverable axial strain generated by the addition of more RC (Figure 3). Moreover, M_R increases as σ'_3 increases (Figure 5b). This is because when σ'_3 increases, the RC becomes more compressible, more contacts between stiffer particles (SFS and CW) is forming, and the skeleton of the specimen becomes much stiffer, so less recoverable axial strain is generated.

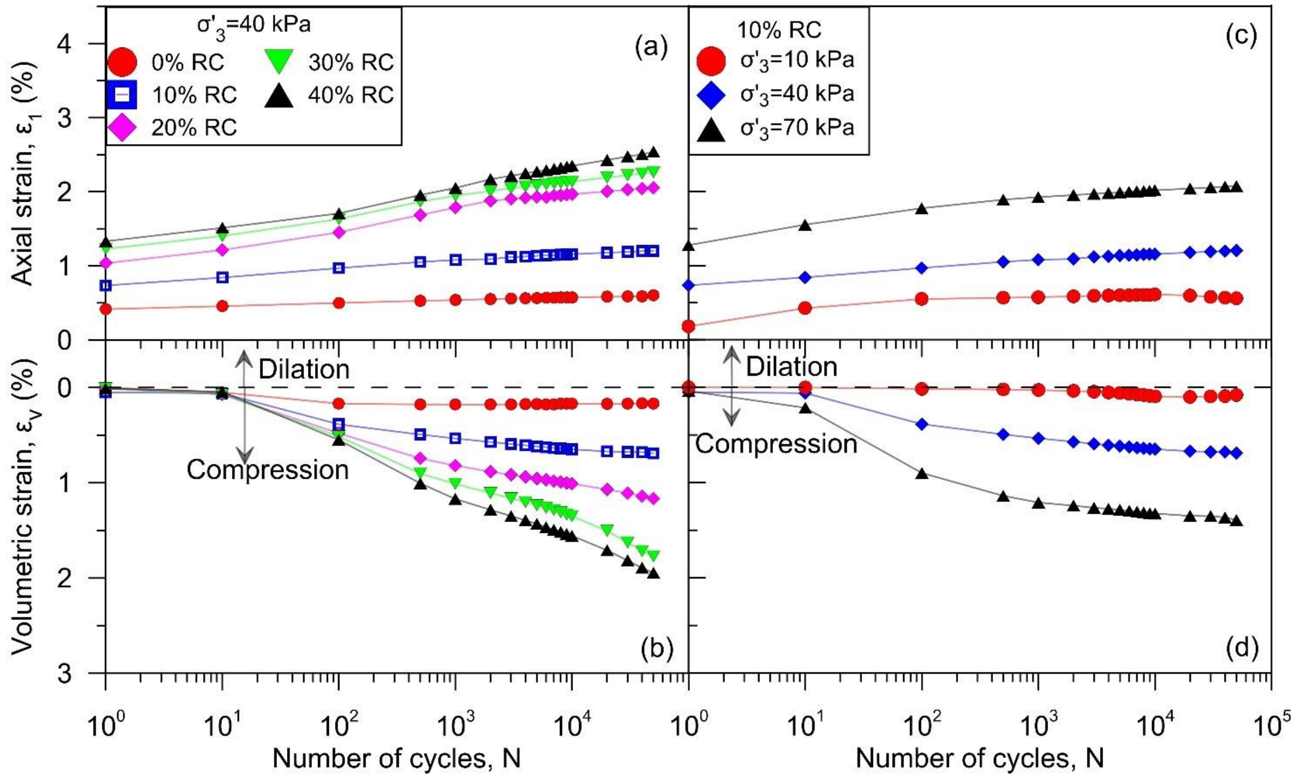

Figure 4 Total axial strain and volumetric strain of SFS+CW+RC mixtures varying with loading cycles (modified after Qi et al., 2018b)

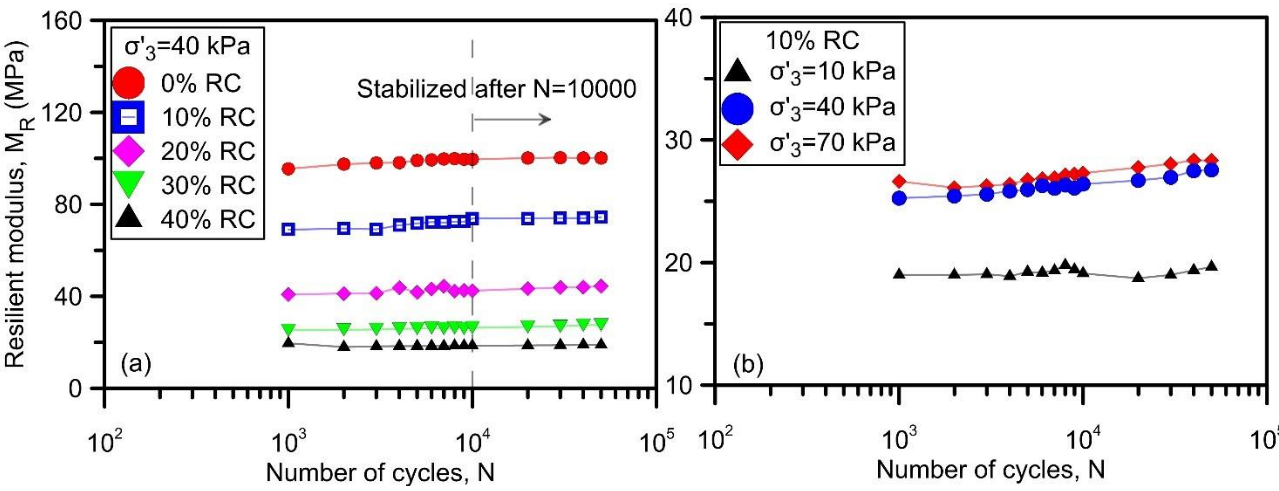

Figure 5 Resilient modulus of SFS+CW+RC mixtures varying with loading cycles (modified after Qi et al., 2018b)

3.3 Empirical Relationships between Strains, Effective Confining Pressure and RC contents

The influence of R_b on the cyclic deformation behaviour of the SFS+CW+RC mixtures can be better evaluated by plotting the total axial strain, total volumetric strain, and resilient modulus at 50,000 cycles (Figure 6 a-c) where the strain tends to be more stable. Note that the total ε_1, ε_v, and M_R increase as σ'_3 increases, while with the inclusion of RC ε_1 and ε_v increase while M_R decreases. To prevent a hazardous impact to a ballast track foundation by excessive settlement, the total axial strain of the waste matrix should be less than 2% under around $\sigma'_3 = 40\ kPa$ (Teixeira et al., 2006; Figure 6a). Therefore, the axial strain of cyclic loading tests indicates that RC contents in the waste matrix should be less than 20%. Moreover, the materials that dilate under cyclic loading should be avoided to be used as subballast, and therefore a waste matrix without RC should not be used as subballast (Figure 6b). Furthermore, the resilient modulus for subballast is expected to be between 60-80 kPa, as suggested by Shahu et al. (1999), so the resilient modulus of the cyclic loading tests of the waste matrix shown in Figure 6 (c) indicates that a waste matrix with 10% RC is suitable for subballast.

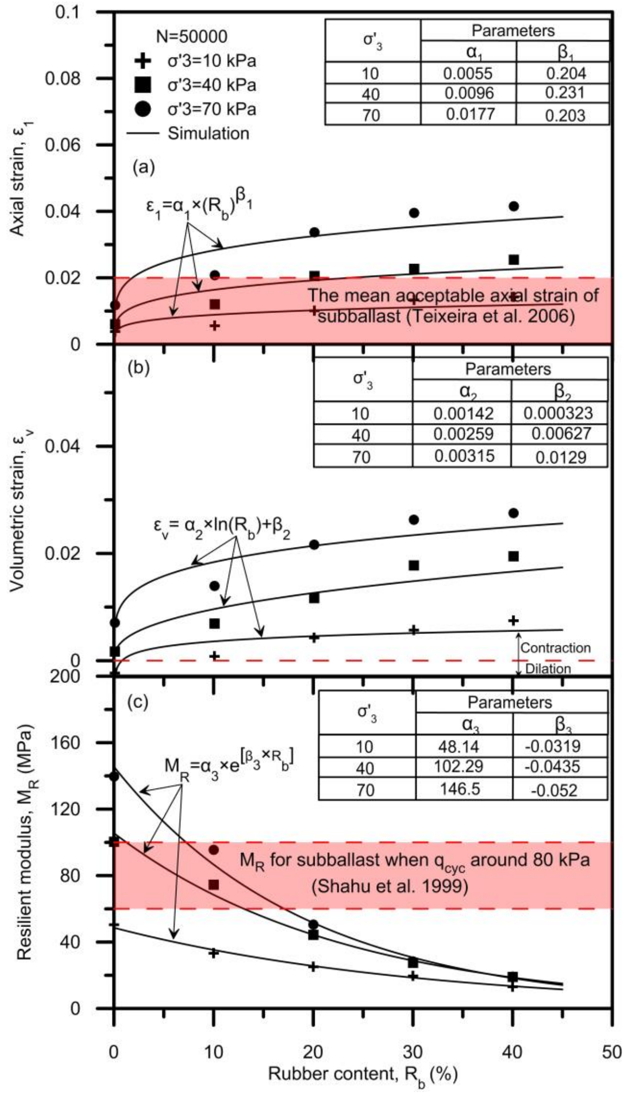

Figure 6 Total axial strain, total volumetric strain and resilient modulus for SFS+CW+RC mixtures at 50,000 cycles (Modified after Qi et al. 2018b)

It is interesting to find that the influence of σ'_3 and R_b on ε_1, ε_v, M_R can be reflected by the empirical equations:

$$\varepsilon_1 = \alpha_1 \times (R_b)^{\beta_1} = (a_1 \times \sigma'_3 + b_1) \times (R_b)^{a_2 \times \sigma'_3 + b_2} \quad (2)$$

$$\varepsilon_v = \alpha_2 \times \ln(R_b) + \beta_2 = (a_3 \times \sigma'_3 + b_3) \times \ln(R_b) + (a_4 \times \sigma'_3 + b_4) \quad (3)$$

$$M_R = \alpha_3 \times e^{\beta_3 \times R_b} = (a_5 \times \sigma'_3 + b_5) \times e^{(a_6 \times \sigma'_3 + b_6) \times R_b} \quad (4)$$

where α_i and β_i $(i = 1, 2, 3)$ are calibration parameters. The value of α_i and β_i are shown in Figure 6 (a-c), and both α_i and β_i have a linear with σ'_3, as is also reflected in Equations (2-4). a_i and b_i $(i = 1, 2, 3, 4, 5, 6)$ are also calibration parameters, and their value are shown in Table 1. To better illustrate the empirical relationship between σ'_3 and R_b and ε_1, ε_v, M_R, the test data and Equations (2-4) are plotted in a 3-D space (Figure 7 a-c). The curved surfaces of ε_1, ε_v, and M_R are formed by the influence of σ'_3 and R_b. Note that the simulated results by Equations (2-4) match the test results very well.

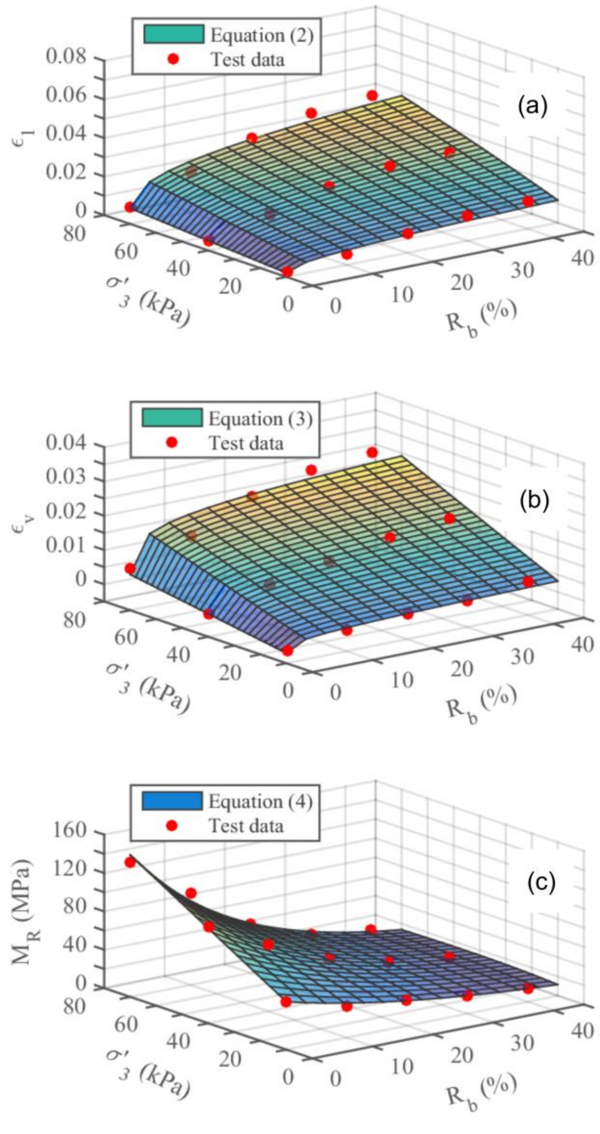

Figure 7 3-D plot of relationships between $\boldsymbol{\sigma'_3}$, $\boldsymbol{R_b}$ and $\boldsymbol{\varepsilon_1}$, $\boldsymbol{\varepsilon_v}$, and $\boldsymbol{M_R}$ (after Qi et al. 2018b; with permission from ASCE)

Table 1 The value of a_i and b_i

i	a_i	b_i
1	1.7×10^{-4}	-4.17×10^{-4}
2	2.28×10^{-3}	0.283
3	3.7×10^{-5}	2.1×10^{-4}
4	4.8×10^{-4}	2.2×10^{-3}
5	1.639	-3.35×10^{-4}
6	33.4	-0.0291

3.4 Shear Modulus and Damping Ratio

The shear modulus G and the damping ratio D are the two key parameters needed to estimate the stiffness and energy absorbing capacity of soil. Damping is the loss of energy within a vibrating or a cyclically loaded system which is usually dissipated in the form of heat or breakage for granular materials; it is commonly used to measure the damping capacity for energy dissipation during dynamic or cyclic loading. The definition of the shear modulus and damping ratio is presented in Figure 8; where the area of the hysteretic loop A_2 in the shear stress-shear strain plain represents the energy dissipated during a loading cycle, while four times the area of the triangle A_1 is the maximum elastic energy absorbed during the cycle (Kokusho, 1980).

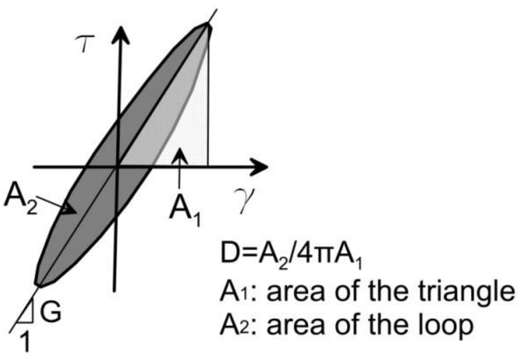

Figure 8 Definition of shear modulus and damping ratio

Figure 9 shows the shear modulus and damping ratio of SFS+CW+RC mixtures with different R_b(%) versus loading cycles in logarithm. It can be noted that the addition of RC has a significant influence on the shear modulus and damping ratio of SFS+CW+RC mixtures. As with previous studies of rubber-sand mixtures (e.g. Zheng and Kavin 2000; Li et al. 2016; Nakhaei et al. 2012), the shear modulus decreases with increasing R_b(%) because of the low stiffness of rubber materials. Unlike shear modulus, the damping ratio of SFS+CW+RC mixtures increases with R_b(%) indicating the high damping properties of rubber materials. However, the SFS+CW+RC mixtures with $R_b \geq 10\%$ tend to achieve a similar damping ratio after 10000 cycles (Figure 3b). This is because the inclusion of rubber crumbs increases the area of the hysteretic loop, but as RC contents increase the hysteretic loop becomes more inclined, which then causes a rapid increase in the area of the triangle A_1, and this also suggests that the damping capacity of the waste mixtures with $R_b \geq 10\%$ is similar at high loading cycles, while for the waste mixtures without rubber the value of the damping ratio is stable albeit a little fluctuation after 10 cycles.

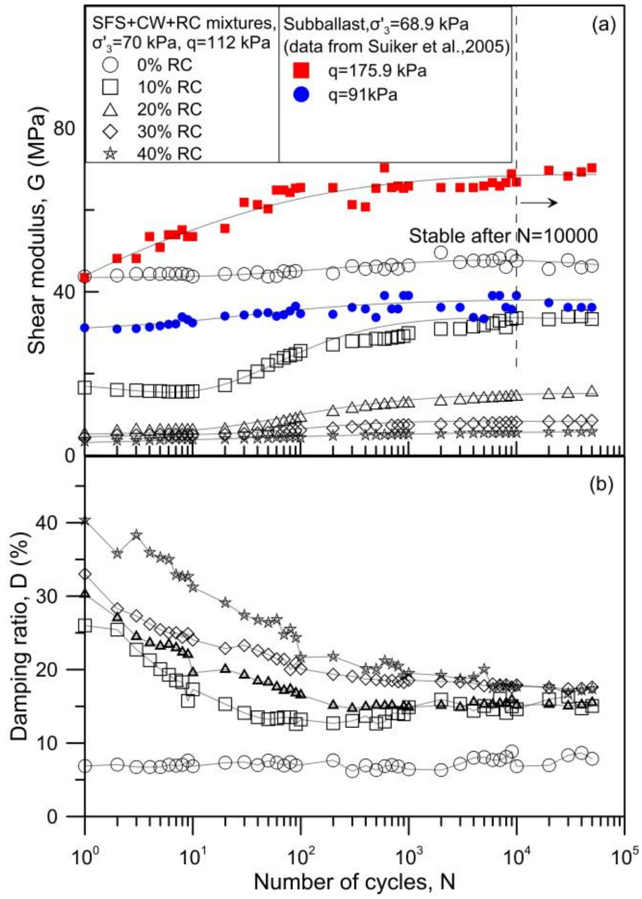

Figure 9 Cyclic loading results of traditional subballast and SFS+CW+RC mixtures with different RC contents: (a) shear modulus, and (b) damping ratio (after Qi et al. 2018, with permission from ASCE)

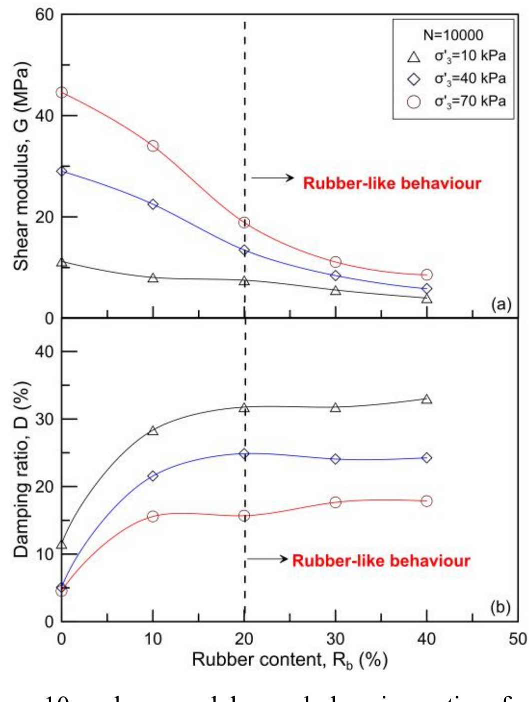

Figure 10 shear modulus and damping ratio of waste mixtures (SFS:CW=7:3) changing with $\mathbf{R_b}$ at 10000 cycles (after Qi et al. 2018, with permission from ASCE)

Figure 10 (a and b) shows the evolution of the shear modulus and damping ratio varying with RC contents and effective confining pressures at 10000 cycles since the value of shear modulus and damping ratio becomes stable after 10000 cycles (e.g. Figure 9). Note that the effect of confining pressures on shear modulus and damping ratio declines as $\boldsymbol{R_b}$ increases, which in line with past studies such as Nakhaee & Marandi (2011). This is because as more RC included, the waste mixes tend to behave more elastic, and the influence of the confining pressure become insignificant (Zheng and Kavin 2000). Therefore, the behaviour of shear modulus and the damping ratio is governed mainly by the RC content. When $\boldsymbol{R_b} < \boldsymbol{20\%}$, the shear modulus decreases and the damping ratio increases as the RC contents increase, while when $\boldsymbol{R_b} > \boldsymbol{20\%}$ both the shear modulus and the damping ratio change a little indicating that the rubber crumbs has formed the skeleton of the whole specimen and the specimen behaves rubber-like. It is worthy to note that when $\boldsymbol{R_b}$ increases in the range of $\boldsymbol{10\%} \leq \boldsymbol{R_b} \leq \boldsymbol{20\%}$, only a minor increase happens to the damping ratio, indicating that 10% RC is sufficient for the purpose of energy absorbing.

4. CONCLUSIONS

In this paper a series of stress-controlled cyclic triaxial tests have been carried out on SFS+CW+RC mixtures with SFS:CW=7:3 and $R_b = 0 - 40\%$ to investigate the influence of R_b and σ'_3 on the cyclic deformation behaviour of the waste matrix. The test results indicate that:

(1) As R_b and σ'_3 increase, the total axial strain increases and the volumetric strain of the waste matrix becomes much more contractive. All the waste matrix samples show contractive behaviour, although the waste mixture without RC dilates under very low effective confining pressure (i.e. $\sigma'_3 = 10\ kPa$). The axial strain and volumetric strain increase as the number of loading cycles increases, and the trend of the increasing rate stabilises after N=10,000.

(2) The magnitude of M_R decreases as R_b increases, but it decreases when σ'_3 increases. M_R is determined after N=1000, while the value of M_R increases very slowly as the number of loading cycles increases, but it gradually stabilises after N=10,000.

(3) The empirical relationships between σ'_3, R_b and ε_1, ε_v, and M_R have been established, and there is a good agreement between the prediction and the measured data.

(4) The addition of RC caused the shear modulus to decrease and the damping ratio to increase. It was also found that the behaviour of shear modulus and damping ratio was controlled by the percentage of the waste mixtures inside the mixtures. The particles that form the skeleton of the specimens changed from rigid particles (SFS and CW) to RC gradually as the RC contents increased, and the transition point was around 20% RC.

Compared to traditional subballast, a waste matrix with 10% RC can be used as subballast because it has less axial strain and volumetric strain, and it has an acceptable resilient modulus and shear modulus; moreover, it can achieve a shakedown condition at around 10,000 cycles.

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