Mining Waste Materials and Recycled Rubber Matrix for Rail Tracks under Cyclic Loading

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ABSTRACT

Incorporating recycled materials (i.e. recycled rubber crumbs, RC) and mining wastes such as coal wash (CW) and steel furnace slag (SFS) in rail tracks helps to improve the track stability, while minimizing the stockpiling of these waste materials. This paper presents two novel methods to use the blended waste materials to replace conventional subballast/ materials in rail track substructure, namely (i) SFS-CW-RC mixtures and (ii) CW-RC mixtures. Two series of cyclic triaxial tests were conducted to investigate the cyclic loading response of the mixtures with different RC contents, including deformation, resilient modulus, shear modulus and damping ratio. Test results show that CW-RC mixtures are more compressive and present less resilient modulus and shear modulus than SFS-CW-RC mixtures for a given RC content. It is recommended that 10% RC is a preferable percentage for both mixtures according to their deformation behaviour, the resilient modulus and the damping ratio.

INTRODUCTION

There is no doubt that the manufacturing and the supply of construction materials contribute to a large proportion of carbon emissions worldwide. It is therefore extremely important to develop and utilise more sustainable construction materials, especially for large-scale transportation infrastructures (e.g. rail tracks). As a result, upcycling waste materials in civil engineering projects has become increasingly popular knowing that it offers social and economic benefits while solving technical problems that are associated with civil-geotechnial foundations.

On another note, the mining industry and the steel industry across Australia produce two common by-products that are generated through the manufacturing process, and these are steel furnace slag (SFS) and coal wash (CW). Coal Wash is produced during the process of washing coal from its impurities using physical or chemical methods, whereas steel furnace slag is generated when converting iron into steel in an oxygen furnace. Therefore, the production of these materials generates several hundreds of millions of tons of waste per year in Australia (Leventhal and De Ambrosis 1985). Scraped vehicles' tyres are another waste material that is stockpiling worldwide. In Australia alone, more than 56 million equivalent passenger unit (EPU) of waste rubber tyres are generated each year (Mohajerani et al. 2020). The stockpiles of waste rubber tyres can induce severe environmental problems, especially if they catch fire. The growing abundance of these waste materials and the lack of an efficient recycling framework have created a rising concern and an urge to manage and recycle these waste materials globally.

To tackle the above issues and the shortage of natural aggregates for transportation infrastructure projects, researchers and practising engineers endeavour to replace traditional materials with these waste materials. However, SFS and CW need to be blended together or with other materials to overcome their adverse geotechnical properties, i.e. the swelling potential of SFS and the particle breakage of CW (Okogbue and Ezeajugh 1991, Khan et al. 2016). For instance, Noureldin and McDaniel (1990) mixed SFS with sand to produce an asphalt paving material. Yildirim and Prezzi (2015) added 15% fly ash to SFS to be used in a landfill. Also, SFS was successfully mixed with CW with an optimal blending ratio and the material was used for port reclamation in Australia (Chiaro et al. 2015). In addition, the use of recycled rubber products has gained increasing attention in rail tracks in recent years. Its high energy absorbing capacity and damping properties can reduce ballast degradation and increase the longevity of the track. For example, recycled rubber elements like under ballast mats and under sleeper pads have been included in the rail track to prevent load concentration and to reduce the ballast breakage (Lakušić et al. 2010, Montella et al. 2012, Navaratnarajah and Indraratna 2017). Moreover, Indraratna et al. (2017) proposed the use of waste tyre cells to reinforce the capping layer of railways by increasing the confining pressure and reducing the settlement of the track. Granulated recycled rubber particles mixed with ballast or with waste granular materials (i.e. SFS and CW) have also been introduced in the railway track in an attempt to improve the energy absorbing capacity of the track and reduce track dilation (Sol-Sánchez et al. 2015, Fernández et al. 2018, Indraratna et al. 2018, Fonseca et al. 2019, Indraratna et al. 2020, Koohmishi and Azarhoosh 2020, Qi and Indraratna 2021).

The purpose of this paper is to review two methods of using recycled rubber crumbs (RC) with SFS and CW to replace traditional subballast/capping materials for railways. The first method was proposed by Indraratna et al. (2018) to blend SFS, CW and RC (i.e. SFS-CW-RC) with standard compaction effort. In the second method (Indraratna et al. 2020), CW was blended with RC (i.e. CW-RC) to avoid the risk of volume expansion due to SFS. To compensate for the absence of the rigid SFS, increased compaction effort was used to prepare CW-RC specimens. To evaluate and compare the dynamic loading behaviour of SFS-CW-RC and CW-RC mixtures, two series of cyclic triaxial tests were conducted on these waste mixtures with different rubber contents. Recommendations on the optimal rubber content for these waste mixtures were then deduced based on the test results.

MATERIALS AND TESTING PROGRAM

Materials. The waste aggregates used in this study are steel furnace slag (SFS) and coal wash (CW), which are by-products from steel manufacturing and coal mining (Wollongong, New South wales, Australia), respectively. The rubber crumbs (RC) were shredded from waste tyres. The gradation curves of SFS (specific gravity $G_s = 3.43$), CW ($G_s = 2.11$) and RC ($G_s = 1.15$) are shown in Figure 1. The typical chemical composition of SFS and CW can be found in Qi et al. (2018). All materials were dried and sieved and then mixed based on mass percentages. SFS-CW-RC mixtures were prepared by mixing SFS and CW with the ratio 7:3 and then different percentages of RC (0, 10, 20, 30 and 40%) were added. The ratio of SFS:CW=7:3 follows the suggestion by Indraratna et al. (2018) and Qi et al. (2019) to ensure the SFS-CW-RC mixtures have enough strength with acceptable swelling potential and particle breakage. CW-RC mixtures were prepared with a narrower range of RC (0, 5, 10, and 15%) inspired by the test results of SFS-CW-RC mixtures from Indraratna et al. (2018). The gradation curves of SFS-CW-RC and CW-RC mixtures are shown in Figure 1. Note that their gradations are within the upper and lower limits suggested by the Australian standard for subballast/capping materials (ARTC 2020). A photo of a SFS-CW-RC mixture with 10% RC is also shown in Figure 1.

Testing Program. To compare the geotechnical behaviours of the SFS-CW-RC and CW-RC mixtures under cyclic loading, the results of the cyclic triaxial tests on these waste mixtures with different RC contents (R_b, %) conducted by Qi et al. (2018) and Tawk et al. (2021) were adopted in this study. The sample size was 100 mm in diameter and 200 mm high, and the waste mixtures were blended with their optimal moisture contents (8-10%) and then compacted in 5 layers in the mould. For the SFS-CW-RC mixtures, the target mixtures were to achieve 95% of their maximum dry density (12.1-20.3 kN/m^3) with standard Proctor compaction effort. For CW-RC mixtures, the samples were compacted to achieve the same void ratio (around 0.29) with increased compaction effort as rubber content increased. The target void ratio was based on the density specification for traditional capping/subballast materials set by the Australian Rail Track Corporation ARTC (2020).

The cyclic triaxial tests were conducted in three stages (i.e. saturation, consolidation and cyclic loading). Saturation was completed when the Skempton's B-value reached 0.98, and the consolidation stage was carried out under the target effective confining pressure (σ'_3 = 40-50 kPa) simulating practical field conditions. Then, cyclic loads were applied with a cyclic stress ratio (CSR=$q_{max}/2\sigma'_3$) of 0.8. Loading frequencies applied for SFS-CW-RC and CW-RC mixtures were 5 Hz and 10 Hz, respectively. Cyclic loading tests were carried out up to 50,000 or 100,000 cycles for SFS-CW-RC and CW-RC mixtures, respectively. Detailed sample preparation and testing program are explained elsewhere by Qi et al. (2018) and Tawk et al. (2021).

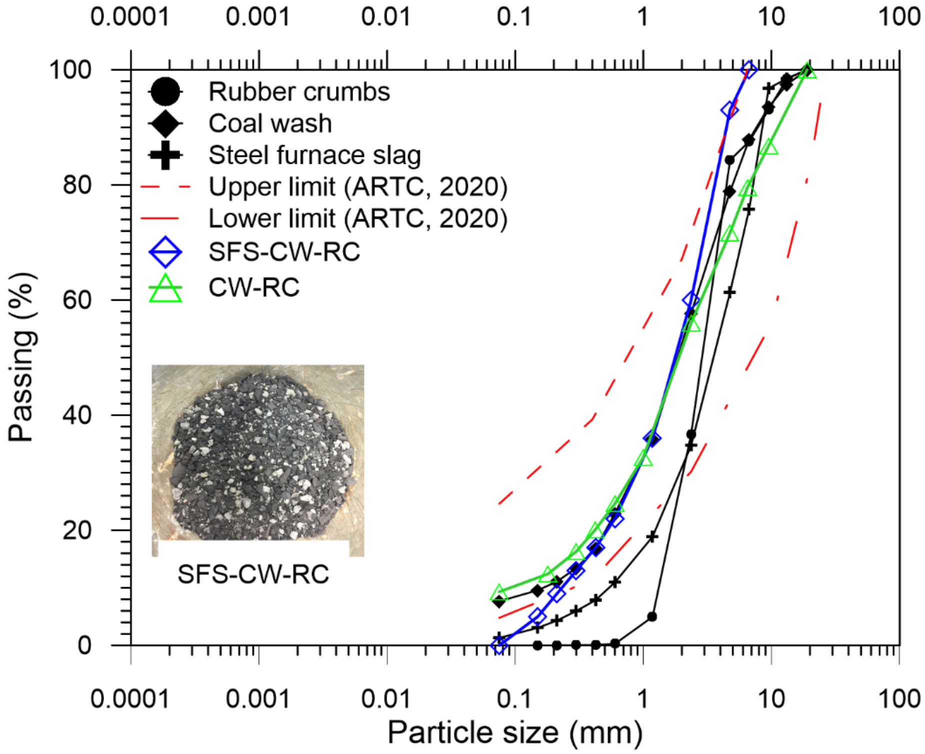

Figure 1. Gradation curves of the waste aggregates (SFS, CW and RC), SFS-CW-RC, CW-RC mixtures, and the upper and lower limits for subballast materials (Sources: Qi et al. 2018, Tawk et al. 2021)

TEST RESULTS

Deformation Behaviour. Due to the loading frequency difference for SFS-CW-RC and CW-RC mixtures, all the test results were interpreted and compared based on time rather than the number of cycles. The axial strain and the volumetric strain of the waste mixtures evolving with time are shown in Figure 2. Figure 2a shows that the axial strain increases rapidly with time before t=1000s (5000 cycles for SFS-CW-RC mixtures and 10,000 cycles for CW-RC mixtures) due to densification. After that point, the axial strains gradually stabilize, except for SFS-CW-RC mixtures having $R_b \geq 30\%$ which experiences an increasing axial strain until the end of the test. The axial strains of all the waste mixtures increase when the rubber contents increase. With the same rubber content, CW-RC mixtures show higher axial strains than SFS-CW-RC mixtures. The development of axial strain of the CW-RC mixture with $R_b = 15\%$ is somewhat similar to that of SFS-CW-RC mixture with $R_b = 20\%$ ($\varepsilon_1 = 2\%$). Teixeira et al. (2006) suggest that the axial strain under cyclic loading with σ'_3 = 40 kPa for conventional subballast materials should be less than 2%. Therefore, R_b should be less than 20% for SFS-CW-RC mixtures and less than 15% for CW-RC mixtures.

From Figure 2b, it can be noted that all specimens show a contractive behaviour for the entire duration of loading. Similar to the axial strain response, the compressive volumetric strain of all specimens, except for the SFS-CW-RC mixtures with 30% and 40% RC, increases rapidly before the time reaches 1000s, and then gradually stabilizes. For the same loading time, the compressive volumetric strain increases as rubber is added to the waste mixture. For the same rubber content, CW-RC mixtures experience a higher compressive volumetric strain than the SFS-CW-RC mixtures. The CW-RC mixture with $R_b = 15\%$ reaches almost the same volumetric strain (1.7%) as the SFS-CW-RC mixture with $R_b = 30\%$. This may be attributed to the higher particle degradation of CW compared to SFS. CW grains are flaky and easy to break, while SFS particles are cuboidal and have a high particle inter-locking property and hardly break during loading. For instance, without rubber, the particle breakage of the CW-RC mixture is almost five times that of the SFS-CW-RC mixture under the same static loading condition (Qi et al. 2020).

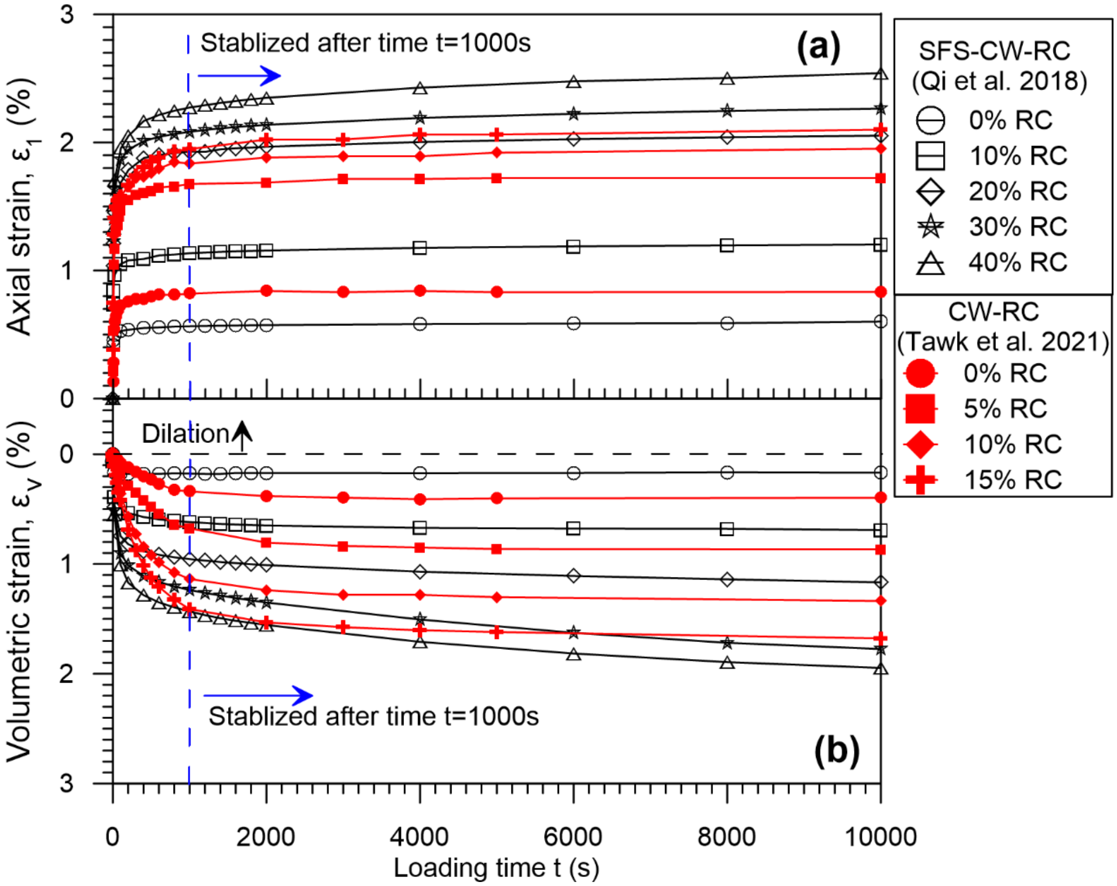

Figure 2. Deformation responses of the waste mixtures under cyclic loading: (a) axial strain and (b) volumetric strain

Resilient Modulus of Waste Mixtures. The resilient modulus (M_R) is a critical parameter when evaluating the dynamic response of any material with respect to the dynamic stress and the corresponding elastic strains. It is also a material characteristic acting as an estimate of modulus of elasticity (E) (Lee et al. 1997). While E is obtained by divide the stress over the strain for a slowly applied load (monotonic loading), M_R is the ratio of maximum deviator stress ($q_{cyc,max}$) and the recoverable strain ($\varepsilon_{1,recoverable}$) for rapidly applied loads (e.g. cyclic loading):

$$M_R = \frac{q_{cyc,max}}{\varepsilon_{1,recoverable}} \tag{1}$$

Figure 3 shows the resilient modulus of SFS-CW-RC and CW-RC mixtures having different rubber contents varying with time. It is noted that the resilient modulus of all mixtures stabilizes after 1000s, indicating that the elastic deformation ($\varepsilon_{1,recoverable}$) of the mixtures also reaches a stable state at that time. As rubber content increases in the waste mixture, M_R decreases from 100.3 to 18.9 MPa for SFS-CW-RC mixtures and from 89.8 to 52.8 MPa for CW-RC mixtures. This is due to the increasing elastic deformation attributed to the rubber component. For the same rubber inclusion, CW-RC mixtures present a lower resilient modulus than SFS-CW-RC mixtures, indicating that the stiffness of SFS-CW-RC mixtures is greater than that of CW-RC mixtures. Since the $q_{cyc,max}$ applied for the waste mixtures is similar, the $\varepsilon_{1,recoverable}$ for CW-RC mixtures is higher than that of SFS-CW-RC mixtures. A relatively high $\varepsilon_{1,recoverable}$ will cause the specimen to bounce up and down during dynamic loading, which may cause instability for rail tracks (Yoshida et al. 2004, Kim and Santamarina 2008). Therefore, the resilient modulus of the waste mixtures should be controlled within an acceptable range. It is reported that for traditional subballast materials, the resilient modulus should be within the range of 60-80 MPa under $q_{cyc,max} \approx 80\ kPa$ (Shahu et al. 1999). To prevent the waste mixture from generating the "bounciness effect", the rubber content should be ≤ 10% in both SFS-CW-RC and CW-RC mixtures.

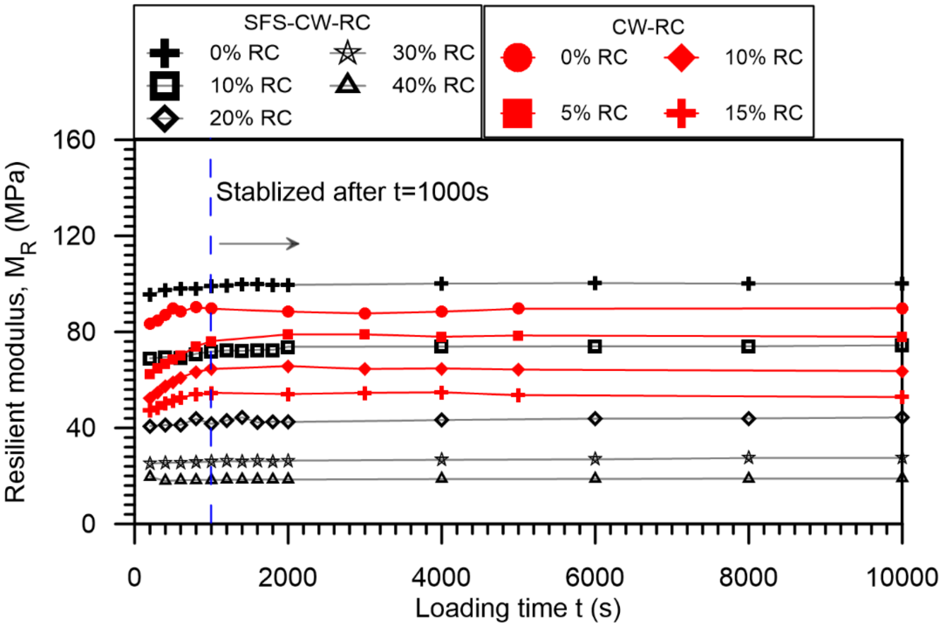

Figure 3. Resilient modulus of the waste mixtures varying with time (Source: Qi et al. 2018, Tawk et al. 2021)

Shear Modulus and Damping Ratio. To evaluate the material stiffness and the efficiency of energy dissipation under cyclic loading of the mixtures, the shear modulus (G) and the damping ratio (D) were measured at the end of the cyclic test (t=10,000s), as shown in Figure 4. The definition of the shear modulus and the damping ratio can be found in Figure 4a, where a hysteretic loop is plotted. It is noted that as the amount of rubber crumbs increases, the shear modulus decreases. This is because the lower shear strength of rubber particles becomes predominant compared to the shear strength of the other two components (i.e. SFS and CW). The damping ratio increases as more rubber is added and reaches a maximum for 10% RC in the CW-RC mixture and 20% RC in the SFS-CW-RC mixture. After that, the damping ratio remains almost constant for higher rubber contents. This indicates that a rubber content of 10% in the CW-RC mixture and 20% in the SFS-CW-RC mixture is sufficient to improve the efficiency of energy dissipation of the waste mixtures. Having the same rubber content, SFS-CW-RC mixtures show a slightly higher shear modulus than CW-RC mixtures. Compaction with higher energy effort somehow compensates for the absence of the very stiff material SFS in the CW-RC mixture. When the rubber content is less than 10%, the damping ratio of CW-RC mixtures is slightly higher than SFS-CW-RC mixtures, while after that, the damping ratio of CW-RC mixtures becomes less than that of SFS-CW-RC mixtures.

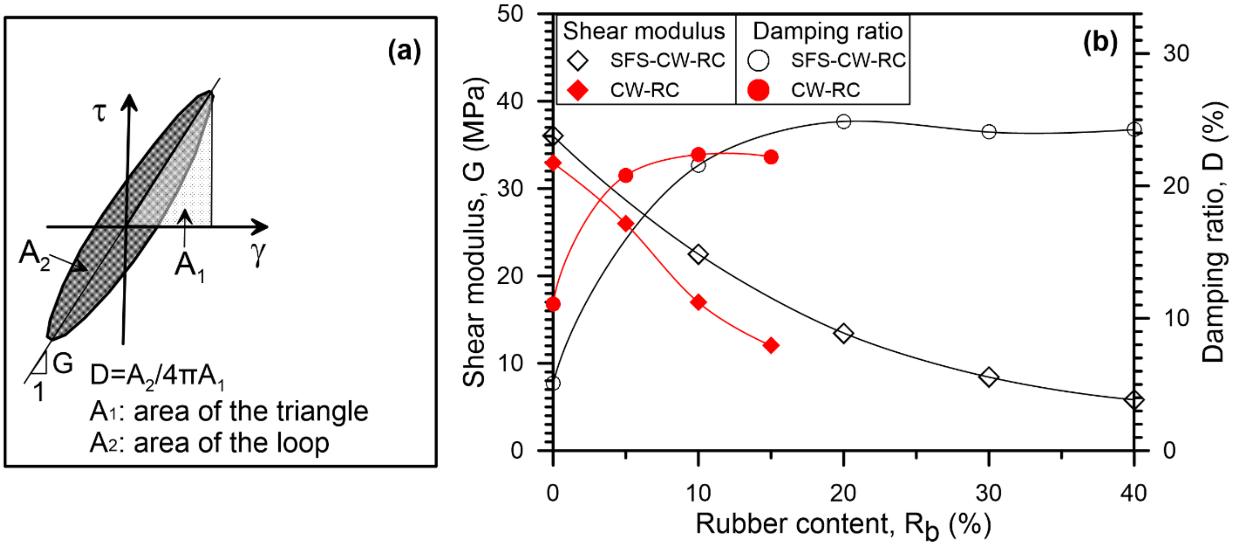

Figure 4. (a) Definitions of shear modulus and damping ratio; (b) shear modulus and damping ratio of the waste mixtures (Sources: Qi et al. 2018, Tawk et al. 2021)

The Optimal Rubber Content. Based on the cyclic loading test results, the addition of rubber increases the compressive volumetric strain and improves the energy dissipation efficiency, which can help to reduce the track dilation and minimize the energy transmitted to underlying layers or the surroundings of the track. However, the inclusion of rubber in the mixtures increases the axial deformation and reduces the resilient modulus and the shear modulus. Therefore, a proper rubber content should be selected with caution to optimize the energy dissipation efficiency of the mixture while avoiding excessive settlements and minimizing the reduction in the stiffness of the mixture when rubber is added.

According to the deformation behaviour, R_b should be less than 20% in SFS-CW-RC mixtures and less than 15% in CW-RC mixtures to maintain an axial strain less than 2% as suggested by Teixeira et al. (2006) for traditional subballast/capping materials (Figure 2). The resilient modulus measurements indicate that R_b should be no more than 10% to prevent the bouncing effect in both mixtures. When referring to the damping ratio, a R_b of 10% and 20% in the CW-RC and SFS-CW-RC mixtures, respectively, provides a maximum energy dissipation efficiency. Therefore, based on the above considerations, $R_b = 10\%$ is suggested as the optimal rubber content for the CW-RC and SFS-CW-RC mixtures under cyclic loading conditions.

It is noteworthy to mention that the above recommended optimal rubber content is based on the analysis of the deformation behaviour, the resilient modulus and the damping ratio of the mixtures under cyclic loading. Other important geotechnical properties such as the permeability, particle degradation, and the friction angle as well as large scale testing (i.e. large-scale physical model or field tests) should also be considered to confirm the optimal rubber content and to evaluate the performance of the full rail track incorporating these waste mixture (e.g. ballast breakage, vibration behaviour, track stiffness). Also, further studies on these mixtures under higher frequencies (>10 Hz) should be considered to expand the applications for high-speed railway.

CONCLUSION

Two innovative methods of using granular mining wastes and recycled tyre products in railway tracks in lieu of traditional subballast materials were reviewed in this paper. The methods entailed (i) mixing steel furnace slag (SFS) and coal wash (CW) with rubber crumbs (RC) as a SFS-CW-RC mixture with standard Proctor compaction effort, and (ii) mixing CW with RC with increased compaction effort to reach the same density as traditional subballast materials. Two series of cyclic triaxial tests conducted by Qi et al. (2018) and Tawk et al. (2021) were adopted in this paper to evaluate the cyclic loading behaviour of these waste mixtures with different rubber contents. The following conclusions can be drawn from the test results:

(1) With increasing rubber contents, the axial strain and the compressive volumetric strain of the waste mixtures increased. Except for the SFS-CW-RC mixtures with $R_b \geq 30\%$, the axial strain and the volumetric strain of all mixtures reached a stable state after a loading time of t=1000s. For the same rubber content, CW-RC mixtures had a higher axial deformation and experienced a higher contractive volumetric strain than SFS-CW-RC mixtures.

(2) The resilient modulus decreased as more rubber was added to both mixtures, and it reached a stable state after a loading time t=1000s. A higher resilient modulus was observed in SFS-CW-RC mixtures compared to CW-RC mixtures.

(3) As the amount of RC increased, the shear modulus decreased and the damping ratio increased and the latter reached a maximum for a rubber content of 10% in CW-RC mixtures and 20% in SFS-CW-RC mixtures. After that point, no significant improvement in the damping

properties of the mixtures was observed as more rubber was added. The shear modulus of SFS-CW-RC mixtures was slightly higher than that of CW-RC mixtures with the same R_b.

(4) Based on the cyclic loading test results, it is recommended that 10% of rubber is added to the CW-RC and SFS-CW-RC mixtures to improve the energy dissipation efficiency without inducing an unacceptable deformation and an excessive reduction in the material stiffness.

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