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The Influence of Rubber Crumbs on the Energy Absorbing Property of Waste Mixtures

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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 civil engineering. While the addition of rubber crumbs (RC) derived from waste tyres can influence the geotechnical properties of the mixtures of SFS and CW significantly, especially the energy absorbing property. In this paper, the energy absorbing property of the SFS+CW+RC mixtures under static loading has been evaluated by the strain energy density. As expected, the energy absorbing capacity of the waste mixture increases with the addition of RC.To further illustrate the influence of rubber crumbs on the energy absorbing property of the waste mixtures, particle degradation has also be examined after finishing the triaxial tests. It has been found that the addition of RC can significantly reduce the particle breakage of the waste mixtures. Therefore, with high energy absorbing property, the SFS+CW+RC mixtures can be further extended to dynamic loading projects, such as railway capping layer.

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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 civil engineering. While the addition of rubber crumbs (RC) derived from waste tyres can influence the geotechnical properties of the mixtures of SFS and CW significantly, especially the energy absorbing property. In this paper, the energy absorbing property of the SFS+CW+RC mixtures under static loading has been evaluated by the strain energy density. As expected, the energy absorbing capacity of the waste mixture increases with the addition of RC. To further illustrate the influence of rubber crumbs on the energy absorbing property of the waste mixtures, particle degradation has also be examined after finishing the triaxial tests. It has been found that the addition of RC can significantly reduce the particle breakage of the waste mixtures. Therefore, with high energy absorbing property, the SFS+CW+RC mixtures can be further extended to dynamic loading projects, such as railway capping layer.

Keywords: *Waste mixtures; Rubber crumbs; Energy absorbing property; Strain Energy density*

1. Introduction

CW and SFS are very common granular by-products of the coal mining and steel industries in Australia, respectively. The production of these wastes in Wollongong (Australia) alone can amount to several millions of tons per year (Leventhal & de Ambrosis, 1985). To prevent the adverse geotechnical properties of these waste materials (i.e. the volumetric expansion for SFS and the breakage potential for CW; Indraratna, 1994; Heitor et al., 2016; Wang, 2010), SFS and CW can be mixed in selected ratios and have been successfully employed as a structural fill for Port Kembla Outer Harbour reclamation (Chiaro et al., 2013; Tasallotti et al., 2015a; Tasallotti et al., 2015b). However, the application of SFS+CW is only limited to static loading as more breakage of coal wash may be generated by dynamic loading. Therefore, the energy absorbing property of the waste mixture needs to be improved before applying it as capping layer to major rail projects.

Due to the rapidly increasing number of vehicles worldwide every year, waste tyres has become a critical environmental problem in many urban cities, and in Australia alone, 500,000 tons of tyres are replaced every year (Mashiri et al., 2015). Recycled tyres are typically granulated or shredded and exhibit low shear strength, low unit weight of solids (the specific gravity generally ranges from 1.00 to 1.36), high compressibility, high hydraulic conductivity, and high energy absorbing capacity (Senetakis et al., 2012; Zheng & Kevin, 2000; Edil & Bosscher, 1994). However, as the low shear strength and high deformation properties, granulated rubber materials cannot be use alone in civil engineering, but their geotechnical properties boost their usage in rubber-soil mixtures.

It has been reported that the inclusion of scrap tyres can increase the hydraulic conductivity, reduce the swelling of soil-rubber mixtures (Racichandran et al., 2016; Indraratna et al., 2018; Qi et al., 2017a). Moreover, in recent years, the high energy absorbing capacity of RC has been well applied in civil works for the purpose of vibration isolation and anti-seismic construction in the form of soil-rubber blends. Tsang et al. (2012) found using rubber-soil mixture as an alternative seismic isolation material could significantly reduce the horizontal and vertical acceleration and displacements. The cyclic loading tests on rubber-waste mixtures conducted by Qi et al. (2017b) reveal that the inclusion of RC could increase the damping ratio of the waste mixtures.

Therefore with the high energy absorbing capacity, the inclusion of RC into the SFS+CW blends will promote enhanced strain energy absorption and reduce particle breakage of the blended mix. The aim of this study is to investigate the effect of RC content (R_b, %) on the energy absorbing property of the waste mixtures by evaluating

the strain energy density and the particle breakage of the SFS+CW+RC mixtures. To further prove the high energy absorbing property improved by adding RC, comparison between the waste materials and traditional capping layer materials will also be provided.

2. Materials

The SFS and CW used in this study were provided by Illawarra Coal and ASMS (Australia Steel Milling Services), respectively. RC was from waste tyres and three different sizes (0-2.3 mm, 0.3-3 mm, and 1-7 mm) of RC were used. The traditional capping layer materials (subballast) which is crushed rock was obtained from Bombo quarry near Wollongong, New South Wales, Australia.

The specific gravity (G_s) of SFS, CW, RC, and traditional subballast used in this study are 3.43, 2.11, 1.15, and 2.7, respectively. Fig.1 presents the particle size distribution (PSD) curves of SFS, CW, RC, and traditional subballast. The dry method was used to sieve oven-dried SFS, traditional subballast and air-dried rubber crumbs whereas the wet method was used for CW. According to the unified soil classification system (USCS), SFS and CW can be classified as well-graded gravel with silty-sand (GW-GM), and well-graded sand with gravel (SW), respectively, while RC can be referred to as granulated rubber.

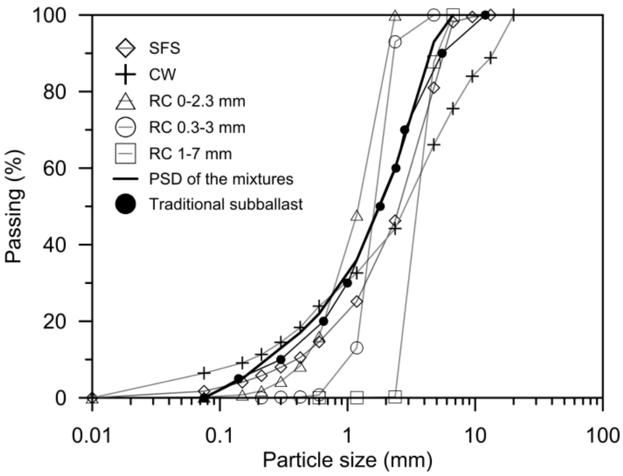

Fig.1 The particle size distribution of SFS, CW, RC, and the target PSD for the SFS+CW+RC

3. Testing Program

To exclude the influence of the gradation, all the waste mixtures are prepared with the same gradation, and the target PSD for the SFS+CW+RC mixtures is shown in Fig.1, and the target PSD is kept similar to traditional subballast. To achieve the target PSD, all the waste materials were sieved and separated into different particle sizes (6.7 mm, 4.75 mm, 2.36 mm, 1.18 mm, 0.6 mm, 0.425 mm, 0.3 mm, 0.212 mm, and < 0.212 mm), and then the exact mass according to a given size range provided by the target PSD was weighed and blended thoroughly until a uniform appearance of the waste mixture was obtained. In this study, the blending ratio of SFS:CW is kept at 7:3 as with blending ratio (by weight), the SFS+CW+RC mixtures present low volume expansion while maintain enough shear strength for a capping layer material (Indraratna et al., 2018). To investigate the influence of RC content (R_b, %) on the energy absorbing property of the waste mixtures, R_b in the blended mixtures varied from 0% to 40% (Table 1, by weight).

All the specimens for the monotonic triaxial tests and swell potential tests were prepared with the optimum moisture content (OMC, %) and compacted to achieve the initial dry unit weight equal to 95% of their maximum dry density ($\gamma_{dmax}, kN/m^3$). The specific gravity, optimum moisture content, and the maximum dry density of SFS+CW+RC mixtures and traditional subballast are shown in Table 1. It can be observed that the specific gravity of the mixtures decreases with the inclusion of RC, which is because of the low unit weight of rubber materials (Table 1). When $R_b \geq 10\%$, the dry unit weight of the SFS+CW+RC mixtures is lower than traditional subballast. This will assist in reducing the surcharge load applied to the subgrade layer. The optimum moisture content for traditional subballast is much lower than that of SFS+CW+RC mixtures.

Table-1 Geotechnial properties of SFS+CW+RC mixtures and traditional subballast

Mixtures	R_b (%)	G_s	γ_{dmax} (kN/m^3)	**OMC** (%)
SFS70+CW30	0	2.89	20.30	11.5
SFS63+CW27 +RC10	10	2.51	17.57	12.5
SFS56+CW24 +RC20	20	2.22	15.50	13
SFS49+CW21 +RC30	30	1.99	13.83	14
SFS42+CW18 +RC40	40	1.80	12.40	15
Traditional subballast	-	-	18.5	4.6

The mixtures are expressed as SFS+CW+RC, and the numbers after SFS, CW, and RC are the percentages of steel furnace slag, coal wash, and rubber crumbs by weight.

The static consolidated drained triaxial tests were carried out in accordance with ASTM D7181 (2011) following three stages, i.e. saturation, consolidation, and shearing. During the saturation stage, the air was firstly expelled by flooding deaired water from the bottom of the specimen (50 mm in diameter and 100 mm in height), then back pressure was applied at a rate of 1 kPa/minute until 500 kPa was achieved. This stage was completed when the Skempton's B-value exceeded 0.98, and then isotropic consolidation was conducted until the desired mean effective confining pressure achieved the target value (e.g. 10, 40, or 70 kPa). To simulate the practical condition of railway subbase and subballast, a low confining pressure was adopted. After consolidation, monotonic shearing was conducted with a relatively slow

constant strain rate of 0.2 mm/min to ensure fully drained conditions. The triaxial tests were completed when 25% axial strain was achieved. Once the tests were completed, sieving procedure was repeated so that particle breakage arising from the shearing process could be evaluated.

4. Results and Discussion

4.1 Stress-strain behaviour

Fig.2 (a) shows the typical stress-strain behaviour of the waste mixtures with different amounts of RC and tested at $\sigma'_3 = 70\ kPa$. It can be observed that the peak deviator stress decreases as the amount of RC increases, which is not surprising considering that rubber has very low shear strength compared to SFS and CW materials. All the specimens exhibited a predominantly strain softening behaviour accompanied by a contractive-dilative response. However, as RC contents increased, the strain softening behaviour was weakened and the axial strain corresponding to the peak deviator stress also increased. This indicates that the stress-strain response changes from brittle to ductile, likely due to an increase in the rubber-to-rubber interaction in the skeleton of the mixtures. Similar observations were also reported by Kim & Santamarina (2008) for sand-rubber mixtures.

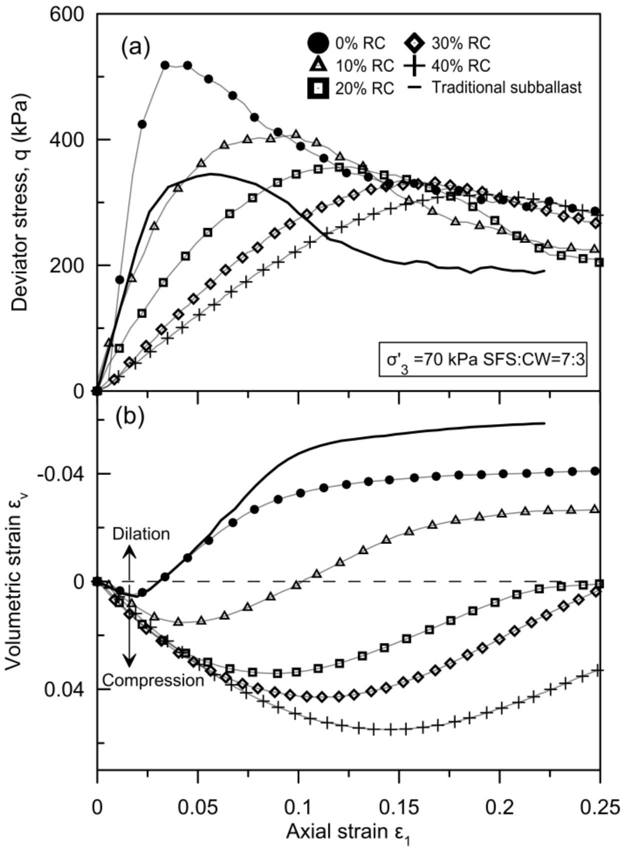

Fig.2 Stress-strain curves of SFS+CW+RC mixtures and traditional subballast under $\sigma'_3 = 70\ kPa$

The curves of axial strain versus volumetric strain of the waste mixtures are presented in Fig.2 (b). It is evident that all specimens were compressed initially, and then dilated until a certain axial strain was achieved. As expected, greater inclusion of RC results in larger compression, which is due to the high compressibility of rubber materials. For the SFS+CW+RC mixtures having 40% RC, the volumetric strain is around 6% in compression.

The stress-strain curves of traditional subballast are also shown in Fig.2. It can be observed that the peak deviator stress of traditional subballast is lower than the waste mixture with 0% and 10% of RC while similar to the waste mixture with 20% of RC. Strain softening is obvious after attaining the peak deviator stress. The volumetric strain-axial strain curve of the traditional subballast shows that the contractive part of the volumetric strain is similar to SFS+CW+RC mixture having 0% RC, but the traditional subballast exhibits more dilation when the axial strain increases. All the waste mixtures with $R_b \geq 10\%$ are more contractive than the traditional subballast. This is because of the high deformation property of rubber materials.

The peak frictional angle ($\emptyset'_{peak}$) of SFS+CW+RC mixtures and traditional subballast is shown in Table 2. It is noted that the peak shear strength decreases as the effective confining pressure increases, which is in agreement Chiaro et al. (2013) for SFS+CW mixtures. Moreover, with $R_b < 10\%$, the SFS+CW+RC mixtures (SFS:CW=7:3) has sufficient shear strength to serve as capping layer materials.

Table-2 Peak friction angle ($\emptyset'_{peak}$) of SFS+CW+RC mixtures and traditional subballast

Mixtures	R_b (%)	$\emptyset'_{peak}$ (°) at $\sigma'_3 = 10\ kPa$	$\emptyset'_{peak}$ (°) at $\sigma'_3 = 40\ kPa$	$\emptyset'_{peak}$ (°) at $\sigma'_3 = 70\ kPa$
SFS70+CW30	0	62.5	54.4	51.9
SFS63+CW27 +RC10	10	60.6	50.8	48.1
SFS56+CW24 +RC20	20	58.1	49.5	45.9
SFS49+CW21 +RC30	30	53.9	47.9	44.7
SFS42+CW18 +RC40	40	52.7	45.9	43.7
Traditional subballast	-	58.9	49.4	45.4

4.2 Energy absorption

The strain energy density is adopted to evaluate the energy absorbed in shearing triaxial tests, and it can be computed considering the area under the shear stress-strain curve up to failure (Fig.3), as represented by Equation (1)

$$E = \int_0^{\gamma_f} \tau d\gamma \tag{1}$$

where E is the strain energy density (kPa), γ_f represents the shear strain (dimensionless) up to failure, and τ is the shear strength (kPa). Failure is defined as the point when the specimen reaches the peak deviator stress, under the

static triaxial conditions, which is in agreement with Kim and Santamarina (2008) for sand-rubber mixtures.

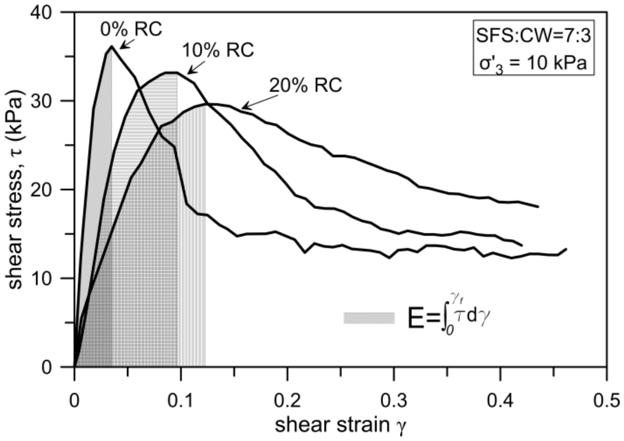

Fig.3 Shear stain-stress curve of SFS+CW+RC mixtures with 0%-20% RC under $\sigma'_3 = 10\ kPa$

Fig.4 presents the strain energy density of the SFS+CW+RC mixtures having different RC contents computed based on the drained triaxial shearing results. It can be seen that the strain energy density of the waste mixtures increases with the effective confining pressure as the peak shear stress increases with the confining pressure. Clearly, it can be observed that the strain energy density of SFS+CW+RC mixtures with $R_b = 10\%$ is around 2 folds greater than the mixtures without rubber indicating the high energy absorbing capacity of rubber materials.

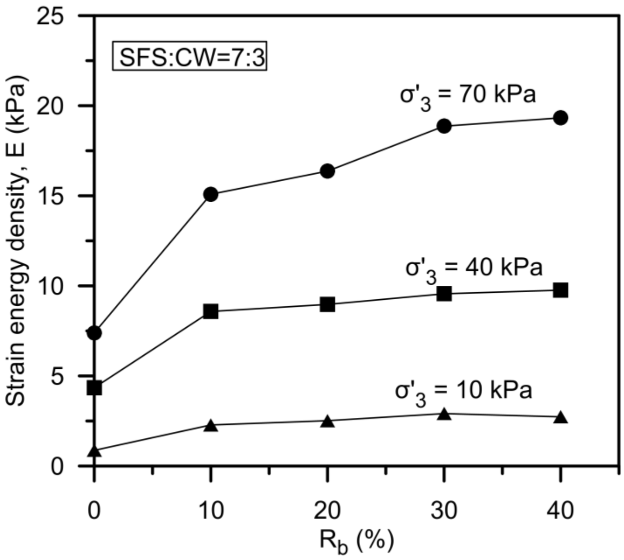

Fig.4 Strain energy density of SFS+CW+RC mixtures varying with RC contents

Furthermore, when RC > 10%, with more RC is included the increase in strain energy density is marginal, especially at lower effective confining pressures (i.e. $\sigma'_3 = 10\ and\ 40\ kPa$). This is likely related to the decrease in shear strength and particle breakage when more RC included, which can be further proved by comparing the shade area under the shear strain curve of the waste mixtures with 10% and 20% RC (Fig.3). On this basis, it seems that 10% RC is sufficient for the mixture to serve as an energy absorbing layer while tolerating an acceptable reduction in shear strength.

In Fig.5 the comparison between the strain energy density of traditional subballast and the waste mixture with 10% RC is depicted. It is obvious that using the SFS+CW+RC mixture (SFS:CW=7:3) with 10% RC can significantly improve the energy absorbing capacity of the capping layer materials. This is even more significant as the effective confining pressure increases, as evidenced by a larger gap between the strain energy density of the traditional subballast and the waste mixture with $R_b = 10\%$.

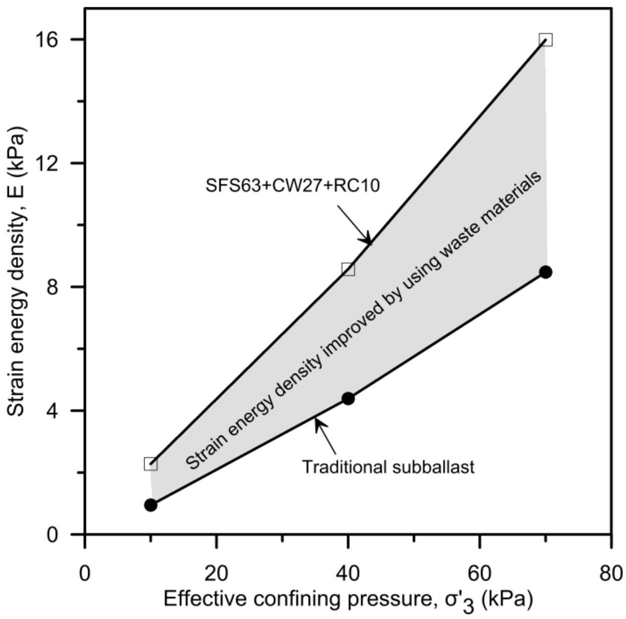

Fig.5 The strain energy density of traditional subballast and the SFS+CW+RC mixtures with 10% RC

4.3 Particle breakage

Another important method to examine the effect of the RC content on the energy absorbing property of the SFS+CW+RC mixtures is to check the particle breakage after compaction and shearing. Particle breakage is also a very important parameter that should be evaluated to quantify the level of degradation that a granular material undergoes when subjected to impact loading and shearing. Typically the incidence of particle breakage can be quantified considering the breakage index (BI) that relies on the evaluation of the initial and final gradations (Indraratna et al., 2005) shown in Fig.6 (a). In this study the BI index was determined for the waste mixtures with different RC contents upon compacting and shearing at $\sigma'_3 = 10, 40,$ and $70\ kPa$, and the test results are shown in Fig.6 (b).

As expected, the addition of rubber crumbs significantly reduced particle breakage in the waste mixtures, and BI of the waste mixtures having 30 and 40% RC is negligible. This is because of the high energy absorbing property of rubber materials the loads can be buffered as the rubber crumbs deform, which then reduces breakage of CW and SFS.

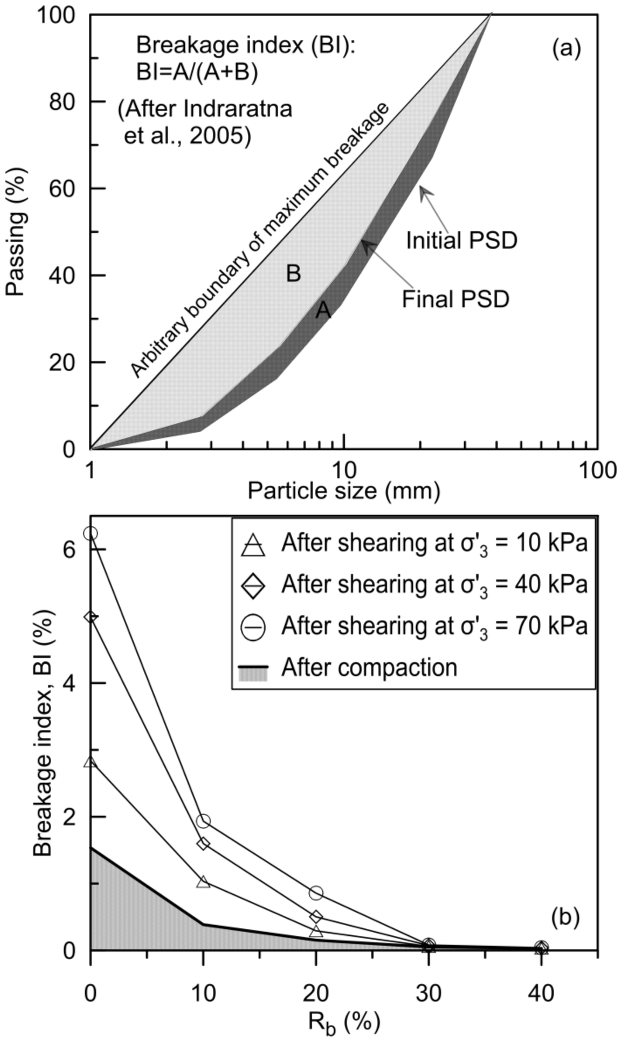

Fig.6 (a) The definition of the breakage index (after Indraratna et al., 2005), (b) BI of the SFS+CW+RC mixtures under different effective confining pressures

Moreover, BI increases as the confining pressure increases. For the waste mixtures having 0% RC, it seems that the majority of particle breakage induced by shearing occurs at low confining pressures (σ'_3 =10 kPa), and only 1% increase in BI when σ'_3 increases from 40 to 70 kPa. To ensure less deformation and less particle degradation the SFS+CW+RC mixtures with <2% BI under $\sigma'_3 = 40\ kPa$ is recommended (Indraratna et al., 2018; Qi et al., 2017a). Therefore, in the waste mixtures, RC contents should not be less than 10% to reduce the particle breakage.

5. Conclusions

In this study, rubber crumbs (0-40%) was mixed into the SFS+CW blends (with SFS:CW=7:3) in the aim of increasing the energy absorbing property of the waste mixtures. Consolidated drained triaxial tests were conducted on the waste mixtures to examine the stress-strain behavior, strain energy density, and the particle breakage of the SFS+CW+RC mixtures. The test results reveal that the inclusion of RC can significantly increase the energy absorbing capacity and reduce the particle breakage of the waste mixtures, albeit a reduction of the shear strength was observed. Therefore, with the high energy absorbing capacity, the SFS+CW+RC mixtures can be extended to dynamic loading projects, such as railway capping layer. Overall, for the SFS+CW+RC mixtures with the blending ratio of SFS:CW=7:3, 10% was suggested as the optimal RC content as with this RC content the waste mixture has sufficient energy absorbing capacity, shear strength, and acceptable particle breakage.

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