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Evaluating the Properties of Mixtures of Steel Furnace Slag, Coal Wash, and Rubber Crumbs Used as Subballast

Buddhima Indraratna
University of Wollongong, indra@uow.edu.au

Yujie Qi
University of Wollongong, qyujie@uow.edu.au

Ana Heitor
University of Wollongong, aheitor@uow.edu.au

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Abstract

Steel furnace slag (SFS) and coal wash (CW) are two common by-products from the coal-mining and steel industries in Australia. Rubber crumbs (RC) is a material derived from waste tires contributing to environmental problems in most developed countries. Reusing and recycling these waste materials is not only economically beneficial and environmentally sustainable, but it also helps to address geotechnical problems such as track degradation. In this study, SFS, CW, and RC are blended to explore the feasibility of obtaining an energy-absorbing capping layer with properties similar or superior to conventional subballast. Comprehensive laboratory investigations have been carried out to study the geotechnical properties of SFS + CW + RC mixtures, from which seven parameters (including gradation, permeability, peak friction angle, breakage index, swell pressure, strain energy density, and axial strain under cyclic loading) were used to evaluate the properties of these mixtures used as subballast. It was found that a mixture with SFS:CW = 7:3 and 10% RC (63% SFS, 27% CW, and 10% RC) is the best mixture for subballast.

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Buddhima Indraratna
PhD (Alberta), MSc and BSc-Hons (London), FTSE, FIEAust, FASCE, FGS, FAusIMM, FIES, DIC, CEng, CPEng
Distinguished Professor, Research Director and Foundation Director, Civil Engineering, Centre for Geomechanics and Railway Engineering, Faculty of Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

Yujie Qi
PhD Candidate
Centre for Geomechanics and Railway Engineering, Faculty of Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

Ana Heitor
PhD
Lecturer, Centre for Geomechanics and Railway Engineering, Faculty of Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

†Author for correspondence:
Prof. Buddhima Indraratna
School of Civil Engineering,
Faculty of Engineering, University of Wollongong
Wollongong, NSW 2522
AUSTRALIA
Ph: +61 2 4221 3046
Fax: +61 2 4221 3238
Email: indra@uow.edu.au

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Abstract: Steel furnace slag (SFS) and coal wash (CW) are two common by-products from coal mining and steel industries in Australia. Rubber crumbs (RC) is a material derived from waste tyres contributing to environmental problems in most developed countries. Reusing and recycling these waste materials is not only economically beneficial and environmentally sustainable, but it also helps to address geotechnical problems such as track degradation. In this study, SFS, CW, and RC are blended to explore the feasibility of obtaining an energy absorbing capping layer with properties similar or superior to conventional subballast. Comprehensive laboratory investigations have been carried out to study the geotechnical properties of SFS+CW+RC mixtures, from which seven parameters (including gradation, permeability, peak friction angle, breakage index, swell pressure, strain energy density, and axial strain under cyclic loading) were used to evaluate the properties of these mixtures used as subballast. It was found that a mixture with SFS:CW=7:3, and 10% RC (63% SFS, 27% CW, and 10% RC) is the best mixture for subballast.

KEYWORDS: Steel furnace slag; coal wash; rubber crumbs; subballast; reuse and recycling of waste materials

Introduction

CW and SFS are granular by-products of the coal mining and steel industries, respectively. CW is produced during the coal washing process to separate coal from its impurities using physical and chemical methods, whereas SFS is produced while converting iron to steel in a basic oxygen furnace (BOF). The production of these wastes in Australia alone can be several hundreds of millions of tonnes per year (Leventhal and de Ambrosis, 1985). While, the reuse of these granular waste by-products has substantial advantages from an economical and environmental perspective, their individual adverse geotechnical properties, i.e. breakage potential for coal wash (Indraratna, 1994, Heitor et al., 2016) and volumetric instability (swelling) for steel furnace slag (Wang, 2010) may prevent their use as individual fill materials. Past research studies have reported that the mixtures of CW and SFS can reduce particle breakage as well as control volumetric expansion (Indraratna, 1994; Chiaro et al., 2013; Heitor et al., 2014), and selected blends ratios were successfully employed as a structural fill for Port Kembla Outer Harbour reclamation (Chiaro et al., 2013).

Furthermore, based on trace element concentration tests, neither coal wash nor steel furnace slag has been found to pose any significant risk of environmental contamination. The commercial use of these engineered fills has already been approved by the Environment Protection Authority of the state of New South Wales (NSW EPA, 2014). Similarly, chemical test results reported by Lim and Chu (2006) indicate that the heavy metal concentrations contained in a typical steel slag leachate were significant lower than the threshold toxicity limits stipulated by the US EPA.

The application of scrap tyres in civil works includes soil reinforcement in road construction, ground erosion control, vibration isolation, non-structural sound barrier fills, slope stabilisation, lightweight materials for backfilling retaining structures, and additive materials to asphalt (Sheikh et al. 2013; Gibson et al., 2012; Qi et al., 2006). Recycled tyres are typically granulated or shredded and exhibit frictional behaviour, low unit weight of solids (the specific gravity generally ranges from 1.00 to 1.36), low bulk density, high hydraulic conductibility, exothermic reactions and high compressibility (Senetakis et al., 2012; Zheng and Kevin, 2000; Edil and Bosscher, 1994).

Although past studies have proposed viable and cost-effective alternative solutions using these waste materials (coal wash, steel furnace slag, and scrap tyres) in construction projects either individually, blended or mixed with soil, no past study has quantified the behaviour of the mixture of these three waste materials. Further, while the behaviour of selected blends of CW and SFS has proven to conform to the performance criteria adopted for Port reclamation (Tasalotti et al., 2015), it was limited to monotonic loading conditions. Under cyclic loads such as those encountered in a track substructure, the incidence of CW particles breakage is likely to be exacerbated. The addition of rubber crumbs to the mixtures can promote enhanced strain energy absorption while simultaneously increasing the overall permeability, reducing particle breakage and controlling the expansion of the blended mix.

This study has attempted to develop an energy absorption mixture using coal wash, steel surface slag, and rubber crumbs as subballast in a railway system in a way that is economically and environmentally friendly, while also minimizing track degradation and the need for freshly quarried natural aggregates.

Parameters Used to Evaluate the Waste Mixtures

The main functions of the subballast layer are filtration, drainage, and controlled stress distribution reaching the soft subgrade soil. While a suitable gradation prevents the upward migration of fine particles from subgrade to the ballast layer, a relatively high permeability sustains effective drainage of the substructure. Further, the subballast also requires adequate stiffness to control load distribution to the subgrade. For selecting the SFS+CW+RC mixtures used as a suitable subballast layer material, the three functional parameters i.e. gradation, permeability coefficient, as well as the peak friction angle should be considered firstly (Table 1). The required range of parameters was set to ensure the optimum composition of SFS+CW+RC mixtures having mechanical properties similar to or superior to traditional subballast materials.

The adverse individual geotechnical properties of the three granular wastes, i.e. breakage, swelling and low shear strength must be controlled properly to enable the SFS+CW+RC mixtures to be used as subballast. Thus three other parameters are used to control the adverse geotechnical properties of the SFS+CW+RC mixtures (Table 1). The breakage index (BI) should not exceed that of conventional subballast (2% for crushed rock upon shearing with $\sigma'_3 = 40$ kPa) in order to maintain its function as a filter. The swell pressure should be less than the minimum overburden and wheel load stresses (i.e. 30kPa; Ferreira & Teixeira, 2012). The axial strain of the optimum mixture under cyclic loading should be less than the mean acceptable axial strain of subballast (0.02; Teixeira et al., 2006).

The addition of rubber crumbs enhances the potential for the waste mixtures to absorb strain energy from external loads, thus contributing to a reduction in ballast degradation and the stresses transmitted to the subgrade. The strain energy density adopted to evaluate the energy-absorbing capacity is another parameter considered when optimizing the waste mixtures (Table 1).

In order to obtain the above parameters, comprehensive and detailed laboratory investigations were carried out on traditional subballast (crushed rock) and SFS+CW+RC mixtures. The testing program consisted of compaction tests, permeability tests, monotonic and cyclic triaxial tests, swell pressure tests and breakage evaluation through wet sieving after compaction and shearing.

Laboratory Testing Program

Materials

The source materials selected were a Dendrobium coal wash produced by Illawarra Coal and a SFS produced ASMS (Australia Steel Milling Services), respectively. Coal wash is predominantly composed quartz and residual coal, with illite and kaolinite as the main clay minerals. Trace quantities of calcite, pyrites and sulphur were also detected in the x-ray diffraction analysis. The CW aggregates are composed of both angular and relatively flaky grains, and typically exhibits dual porosity. The steel furnace slag is composed mainly of metal compounds (e.g. Fe_2O_3, SiO_2) and free lime (CaO). The chemical composition of CW and SFS determined by X-ray diffraction analysis provided by the ASMS and the BHP Illawarra Coal is shown in Table 2.

RC was from waste tyres and in this study three different size (0-2.3mm, 0.3-3mm, and 1-7 mm) rubber crumbs were used. The traditional subballast material (crushed rock) was obtained from Bombo quarry near Wollongong, New South Wales, Australia. The particle size distribution (PSD) curves of SFS, CW, RC, and crushed rock are shown in Fig. 1. The dry method was used to sieve oven-dried SFS, crushed rock, and air-dried rubber crumbs whereas the wet method was used for CW. SFS and CW can be classified as well-graded gravel with silty-sand (GW-GM), and well-graded sand with gravel (SW) (unified soil classification system, USCS), respectively, while RC can be referred to as granulated rubber (ASTM D6270, 2008).

Specimen preparation and testing program

In order to satisfy the filter criteria of subballast and exclude the influence of gradation, all the mixtures tested in this study were mixed to the same gradation (the target PSD) selected based on conventional subballast gradation adopted in Victoria and Queensland (Australia) also shown in Fig.1. Three waste materials (SFS, CW, and RC) were blended into mixtures with different ratios of SFS:CW (5:5, 6:4, 7:3, 8:2, and 9:1) and different amounts of rubber crumbs (RC) (0%, 10%, 20%, 30%, and 40%). The waste mixtures with selected blend ratios were prepared by mixing different percentages of oven-dried SFS and CW, and air-dried RC by weight in order to reach the target PSD. In this study the three materials were mixed by weight rather than by volume. This is because "by weight" percentage could be more accurately measured during mixture preparation, as the volume of solids depends on the specific gravity and will also vary with the temperature, water content, and the age of rubber particles (Edil and Bosscher, 1994; Zheng & Kiven, 2000). Previous studies such as Navarro and Gamez, (2012), Xu et al., (2013), and Al-Khateeb & Ramadan (2015) also prepared the rubber-soil mixtures based on weight%.

To achieve the target PSD, the waste materials were sieved and separated into different particle sizes, and the exact mass corresponding to a given size range provided by the target PSD was weighed and blended thoroughly to obtain a uniform blend. A past study by Tasalloti et al. (2015) has demonstrated this method earlier. All the specimens for permeability tests, monotonic and cyclic triaxial tests, and swell pressure tests were prepared with the optimum moisture content and compacted to achieve the initial dry unit weight equal to 95% of their γ_{dmax} to simulate subballast behaviour under typical placement conditions. The specimens for monotonic and cyclic triaxial tests are 50 mm in diameter and 100 mm in height. The maximum particle size of the materials is around 7 mm, thus the ratio of specimen diameter (50 mm) to the maximum particle size is around 7.1. Previous studies have shown that the equipment boundary size effects can be neglected when this ratio exceeds at least 6 (Marachi et al., 1972; Indraratna, 1994).

The monotonic 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 the deaired water from the bottom of the specimen, then back pressure was applied with the increasing 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 was achieved to 40 kPa to simulate common *in situ* heavy haul track conditions. The confining pressure for subballast materials of heavy haul tracks is typically ≤40 kPa in the field, and it depends upon the axle loads, embankment heights and the depth of subballast and structural fill (Indraratna et al., 2011; Indraratna et al, 2014). After consolidation, monotonic shearing was conducted with a relatively slow constant strain rate of 0.2 mm/min to ensure fully drained conditions were maintained during shearing, and the triaxial tests were completed when 25% axial strain was achieved. Once the tests were completed, sieving procedure was repeated and particle breakage was evaluated. Membrane correction was applied using ASTM D7181 (2011) procedure assuming an axial strain of 25%, rubber membrane thickness of 0.25 mm, and Young's modulus of rubber membrane of 1100 kPa, resulting in a deviator stress correction of 5.7 kPa which is insignificant (<3% error) for the test specimens.

The stress-controlled drained cyclic triaxial tests were carried out to investigate the axial displacement of SFS+CW+RC mixtures with SFS:CW=7:3 and different amounts of RC (0%, 10%, 20%, 30%, and 40%) following the procedure suggested by ASTM D5311/D5311M (2013). The specimens were 50 mm in diameter and 100 mm in height. The cyclic loading tests were conducted following three stages, i.e. saturation, consolidation, and cyclic loading.

The saturation and consolidation stages were the same with monotonic triaxial tests. The cyclic loading stage was conducted at CSR=0.8 (cyclic stress ratio, Eq. 1). Accordingly, the deviator stress used is governed by σ'_3 and the cyclic stress ratio, CSR. For CSR=0.8, and a confining pressure of $\sigma'_3 = 40\ kPa$, the corresponding deviator stress (axial stress) is 64 kPa. This value is in line with the observed capping stress conditions (axial stress σ'_a ≤70 kPa) in typical freight tracks in NSW, Australia (Indraratna et al., 2011). A loading frequency $f = 5\ Hz$ was used to simulate a quasi-static condition which is usually adopted in track design procedures, so that the mass inertia effects of the specimen can be neglected (Suiker et al., 2005). The cyclic loading test was continued for 50000 cycles to ensure that all the tests would end with an approximately stable axial strain.

$$\boldsymbol{CSR = \frac{\sigma_a}{2\sigma'_3}} \quad (1)$$

In the above, CSR is the cyclic stress ratio; $\boldsymbol{\sigma_a}$ is the average single amplitude cyclic axial stress; and $\boldsymbol{\sigma'_3}$ is the effective confining pressure.

The swell pressure of the selected blends was evaluated through constant volume tests using CBR moulds and a hot water bath at temperature of 40°C (as rubber materials melt around 50-60°C) to accelerate the tests procedure. In these tests, the swelling of the specimen (158 mm in diameter and 112 mm high) was prevented by constraining the vertical swell, and the maximum pressure measured by a load cell was monitored (Basma et al., 1995). The swell pressure can be inferred after a period of typically 20 days, upon which variations in the vertical pressure were considered negligible.

Results and Discussion

Index properties

The basic geotechnical properties (specific gravity $\mathrm{G_s}$, maximum dry density γ_{dmax}, optimum moisture content (OMC), and permeability coefficient k) of SFS, CW, RC, their mixtures, and crushed rock are shown in Table 3. Of these three waste materials, SFS is the densest ($\mathrm{G_s} = 3.43$), and RC is the lightest ($\mathrm{G_s} = 1.15$). Thus, the maximum dry unit weight (γ_{dmax}) increases as the amount of SFS increases, and decreases as the amount of RC increases. The optimum moisture content changes slightly from 12.5% to 15% as the ratio of SFS:CW, and the amount of RC changes. It is of interest to note that the void ratio (e_0) of the mixtures after compaction at OMC increases as the RC content and the ratios of SFS:CW increase. This will partially explain the change of permeability coefficient of the mixtures in the following discussion.

The permeability coefficients for the SFS+CW+RC mixtures were evaluated by constant head permeability tests (ASTM D2434, 2006b). The tests results for specimens with different amounts of rubber compacted at their OMC are plotted in Fig. 2. The permeability of these waste mixtures increases with larger content of rubber crumbs as well as the increasing ratios of SFS:CW, because a larger amount of RC or SFS results in an increase in the corresponding void ratio. This is consistent with observations reported by Chiaro et al. (2013) for SFS and CW blends. It seems that all the waste mixtures with SFS:CW$\geq 5:5$, and RC$\geq 10\%$ could ensure a good drainage condition, as the 'good drainage' permeability range for subballast was between 10^{-5} m/sec and 10^{-3} m/sec (Trani and Indraratna, 2010).

Stress-strain behaviour

Figs. 3 (a) and (b) show the typical stress-strain and volumetric strain behaviour of the waste mixtures with different amounts of RC and different ratios of SFS:CW, respectively. It can be observed that the peak deviator stress decreases as the amount of RC increases (Fig. 3a), and increases as the dosage of SFS:CW increases (Fig. 3b). This is not surprising considering that rubber has very low shear strength comparatively to SFS and CW materials, and SFS has superior stiffness compared to CW. Similar observations were reported by Tasalloti et al., (2015) for CW-SFS blends. All the specimens exhibited a predominantly strain softening behaviour accompanied by a contractive-dilative response. As expected, an increase in RC results in larger compression, and an increase in the ratios of SFS:CW generates greater dilation, but no variation of the peak compression volumetric strain was observed for different ratios of SFS:CW while maintaining the same RC content. This indicates that the contraction response is mainly governed by the amount of RC. Moreover, the axial strain corresponding to the peak deviator stress increases with the addition of RC indicating the stress-strain behaviour changes from brittle to a predominantly ductile response, likely due to an increasing rubber-to-rubber interaction in the skeleton of the mixtures. Similar observations have been reported by Kim and Santamarina (2008) for mixtures of sand and rubber tyre crumbs.

Peak friction angle

The friction angle of the waste mixtures determined considering the peak deviator stress ($\emptyset'_{peak}$) is shown in Fig. 4 (a) and Table 4. As with the peak stress, the peak friction angle decreases as the amount of RC increases, and it increases as the ratio of SFS:CW increases. It is noteworthy that for the ratios of SFS:CW smaller than 5:5, the addition of RC exceeding 10% results in $\emptyset'_{peak}$ being smaller than those typically adopted for traditional subballast (e.g. crushed rock, $\emptyset'_{peak} = 49°$). In contrast, the waste mixtures having ratios of SFS:CW$\geq$ $7:3$, and RC $\leq 20\%$ exhibit a higher shear strength than conventional subballast (Fig. 4a).

Particle breakage

Particle breakage 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 the top right corner of Fig. 4 (b). In this study the BI index was determined for the selected waste mixtures with different ratios of SFS:CW and RC content upon shearing at $\sigma'_3 = 40\ kPa$. The summary of results is shown in Fig. 4 (b), while the experimental data is listed in Table 4. As expected, the addition of rubber crumbs significantly reduced particle breakage in the waste mixtures. This suggests that loads can be buffered as the rubber crumbs deform (i.e. strain energy absorption), which then reduces breakage of CW and SFS. Moreover, when the ratio of SFS:CW increases, particle breakage also decreases due to the smaller content of CW.

The breakage index (BI) of conventional subballast (crushed rock) measured was 2%, as also noted in Fig. 4 (b). If a similar performance to that of conventional subballast is to be achieved, it seems that blends having ratios of SFS:CW≥7:3 and 10% RC will be sufficient to ensure particle breakage within acceptable limits (Fig. 4b).

Energy absorption

The strain energy density is the parameter usually adopted for evaluating the energy absorbed in shearing tests, and it can be computed considering the area under the shear stress-strain curve up to failure (Fig. 4c), as represented by Eq. 2

$$\boldsymbol{E} = \int_{\mathbf{0}}^{\gamma_f} \boldsymbol{\tau d \gamma} \tag{2}$$

where E is the strain energy density (kPa), γ_f is the shear strain (dimensionless) up to failure, and τ is the shear strength (kPa).

The strain energy density up to the failure of various waste mixtures computed based on the triaxial drained shearing results is plotted in Fig. 4 (c). When the same RC content was maintained, increasing the rate of SFS:CW only generated little increase of the strain energy density. However, there is a substantial increase in strain energy density as the RC content increases indicating the high ductility of rubber crumbs. Interestingly, the strain energy density of the waste mixtures without rubber crumbs is similar to traditional subballast, which confirms that it is the addition of RC to the waste mix that enhanced its energy absorbing capacity (Fig. 4c), although once 10% of RC is exceeded the increase is marginal. This is likely related to the decrease in shear strength (e.g. Fig. 4a) and decrease in particle breakage (e.g. Fig. 4b). 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.

Swell pressure

Fig. 5 and Table 4 report the results of swell pressure P_{swell} of the SFS+CW+RC mixtures obtained. As expected, the increase in CW and RC proportions in the mixtures effectively contributes to a reduction in the swell pressure of the waste mixtures. For instance, for the same amount of RC, the swell pressure of the waste mixtures decreases with the decreasing ratio of SFS:CW in the mixtures (Fig. 5a). Similarly, the addition of RC while maintaining the same ratio of SFS:CW contributes to a reduction in the swell pressure because the volumetric expansion caused by the hydration of free lime present in SFS can be partially counteracted as the rubber crumbs deform. However, for RC content greater than 10%, the swell pressure of the waste mixtures only decreases marginally (Fig. 5b). This indicates that 10% would be an optimum percentage of RC to control the swelling of the SFS+CW+RC mixtures.

Axial displacement under cyclic loading

Fig. 6 shows the axial strain ε_a of SFS+CW+RC mixtures for different RC content changing with loading cycles. Almost 90% axial strain of the all the specimens is achieved in the first 500 cycles; axial displacement increases marginally in the subsequent cycles and becomes relatively stable after 50000 cycles. It was noted that with the increasing amount of RC, the axial strain of the SFS+CW+RC mixtures increased but at a decreasing rate (Fig. 7). The presence of RC in the waste material mix makes it increasingly compressible. Both field measurements and laboratory triaxial testing indicate that the mixtures undergo overall compression upon cyclic loading, and there is no volumetric dilation as the radial (lateral) strains are very small. For a maximum axial strain of 0.012 for the mix with SFS:CW=7:3, and 10% RC, the associated lateral tensile strain is less than 0.002 (0.2 %), which is very small to be of concern. Also, no test specimens have indicated any cracking during triaxial compression which confirms that the occurrence of adverse tensile strains is not a concern. The average axial strain of conventional subballast is in the proximity of 0.02 (Teixeira et al., 2006), and therefore based on these test results, the amount of RC in the waste mixtures should not exceed about 18%.

Identifying the optimum SFS+CW+RC Mixture

In the test program, all the waste mixtures were suitably graded because they have the same gradation as conventional subballast. Moreover, the permeability, energy-absorbing capacity and particle breakage characteristics of all the waste mixtures with RC ≥ 10 % and SFS:CW≥5:5 satisfy the required range in Table 1. However, having a greater proportion SFS induces increased swelling, and greater the CW content, the lower the shear strength, i.e. the ratio of SFS:CW plays a crucial role in governing the level of shear strength and the swell pressure of the waste mixtures. To select the optimum mixture, the ratio of SFS:CW was first justified by using the test results of the shear strength and swell pressure of waste mixtures with 10% RC, and then the amount of RC was optimised using the comprehensive test results of the waste mixtures with the selected ratio of SFS:CW.

Fig. 8 shows the ratio of SFS:CW was justified in the optimum mixture according to the peak friction angle and swell pressure. To ensure that the optimum mixture has a higher shear strength than conventional subballast and less swell pressure compared to the typical loads applied to the capping layer, the waste mixtures should satisfy $\emptyset'_{peak} \geq 49°$, and $P_{swell} < 30kPa$ (shaded region in Fig. 8), thus the ratio of SFS:CW = 7:3 could be selected as an optimum ratio.

The permeability k and energy absorption property of all the mixtures with SFS:CW=7:3 satisfied the required range in Table 1. Fig. 9 shows that only mixtures with RC from 8~18.5% satisfy the required range based on particle breakage (BI$\leq$ 2%) and shear strength ($\emptyset_{peak} \geq 49°$), and only mixtures with RC from 2~18% satisfy the required range of axial strain under cyclic loading ($\leq 2\%$) and swell pressure ($P_{swell} < 30kPa$). Therefore, the combined acceptable range of particle breakage, shear strength, axial strain, and swell pressure, the amount of RC in the waste mixtures should be between 8~18%. It is interesting to note that 10% of RC is sufficient to improve substantially the energy-absorbing capacity of the waste mixtures, without influencing significantly the axial displacement and associated shear strength in both static and cyclic loading conditions. On this basis, 10% of RC can be taken as the optimum amount of RC.

In summary, the optimum mixture could be established as SFS63+CW27+RC10 (SFS:CW=7:3, and 10% RC). While the results reported herein are promising, it is important to note that findings reported in this paper may not be applicable to all types of SFS+CW+RC mixtures because the geotechnical properties of these waste materials depend strongly on the original source and manufacturing processes. For this reason, it is strongly recommended that field trials be carried out on the selected SFS+CW+RC mixtures to investigate their actual performance under cyclic loading.

Conclusions

A comprehensive laboratory testing program was carried out for SFS+CW +RC mixtures to investigate the relevant geotechnical properties (permeability, stress-strain behaviour, strain energy absorption, particle breakage, swell pressure and axial displacement under cyclic loading). The testing program consisted of permeability tests, compaction tests, drained consolidated monotonic and cyclic triaxial tests, swell pressure tests and sieving tests.

It was found as the amount of RC was increased in the waste mixtures, the permeability coefficient increased, particle breakage decreased, extent of energy absorbed increased, and the swell pressure decreased. However, the addition of RC should have an upper limit, because a higher RC content also results in reduced shear strength and greater axial displacement.

The ratio of SFS:CW governs the swell pressure and shear strength of the waste mixtures. The increasing ratios of SFS:CW enhance the shear strength, but also induce higher swell pressure.

In order to identify a suitable SFS+CW+RC mixture for subballast, the required range of the seven parameters (including gradation, permeability, peak friction angle, breakage index, swell pressure, strain energy density, and axial strain under cyclic loading) was formulated by comparing the geotechnical characteristics of conventional subballast. A ratio of 7:3 of SFS:CW was selected based on the test results of swell pressure and shear strength. Then the optimal RC content (10%) was proposed based on the shear strength, particle breakage, swell pressure, and the axial strain subjected to cyclic loading. Finally, the optimum mixture to replace conventional subballast was established as SFS63+CW27+RC10 (63% SFS, 27% CW, and 10% RC).

Typically, capping materials used for rail substructure includes crushed rock, coarse sands and natural gravels and these materials cost around $45 per tonne, whereas waste materials such as CW and SFS costs less than half. Therefore it will be economical attractive and environmental friendly to replace the natural subballast materials.

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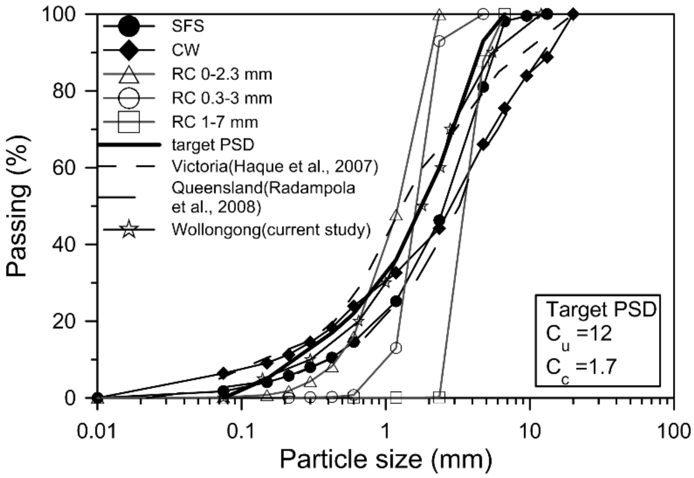

Fig. 1 PSD of the individual waste materials and the mixtures

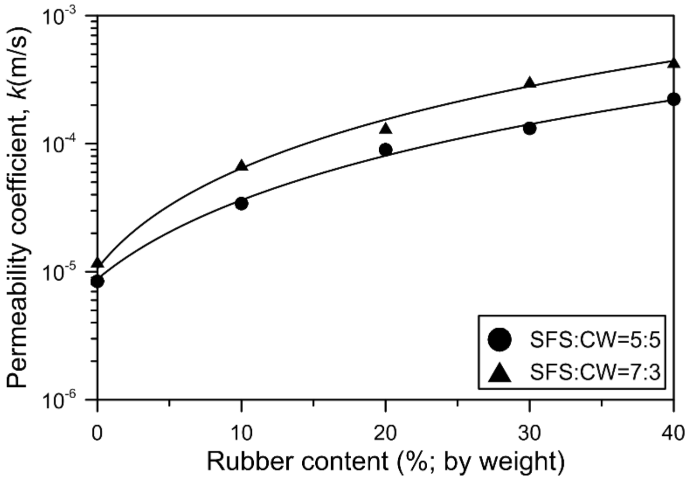

Fig. 2 Permeability coefficient for different ratios of SFS:CW and different amount of RC

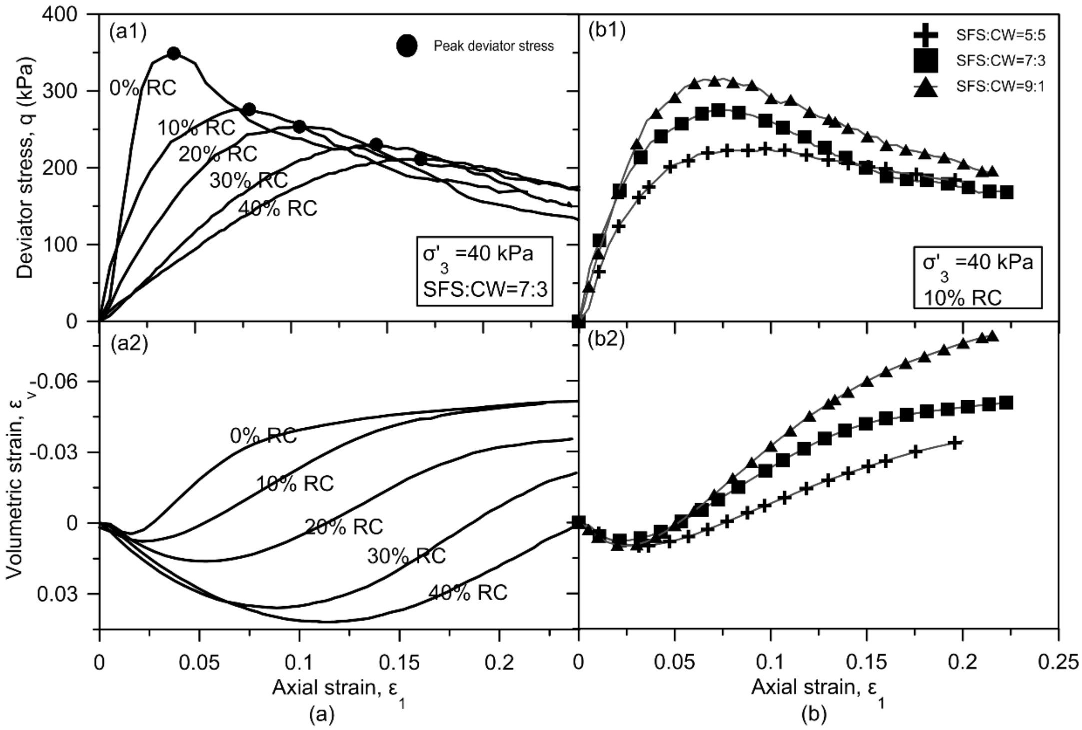

Fig. 3 Triaxial consolidated drained shearing of waste mixtures: (a) for different amount of RC with SFS:CW=7:3; (b) for different ratios of SFS:CW with 10% RC

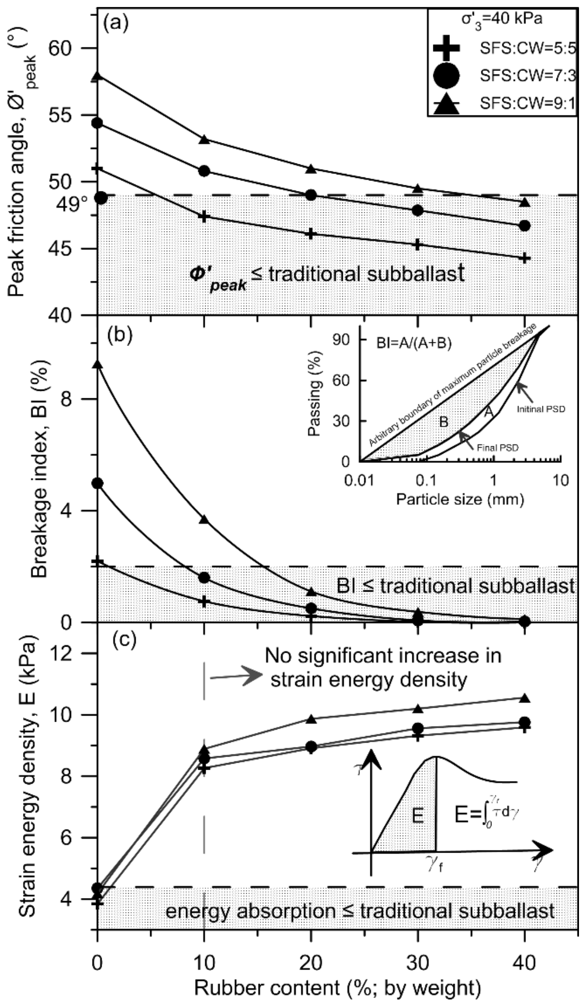

Fig. 4 Peak friction angle, breakage index, and strain energy density for different ratios of SFS:CW and different amount of RC

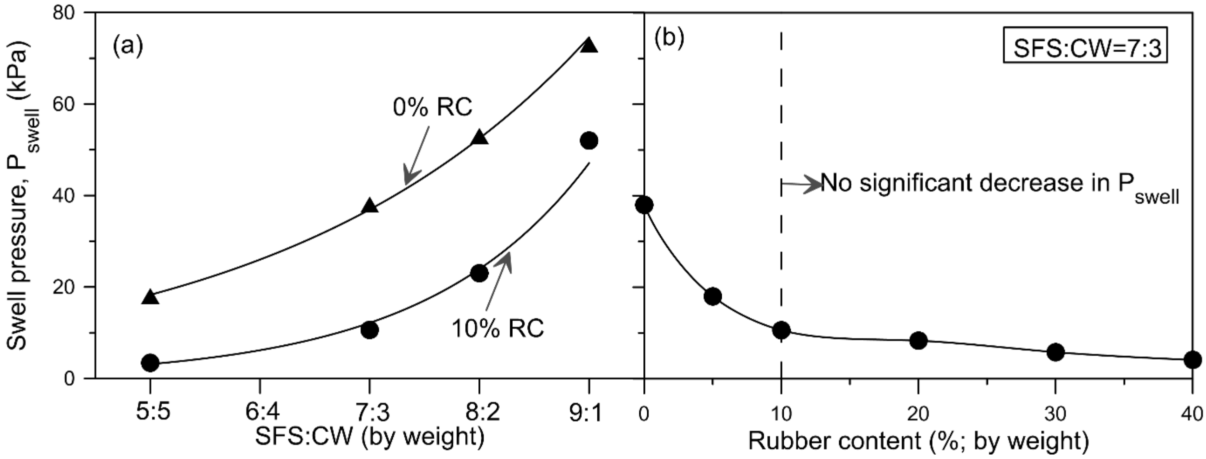

Fig. 5 (a) Swell pressure for SFS+CW+RC mixtures with different ratios of SFS:CW; (b) Swell pressure of SFS+CW+RC mixtures for different amount of RC (SFS:CW=7:3)

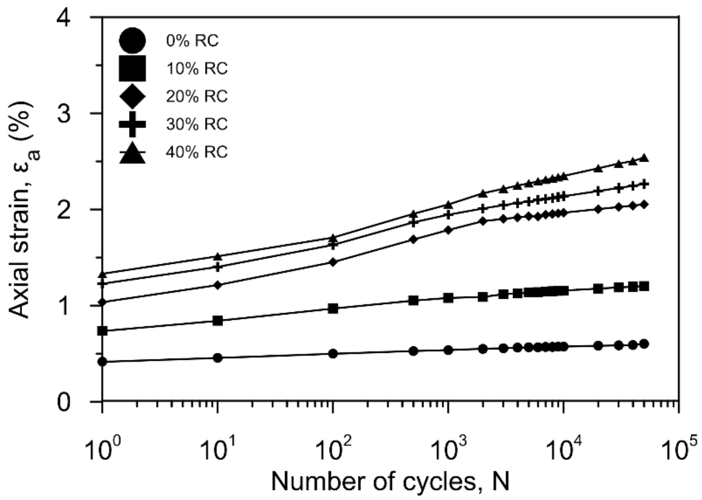

Fig. 6 Axial strain of SFS+CW+RC mixtures for different RC content

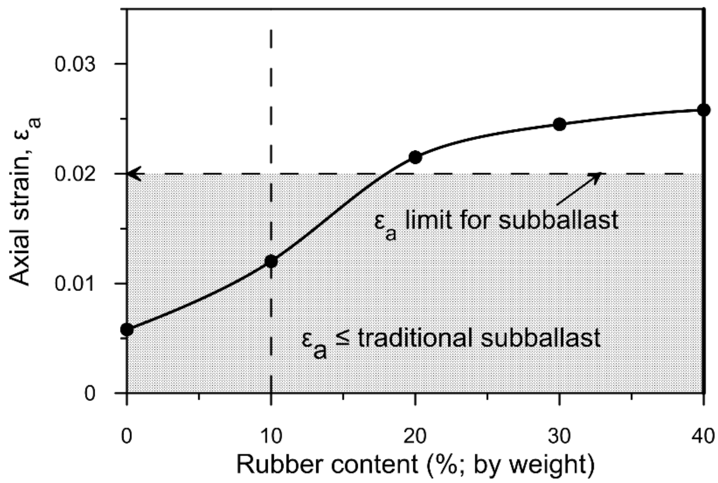

Fig. 7 Axial strain of SFS+CW+RC mixtures with different amount of RC after 50000 cycles

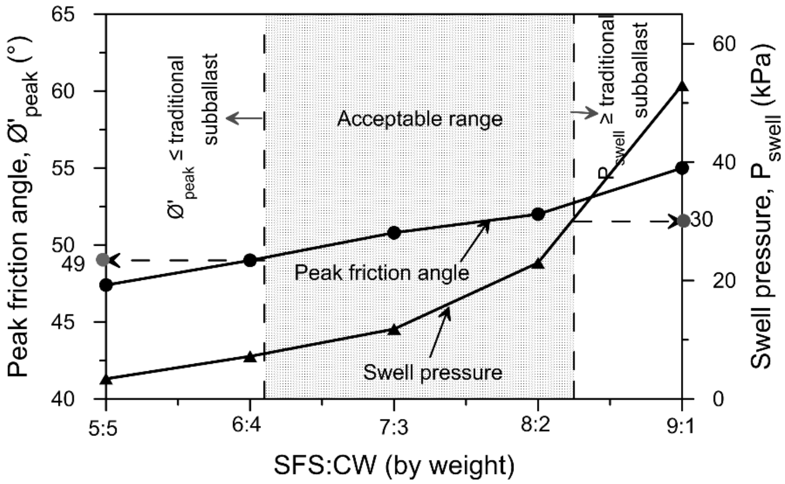

Fig. 8 Optimisation of the ratio of SFS:CW based on the shear strength and swell pressure of waste mixtures with 10% RC

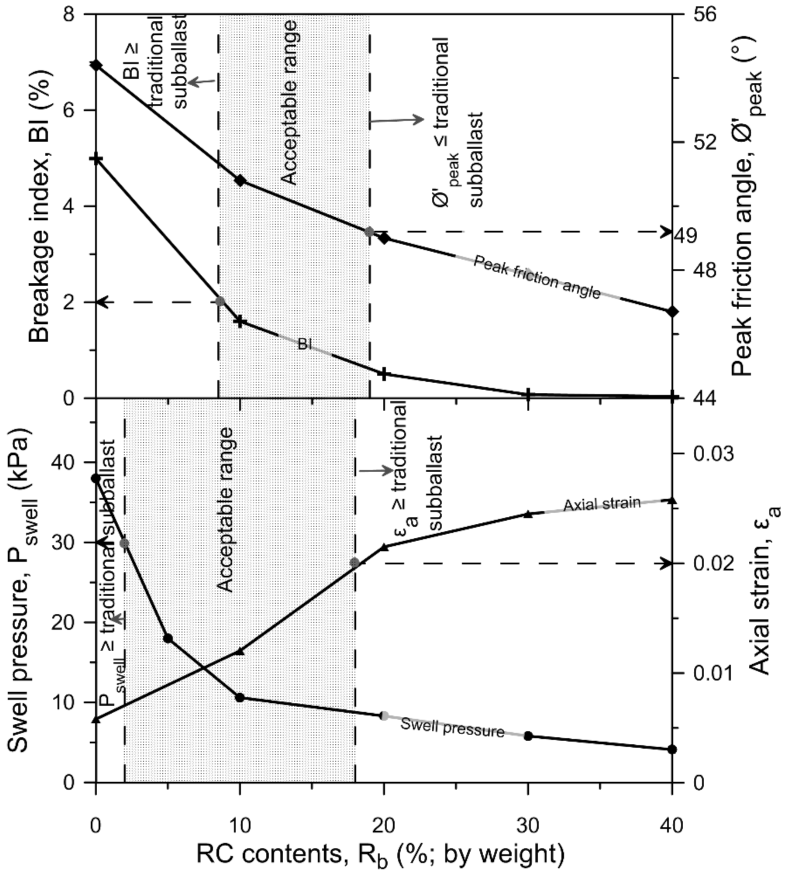

Fig. 9 Optimisation of RC content based on the peak friction angle, BI, swell pressure and axial strain of waste mixtures with SFS:CW=7:3

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Table 1 Parameters and the required range used to evaluate SFS+CW+RC mixtures for subballast

Parameters	**Required range**	**References**
Gradation	similar with traditional subballast	Haque et al., 2007; Radampola et al., 2008
Permeability coefficient	$10^{-5} \leq k \leq 10^{-3}$ m/sec	Trani & Indraratna, 2010
Peak friction angle	$\emptyset'_{\boldsymbol{peak}} \geq 49°$	current study
The breakage index	BI < 2%	current study
swell pressure	$P_{swell} < 30$ kPa	Ferreira &Teixeira, 2012
Mean acceptable axial strain (cyclic)	$\varepsilon_a \leq 0.02$	Teixeira et al., 2006
Strain energy density	E≥ 4.39 kPa	current study

Table 2 Typical chemical composition of CW and SFS

SFS		**CW**	
Components	Proportion (%)	Components	Proportion (%)
SiO_2	12.5	Ash	65.6
Al_2O_3	2.8	Carbon	24.3
CaO	38.3	Volatiles	14.4
MgO	9.9	Hydrogen	1.90
Fe_2O_3	30	Nitrogen	0.55
MnO	3.7	Sulphur	0.23
TiO_2	1.2	Phospor	0.02
Others	1.6		

*Provided by the ASMS and the BHP Illawarra Coal.

Table 3 Basic geotechnical properties of SFS, CW, RC, the SFS+CW+RC mixtures, and the traditional subballast

Material	**SFS:CW**	**RC (%)**	G_s	γ_{dmax} (kN/m^3)	**OMC (%)**	e_0	k **(m/sec)**
SFS	-	-	3.43	-	-	-	-
CW	-	-	2.11	-	-	-	-
RC	-	-	1.15	-	-	-	-
SFS50+CW50		0	2.61	18.60	12.5	0.449	8.4×10^{-6}
SFS45+CW45+RC10		10	2.32	16.45	13	0.455	3.4×10^{-5}
SFS40+CW40+RC20	5:5	20	2.08	14.70	15	0.461	8.95×10^{-5}
SFS35+CW35+RC30		30	1.89	13.28	13.5	0.469	1.32×10^{-4}
SFS30+CW30+RC40		40	1.73	12.1	15	0.476	2.23×10^{-4}
SFS54+CW36+RC10	6:4	10	2.41	16.77	13.5	0.471	-
SFS70+CW30		0	2.89	20.30	11.5	0.470	1.2×10^{-5}
SFS63+CW27+RC10		10	2.51	17.57	12.5	0.474	6.86×10^{-5}
SFS56+CW24+RC20	7:3	20	2.22	15.50	13	0.479	1.13×10^{-4}
SFS49+CW21+RC30		30	1.99	13.83	14	0.485	3.05×10^{-4}
SFS42+CW18+RC40		40	1.80	12.40	15	0.499	4.35×10^{-4}
SFS72+CW18+RC10	8:2	10	2.61	18.2	13.5	0.480	-
SFS90+CW10		0	3.23	22.6	13	0.475	-
SFS81+CW9+RC10		10	2.74	19.0	14	0.483	-
SFS72+CW8+RC20	9:1	20	2.37	16.4	14.5	0.492	-
SFS63+CW7+RC30		30	2.09	14.4	15	0.498	-
SFS54+CW6+RC40		40	1.87	12.8	15	0.508	-
Traditional subballast (crushed rock)	-	-	2.7	18.5	4.6	0.423	-

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.

Table 4 Peak friction angle, post-shearing breakage index (BI), and strain energy density (after shearing at $\sigma'_3 = 40\ kPa$), and swell pressure of SFS+CW+RC mixtures and traditional subballast

Materials	**SFS:CW**	**RC (%)**	$\emptyset'_{peak}$ (°)	**P_{swell} (kPa)**	**BI (%)**	**E (kPa)**
SFS50+CW50	5:5	0	51	18	9.27	3.85
SFS45+CW45+RC10		10	47.4	3.4	3.71	8.27
SFS40+CW40+RC20		20	46.1	-	1.11	8.91
SFS35+CW35+RC30		30	44.5	-	0.38	9.32
SFS30+CW30+RC40		40	43.9	-	0.13	9.59
SFS54+CW36+RC10	6:4	10	49	-	-	-
SFS70+CW30	7:3	0	54.4	38	4.99	4.35
SFS66.5+CW28.5+RC5		5	-	18.2	-	-
SFS63+CW27+RC10		10	50.8	10.6	1.60	8.58
SFS56+CW24+RC20		20	49	8.3	0.503	8.97
SFS49+CW21+RC30		30	47.86	5.8	0.073	9.56
SFS42+CW18+RC40		40	46.6	4.1	0.038	9.76
SFS80+CW20	8:2	0	-	53	-	-
SFS72+CW18+RC10		10	52	23	-	-
SFS90+CW10	9:1	0	60	73	2.2	4.18
SFS81+CW9+RC10		10	55	52	0.76	8.89
SFS72+CW8+RC20		20	52	-	0.23	9.87
SFS63+CW7+RC30		30	50.5	-	0.02	10.20
SFS54+CW6+RC40		40	49	-	0	10.56
Traditional subballast (crushed rock)		-	49	-	2.0	4.39