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Indraratna, Buddhima; Qi, Yujie; and Heitor, Ana, "Evaluating the Properties of Mixtures of Steel Furnace Slag, Coal Wash, and Rubber Crumbs Used as Subballast" (2018). *Faculty of Engineering and Information Sciences - Papers: Part B*. 1407.

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

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.

Disciplines

Engineering | Science and Technology Studies

Publication Details

Indraratna, B., Qi, Y. & Heitor, A. (2018). Evaluating the Properties of Mixtures of Steel Furnace Slag, Coal Wash, and Rubber Crumbs Used as Subballast. *Journal of Materials in Civil Engineering*, 30 (1), 04017251-1-04017251-9.

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

4

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35 **To be submitted to: Journal of Materials in Civil Engineering**

36

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

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

52

53 **Introduction**

54 CW and SFS are granular by-products of the coal mining and steel industries, respectively.
55 CW is produced during the coal washing process to separate coal from its impurities using
56 physical and chemical methods, whereas SFS is produced while converting iron to steel in a
57 basic oxygen furnace (BOF). The production of these wastes in Australia alone can be several
58 hundreds of millions of tonnes per year (Leventhal and de Ambrosis, 1985). While, the reuse
59 of these granular waste by-products has substantial advantages from an economical and
60 environmental perspective, their individual adverse geotechnical properties, i.e. breakage
61 potential for coal wash (Indraratna, 1994, Heitor et al., 2016) and volumetric instability
62 (swelling) for steel furnace slag (Wang, 2010) may prevent their use as individual fill
63 materials. Past research studies have reported that the mixtures of CW and SFS can reduce
64 particle breakage as well as control volumetric expansion (Indraratna, 1994; Chiaro et al.,
65 2013; Heitor et al., 2014), and selected blends ratios were successfully employed as a
66 structural fill for Port Kembla Outer Harbour reclamation (Chiaro et al., 2013).

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

74 The application of scrap tyres in civil works includes soil reinforcement in road construction,
75 ground erosion control, vibration isolation, non-structural sound barrier fills, slope
76 stabilisation, lightweight materials for backfilling retaining structures, and additive materials

77 to asphalt (Sheikh et al. 2013; Gibson et al., 2012; Qi et al., 2006). Recycled tyres are
78 typically granulated or shredded and exhibit frictional behaviour, low unit weight of solids
79 (the specific gravity generally ranges from 1.00 to 1.36), low bulk density, high hydraulic
80 conductivity, exothermic reactions and high compressibility (Senetakis et al., 2012; Zheng
81 and Kevin, 2000; Edil and Bosscher, 1994).

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

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

96 **Parameters Used to Evaluate the Waste Mixtures**

97 The main functions of the subballast layer are filtration, drainage, and controlled stress
98 distribution reaching the soft subgrade soil. While a suitable gradation prevents the upward
99 migration of fine particles from subgrade to the ballast layer, a relatively high permeability
100 sustains effective drainage of the substructure. Further, the subballast also requires adequate

101 stiffness to control load distribution to the subgrade. For selecting the SFS+CW+RC mixtures
102 used as a suitable subballast layer material, the three functional parameters i.e. gradation,
103 permeability coefficient, as well as the peak friction angle should be considered firstly (Table
104 1). The required range of parameters was set to ensure the optimum composition of
105 SFS+CW+RC mixtures having mechanical properties similar to or superior to traditional
106 subballast materials.

107 The adverse individual geotechnical properties of the three granular wastes, i.e. breakage,
108 swelling and low shear strength must be controlled properly to enable the SFS+CW+RC
109 mixtures to be used as subballast. Thus three other parameters are used to control the adverse
110 geotechnical properties of the SFS+CW+RC mixtures (Table 1). The breakage index (BI)
111 should not exceed that of conventional subballast (2% for crushed rock upon shearing with
112 $\sigma'_3 = 40$ kPa) in order to maintain its function as a filter. The swell pressure should be less
113 than the minimum overburden and wheel load stresses (i.e. 30kPa; Ferreira & Teixeira,
114 2012). The axial strain of the optimum mixture under cyclic loading should be less than the
115 mean acceptable axial strain of subballast (0.02; Teixeira et al., 2006).

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

121 In order to obtain the above parameters, comprehensive and detailed laboratory investigations
122 were carried out on traditional subballast (crushed rock) and SFS+CW+RC mixtures. The
123 testing program consisted of compaction tests, permeability tests, monotonic and cyclic

124 triaxial tests, swell pressure tests and breakage evaluation through wet sieving after
125 compaction and shearing.

126 **Laboratory Testing Program**

127 *Materials*

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

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

146

147 *Specimen preparation and testing program*

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

162 To achieve the target PSD, the waste materials were sieved and separated into different
163 particle sizes, and the exact mass corresponding to a given size range provided by the target
164 PSD was weighed and blended thoroughly to obtain a uniform blend. A past study by
165 Tasalloti et al. (2015) has demonstrated this method earlier. All the specimens for
166 permeability tests, monotonic and cyclic triaxial tests, and swell pressure tests were prepared
167 with the optimum moisture content and compacted to achieve the initial dry unit weight equal
168 to 95% of their γ_{dmax} to simulate subballast behaviour under typical placement conditions.
169 The specimens for monotonic and cyclic triaxial tests are 50 mm in diameter and 100 mm in
170 height. The maximum particle size of the materials is around 7 mm, thus the ratio of
171 specimen diameter (50 mm) to the maximum particle size is around 7.1. Previous studies

172 have shown that the equipment boundary size effects can be neglected when this ratio
173 exceeds at least 6 (Marachi et al., 1972; Indraratna, 1994).

174 The monotonic triaxial tests were carried out in accordance with ASTM D7181 (2011)
175 following three stages, i.e. saturation, consolidation, and shearing. During the saturation stage,
176 the air was firstly expelled by flooding the deaired water from the bottom of the specimen,
177 then back pressure was applied with the increasing rate of 1 kPa/minute until 500 kPa was
178 achieved. This stage was completed when the Skempton's B-value exceeded 0.98, and then
179 isotropic consolidation was conducted until the desired mean effective confining pressure
180 was achieved to 40 kPa to simulate common *in situ* heavy haul track conditions. The
181 confining pressure for subballast materials of heavy haul tracks is typically ≤ 40 kPa in the
182 field, and it depends upon the axle loads, embankment heights and the depth of subballast and
183 structural fill (Indraratna et al., 2011; Indraratna et al, 2014). After consolidation, monotonic
184 shearing was conducted with a relatively slow constant strain rate of 0.2 mm/min to ensure
185 fully drained conditions were maintained during shearing, and the triaxial tests were
186 completed when 25% axial strain was achieved. Once the tests were completed, sieving
187 procedure was repeated and particle breakage was evaluated. Membrane correction was
188 applied using ASTM D7181 (2011) procedure assuming an axial strain of 25%, rubber
189 membrane thickness of 0.25 mm, and Young's modulus of rubber membrane of 1100 kPa,
190 resulting in a deviator stress correction of 5.7 kPa which is insignificant (<3% error) for the
191 test specimens.

192 The stress-controlled drained cyclic triaxial tests were carried out to investigate the axial
193 displacement of SFS+CW+RC mixtures with SFS:CW=7:3 and different amounts of RC (0%,
194 10%, 20%, 30%, and 40%) following the procedure suggested by ASTM D5311/D5311M
195 (2013). The specimens were 50 mm in diameter and 100 mm in height. The cyclic loading
196 tests were conducted following three stages, i.e. saturation, consolidation, and cyclic loading.

197 The saturation and consolidation stages were the same with monotonic triaxial tests. The
198 cyclic loading stage was conducted at CSR=0.8 (cyclic stress ratio, Eq. 1). Accordingly, the
199 deviator stress used is governed by σ'_3 and the cyclic stress ratio, CSR. For CSR=0.8, and a
200 confining pressure of $\sigma'_3 = 40 \text{ kPa}$, the corresponding deviator stress (axial stress) is 64 kPa.
201 This value is in line with the observed capping stress conditions (axial stress $\sigma'_a \leq 70 \text{ kPa}$) in
202 typical freight tracks in NSW, Australia (Indraratna et al., 2011). A loading frequency
203 $f = 5 \text{ Hz}$ was used to simulate a quasi-static condition which is usually adopted in track
204 design procedures, so that the mass inertia effects of the specimen can be neglected (Suiker et
205 al., 2005). The cyclic loading test was continued for 50000 cycles to ensure that all the tests
206 would end with an approximately stable axial strain.

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

207 In the above, CSR is the cyclic stress ratio; σ_a is the average single amplitude cyclic axial
208 stress; and σ'_3 is the effective confining pressure.

209 The swell pressure of the selected blends was evaluated through constant volume tests using
210 CBR moulds and a hot water bath at temperature of 40°C (as rubber materials melt around
211 50-60°C) to accelerate the tests procedure. In these tests, the swelling of the specimen (158
212 mm in diameter and 112 mm high) was prevented by constraining the vertical swell, and the
213 maximum pressure measured by a load cell was monitored (Basma et al., 1995). The swell
214 pressure can be inferred after a period of typically 20 days, upon which variations in the
215 vertical pressure were considered negligible.

216 **Results and Discussion**

217 *Index properties*

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

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

237 ***Stress-strain behaviour***

238 Figs. 3 (a) and (b) show the typical stress-strain and volumetric strain behaviour of the waste
239 mixtures with different amounts of RC and different ratios of SFS:CW, respectively. It can be
240 observed that the peak deviator stress decreases as the amount of RC increases (Fig. 3a), and
241 increases as the dosage of SFS:CW increases (Fig. 3b). This is not surprising considering that

242 rubber has very low shear strength comparatively to SFS and CW materials, and SFS has
243 superior stiffness compared to CW. Similar observations were reported by Tasalloti et al.,
244 (2015) for CW-SFS blends. All the specimens exhibited a predominantly strain softening
245 behaviour accompanied by a contractive-dilative response. As expected, an increase in RC
246 results in larger compression, and an increase in the ratios of SFS:CW generates greater
247 dilation, but no variation of the peak compression volumetric strain was observed for
248 different ratios of SFS:CW while maintaining the same RC content. This indicates that the
249 contraction response is mainly governed by the amount of RC. Moreover, the axial strain
250 corresponding to the peak deviator stress increases with the addition of RC indicating the
251 stress-strain behaviour changes from brittle to a predominantly ductile response, likely due to
252 an increasing rubber-to-rubber interaction in the skeleton of the mixtures. Similar
253 observations have been reported by Kim and Santamarina (2008) for mixtures of sand and
254 rubber tyre crumbs.

255 ***Peak friction angle***

256 The friction angle of the waste mixtures determined considering the peak deviator stress
257 (ϕ'_{peak}) is shown in Fig. 4 (a) and Table 4. As with the peak stress, the peak friction angle
258 decreases as the amount of RC increases, and it increases as the ratio of SFS:CW increases. It
259 is noteworthy that for the ratios of SFS:CW smaller than 5:5, the addition of RC exceeding
260 10% results in ϕ'_{peak} being smaller than those typically adopted for traditional subballast
261 (e.g. crushed rock, $\phi'_{peak} = 49^\circ$). In contrast, the waste mixtures having ratios of SFS:CW \geq
262 7: 3, and RC \leq 20% exhibit a higher shear strength than conventional subballast (Fig. 4a).

263 ***Particle breakage***

264 Particle breakage should be evaluated to quantify the level of degradation that a granular
265 material undergoes when subjected to impact loading and shearing. Typically the incidence

266 of particle breakage can be quantified considering the breakage index (BI) that relies on the
267 evaluation of the initial and final gradations (Indraratna et al. 2005) shown in the top right
268 corner of Fig. 4 (b). In this study the BI index was determined for the selected waste mixtures
269 with different ratios of SFS:CW and RC content upon shearing at $\sigma'_3 = 40 \text{ kPa}$. The
270 summary of results is shown in Fig. 4 (b), while the experimental data is listed in Table 4. As
271 expected, the addition of rubber crumbs significantly reduced particle breakage in the waste
272 mixtures. This suggests that loads can be buffered as the rubber crumbs deform (i.e. strain
273 energy absorption), which then reduces breakage of CW and SFS. Moreover, when the ratio
274 of SFS:CW increases, particle breakage also decreases due to the smaller content of CW.

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

279 *Energy absorption*

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

$$E = \int_0^{\gamma_f} \tau d\gamma \quad (2)$$

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

285 The strain energy density up to the failure of various waste mixtures computed based on the
286 triaxial drained shearing results is plotted in Fig. 4 (c). When the same RC content was
287 maintained, increasing the rate of SFS:CW only generated little increase of the strain energy

288 density. However, there is a substantial increase in strain energy density as the RC content
289 increases indicating the high ductility of rubber crumbs. Interestingly, the strain energy
290 density of the waste mixtures without rubber crumbs is similar to traditional subballast, which
291 confirms that it is the addition of RC to the waste mix that enhanced its energy absorbing
292 capacity (Fig. 4c), although once 10% of RC is exceeded the increase is marginal. This is
293 likely related to the decrease in shear strength (e.g. Fig. 4a) and decrease in particle breakage
294 (e.g. Fig. 4b). On this basis, it seems that 10% RC is sufficient for the mixture to serve as an
295 energy absorbing layer while tolerating an acceptable reduction in shear strength.

296 *Swell pressure*

297 Fig. 5 and Table 4 report the results of swell pressure P_{swell} of the SFS+CW+RC mixtures
298 obtained. As expected, the increase in CW and RC proportions in the mixtures effectively
299 contributes to a reduction in the swell pressure of the waste mixtures. For instance, for the
300 same amount of RC, the swell pressure of the waste mixtures decreases with the decreasing
301 ratio of SFS: CW in the mixtures (Fig. 5a). Similarly, the addition of RC while maintaining
302 the same ratio of SFS: CW contributes to a reduction in the swell pressure because the
303 volumetric expansion caused by the hydration of free lime present in SFS can be partially
304 counteracted as the rubber crumbs deform. However, for RC content greater than 10%, the
305 swell pressure of the waste mixtures only decreases marginally (Fig. 5b). This indicates that
306 10% would be an optimum percentage of RC to control the swelling of the SFS+CW+RC
307 mixtures.

308 *Axial displacement under cyclic loading*

309 Fig. 6 shows the axial strain ϵ_a of SFS+CW+RC mixtures for different RC content changing
310 with loading cycles. Almost 90% axial strain of the all the specimens is achieved in the first
311 500 cycles; axial displacement increases marginally in the subsequent cycles and becomes

312 relatively stable after 50000 cycles. It was noted that with the increasing amount of RC, the
313 axial strain of the SFS+CW+RC mixtures increased but at a decreasing rate (Fig. 7). The
314 presence of RC in the waste material mix makes it increasingly compressible. Both field
315 measurements and laboratory triaxial testing indicate that the mixtures undergo overall
316 compression upon cyclic loading, and there is no volumetric dilation as the radial (lateral)
317 strains are very small. For a maximum axial strain of 0.012 for the mix with SFS:CW=7:3,
318 and 10% RC, the associated lateral tensile strain is less than 0.002 (0.2 %), which is very
319 small to be of concern. Also, no test specimens have indicated any cracking during triaxial
320 compression which confirms that the occurrence of adverse tensile strains is not a concern.
321 The average axial strain of conventional subballast is in the proximity of 0.02 (Teixeira et al.,
322 2006), and therefore based on these test results, the amount of RC in the waste mixtures
323 should not exceed about 18%.

324 **Identifying the optimum SFS+CW+RC Mixture**

325 In the test program, all the waste mixtures were suitably graded because they have the same
326 gradation as conventional subballast. Moreover, the permeability, energy-absorbing capacity
327 and particle breakage characteristics of all the waste mixtures with $RC \geq 10\%$ and
328 $SFS:CW \geq 5:5$ satisfy the required range in Table 1. However, having a greater proportion
329 SFS induces increased swelling, and greater the CW content, the lower the shear strength, i.e.
330 the ratio of SFS:CW plays a crucial role in governing the level of shear strength and the swell
331 pressure of the waste mixtures. To select the optimum mixture, the ratio of SFS:CW was first
332 justified by using the test results of the shear strength and swell pressure of waste mixtures
333 with 10% RC, and then the amount of RC was optimised using the comprehensive test results
334 of the waste mixtures with the selected ratio of SFS:CW.

335 Fig. 8 shows the ratio of SFS:CW was justified in the optimum mixture according to the peak
336 friction angle and swell pressure. To ensure that the optimum mixture has a higher shear
337 strength than conventional subballast and less swell pressure compared to the typical loads
338 applied to the capping layer, the waste mixtures should satisfy $\phi'_{peak} \geq 49^\circ$, and $P_{swell} <$
339 $30kPa$ (shaded region in Fig. 8), thus the ratio of SFS:CW = 7:3 could be selected as an
340 optimum ratio.

341 The permeability k and energy absorption property of all the mixtures with SFS:CW=7:3
342 satisfied the required range in Table 1. Fig. 9 shows that only mixtures with RC from 8~18.5%
343 satisfy the required range based on particle breakage ($BI \leq 2\%$) and shear strength ($\phi_{peak} \geq$
344 49°), and only mixtures with RC from 2~18% satisfy the required range of axial strain under
345 cyclic loading ($\leq 2\%$) and swell pressure ($P_{swell} < 30kPa$). Therefore, the combined
346 acceptable range of particle breakage, shear strength, axial strain, and swell pressure, the
347 amount of RC in the waste mixtures should be between 8~18%. It is interesting to note that
348 10% of RC is sufficient to improve substantially the energy-absorbing capacity of the waste
349 mixtures, without influencing significantly the axial displacement and associated shear
350 strength in both static and cyclic loading conditions. On this basis, 10% of RC can be taken
351 as the optimum amount of RC.

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

359 **Conclusions**

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

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

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

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

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

386 **Acknowledgements**

387 The first author would like to acknowledge the financial assistance provided by the China
388 Scholarship Council. The assistance provided by industry (ASMS and South 32) in relation to
389 the procurement of material used in this study is gratefully acknowledged. The assistance in
390 the laboratory from Mr. Richard Berndt and the occasional technical feedback from A/Prof
391 Cholachat Rujikiatkamjorn and Dr Vinod S. Jayan are appreciated.

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487

488 **List of Figures**

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

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

491 Fig. 3 Triaxial consolidated drained shearing of waste mixtures: (a) for different amount of

492 RC with SFS:CW=7:3; (b) for different ratios of SFS:CW with 10% RC

493 Fig. 4 Peak friction angle, breakage index, and strain energy density for different ratios of

494 SFS:CW and different amount of RC

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

496 Swell pressure of SFS+CW+RC mixtures for different amount of RC (SFS:CW=7:3)

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

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

499 Fig. 8 Optimisation of the ratio of SFS:CW based on the shear strength and swell pressure of

500 waste mixtures with 10% RC

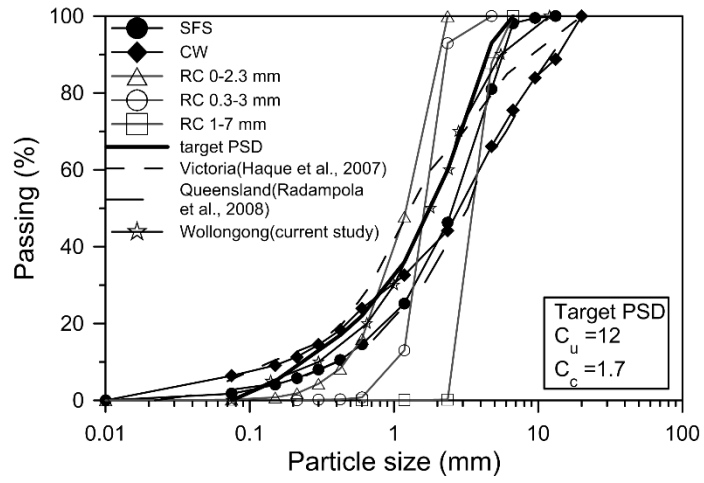
501 Fig. 9 Optimisation of RC content based on the peak friction angle, BI, swell pressure and

502 axial strain of waste mixtures with SFS:CW=7:3

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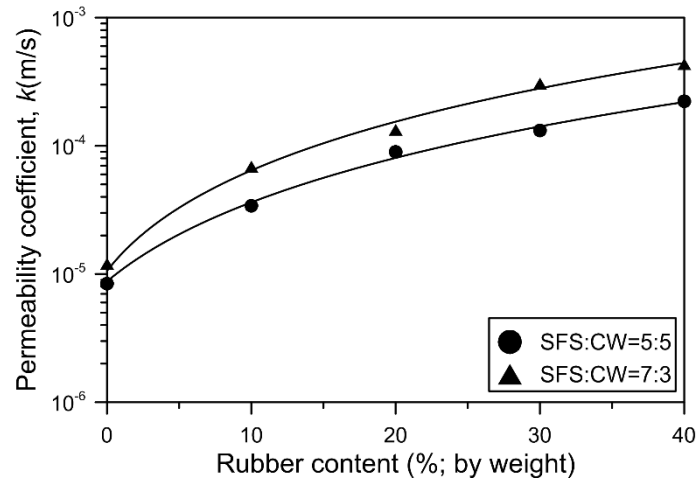
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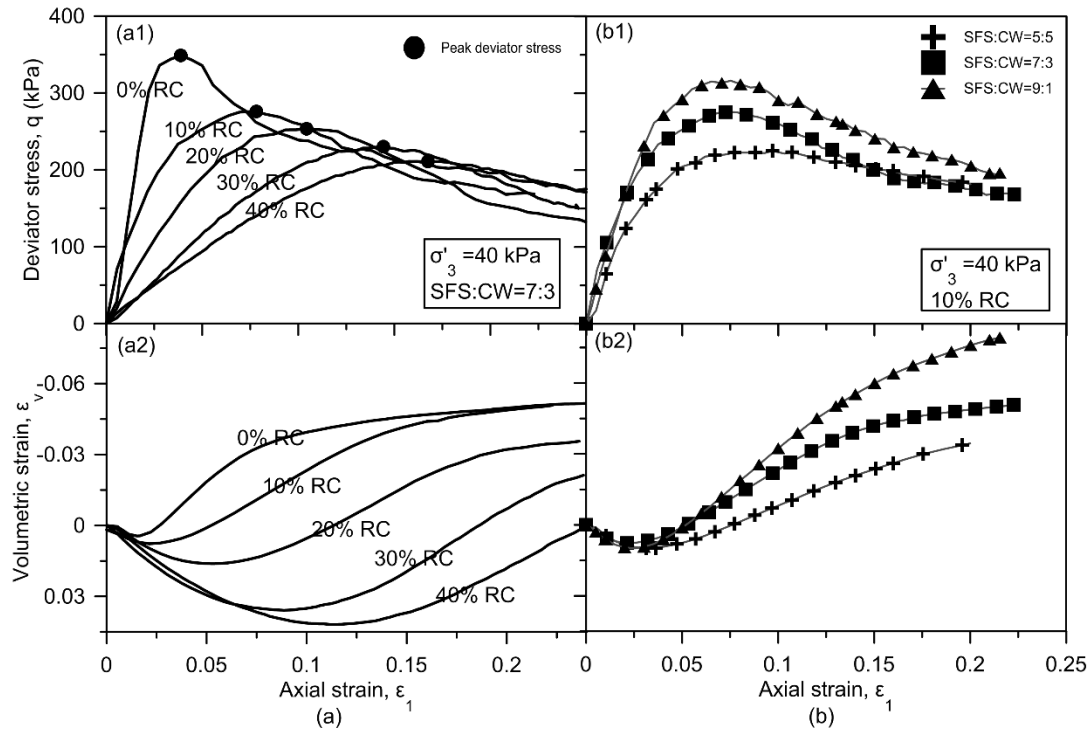
Fig. 1 PSD of the individual waste materials and the mixtures



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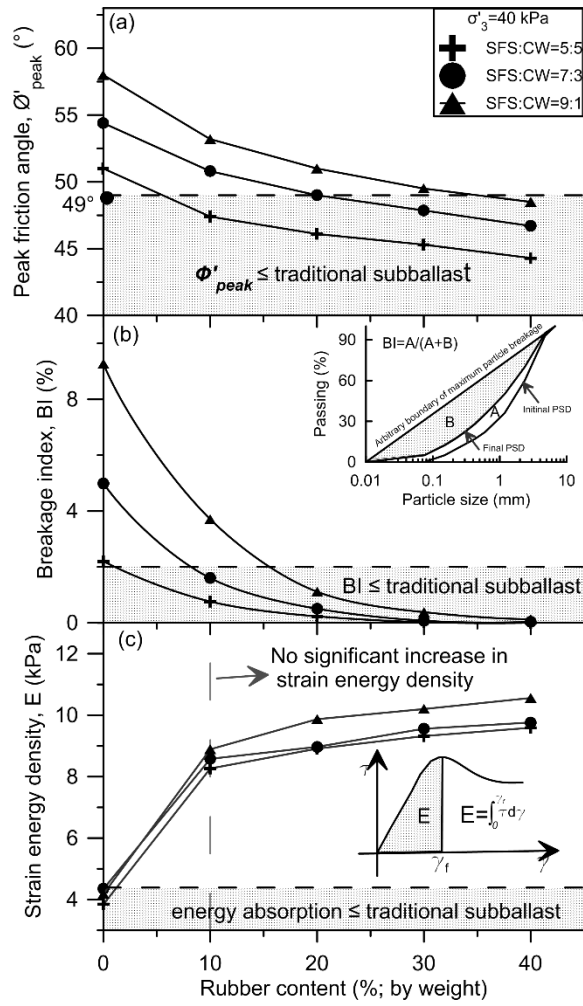
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512 RC with SFS: CW=7:3; (b) for different ratios of SFS: CW with 10% RC

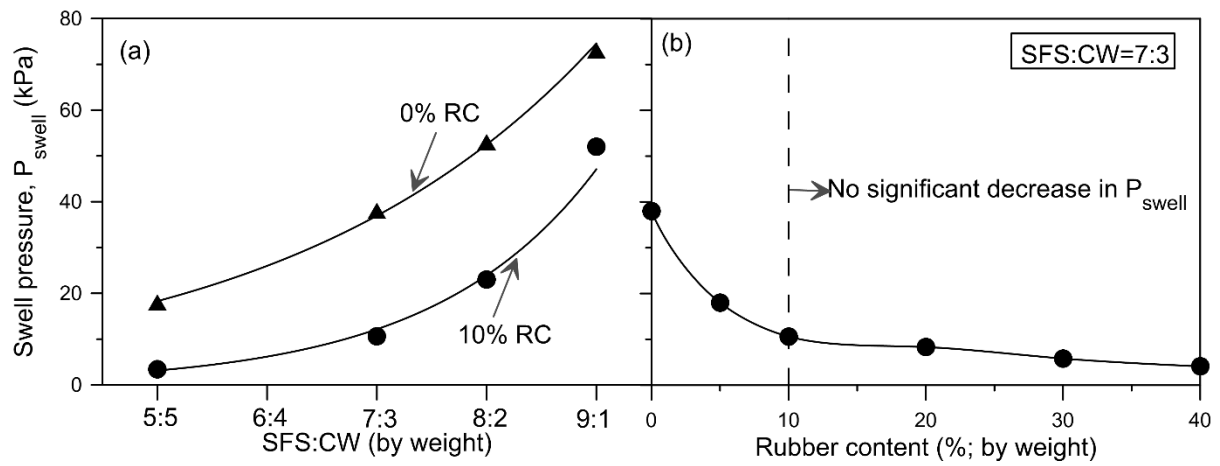


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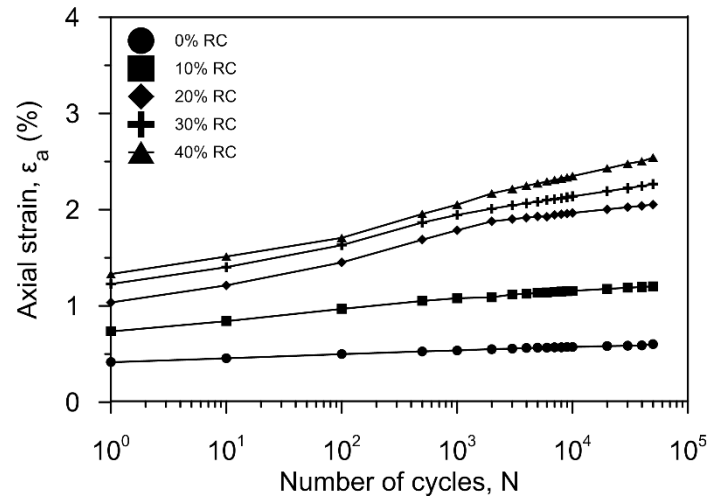
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Fig. 4 Peak friction angle, breakage index, and strain energy density for different ratios of SFS:CW and different amount of RC



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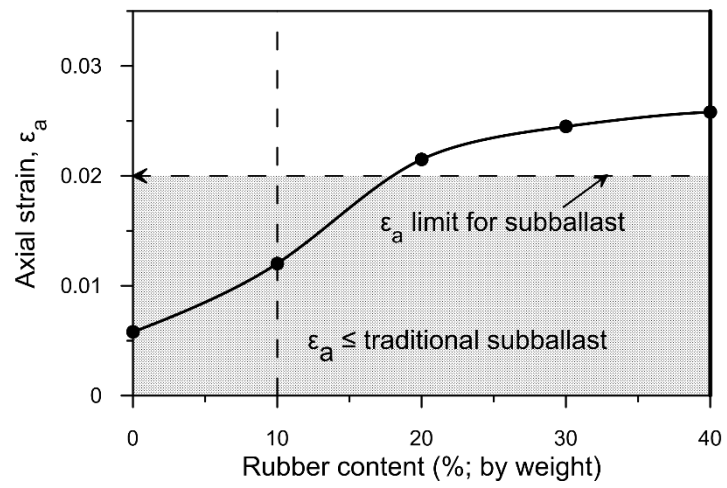
517 Fig. 5 (a) Swell pressure for SFS+CW+RC mixtures with different ratios of SFS:CW; (b)
 518 Swell pressure of SFS+CW+RC mixtures for different amount of RC (SFS:CW=7:3)



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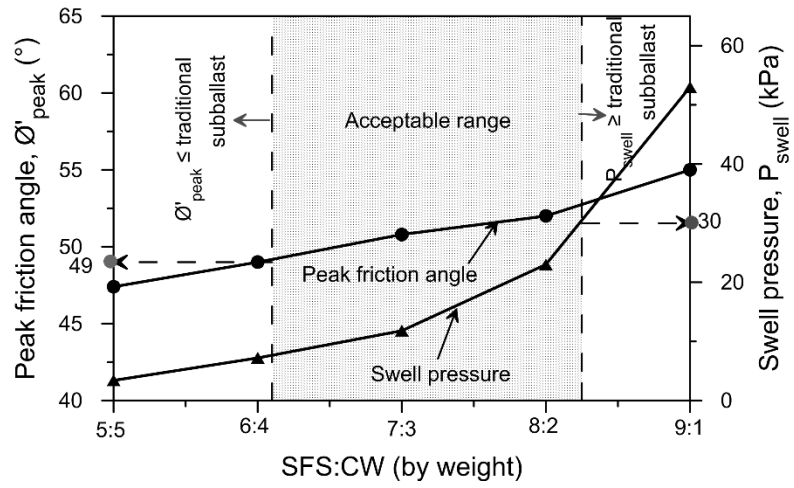
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Fig. 6 Axial strain of SFS+CW+RC mixtures for different RC content



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

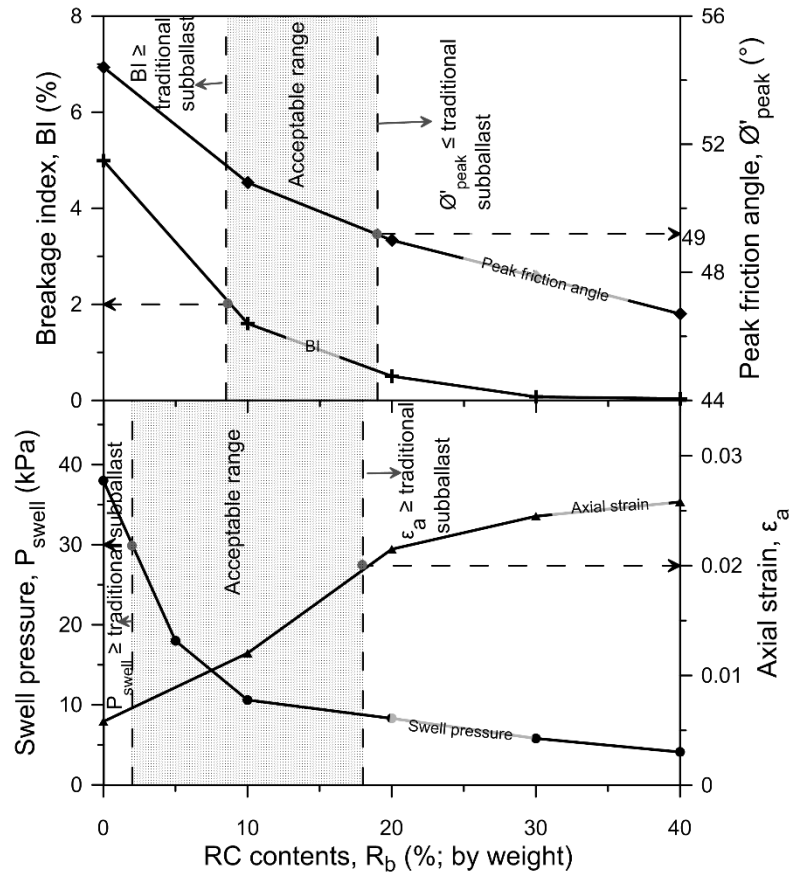


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524 Fig. 8 Optimisation of the ratio of SFS: CW based on the shear strength and swell pressure of

525

waste mixtures with 10% RC



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527

Fig. 9 Optimisation of RC content based on the peak friction angle, BI, swell pressure and

528

axial strain of waste mixtures with SFS: CW=7:3

529

530 **List of Tables**

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

532 Table 2 Typical chemical composition of CW and SFS

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

534 traditional subballast

535 Table 4 Peak friction angle, post-shearing breakage index (BI), and strain energy density

536 (after shearing at $\sigma'_3 = 40 \text{ kPa}$), and swell pressure of SFS+CW+RC mixtures and the

537 traditional subballast

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540

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	$\phi'_{peak} \geq 49^\circ$	current study
The breakage index	BI < 2%	current study
swell pressure	$P_{swell} < 30$ kPa	Ferreira &Teixeira, 2012
Mean acceptable axial strain (cyclic)	$\epsilon_a \leq 0.02$	Teixeira et al., 2006
Strain energy density	$E \geq 4.39$ kPa	current study

541

542

Table 2 Typical chemical composition of CW and SFS

SFS		CW	
Components	Proportion (%)	Components	Proportion (%)
SiO ₂	12.5	Ash	65.6
Al ₂ O ₃	2.8	Carbon	24.3
CaO	38.3	Volatiles	14.4
MgO	9.9	Hydrogen	1.90
Fe ₂ O ₃	30	Nitrogen	0.55
MnO	3.7	Sulphur	0.23
TiO ₂	1.2	Phospor	0.02
Others	1.6		

544 *Provided by the ASMS and the BHP Illawarra Coal.

546 Table 3 Basic geotechnical properties of SFS, CW, RC, the SFS+CW+RC mixtures, and the
547 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	-

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

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

Materials	SFS:CW	RC (%)	ϕ'_{peak} (°)	P_{swell} (kPa)	BI (%)	E (kPa)
SFS50+CW50		0	51	18	9.27	3.85
SFS45+CW45+RC10		10	47.4	3.4	3.71	8.27
SFS40+CW40+RC20	5:5	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		0	54.4	38	4.99	4.35
SFS66.5+CW28.5+RC5		5	-	18.2	-	-
SFS63+CW27+RC10	7:3	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		0	-	53	-	-
SFS72+CW18+RC10	8:2	10	52	23	-	-
SFS90+CW10		0	60	73	2.2	4.18
SFS81+CW9+RC10		10	55	52	0.76	8.89
SFS72+CW8+RC20	9:1	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

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