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A Sustainable Foundation: Recycling Waste Rubber Tyres in the Railway Track

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ABSTRACT

Today's world is faced with many challenges that necessitate changes to the traditional approaches used to provide products and services to growing populations. In this context, the engineering discipline, and specifically the field of geotechnics, is witnessing a shift towards adopting sustainable practices in the field to reduce its carbon footprint. The use of waste materials as substitutes to traditional quarried aggregates in ground engineering projects is one of the research fields that has gained wide popularity in recent years. In this paper, three approaches are presented where different types of waste materials, namely, rubber crumbs/shreds (RC), coal wash (CW), and steel furnace slag (SFS) are used to replace or complement traditional aggregates in the sublayers of the rail substructure. In all three approaches rubber crumbs/shreds, produced by shredding waste rubber tyres, are added to the mixture to minimize particle breakage, and improve its energy absorbing property. The paper shows that mixtures of CW+RC+SFS and CW+RC can be used as a capping material in railways. Also, a methodically blended mixture of ballast and rubber granules (Rubber Intermixed Ballast Stratum - RIBS) shows proven characteristics that technologically satisfy the current standards stipulated for conventional ballast. Finally, the paper highlights the economic and the environmental benefits of using waste materials in engineering projects.

Keywords: Sustainable Materials, Coal Wash, Rubber Crumbs, Railways

1 INTRODUCTION

The concept of sustainable development has become a key topic in today's world. In this context, engineers are determined to offer alternative practices in their respective fields to minimize the environmental footprint of engineering activities. The reuse of waste materials in ground engineering projects as substitutes to natural quarried aggregates is an emerging research topic that serves, in part, the goals of sustainable development. Coal wash (Rujikiatkamjorn et al., 2013), fly ash (Kim et al., 2005, Wang et al., 2019), steel slag (Tasalloti et al., 2015, Indraratna et al., 2018), rubber crumbs (Qi et al., 2020a, Lee et al., 1999, Signes et al., 2015), demolition waste (Naeini et al., 2019, Saberian et al., 2018, Arulrajah et al., 2015), and recycled glass (Disfani et al., 2017, Saberian et al., 2019, Naeini et al., 2019) are examples of popular waste materials that, when blended together, can replace the traditional construction materials sourced from natural quarries. Although the research on waste materials began almost three decades ago, their reuse in real-life ground engineering projects has been limited over the years. This is a fact associated mainly with technical barriers (i.e., lack of testing, evidence, and supporting standards and specifications). In this context, advanced research in the field of waste materials is very important to promote these waste aggregates as a construction material and encourage the industry sector to sponsor more sustainable practices when expanding the built environment.

A typical ballasted railway track structure is composed of two main foundation constituents: ballast layer and subballast/capping layer. Indraratna et al. (2017) developed a synthetic energy absorbing layer (SEAL) for railway subballast using waste mixtures containing steel furnace slag (SFS), coal wash (CW) and rubber crumbs (RC). The comprehensive tests carried out by the authors revealed that a SEAL with a proper blending ratio of SFS, CW and RC has better geotechnical properties than traditional sub-ballast materials (Qi et al., 2018, Qi et al., 2020b, Indraratna et al., 2022). However, the SEAL mixtures were studied using only small scale testing. Qi et al. (2018) proposed an energy consumption concept which indicated that if the energy absorbing capacity of the subballast layer is improved, less energy will be transferred to the ballast and the subgrade layers, and hence ballast degradation and track deformation will be reduced. This paper presents the main findings of a large-scale physical model that tested the performance of the full track substructure including the SEAL, the ballast layer, and the subgrade layer using a large-scale cubical test apparatus.

Under the same topic, Indraratna et al. (2019) proposed the use of a mixture of CW and RC, thus eliminating SFS used in the SEAL, to replace the traditional capping material in the railway foundation. The study evaluated the compaction characterises of the mixture, given that rubber is energy absorbing and might adversely affect the compaction efficiency of the mixture in practice. The properties of the mixture we also evaluated using static triaxial tests and tests showed that the deformation and strength properties of the mixture are within allowable limits for a capping layer. To fully characterize the mixture, its properties had to be tested under cyclic loading conditions, which better simulate field conditions for the railway track. This paper emphasizes on the main findings of the cyclic tests in terms of deformation, energy absorption, and degradation, with and without a rest period.

While the above-mentioned mixtures were developed to replace the subballast/capping layer, the third approach discussed in this paper focuses on the ballast layer. In practice, the deterioration of ballast subjected to dynamic loading cycles is inevitable. The bearing stresses cause abrasion between ballast particles leading to the breakage and rounding of the angular ballast edges overtime. The use of rubber inclusions from waste tyres mixed with ballast proved to be practically feasible to minimize the degradation of ballast particles (Arachchige et al., 2022b, Arachchige et al., 2022a). The geotechnical (mechanical and compressibility) characteristics of the Rubber Intermixed Ballast System (RIBS) was evaluated through a series of large-scale static triaxial tests. This paper underlines the benefits of replacing traditional ballast with a RIBS in terms of long-term settlement, energy absorption, dilation, and ballast breakage.

In addition to discussing promising experimental results, this paper also highlights the economic and environmental benefits of using waste materials in engineering projects, and specifically in the foundation of the railway track, to promote the implementation of sustainable practices by the construction industry.

2 MATERIALS AND EXPERIMENTAL PLAN

2.1 CW+SFS+RC

The steel furnace slag (SFS) by-product is a direct result of steelmaking produced by processing iron and steel scrap with lime at high temperatures in Basic Oxygen and Electric Arc Furnaces. Coal wash (CW) is generated from the washery process used to refine run-of-mine coal. The source materials for SFS and CW used in this study were procured from Illawarra Coal and Australia Steel Milling Services, respectively, and the rubber crumbs (wireless) (RC) shredded from waste tyres were sourced from Tyre Crumbs Australia. The particle size distribution (PSD) curves of the RC, SFS and CW are shown in Figure 1a. The physical model used in this study consisted of a ballast layer, a subballast (SEAL) layer, and a layer of structural fill (Figure 1b). The ballast and structural fill were obtained from a local quarry near the University of Wollongong and their PSD curves are shown in Figure 1a. The ballast was prepared according to Australian Standard (AS-2758.7, 2015). The SEAL mixture prepared with an optimal blending ratio of SFS:CW=7:3 (by weight), as suggested by Indraratna et al. (2017), was mixed with various percentages of RC (i.e. 0, 10, 20, 30 and 40%). The PSD of the SEAL mixtures with different amounts of RC (R_b, %) are also shown in Figure 1a; the number after SEAL refers to R_b (%).

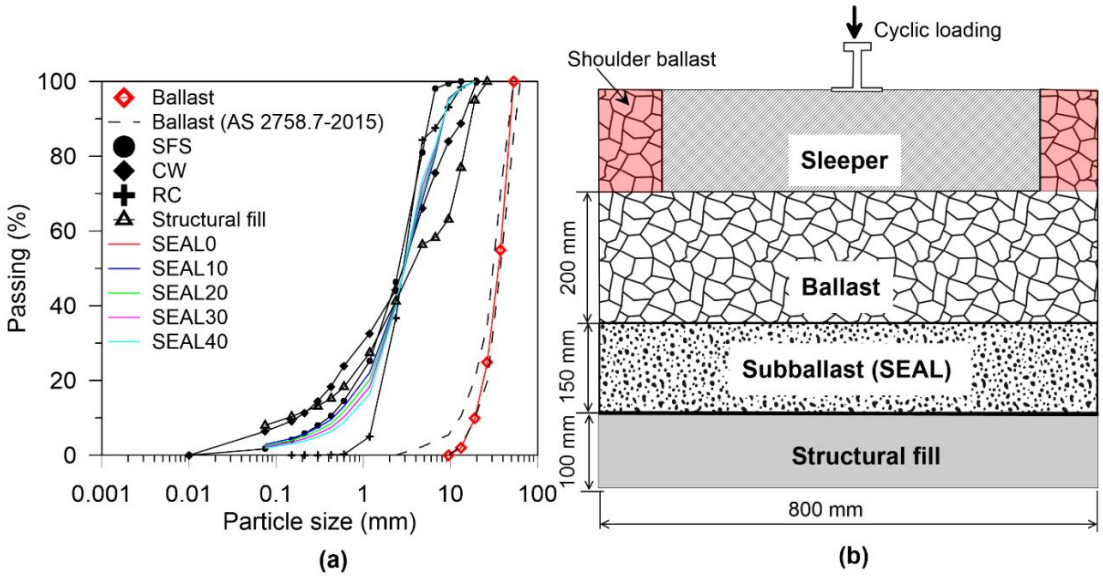


Figure 1. *(a) Particle size distribution (PSD) curves of the using materials; (b) a schematic view of the large scale physical model (modified after Qi and Indraratna, 2020)*

The test specimen was prepared in a 600mm wide by 800mm long by 600mm deep cubical triaxial testing cell. Before being tested the 200mm high ballast, the 150mm high subballast, and the 100mm high subgrade were compacted to field conditions with a dynamic compactor. A 150mm thick concrete sleeper was then placed on top and (red) shoulder ballast was placed around it (Figure 1b). Five large-scale triaxial tests were carried where the amount of RC (0, 10, 20, 30 and 40%) in the SEAL was changed. A maximum cyclic vertical stress of 230 kPa and a loading frequency of 15 Hz was adopted to simulate a train with a 25-tonne axle load running at 110km/h (Navaratnarajah and Indraratna, 2017, Jayasuriya et al., 2019, Indraratna et al., 2014). A lateral confining pressure σ'_3 = 15 kPa was applied in the transverse direction of the track to simulate the pressure provided by the crib and shoulder ballast in real track conditions (Navaratnarajah et al., 2018). After each test, the ballast under the sleeper was sieved to examine the particle breakage. During the test, the specimen with 40% RC failed at around 1,500 cycles due to severe vibration and settlement, while all the other tests were completed successfully up to 500,000 cycles.

2.2 CW+RC

CW used in this study was sourced from West Cliff colliery (New South Wales, Australia), and RC were sourced from Tyre Crumbs Australia. The particle size distribution of CW and RC are shown in Figure 2. Four mixtures with 0%, 5%, 10% and 15% RC to CW (RC:CW) were considered in the laboratory experimental plan. The samples for the cyclic triaxial tests were 100 mm in diameter and 200 mm in height and were compacted to the same initial void ratio of approximately 0.29. The tests were conducted under a confining pressure of 25 kPa and a cyclic deviator stress of 100 kPa, typical conditions for a subballast/capping layer. For the first series of tests, no rest period was introduced, and the tests were run for 200,000 cycles. Another series of tests was performed where a rest period was introduced every 40,000 cycles and the samples were subjected to 480,000 cycles in total. More details about the materials, sample preparation and the procedure of testing can be found in Tawk et al. (2021).

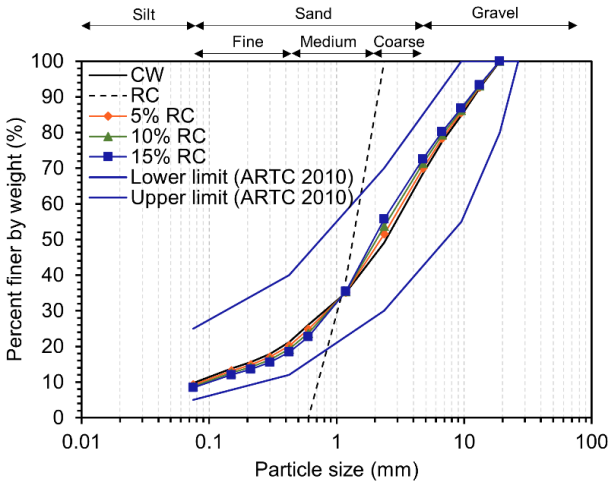


Figure 2. *Particle size distribution curves of CW, RC and CWRC mixtures.*

2.3 RIBS

Fresh ballast for RIBS were obtained from Bombo quarry in New South Wales, Australia, and the rubber granules were sourced from Tyrecycle Australia. The gradation of proposed blended mixture of ballast and rubber granules were prepared according to the Australian nominal 60-graded ballast gradation specified in the Australian Standard AS 2758.7 (Standards Australia, 2015). The particle size distribution of RIBS materials with varying rubber content ($R_b\%$) is shown in Table 1. The laboratory experiments for RIBS were conducted under monotonic and cyclic loads using the large-scale triaxial test apparatus (sample size: 600 mm high by 300 mm in diameter). Tests were conducted at confining pressures of 30 kPa and 60 kPa under drained conditions. Representing a train with a 25-tonne axle-load travelling at a speed of 150 km/hr (Hussaini et al., 2015), a maximum cyclic stress $(q_{max,cyc})$ of 230 kPa was applied on the specimens with a loading frequency of 20Hz.

Table 1. *Particle size distribution of RIBS mixtures*

Sieve Size (mm)	**Particles, % passing**						
	Pure Ballast	**RIBS (R_b = 5%)**		**RIBS (R_b = 10%)**		**RIBS (R_b = 15%)**	
	(R_b = 0%)	Ballast	R_b	Ballast	R_b	Ballast	R_b
53	100	100	-	100	-	100	-
37.5	65	65	-	65	-	65	-
26.5	30	30	-	30	-	30	-
19	15	15	-	10	5	5	10
13.2	5	-	5	-	5	-	5
9.5	-	-	-	-	-	-	-

3 Experimental Results

3.1 CW+SFS+RC

3.1.1 Deformation

The settlement and lateral displacement of the test specimen are shown in Figure 3. Note that the settlement increased as the loading cycles increased, while the vertical deformation of most specimens stabilised after 100,000 cycles with a strain accumulation rate of less than 5×10^{-8}, indicating that they have reached the shakedown state (Qi and Indraratna, 2022a, Sai Malisetty et al., 2022). The only exception was the specimen with SEAL40 which failed within 1,500 cycles at a settlement of more than 40 mm. These results indicate that increasing the RC content in SEAL increases the rate of settlement due to the high compaction of rubber material. Lateral displacement of the test specimen showed a reduced dilation when the amount of RC in the SEAL mixtures increased up to 20%. For a rubber content greater than 20%, the lateral displacement fluctuated as more RC was added; this indicates that higher amounts of RC may destabilise the lateral deformation of a track. Adding rubber makes the SEAL layer

more compressible, hence all the mixtures having rubber are more contractive than the conventional material. However, when rubber content increases from 10% to 20% or more, the skeleton of the mixture is governed by the deformable material (rubber), rather than the rigid particles (SFS+CW). During cyclic loading, the compressed rubber will bounce back when unloaded, hence causing lateral instability of the mixtures having (20-40%) rubber.

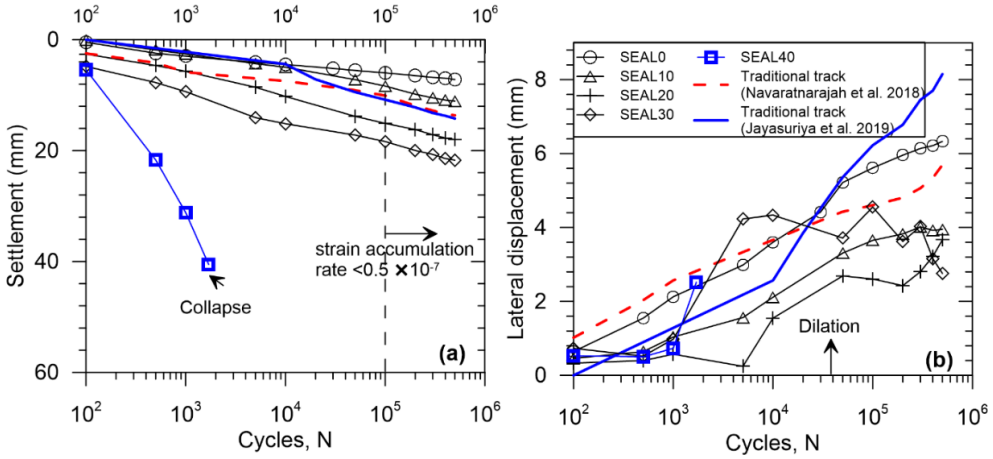


Figure 3. *Settlement and lateral displacement of the test specimen under cyclic loading (modified after Qi and Indraratna, 2022b)*

3.1.2 Ballast degradation (breakage)

The particle degradation of ballast during cyclic loading was evaluated using the ballast breakage index (BBI) initially proposed by Indraratna et al. (2005). It is calculated based on the PSD shown before and after the test; the details are shown in Figure 4a. The BBI of the test specimen with different amounts of RC is shown in Figure 4b. As expected, the addition of RC in SEAL up to 10% reduced ballast breakage. However, when more RC was added there was no significant reduction in the BBI. In contrast, the BBI increased for the specimen with SEAL20. When more than 20% RC is added to the subballast, the skeleton of the SEAL materials is governed by the rubber particles. Therefore, the specimen with $R_b \geq 20\%$ exhibited a rubber-like behaviour which generated a lot of vibration when subjected to dynamic loading (Qi et al., 2018); vibration in turn induced increased ballast degradation.

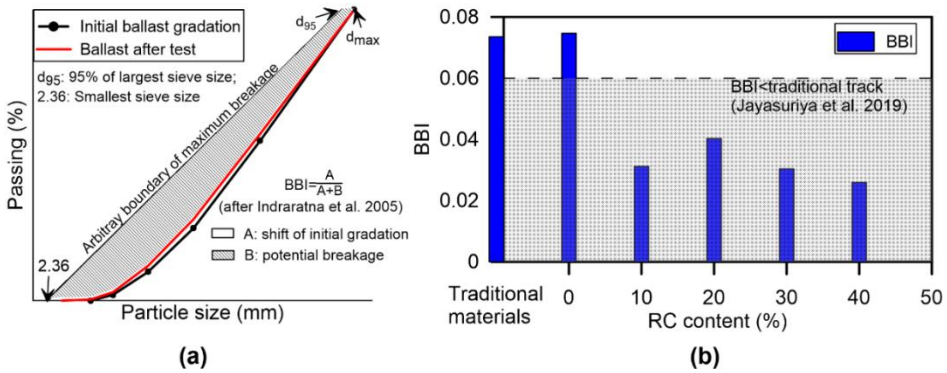


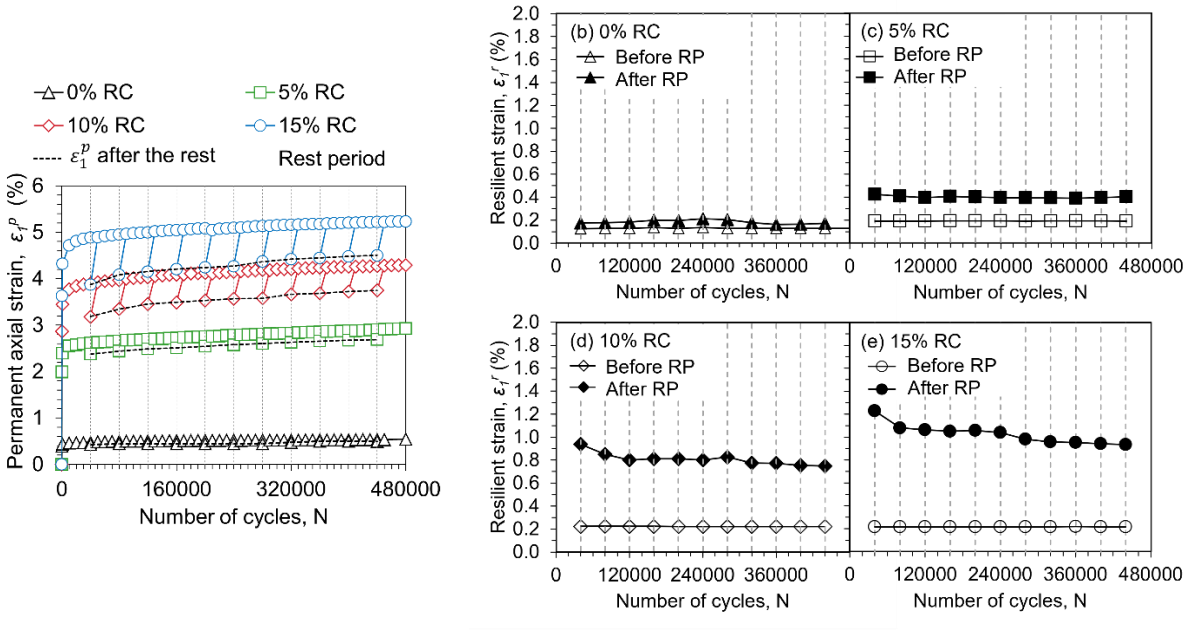
Figure 4. *(a) Definition of BBI; (b) BBI of the test specimen with traditional materials and SEAL having different RC contents*

3.2 CW+RC

3.2.1 Deformation

The permanent axial strain of CWRC mixtures with and without a rest period determined at the minimum cyclic deviator stress is shown in Figure 5a. It is evident that the permanent axial strain increased with increasing rubber content for both testing schemes, an expected outcome associated with the compressibility of rubber. However, at any rubber content, the permanent axial strain decreased when a rest period is introduced between the loading cycles. This indicates that part of the permanent axial strain recorded during cyclic loading is recoverable after the load is stopped for a given duration. The

resilient strain (recoverable strain), ε_1^r, is defined as the difference between the maximum and the minimum axial strain for a load cycle. Figure 5b shows that the resilient strain increased with increasing rubber content. More importantly, it is evident from Fig. 5b that the resilient strain measured during the first cycle after the rest period was higher than that recorded during the last cycle before the rest period. This indicates that part of the energy that is absorbed by the mixture during loading, is recovered when the load is stopped.

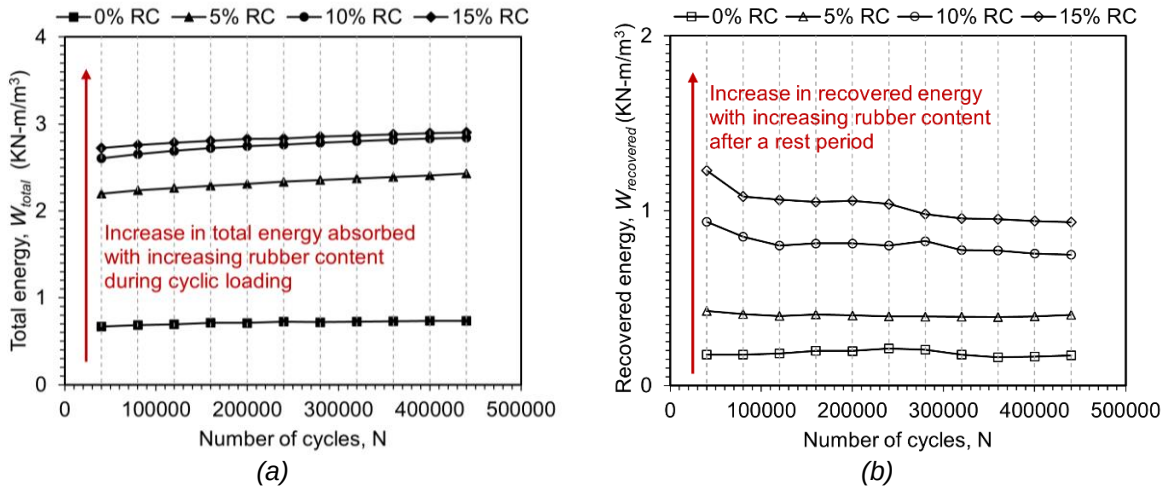


(a) *(b)*

Figure 5. *(a) permanent axial strain and (b) resilient axial strain of CWRC mixtures (modified after Tawk et al. (2021))*

3.2.2 Energy dissipation

Figure 6a shows the total energy dissipated during cyclic loading. It is evident that the inclusion of rubber crumbs improved the energy absorption capacity of the mixture. The total energy dissipated increased significantly for a rubber content of 10%, after which there was no significant improvement in energy dissipation. Moreover, the energy that is recovered after the rest period increased with increasing rubber content. This is in turn lead to a reduced particle degradation as shown by (Tawk et al., 2021). When a rest period is introduced and the RC partially recover their volume, they also recover their energy dissipation potential that was gradually lost during cyclic densification, thus reducing particle degradation as less energy is dissipated through the breakage of particles when the load is applied again.



(a) *(b)*

Figure 6. *(a) total dissipated energy and (b) recovered energy after the rest period for CWRC mixtures*

3.3 RIBS

3.3.1 Resilient modulus and energy dissipation of RIBS

The ratio of applied maximum cyclic stress to recoverable axial strain is defined as the Resilient modulus, M_R (Figure 7a). The resilient modulus of RIBS decreases with increased rubber content and increases with number of loading cycles. The reduction of M_R after 400000 cycles are 28%, 40% and 50% for RIBs specimens with rubber content 5%, 10% and 15% respectively. However, M_R is an important design parameter so that it should not be compromised substantially for RIBS that replace the ballast layer. By considering resilient modulus of ballast in general, it is recommended not to increase R_b in the RIBS more than 10%. The definition of energy dissipation per unit cycle (E_d) and the calculated E_d at different loading cycles are shown in Figure 7b. Due to the increased energy absorption capacity of rubber, E_d increases for RIBS with increased R_b%. Change in M_R and E_d after around 100000 cycle is incomparable as the particles are rearranged to a densified setting.

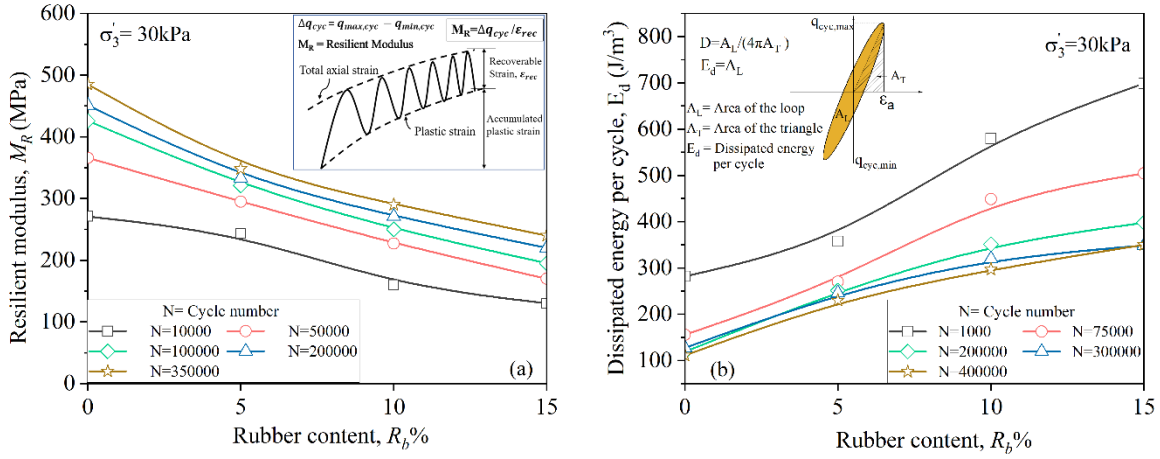


Figure 7. *Variation of (a) resilient modulus and (b) energy absorption with the rubber content at different loading cycles*

3.3.2 Particle breakage and changing void ratio of RIBS

As shown in Figure 8a cyclic loading was applied after a conditioning phase in which RIBS specimens experienced considerable reduction of void ratio compared to the pure fresh ballast. That's mainly because of the compressibility of the rubber particles. Even though the rubber particles have irregular shape, they are less stiff compared to natural rock aggregates. A reduction in the void ratio is due to the compression of rubber particles, which fill part of the voids between larger granular particles. The change in void ratio (Δe) shown in Figure 8b is the difference of initial void ratio at the start of cyclic loading (e_0) and final void ratio at the end of cyclic loading (e_f). As shown in Figure 4a, the particle breakage has been quantified according to the ballast breakage index BBI (Indraratna et al., 2005). Figure 8b presents the variation of BBI and Δe with the rubber content of the tested mixtures. It is clear that, Δe due to the cyclic loading after conditioning phase is certainly not significant for RIBS specimens ($R_b > 0$). The reason is that rubber and rock particles were well interlocked during the conditioning phase resulting in a densified granular formation and reduced particle breakage. In other words, change in void ratio during the cyclic loading phase (after initial conditioning phase) is minimum when rubber is added. This is explained by the fact that the particle rearrangement during the conditioning phase is more critical for RIBS with higher rubber content.

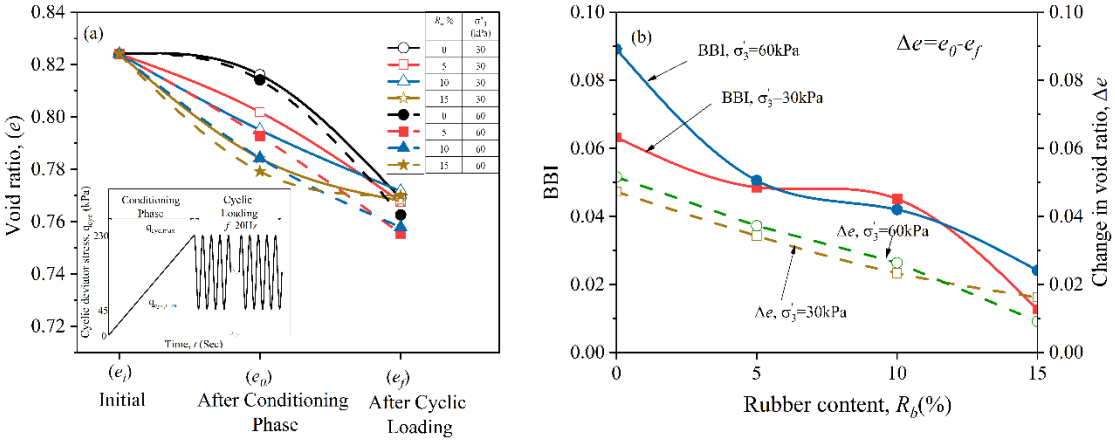


Figure 8. *(a) Void ratio* (e) *of the specimens at the beginning of the test* (e_i)*, after the conditioning phase* (e_0) *and at the end of the test* (e_f) *(b) BBI and* Δe *with respect to* R_b%

4 DISCUSSION

4.1 Environmental Benefits

Quarries, needed to provide aggregates for the construction industry, can have serious environmental impacts such as land degradation, land subsidence, and landslides. Quarrying operations can also lead to water pollution, occupational noise pollution, and air pollution. Such outcomes result in health-related problems and loss of biodiversity as these operations can adversely change pre-existing ecosystems and alter hydrogeological and hydrological regimes (Ozcan et al., 2012). In this context, using waste aggregates like CW as substitutes to traditional natural aggregates will reduce the stress on natural resources which will have a profound effect on the environment. From another perspective, waste materials like CW, waste rubber tyres and steel slag occupy larges areas of land and may eventually contaminate the soil in landfills and lead to more environmental problems. Hence, recycling these waste materials as aggregates in the construction industry will reduce the need for more landfills. Moreover, granulation of rubber is a well-established and straightforward process, and there are no significant or scientifically justified risks associated with using rubber granules made from end-of-life tyres (ETRMA, 2016). The three approaches discussed in this paper provide a viable solution for this non-biodegradable waste material that is generated by the tyre industry at a low cost by reusing it as an aggregate in railways.

4.2 Economic Benefits

While the positive environmental impact of waste recycling should be enough to incentivize the reuse of waste materials, such initiative can also have an impact on several industries. First, waste materials like CW are much cheaper than traditional aggregates, making them more economical for the construction industry involved in the construction or maintenance of transportation corridors. Also, in some places where coal reject is stockpiled and good quality rock aggregates are not available, the reuse of CW minimizes the cost of transporting materials from the source to the site. On another note, using rubber in the rail track is shown to minimize the degradation of the other hard particle in the subballast and ballast layer. For instance using RIBS instead of the tradition ballast layer enhances track longevity by reducing track degradation. Therefore, less maintenance cycle will be needed which will reduce to maintenance expenses throughout the track operations. Finally, the disposal of waste materials often incur additional costs on the industry generating these wastes. For example In Australia, the landfilling of CW is levied at $14 per ton, which is equivalent to spending millions of dollars per year on stockpiles of CW. Therefore, selling coal wash to the construction industry instead of stockpiling it for a levy is a double win for the coal mining industry.

5 CONCLUSIONS

A physical model using a large-scale cubical tri-axial apparatus was developed to investigate the performance of a synthetic energy absorbing layer (SEAL) for railway sub-ballast. The results indicate

that when a proper range (i.e., 10%) of rubber crumbs (RC) are added to the SEAL waste mixture, the track specimen has comparable settlement, less lateral displacement, and less ballast degradation than the traditional subballast material. However, adding too much RC (>20%) to the SEAL will cause dramatic settlement, lateral instability, and higher ballast breakage. Cyclic triaxial tests performed on a mixture of CW and RC also showed that adding 10% rubber improves the energy absorption capacity of the mixture and reduced particle breakage. Tests also showed that RIBS absorbs more energy in contrast to pure ballast resulting in less energy transfer to sublayers and track deterioration. Care should be taken when increasing the rubber content in the RIBS mixture because the resilient modulus should drop below the standardised value. Moreover, particle densification of the RIBS occurs quickly due to the compression of rubber particles. Under large number of cyclic loading (long-term service) RIBS demonstrated reduced particle breakage compared to pure ballast.

Experimental results showed that waste materials can be potentially used as alternative aggregates in the railway track. It will be useful to perform large-scale field tests in the future and monitor the performance of the mixtures in an actual rail track under real-life conditions. Results from such tests will incentivise the industry to adopt these materials in practice. In addition, it is important to develop models describing the response of these waste materials to be able to predict their performance under different loading conditions. Finally, the possibility of causing ground/subsoil contamination from leachates is a prospective topic that should be addressed in future studies.

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