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Sustainable Performance of Recycled Rubber and Mining Waste Utilized for Efficient Rail Infrastructure

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Abstract Utilizing waste byproducts from mining industries and recycled rubber as alternate materials in railway tracks promotes sustainability of transportation infrastructure, while also increasing track longevity by reducing ballast degradation. This paper provides an overview of two such applications including (i) rubber-intermixed ballast stratum (RIBS) by replacing 10% ballast aggregates with granulated rubber particles with the particle sizes carefully selected according to Australian Standards, (ii) synthetic energy absorbing layer using a mixture of steel furnace slag, coal wash and rubber crumbs to replace traditional capping layer. These materials when tested using large-scale triaxial apparatus and field trials proved that tracks with waste materials performed better than the conventional ballasted tracks by reducing ballast breakage and exploiting the higher damping potential of these materials. Though the vertical deformations of the track slightly increased by using these materials albeit within the specified standards, the overall stability improved by reduced dilation and track vibrations. Increasing the life of ballast layer can lead to long-term cost benefits by saving millions of dollars in track maintenance and provide environment benefits through minimizing quarrying of natural rock aggregates and reducing the carbon footprint of mining industries.

Keywords Rail infrastructure · Rubber · Recycled mining waste · Cyclic loading

Introduction

Rapid industrialization in the twenty-first century across the world has increased the demand for mining production resulting in the generation of large amounts of waste byproducts. In Australia, millions of tons of waste byproducts such as coal wash (CW) and Basic Oxygen Steel Furnace Slag (SFS) are generated every year from coal and steel industries [1]. For e.g., 2.1 million tonnes per year of mining waste is generated in Illawarra region along the south-eastern Australian coast. These materials are usually dumped in landfills occupying usable lands and create potential hazard for the environment. On the other hand, over 50 million rubber tyres are discarded every year in Australia including those from domestic freight and passenger transportation as well as discarded off-the-road (OTR) tyres produced by mining industries. It is reported that only a quarter of these tyres are recycled, and a significant portion goes into dumping yards where these scrap tyres cause a serious challenge for environment as these tyres get caught in fires that release toxic emissions. On the other hand, the ever-growing transportation needs of industrialized society increased road and rail infrastructure projects by multiple folds in the past 4 decades. There is a particular requirement of railway tracks to be able to cater to freight industry with ultra long trains and heavy axle

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loads up to 40 tonnes, while also being more sustainable and cost-effective [2]. These infrastructure developments provide a good opportunity to recycle and reuse the waste materials from mining and automotive industries as a sustainable alternative to conventional materials.

The use of steel furnace slag and coal wash in road and railway projects was investigated by different researchers through various laboratory and field studies [3–5]. Though reusing these materials provide environmental benefits, their adverse geotechnical properties such as high breakage potential of CW and swelling potential of SFS prevent their individual usage [6]. However, mixtures of CW and SFS tested using laboratory investigations and used for land reclamation in port expansion project in New South Wales proved to be beneficial in countering individual deficiencies [7, 8]. Laboratory and field investigations of these mixtures showed their capability to meet the expected requirements of shear strength, drainage, swelling potential, compaction and bearing capacity [9].

Waste rubber tyres are recycled and reused in transportation infrastructure in different forms such as tyre cells, rubber mats, rubber crumbs (RC), rubber geogrids etc. The degradation of rubber materials is due to oxygen or ozone. When rubber materials are isolated with air (e.g. buried underground in rail tracks), their durability can increase dramatically. For instance, it is estimated that it takes hundreds or thousands of years for the tyre to break down when buried underground [10] A mixture of SFS, CW and RC was investigated as a potential alternative to traditional capping layer in railway tracks and proved beneficial in increasing the energy absorption capacity and damping potential of the capping layer [11, 12]. Further, using granulated rubber particles to replace a portion of ballast layer in railway track construction prevented ballast breakage providing an innovative solution to handling heavy axle loads and faster train speeds [13, 14].

For granular waste materials to perform well under railway loading, it is necessary to understand their geotechnical properties when subjected to a large number of loading cycles that is typically observed in railway tracks. This paper describes two innovative applications of the abovementioned waste materials in railway track construction including (i) mixtures of CW, SFS and RC in different proportions to substitute conventional capping layer and (ii) ballast intermixed with rubber granules as alternate ballast layer. Large-scale laboratory tests using large-scale cylindrical triaxial apparatus conducted on these waste mixtures are detailed with special focus on their permanent deformation and shakedown response under cyclic loading. Further, observations from a recent field application of granulated rubber in railway tracks at Chullora in New South Wales are presented.

Performance of SFS, CW and RC Mixtures

Two distinct approaches are explored for utilizing recycled rubber crumbs (RC) in conjunction with steel furnace slag (SFS) and coal wash (CW) as potential substitutes for conventional subballast and capping materials within the realm of railway construction. These innovative methodologies were initially proposed by Indraratna et al. [9] and Tawk et al. [12], with each method addressing unique considerations and challenges.

The first approach, as detailed by Indraratna et al. [9], proposed a composite by mixing SFS, CW and RC denoted as SFS-CW-RC. SFS-CW-RC is prepared using standard compaction techniques. The aim here is to explore the synergy between these materials and evaluate their performance when subjected to traditional compaction methods. In contrast, the second method, as elucidated in Tawk et al. [12], revolves around the blending of CW and RC exclusively, known as CW-RC. This approach seeks to mitigate the potential issue of volume expansion that may arise when incorporating SFS. To counterbalance the absence of the rigid SFS component, this method necessitates an increase in compaction effort during the preparation of CW-RC specimens. Both methodologies offer innovative alternatives for railway subballast and capping materials, and their cyclic loading behaviour in terms of deformation and resilient modulus will be provided in this section.

Materials and Test Program

The granular aggregates SFS and CW are by-products from steel manufacturing and coal mining operations in Wollongong, New South Wales, Australia. Additionally, rubber crumbs (RC) used in this research were obtained through the shredding of waste tyres. CW consists primarily of quartz and residual coal, with illite and kaolinite serving as the principal clay minerals. Its aggregates contain a combination of angular and relatively flaky grains, showcasing dual porosity characteristics. SFS primarily comprises metal compounds such as Fe_2O_3 and SiO_2, along with free lime (CaO) [9]. According to the Unified Soil Classification System (USCS), CW and SFS are categorized as well-graded gravel with silty-sand (GW-GM) and well-graded sand with gravel (SW), respectively. According to ASTM D6270 [15] RC can be referred to as granulated rubber. The modulus of elasticity of rubber crumbs is in the range of 0.77–1.33 MPa [16]. To ensure consistency and uniformity, all materials underwent a meticulous process of drying and sieving before being combined according to mass percentages. Moreover, the used rubber crumbs were from the same batch of products manufactured from a recycled tyre company, and to ensure a uniform mix they were mixed thoroughly before blending with other materials in the proposed studies. The preparation of SFS-CW-RC mixtures involved blending SFS and CW in a 7:3 ratio, followed by the incorporation of various proportions of RC (ranging from 0 to 40%). The selection of the SFS:CW ratio at 7:3 aligns with recommendations from Indraratna et al. [9] and Qi et al. [17], aiming to strike a balance between achieving sufficient strength in the mixtures while maintaining acceptable levels of swelling potential and particle breakage. Conversely, for the creation of CW-RC mixtures, a narrower range of RC percentages (ranging from 0 to 15%) was utilized, guided by the test results obtained from SFS-CW-RC mixtures in earlier studies [9, 17–19]. The gradation curves for all the waste materials, as well as their respective mixtures, are visually presented in Fig. 1. Importantly, these gradations for both SFS-CW-RC and CW-RC mixtures conform to the upper and lower limits recommended by the Australian standard for subballast/capping materials [20].

To investigate the cyclic loading behaviour of these waste blends, cyclic consolidated drained triaxial tests on the SFS-CW-RC and CW-RC mixtures were conducted by Qi et al. [11] and Tawk et al. [12], respectively. The test specimens (100 mm high with 50 mm diameter) of CW-RC were compacted to the same void ratio (0.29) with increased compaction effort (i.e. compaction energy 1588 kJ/m^3) [21], while the specimens of SFS-CW-RC were compacted to 95% of their maximum dry density with standard Proctor method (i.e. compaction energy 596 kJ/m^3). Cyclic loads were applied with a cyclic stress ratio of 0.8 (CSR $= q_{max}/2\sigma'_3$), with a cyclic deviatoric stress q_{max} of 64 kPa and the effective confining pressure σ'_3 is of 40–50 kPa [11]. A loading frequency of 5 and 10 Hz was employed, and the test was completed with 50,000 or 100,000 cycles for SFS-CW-RC and CW-RC mixtures, respectively.

Deformation of SFS, CW and RC Mixtures Under Cyclic Loading

Axial strain

In the light of the varying loading frequencies between two mixtures, it was imperative to analyze and compare all test results based on time rather than the number of cycles. The evolution of axial strain and volumetric strain in the waste mixtures over time is presented in Fig. 2. Figure 2a illustrates the behaviour of axial strain, showcasing a rapid increase with time until reaching t = 1000 s. This corresponds to 5000 cycles for SFS-CW-RC mixtures and 10,000 cycles for CW-RC mixtures, primarily attributed to the process of densification. Subsequently, the axial strains exhibit a gradual stabilization trend, except for SFS-CW-RC mixtures with the proportion of RC ≥ 30%, which continue to experience an increasing axial strain until the conclusion of the test. Notably, as the rubber content increases, the axial strains of all waste mixtures show an upward trajectory. Furthermore, it is observed that, for equivalent rubber content levels, CW-RC mixtures tend to exhibit higher axial strains compared to SFS-CW-RC mixtures. Drawing parallels between the axial strain development, the behaviour of the CW-RC mixture with RC content of 15% closely resembles that of the SFS-CW-RC mixture with RC content of 20% (axial strain, $\varepsilon_1 = 2\%$). As indicated by previous findings [23], under cyclic loading conditions with the effective confining pressure $\sigma'_3 = 40$ kPa for conventional subballast materials, the axial strain should ideally remain below 2%. Consequently, it is advisable to maintain the RC content below 20% for SFS-CW-RC mixtures and below 15% for CW-RC mixtures to meet this criterion.

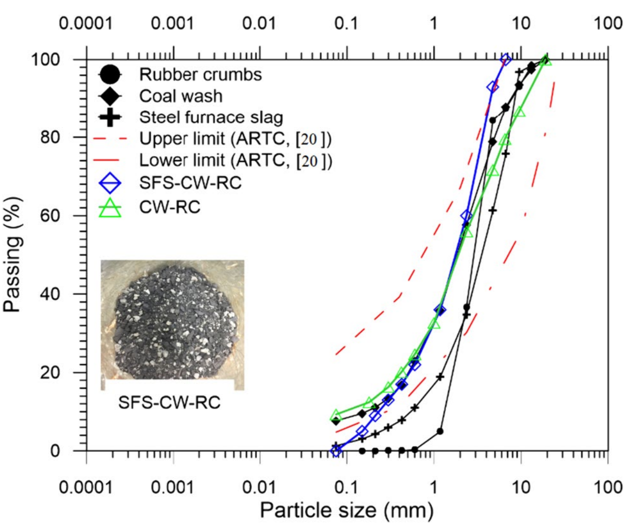

Fig. 1 Grading curves of the waste materials and their mixtures (modified after Indraratna et al. [22])

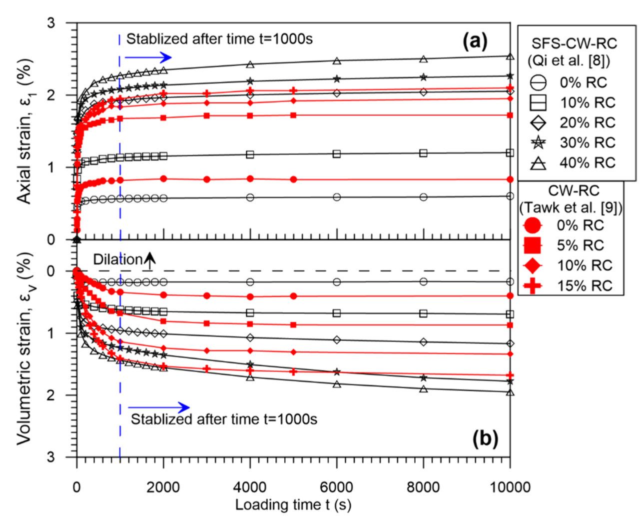

Fig. 2 Axial and volumetric strain of the waste mixtures changing with time (modified after Indraratna et al. [22])

Volumetric Strain

Figure 2b indicates a consistent trend wherein all tested specimens exhibit a contractive behaviour throughout the entire duration of loading. Much like the axial strain response, the compressive volumetric strain of all specimens undergoes a notable increase before reaching the 1000-s mark, followed by a gradual stabilization. Intriguingly, as rubber is introduced into the waste mixture, the compressive volumetric strain consistently escalates, emphasizing the influence of rubber content on this behaviour. Moreover, CW-RC mixtures, when compared at equivalent rubber content levels, consistently exhibit a higher compressive volumetric strain than their SFS-CW-RC counterparts. Of particular interest is the comparison between the CW-RC mixture with RC content of 15% and the SFS-CW-RC mixture having RC content of 30%, where their volumetric strains almost align at approximately 1.7%. This observation can be attributed to the distinct characteristics of CW and SFS particles. Specifically, CW grains possess a flaky and brittle nature, rendering them prone to breakage during loading. Conversely, SFS particles are cuboidal in shape and possess a high degree of particle interlocking, making them considerably more resistant to breakage during loading scenarios [24]. For instance, under identical static loading conditions and without the inclusion of rubber, the particle breakage of the CW-RC mixture is nearly five times more pronounced than that of the SFS-CW-RC mixture, as reported in a study by reference [25].

Resilient Modulus

The resilient modulus (M_R) holds significant importance in the assessment of a material's dynamic response in relation to dynamic stress ($q_{cyc,max}$) and the resulting elastic strains ($\varepsilon_{1,elastic}$) as $M_R = \frac{q_{cyc,max}}{\varepsilon_{1,elastic}}$. Figure 3 compares the resilient modulus of the two mixtures with varying rubber contents over time. Notably, it becomes evident that the resilient modulus stabilizes for all mixtures after 1000 s, signifying that the $\varepsilon_{1,elastic}$ within these mixtures reaches a state of stability at this specific point in time. As the rubber content within the waste mixture increases, a notable decrease in M_R is observed. For SFS-CW-RC mixtures, the resilient modulus drops from 100 to 19 MPa, while for CW-RC mixtures, it decreases from 90 to 53 MPa. This decline can be attributed to the growing elastic deformation attributed to the presence of rubber within the mixture, which inherently reduces stiffness. Interestingly, when comparing mixtures with equivalent rubber content levels, CW-RC mixtures consistently exhibit a lower resilient modulus compared to SFS-CW-RC mixtures, indicating that the stiffness of the latter is

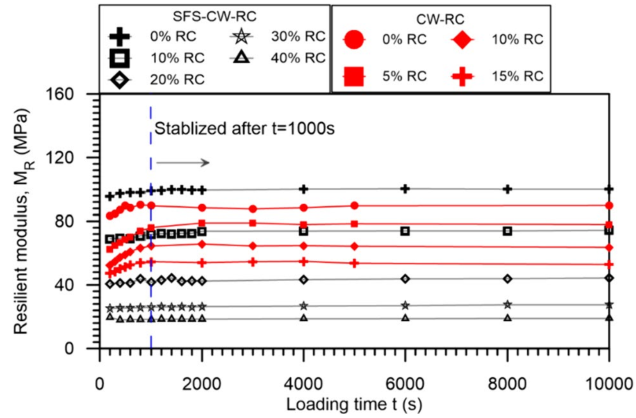

Fig. 3 Resilient modulus of the waste blends (after Indraratna et al. [22] with permission from ASCE)

notably higher. This difference can be attributed to the fact that, despite applying a similar cyclic maximum load to both waste mixture types, CW-RC mixtures tend to have a higher $\varepsilon_{1,elastic}$. A relatively high elastic deformation can lead to specimens bouncing up and down during dynamic loading, potentially causing instability in rail tracks [26, 27]. Hence, it is crucial to maintain the resilient modulus of waste mixtures within an acceptable range. Traditional subballast materials, for instance, are expected to possess a resilient modulus falling within the range of 60–80 MPa under a similar cyclic maximum load condition ($q_{cyc,max} \approx$ 80kPa) [28]. To mitigate the potential for the "bounciness effect" and ensure stability in rail tracks, it is advisable to restrict the rubber content to 10% or less in both SFS-CW-RC and CW-RC mixtures. This limitation helps maintain the desired resilient modulus while preserving the structural integrity of railway components.

Influence of SFS-CW-RC Mixtures on Ballast Degradation

The advantages of using SFS, CW and RC mixtures as an alternative capping layer were investigated using track process simulation testing apparatus (cubical triaxial testing apparatus) as shown in Fig. 4. This apparatus simulates a unit cell of ballasted track with dimensions of 800 mm (L) × 600 mm (W) × 600 mm (H) that was effectively loaded under a train wheel in real field conditions. The testing unit was filled with 100 mm structural fill at the bottom, followed by 150 mm traditional capping layer, 200 mm bottom ballast and 150 mm shoulder ballast as shown in Figure. The traditional capping layer was replaced with SFS-CW-RC mixtures with different R_b for comparison. In Fig. 4, σ_1 represents the vertical load applied on the rail, while σ_2 and σ_3 are the confining stresses in longitudinal and lateral direction of the track,

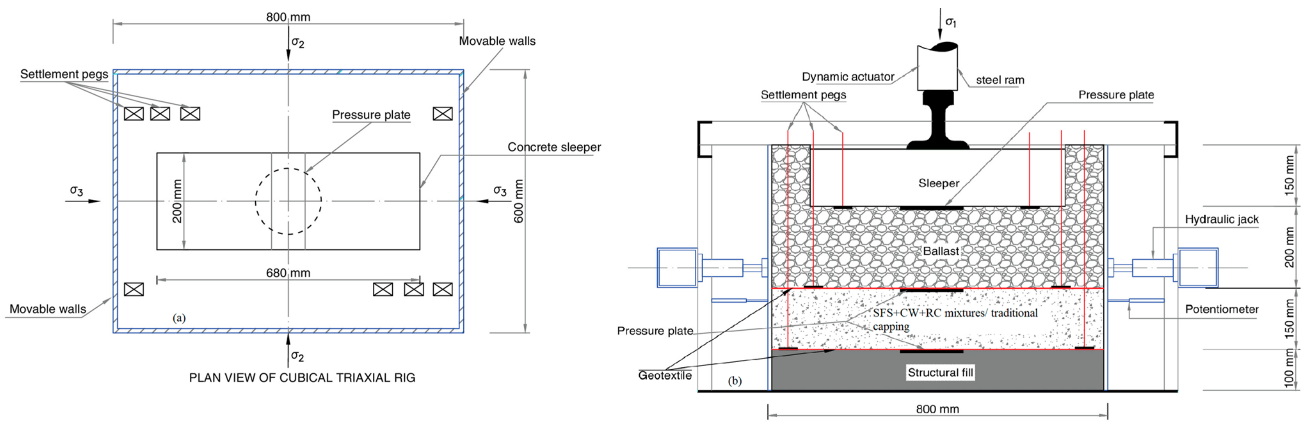

Fig. 4 Schematic of cubical triaxial testing apparatus (**a**) plan view (**b**) elevation view with layer description (after Qi and Indraratna [26] with permission from ASCE)

respectively. In the test apparatus, the lateral boundary walls can be moved during testing so as to maintain a constant σ_3, while the longitudinal boundary walls were restricted to mimic plane strain conditions. A servohydraulic actuator was used to impart cyclic loads onto the rail-tie assembly which was placed on top of ballast layer. Settlement pegs and pressure plates were installed at layer interfaces to monitor the deformation and stresses of different layers during testing, while potentiometers were installed along the lateral boundary walls to monitor the confining stress. Further details of the setup, instrumentation and loading parameters can be found in Qi and Indraratna [26].

Indraratna et al. [2] reported that increase in particle breakage of ballast measured by Ballast Breakage Index (BBI) reduces the internal friction angle of ballast and the associated dilation angle, eventually increasing compression. Moreover, degraded ballast leads to frequent track maintenance and should be minimized to reduce the maintenance costs. Figure 5 shows the BBI of bottom ballast samples when different capping materials are used after 500,000 loading cycles of 25 tonnes axle load at a frequency of 15 Hz and $\sigma_3 = 15$ kPa, simulating 110 km/h train speed. BBI was calculated based on the method proposed by Indraratna et al. [3]. BBI was found to be highest when traditional capping and SFS-CW ($R_b = 0\%$) mixtures were used, with only a slight variation between them. However, a 50–60% reduction in BBI was observed when rubber crumbs are added to SFS-CW mixtures. BBI increased for $R_b \geq 20\%$ because of the increased vibrations observed in the sleeper due to high content of rubber crumbs, albeit lower than that compared to the case of traditional capping layer. Most desirable results were observed when $R_b = 10\%$, which can be considered as optimum rubber content.

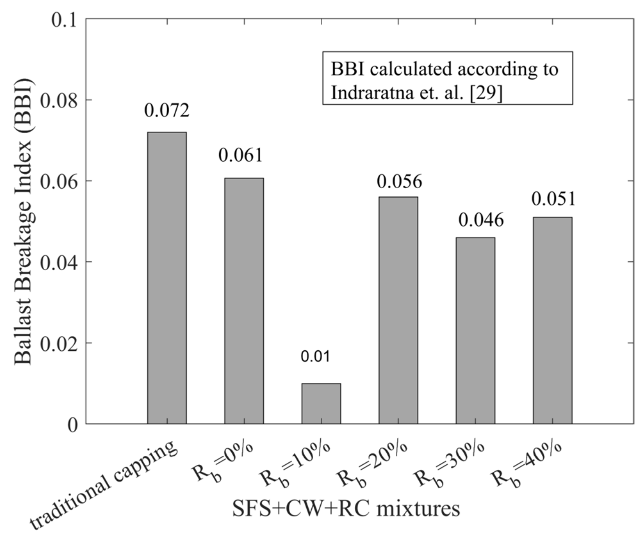

Fig. 5 Ballast Breakage Index comparison for different capping materials, data from Qi and Indraratna [26]

Performance of Rubber-Intermixed Ballast System as Ballast

This section, Rubber-Intermixed Ballast System (RIBS), promotes the use of rubber granules made out of end-of-life tyres in the ballast as a sustainable and economical solution to enhance the track longevity. Granulation of scratch tyres is overall a straightforward well-established process, and the main advantage of this concept is there is no need for processing after the granulation in order to apply as an unbounded geosynthetic in the ballast layer. RIBS is a 9:1 (by weight) proportional mixture of natural rock ballast aggregates and tyre-derived rubber granules in which the particle size distribution was per nominal 60 graded specifications specified by the Australian Standard (AS2758.7:2015). The rubber granules varied from 9.5 to

19 mm and were selected on the basis of reducing the breakage of stiffer, larger aggregates and minimizing the level of ballast fouling [14]. It is essential to control ballast fouling because the lack of void spaces due to ballast fouling restricts effective drainage within the track substructure, which results in poor track geometry. This section evaluates the performance in terms of axial strains, particle breakage, material resiliency and energy dissipation of RIBS under cyclic loads by running large-scale triaxial tests under changing confining pressures (30–60 kPa) that represent typical field confinement pressures.

Materials and Testing Program

The focused particle size distribution (PSD) curve of RIBS material along with the specified upper and lower limits are shown in Fig. 6. The coefficient of uniformity (C_u) of the tested RIBS was 2.6 and the coefficient of gradation (C_c) was 1.4. The maximum particle size (D_{max}) and the minimum particle (D_{min}) size considered for the focused blend are 53 mm and 9.5 mm, respectively.

Physical modelling for the test samples was conducted with the Large-scale triaxial test apparatus which consists of six major components; chamber, loading actuator and servo controller, pressure control unit (confining and back pressure), volume change measurement device and data acquisition unit. To minimize the influence of boundaries on larger particles, the selected sample size for tests was 600 mm in height and 300 mm in diameter. More details of the test apparatus and sample preparation can be found in Arachchige et al. [14]. Prepared RIBS were placed and slightly tamped in four layers inside a 7-mm thick rubber membrane to obtain specimens with an initial void ratio of 0.824, resulting in the typical field density of the pure ballast sample being 1535 kg/m^3. The rubber membrane facilitates sufficient stiffness for the sample deformations under controlled confining pressures, and the membrane correction was applied to the data according to ASTM D7181-20.

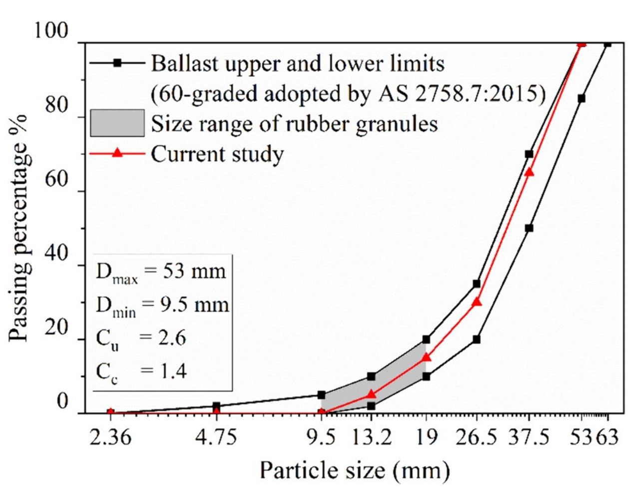

Fig. 6 Particle size distribution of RIBS and rubber granules (modified after Arachchige et al. [13])

To address the significant initial settlement observed under strain-controlled static loading tests, a conditioning phase was incorporated at the beginning of the cyclic loading testing process. It was considered safer to gradually load the samples to their maximum cyclic stress level during an initial conditioning phase before subjecting them to cyclic loads at a frequency of 20 Hz. This approach mirrors the slow movement of trains in practice, where reduced axle loads are applied at the start of track operation to accommodate initial settlementsDuring this conditioning phase, the test specimens were subjected to a monotonically applied load, gradually reaching the maximum cyclic deviator stress ($q_{cyc,max}$) of 230 kPa before initiating loading cycles at a frequency of 20 Hz. Cyclic loading tests were carried out up to 400,000 cycles. After the completion of each test, the granular material underwent a sieving process to assess particle breakage that occurred during the testing.

Permanent Axial Deformation Behaviour Under Cyclic Loads

Figure 7 illustrates the loading procedure and the corresponding permanent axial strains. The cyclic loading procedure followed by the monotonic conditioning phase is presented in Fig. 7a. Figure 7b presents the permanent axial strain during the conditioning phase before commencing cyclic loading. Compression of rubber during the initial conditioning phase is promising in RIBS as the rubber content increases. This phenomenon reasonably fits with the real-life applications where the trains initially operate at reduced speeds in order to allow the track to settle securely and minimize the risk of buckling. Therefore, the increased settlements in RIBS compared to pure ballast at this stage may not adversely affect the operation of railway tracks. Figure 7c shows the permanent axial strain (ε_a) against the number of loading cycles (N) for the specimens tested under the confining pressures of 30 and 60 kPa. The permanent axial strain under cyclic loading decreased for the samples with increased rubber contents ($R_b = 15\%$). This is mainly due to the irrecoverable particle rearrangement that occurred quickly during the conditioning phase, subsequently, additional cyclic loading did not result in notable compression. During the conditioning phase, slight compression of rubber facilitates smaller particles to occupy the voids between larger particles to some extent, thereby densifying the particle mixture before applying the cyclic loads.

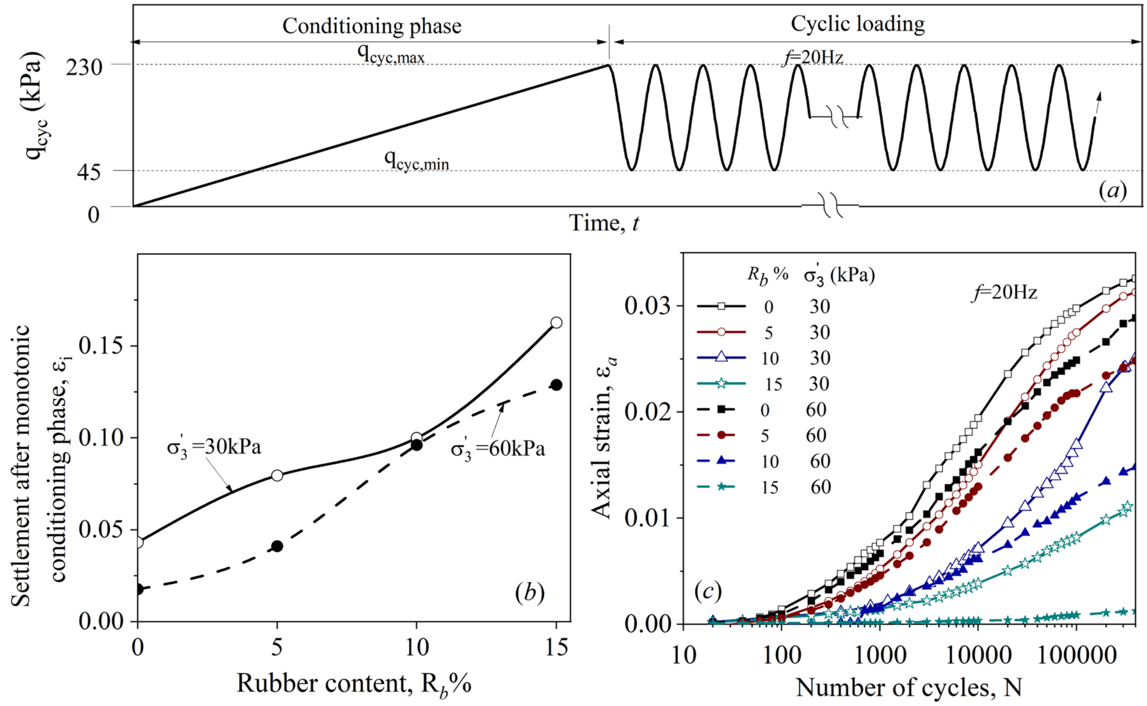

Fig. 7 **a** Loading procedure; **b** Axial strain response of RIBS mixtures after monotonic conditioning phase; **c** Axial strain response of RIBS mixtures during the cycling loading phase

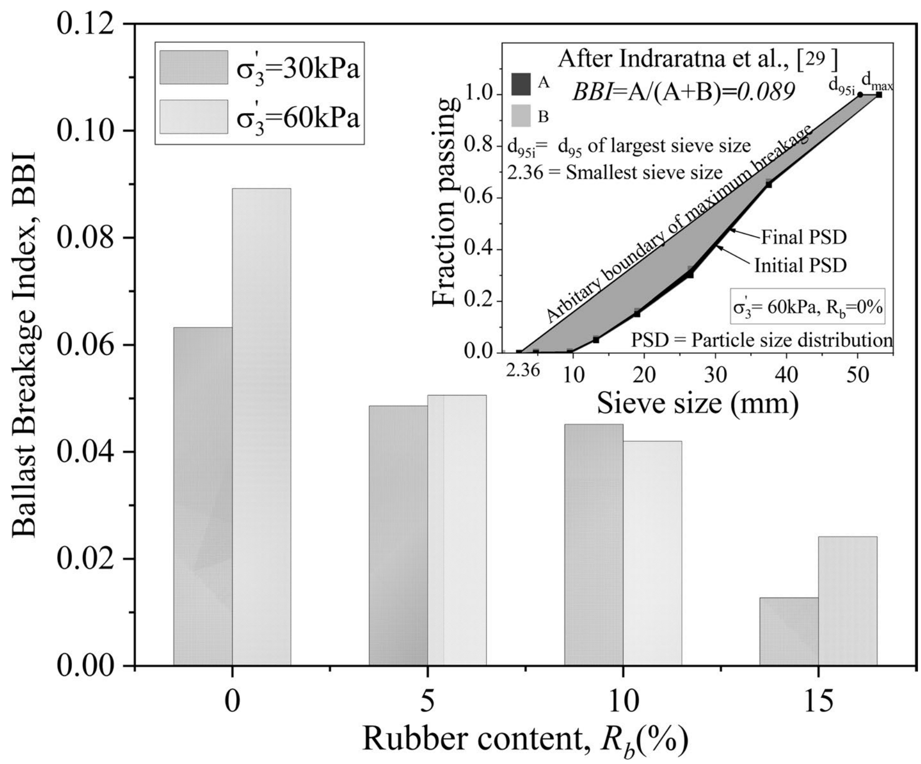

Fig. 8 Ballast Breakage Index, BBI under cyclic loading

Ballast Breakage

The assessment of particle breakage during cyclic loading was conducted using the Ballast Breakage Index (BBI) introduced by Indraratna et al. [29]. The definition of BBI is illustrated in Fig. 8. Notably, as the rubber content in the RIBS mixture increases up to 5%, there is a significant reduction in BBI, with a decrease of 43% and 23% observed under confining pressures of 60 kPa and 30 kPa, respectively. However, the decrease in BBI becomes less pronounced when the rubber content goes from 5 to 10%. Furthermore, the introduction of 15% rubber ($R_b = 15\%$) leads to a substantial reduction in BBI, with reductions of 73% and 80% observed when compared to pure ballast under confining pressures of 30 kPa and 60 kPa, respectively.

Resilient Modulus and Energy Dissipation

The resilient modulus (M_R), the energy dissipation per unit cycle (E_d) and the calculation methods are shown in Figs. 9a and b. As a result of the greater recoverable deformation in each cycle of RIBS in comparison to conventional ballast material, the Resilient Modulus (M_R) decreases as R_b increases. It is worth noting that all specimens gradually become denser as the number of cycles increases, making the changes in M_R after around 100,000 cycles relatively insignificant (as depicted in Fig. 9a). On the other hand, an increase in R_b in RIBS increases the dissipation of energy because the compressibility of rubber granules surpasses the energy dissipated due to local particle movements (Fig. 9b). Although the energy dissipation of RIBS with $R_b \geq 5\%$ increases, there is no distinct increase seen when $R_b > 10\%$. This is probably because an increased amount of rubber in RIBS deviate from the behaviour of unbounded granular media.

Shakedown behaviour

One of the important properties of granular materials under loading is their ability to reach a stable state under cyclic loading, where the material does not undergo any further permanent deformations with increasing loading cycles. This behaviour is often termed as 'Shakedown' and is used as an indicator of the stability of granular mixtures. Based on the rate of permanent strain increment at each loading cycle,

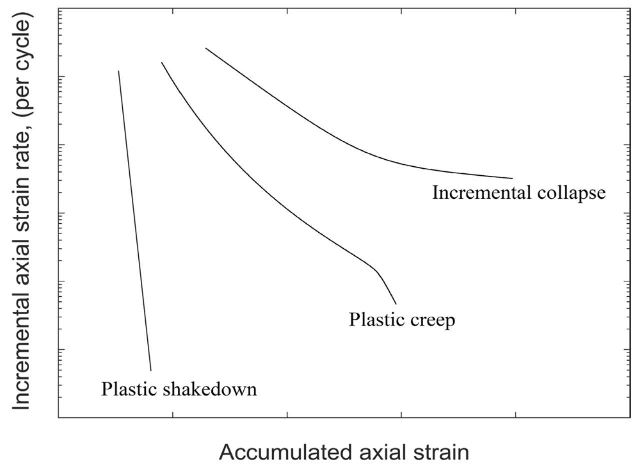

Fig. 10 Different shakedown responses observed for granular mixtures under cyclic loading

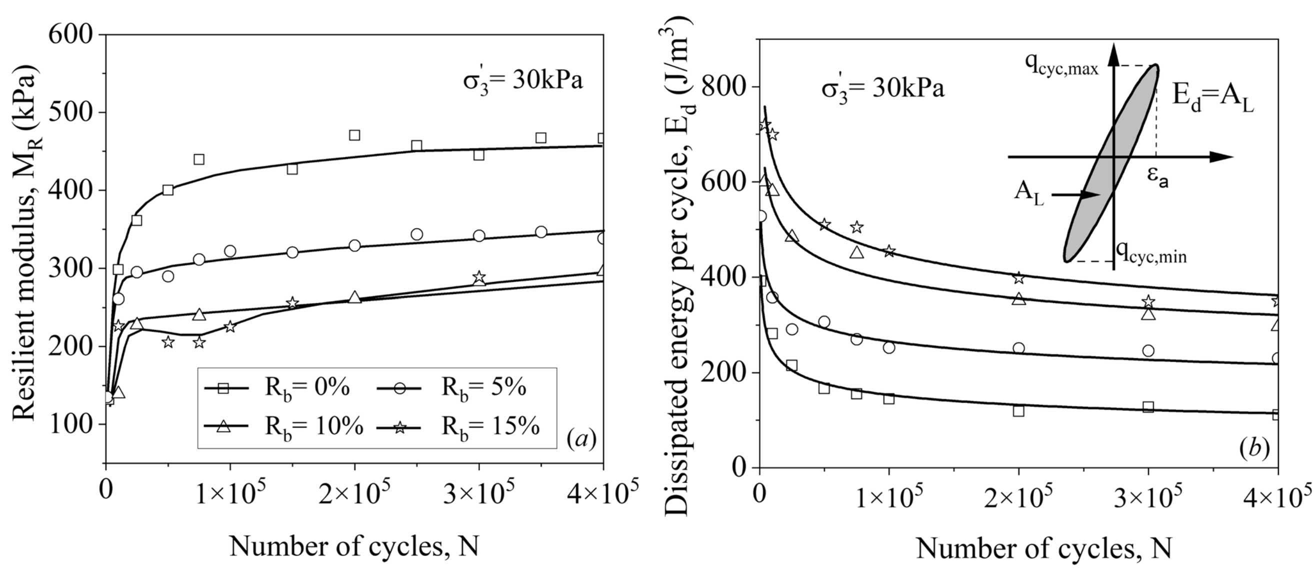

Fig. 9 **a** Variation of resilient modulus of RIBS mixtures against $R_b\%$ **b** variation of dissipation energy against the number of cycles (modified after Arachchige et al. [14])

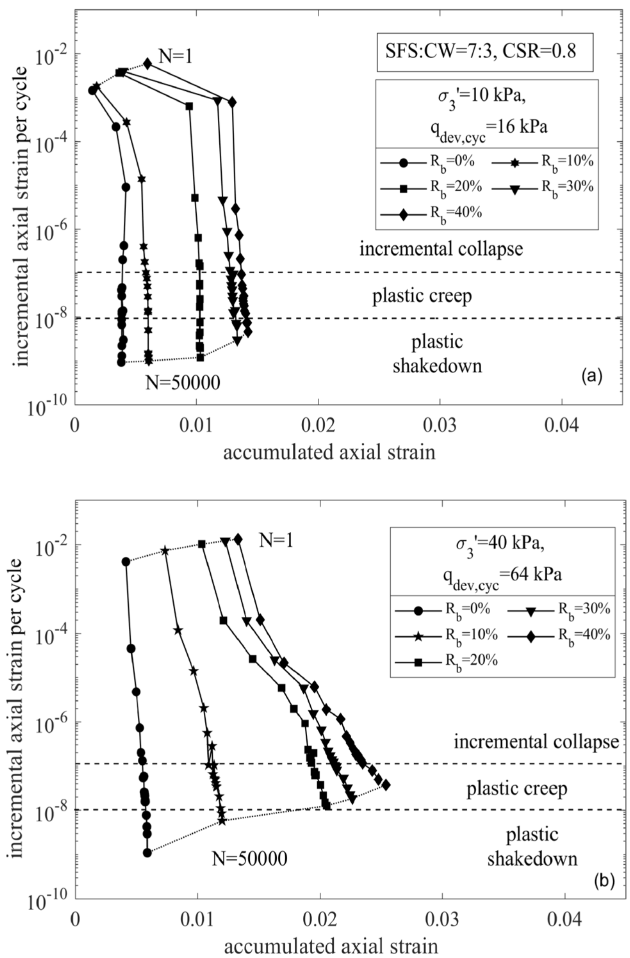

Fig. 11 Shakedown behaviour of SFS-CW-RC mixtures at two confining stresses **a** 10 kPa and **b** 40 kPa (modified after Malisetty et al. [31])

three shakedown states are defined for granular mixtures including plastic shakedown, plastic creep and incremental collapse as shown in Fig. 10. As seen from Fig. 10, steeper curves show more stable response and stability reduces as the curve flattens. For granular waste mixtures with rubber, it is important to analyse the shakedown behaviour as the addition of compressible rubber aggregates will affect the rate of permanent strains under loading. In this section, the influence of rubber crumbs on the shakedown response of SFS-CW-RC, CW-RC mixtures and RIBS is analysed.

Figure 11a and b show the rate of permanent axial strain with number of loading cycles plotted for SFS-CW-RC, CW-RC and RIBS, respectively. For each mixture, curves are plotted for different rubber contents varying from 0 to 40% and it is evident that increasing the rubber content affected the slope of the curves. Qi and Indraratna [30] proposed new limits for SFS-CW-RC mixtures based on the permanent axial strain rate ($\delta\varepsilon_a^p$) after 50,000 cycles to distinguish the three shakedown states which include:

- Plastic shakedown:$\delta\varepsilon_a^p < 10^{-8}$
- Plastic creep: $10^{-8} < \delta\varepsilon_a^p < 10^{-7}$
- Incremental collapse: $\delta\varepsilon_a^p > 10^{-7}$

Following these limits, it can be concluded that at low deviatoric stresses, SFS-CW-RC mixtures with all selected rubber contents showed plastic shakedown and the response changed for higher cyclic deviatoric stress. For the $q_{dev,cyc} = 64$ kPa, even though the confining stress is increased keeping the CSR constant, the mixture showed plastic creep response for $R_b > 20\%$. Similar response is observed for CW-RC mixtures as shown in Fig. 12a, where the material response slowly deviated from plastic shakedown as the rubber content is increased.

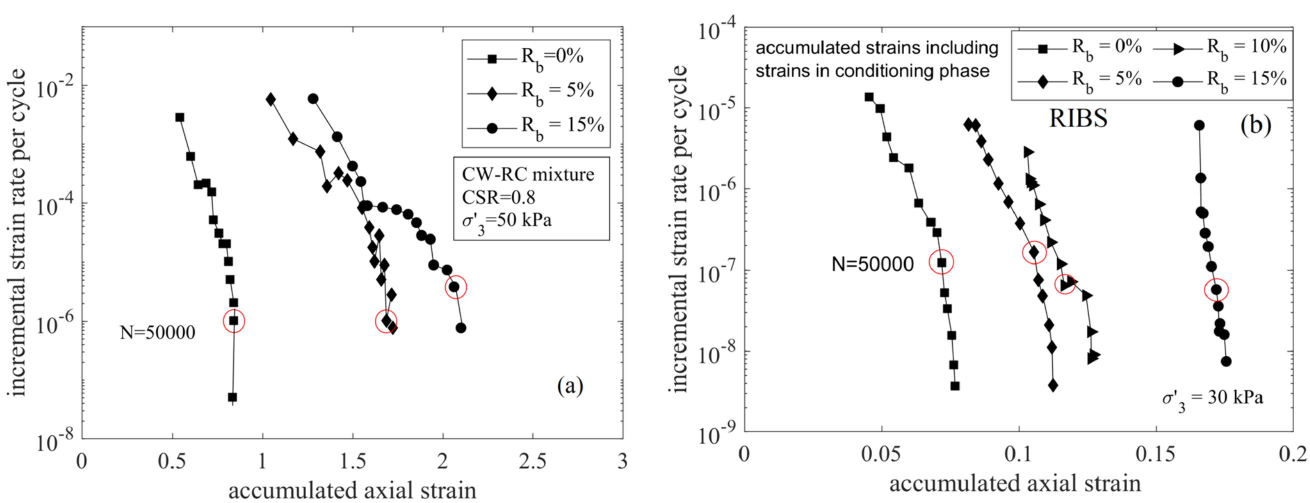

Fig. 12 Shakedown behaviour of **a** CW-RC (data from Tawk et al. [12]) and **b** RIBS mixture under cyclic loading (data from Arachchige et al. [14])

Figure 12b illustrates that for pure ballast (RIBS with $R_b = 0\%$), the permanent axial strain rate ($\delta\varepsilon_a/\delta N$) steadily decreases to a relatively low level of plastic axial strain rate (approximately up to 10^{-8}) and stabilises after about 50,000 cycles attaining plastic shakedown state. Even though adding rubber caused higher strains for RIBS during the first conditioning phase, the axial strain rate after the initial conditioning phase reduces quickly (steep slope) with increase in R_b. Also, this behaviour is more pronounced for higher R_b. It is to be noted that the influence of R_b on the shakedown response for RIBS is found to be opposite to that of SFS-CW-RC mixtures where addition of rubber ($R_b > 20\%$) caused plastic creep (slope becomes flatter). This contrasting response in RIBS might be because the larger rubber granules compress elastically more during the initial conditioning phase acting as an energy reservoir and reduces the load absorbed by ballast granules in subsequent cycles.

Field Application of RIBS

Apart from laboratory investigations, field trials were conducted through a newly built railway track with RIBS at Chullora, New South Wales in collaboration with Sydney Trains to evaluate its performance. Conventional ballast was replaced with RIBS with an optimum rubber content of 10% in a 20-m-long trial track section. A volumetric mixer (see Fig. 13a) was used to mix ballast aggregates with rubber granules on site and the standard procedure used for constructing ballasted tracks was slightly modified to accommodate the placement of RIBS from reduced heights to minimise separation of rubber granules. Instruments such as pressure plates and settlement pegs were placed at sleeper bottom, ballast-capping and capping-subgrade interfaces (See Fig. 11b) to monitor vertical stresses and deformations during track operation. RIBS was placed on the capping layer separated by a geotextile to a height of 150 mm, while the rest was filled with conventional ballast to prevent sun exposure of rubber granules and prevent the lightweight rubber granules from being washed away during heavy rainfall. To achieve sufficient compaction of RIBS, the RIBS tracks were compacted with a higher number of roller-passes compared to that of conventional ballast layer. Visual observations revealed that the roller compaction of RIBS resulted in significantly less particle breakage compared to the breakage observed when compacting conventional ballast. A reference track section was also built with conventional ballast layer as benchmark to compare the benefits of RIBS. Data collection

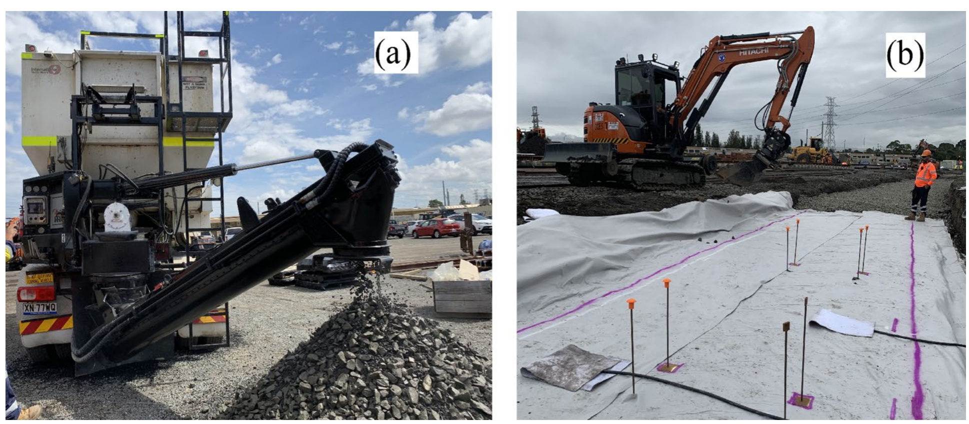

Fig. 13 **a** Ballast volumetric mixer used for RIBS preparation, **b** instrumentation in RIBS track

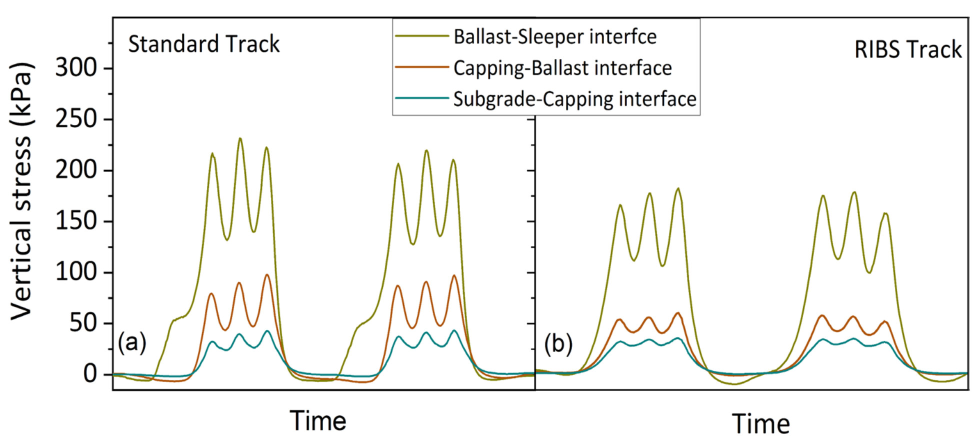

Fig. 14 Vertical stress measured for **a** Standard section **b** RIBS section

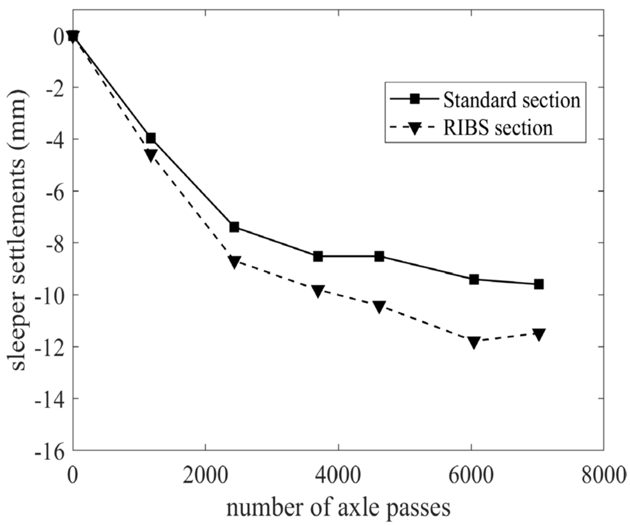

Fig. 15 Measured sleeper settlements in RIBS section compared to Standard section

was carried out on RIBS track as well as standard track section using a solar-powered data acquisition system.

Figure 14 shows the stress distribution at different layer interfaces in the RIBS section when compared to that of Standard track section, under a 21.5 tonne axle load. While the sleeper-ballast interface stresses only slightly changed, a 30% reduction in the vertical stress transferred to capping layer is observed in RIBS section (Fig. 12b) when compared to that of the Standard section (Fig. 12a). This resulted in slightly lower stresses at the subgrade interface in RIBS section. Higher energy absorption potential of RIBS is evident from these values which will be beneficial in protecting the track layers underneath from vertical stress-related failures such as mud-pumping and also reducing particle breakage. When the sleeper settlements in the track are compared as shown in Fig. 15, RIBS section showed slightly higher overall settlements than Standard section but well within acceptable limits. This behaviour is expected due to the lower overall stiffness of RIBS section attributed by relatively softer rubber granules compared to ballast aggregates. Also, the difference is mainly found in the initial 2000 axle passes and then stabilizes. Moreover, initial assessment showed lower ballast particle breakage in RIBS section when compared to Standard section increasing the durability of ballast. More benefits of RIBS are expected to be in long-term where any further settlements of the track caused by ballast breakage and subgrade problems.

Conclusions

In this paper, two innovative and environmentally sustainable applications of mining waste and discarded rubber tyres in railway track construction are presented including (i) alternate capping layer made of steel furnace slag, coal wash and rubber crumb mixtures (ii) replacing conventional ballast layer using rubber intermixed with ballast granules. Extensive laboratory tests and a field trial were conducted to assess how these materials perform under heavy haul railway loading conditions. The findings from these investigations reveal significant observations as outlined below:

- Steel furnace slag, coal wash and rubber crumb mixtures with a rubber content of 10% showed optimum performance while maximizing the benefits of ballast breakage index and keeping the values of resilient modulus and permanent axial strains within the acceptable limits.
- Cyclic triaxial tests indicated that as rubber content increased, both axial strain and compressive volumetric strain within the waste mixtures exhibited an upward trend while the resilient modulus decreased. Notably, when comparing mixtures with equivalent rubber content, CW-RC mixtures displayed higher axial deformation and experienced more pronounced contractive volumetric strain than their SFS-CW-RC counterparts. Moreover, SFS-CW-RC mixtures consistently displayed a higher resilient modulus in comparison to CW-RC mixtures.
- An increase in rubber content within RIBS led to a decrease in ballast dilation and particle breakage, though with a slight rise in permanent axial strains. Similar to mining waste mixtures with rubber crumbs, 10% rubber granules by weight in RIBS yielded the best results. With this rubber content, RIBS exhibited a substantial reduction of approximately 70% in particle breakage, while experiencing only a minor reduction of less than 6% in shear strength and maintaining an acceptable axial strain when compared to pure ballast.
- Shakedown analysis showed that at a CSR of 0.8 experienced by SFS-CW-RC and CW-RC mixtures in capping layer, these materials showed a stable plastic shakedown response below 20% rubber content, while increasing rubber content beyond 20% caused plastic creep. However, for RIBS with a CSR of 3.83 expected in ballast layer, increase in percentage of rubber granules slightly changed the shakedown response while still exhibiting stable plastic shakedown.
- Field trials with RIBS replacing conventional ballast proved 40% higher absorption of vertical stresses by RIBS and protecting capping and subgrade layers.
- The observations presented in this study proves that using industrial granular waste materials in railway tracks will benefit the environment by reducing the amount of quarried material while also contributing towards a durable and cost-effective railway infrastructure.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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