INNOVATIVE USE OF WASTE MATERIALS INCLUDING RECYCLED RUBBER IN RAIL INFRASTRUCTURE

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Abstract

Facing the high demand for faster and heavier freight trains in Australia, researchers and practitioners are endeavouring to develop more innovative and sustainable ballasted tracks. In recent years, many studies have been conducted by the researchers from Transport Research Centre at the University of Technology Sydney to examine the feasibility of incorporating recycled tyre/rubber into rail tracks. This paper reviews three innovative applications using recycled tyre products such as using recycled tyre cells to reinforce capping layer, granulate rubber mixed with ballast (Rubber Intermixed Ballast System - RIBS), and under ballast mats based on the trest results obtained from the large-scale triaxial apparatus, the process simulation prismoidal triaxial apparatus (PSPTA), and the plate load test facility. The test results reveal that the incorporation of these rubber products could increase the energy absorbing capacity of the track, mitigates the ballast breakage and settlement significantly, hence increasing the track stability. The research outcomes will facilitate a better understanding of the performance of ballast tracks incorporating these resilient waste tyre materials while promoting more economic and environmentally sustainable tracks for greater passenger comfort and increased safety.

Keywords: waste materials, rail track, recycled rubber, large-scale laboratory testing

1 Introduction

Ballasted track is the dominant track type in Australian railway systems and it deteriorates over time because of ballast breakage, lateral movement, ballast fouling, track bulking due to insufficient confinement, etc. [1]. This becomes extremely severe due to the increasing demand for heavier and faster trains to cater to the fast expansion of population and bulk transportations, which leads to costly and frequently track maintenance, and a growing burden as well as inconvenience to taxpayers and passengers.

To mitigate the track deterioration researchers and practitioners are trying to introduce synthetic inclusions into the track foundations such as geogrids, geocells, elastic rubber products etc., and among them, the inclusion of recycled tyre rubber materials becomes increasingly popular due to their high damping properties, higher energy absorbing capacity and high durability feature [2-7]. Moreover, it is environmental-friendly to reuse the waste tyres into railways to prevent a large quantity of them from being dumped in landfills as in Australia alone, there are more than 50 million waste tyres generated per year [8-10]. Since the last decades, researchers have been investigating different types of recycled tyre materials in

DOI: https://doi.org/10.5592/CO/CETRA.2022.1417

railways. For example, recycled rubber aggregates/crumbs have been mixed with ballast to help reduce the ballast degradation, or with other marginal materials (e.g. steel furnace slag, coal wash, demolished concrete) to form an energy-absorbing capping layer, hence reducing the noise and vibration and the load transmitted to the subgrade [11-15]. Recycled rubber mats/pads (i.e. under ballast mats, under sleeper pads, rubber shock-absorbing mats) were also added to rail tracks to mitigate the track damage due to dynamic load and/or impact loads [6,16-21]. Recycled tyre cells which is another type of waste tyre product that was proposed by Indraratna et al. [22] to confine the subballast of railways hence reducing the lateral movement and increasing the overall strength of the track while increasing the energy absorption when the moving heavy haul is passing by. This paper aims to overview three novel applications of recycled tyre materials in railways, including:

- rubber intermixed ballast system by mixing ballast with recycled rubber aggregates
- under ballast mats over stiff subgrade conditions
- recycled tyre cells in capping layers.

Large-scale laboratory tests were conducted to investigate the track performance (e.g. vertical and lateral movement, ballast breakage, overall stiffness) incorporating these novel inclusions.

2 Rubber Intermixed Ballast System (RIBS)

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 end of life 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 is applied as a geosynthetic in the ballast layer. This section evaluates the characteristics and performance of RIBS subjected to monotonic shearing and cyclic loads by conducting large-scale triaxial tests for changing rubber contents (-15 %, by weight) under changing confining pressures (10-60 kPa).

2.1 Materials and testing program

Arachchige et al. [12] identified that the angular rubber particles ranging from 9.5 to 19 mm perform better in reducing the breakage of larger ballast particles, thus, controlling ballast fouling so that the maximum particle size of the ballast (Latite Basalt) was limited to 1/6th of the sample diameter to avoid any influence from the boundary [23].
The target particle size distribution (PSD) curve of RIBS material along with the upper and lower limits of the Australian nominal 60 graded ballast specification [24] are shown in Fig. 1. The coefficient of uniformity (Cu) and the coefficient of gradation (Cc) of the tested RIBS were 2.6 and 1.4, respectively.
Physical modelling for the test samples was conducted with the Large-scale triaxial test apparatus (sample size: 600 mm high with 300 mm in diameter) 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. More details of the test apparatus and sample preparation can be found in [12, 25]. Prepared RIBS was placed and slightly tamped in four layers inside a 7-mm thick rubber membrane and obtained specimens with an initial void ratio of 0.824.

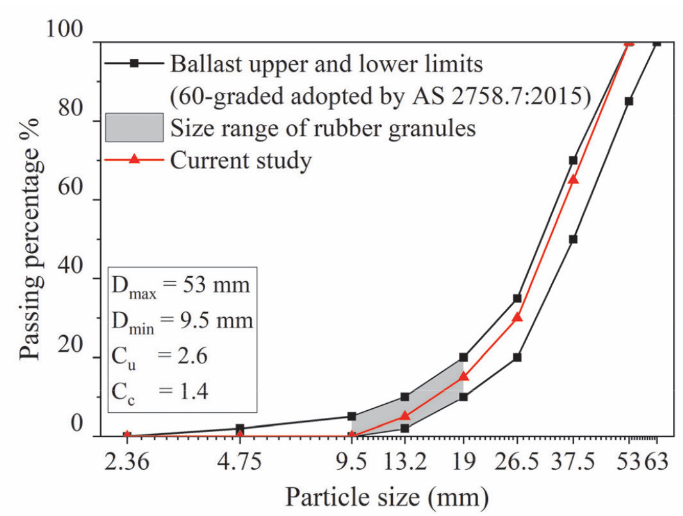

Figure 1 Particle size distribution of RIBS and rubber granules (modified after [12])

Drained triaxial tests were conducted by applying monotonic shearing at a 1.5 mm/min rate for the saturated specimens under selected effective confining pressures (i.e., 10 - 60 kPa) representing typical track confining pressures [26]. The maximum and minimum cyclic deviator stress ($q_{cyc,max}$ = 230 kPa, and $q_{cyc,min}$ = 45 kPa) were applied as a sinusoidal wave for the cyclic loading tests. $q_{cyc,max}$ is equivalent to 25 tonnes of axle load and $q_{cyc,min}$ is equivalent to in-situ stresses in the unloaded track [26].
As notable initial settlement with increased rubber under static loading could be observed, a conditioning phase was introduced at the outset of testing, where up to the maximum cyclic stress magnitude was applied monotonically to the test specimens before applying the cyclic loads at a frequency of 20 Hz. This phenomenon reasonably fits with the real-life applications where trains are running at a slower speed at the beginning to ensure the track settles safely and reduce the chance of buckling. All the cyclic loading tests were conducted up to 400,000 cycles and after completing each test, the tested material was sieved to determine particle breakage during the testing.

2.2 Strength-strain response under monotonic shearing

Fig. 2 shows the stress and strain relationship for RIBS and pure ballast under changing confining pressures. The peak deviator stress (of RIBS at relatively similar to that of pure ballast regardless of confining pressure. Increase in decreases (whereas increasing effective confining pressure increases). The reason can be that the increasing rubber-ballast and rubber-rubber contacts with the increased reducing the overall deviator stress as well as. Increased ductility due to the rubber delays the specimens from reaching their, hence RIBS with increased reach their at a larger axial strain (Fig. 2a to 2c). With the increased applied loads and increased effective confining pressures, rubber particles in the RIBS mixtures deform, hence experiencing significant initial compressive volume changes at the beginning compared to the pure ballast (Fig. 2d to 2f). Rubber grains in the compressed state trigger the particle interlocking ability (decreases the volume of voids) in the mixture and make the material denser than the initial state. Similar to the increased effective confining pressure reducing the dilation, the increased density delays the dilation of RIBS material. Permanent axial deformation behavior under cyclic loads.

2.3 Permanent axial deformation behavior under cyclic loads

Figs. 3a and 3b present the permanent axial strain (with the number of cycles) for the specimens subjected to the confining pressures of 30 and 60 kPa. The cyclic loading procedure is presented in Fig. 3a. Unlike under static loading, the axial strain response for long-term cyclic loading (after 400,000 cycles) indicates the lowest axial strains for the samples with increased rubber contents (= 15 %). This is mainly attributed to the irrecoverable particle rearrangement that occurred quickly during the initial loading in the conditioning phase, after which further cyclic loading could not generate significant compression.
From Fig. 3b it is also clear that when % increases, the permanent axial strain rate (/ progressively decreases to a reasonably low plastic axial strain rate (up to around 10^{-8}) and attains a stable rate at a reduced axial strain. Hence, RIBS behavior can also be categorised into the plastic shakedown state (negligible accumulation of plastic strain) irrespective of the rubber content. The approximate cycle numbers where the RIBS reaches the plastic shakedown are marked in Fig. 3b as solid circles. It is clear that RIBS, with 10 %, reaches the plastic shakedown at a slower rate, and it is favourable in practice to reduce track maintenance cycles required when the track settlements exceed the tolerable limit.

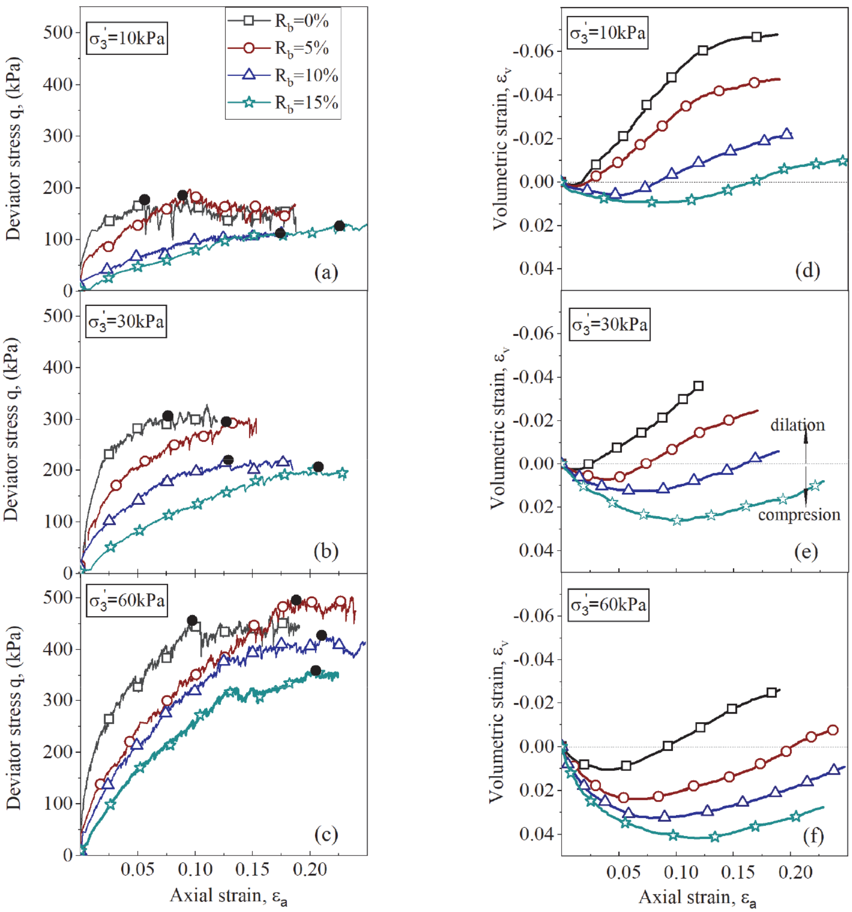

Figure 2 Effects of the rubber content: (a–c) deviator stress-axial strain curves; (d–f) volumetric strain-axial strain curves (modified after [12])

2.4 Ballast breakage

The particle breakage during cyclic loading was evaluated using the ballast breakage index (BBI) proposed by Indraratna et al. [27]. The definition of BBI is shown in Fig. 4. It can be observed that the increase of rubber content in the RIBS mixture up to 5 % considerably decrease the BBI (43 % and 23 % reduction in BBI under the confining pressures of 60 kPa and 30 kPa, respectively). However, a further reduction of BBI is insignificant when the rubber content increases from 5 % to 10 % (17 % and 7 % further reduction under the confining pressures of 60 kPa and 30 kPa, respectively). Again, the addition of 15 % rubber (= 15 %), provides a considerable reduction in BBI (73 % and 80 %) compared to the pure ballast under the confining pressures of 60 and 30 kPa, respectively).

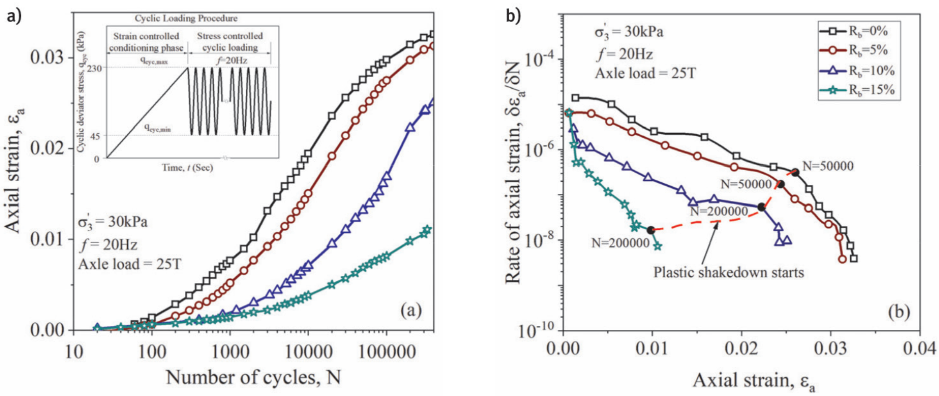

Figure 3 a) Axial strain response of RIBS mixtures under effective confining pressures of 30 kPa; b) rate of axial strain variation of RIBS mixtures of 30 kPa

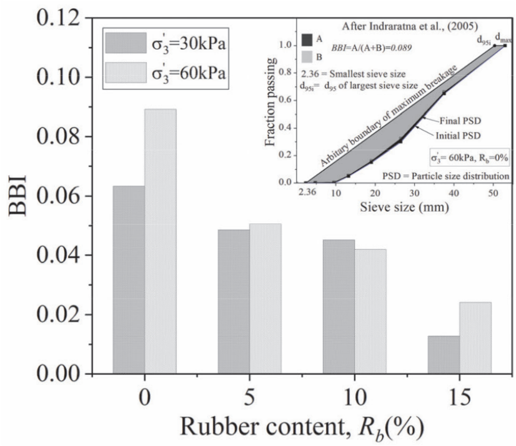

Figure 4 Influence of on Ballast Breakage Index, BBI under cyclic loading

3 Use of recycled rubber as under ballast mat (UBM)

Accelerated track deterioration is inevitable in isolated track locations such as rail tracks at the tunnels and bridges where the stiffness of the track substructure is much higher than the regular open track substructures. The deterioration becomes severe in shared rail tracks where passenger trains with higher speeds and heavy haul freight trains are running on the same track. Frequent maintenance and repairs of substructure elements are unavoidable in these track sections, and that usually leads to train speed limits, delays, and stoppages [28]. A stiff substructure underneath the ballast layer reduces overall track resiliency. Therefore, the wheel load transfer through rail is distributed to fewer numbers of neighbouring sleepers, increasing dynamic load amplification which eventually increases rail to sleeper seat loads and stress on the ballast ultimately leading to undue track damage and degradation [29]. One measure to overcome track damage at these places is the use of materials like energy-absorbing (damping) rubber layers largely called under ballast mats (UBMs) placed underneath the layer of ballast. The UBMs installed to stabilise stiffer track foundations are more effective than UBMs used in surface tracks [30, 31]. In this section, large-scale triaxial tests were done to investigate the performance of ballast stabilized with UBMs over stiff track conditions simulated at the laboratory triaxial testing. This section presents the results of large-scale testing with and without UBMs and its implications for ballast performance.

3.1 Large-scale laboratory testing

In this study, a large-scale process simulation prismoidal triaxial apparatus (PSPTA) was used to assess the role of UBM in the reduction of ballast strain, stress and degradation. Cyclic loads representing fast trains with varying speeds and heavy haul trains with varying axle loads were used to simulate a relatively stiff track foundation. UBMs made of waste tyres as construction material give valuable addition to the waste materials. Therefore, the UBMs used here were manufactured locally using recycled waste tyres. The stiffer track conditions were simulated by placing a concrete slab underneath the ballast layer. The triaxial cubicle chamber, concrete base, placement of UBM over the concrete slab, preparation of ballast layer, placement of instruments to measure deformation and pressure, placement of the rail-sleeper unit and cyclic loading setup are presented in Fig. 5.

3.1.1 Laboratory sample preparation

The fresh latite basalt material extracted from Bombo Quarry, New South Wales used as a ballast layer for laboratory testing. These ballast particles are dark, highly angular, fine-grained and very dense aggregates (maximum and minimum particle sizes are 63 mm and 19 mm, respectively). A 300 mm layer of uniformly graded (C_u = 1.6 and C_c = 1.2) ballast aggregates compacted to a bulk density of 1560 kg/m^3 were prepared following current Australian practices. To estimate the variation of degradation of this ballast layer with depth, the ballast layer in each test was divided and colour coded separately and compacted into three equal 100 mm thick layers and then, the particle breakages of each layer were assessed separately based on the colour of the ballast aggregates at the end of the cyclic load test. The UBMs used were 10 mm thick and weighed 9.2 kg/m^2. These UBMs were made by recycling the waste tyres by making rubber granulates which were then encapsulated within a polyurethane elastomer sheet. The static stiffnesses (C_{stat} = 0.20 N/mm^2) and dynamic stiffnesses (C_{dyn1} = 0.46 – 0.59 N/mm^2 for the loading frequency ranging from 5 Hz to 30 Hz) were evaluated in the laboratory before placing a single layer of UBM on top of a concrete slab of thickness 150 mm to simulate the stiffer track condition [18].

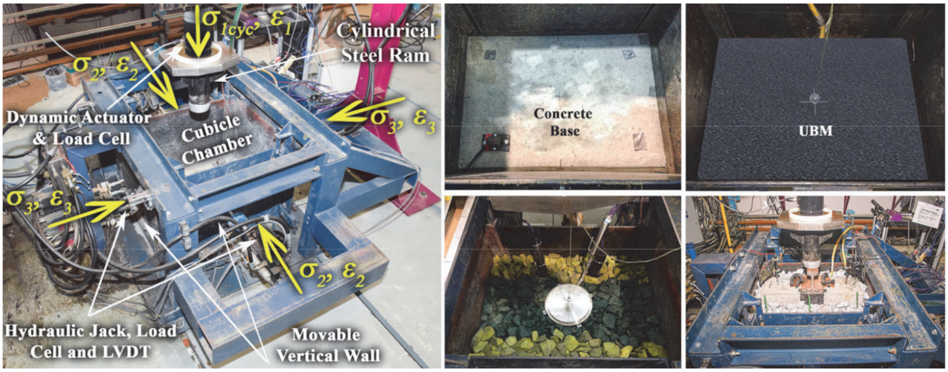

Figure 5 Photographs showing PSPTA cubicle chamber and sample preparation (modified after [18])

The PSPTA triaxial chamber can accommodate a cubical test specimen of size 800 mm × 600 mm × 600 mm which is considered a unit cell of an actual rail track. Movable vertical walls in the cubical chamber allow the longitudinal and lateral strains (ε_2 and ε_3) against the corresponding confining pressure (σ_2 and σ_3) encountered at the boundaries of the actual rail track (unit cell). Plane strain condition is assumed in the longitudinal direction because the strain in the longitudinal direction is often near-zero for a long straight section of track. Therefore, in the laboratory, a plane strain condition is simulated at the walls in the longitudinal directions (i.e. $\varepsilon_2 = 0$, perpendicular to sleeper). In the lateral direction, shoulder ballast generally gives lateral confinement (σ_3). Hydraulic jacks connected to movable vertical walls in the two lateral directions were used to apply low confinement with a stress of 15 kPa. The strain in the lateral directions was measured using Linear Variable Differential Transducers (LVDTs) connected between vertical walls and fixed points in the PSPTA frame. Pressure plates were used to measure the pressure exerted by ballast at the top, middle and bottom of the ballast layer.

3.1.2 Cyclic loading

The tests have been conducted by varying loading frequency and axle loads which simulate fast and heavy haul trains. The applied cyclic loading was the equivalent of a 25 t axle load to simulate passenger trains and 35 t axle load to simulate freight trains. The loading frequencies were varied by 15 Hz, 20 Hz, 25 Hz for 25 t axle load and 10 Hz, 15 Hz, 20 Hz for 35 t axle load. These loading frequencies were corresponding to a train speed varying from 70 to 180 km/h [17]. The sinusoidal waveform of the cyclic loading corresponding to the conditioning phase and loading phase is shown elsewhere [18]. The effectiveness of UBM is examined with and without placing the UBM on top of the concrete slab inside the cubical chamber using large-scale PSPTA with the application of 500,000 load repetitions.

3.2 Test results and discussion

3.2.1 Axial and lateral strain of ballast

The vertical and lateral ballast deformation under varying cyclic loads was measured with and without UBM. Data were collected at the selected number of load cycles (N = 1, 100, 500, 1,000, 5,000, 10,000, 50,000, $1{\times}10^5$, $2{\times}10^5$, $3{\times}10^5$, $4{\times}10^5$, $5{\times}10^5$). The corresponding axial (ε_1) and lateral (ε_3) plastic strains with N for varying axle loads and load frequencies for ballast with and without UBM are shown in Figs. 6a and 6b, respectively. The results show that the increase of axle load and loading frequencies increases the axial and lateral plastic strains.

The results also show that the ballast deforms rapidly at the initial stage of cyclic loading (from start to about N = 10,000 cycles) due to its initial densification and further packing after the ballast aggregates begin to break. This rapid plastic deformation arises from differently sized ballast aggregates sliding and being rearranged in the ballast mass, and from the contribution of the abrasion and attrition of sharp angular-cornered fresh ballast [18]. Once stabilises after around 1×10^5 cycles (stable zone shown in Fig. 6), the rate of deformation decreases and reaches almost a constant strain near the end of 5×10^5 cycles. As anticipated, ε_1 and ε_3 are high due to the stiffer track condition simulated with a concrete slab. However, when the softer UBM was placed on top of the concrete slab, the plastic strain in the ballast layer got reduced significantly. ε_1 is reduced by 10–20 %, and the ε_3 is reduced by 5–10 % for the varying axle loads (25 t and 35 t) and loading frequencies (10–25 Hz) simulated in this study.

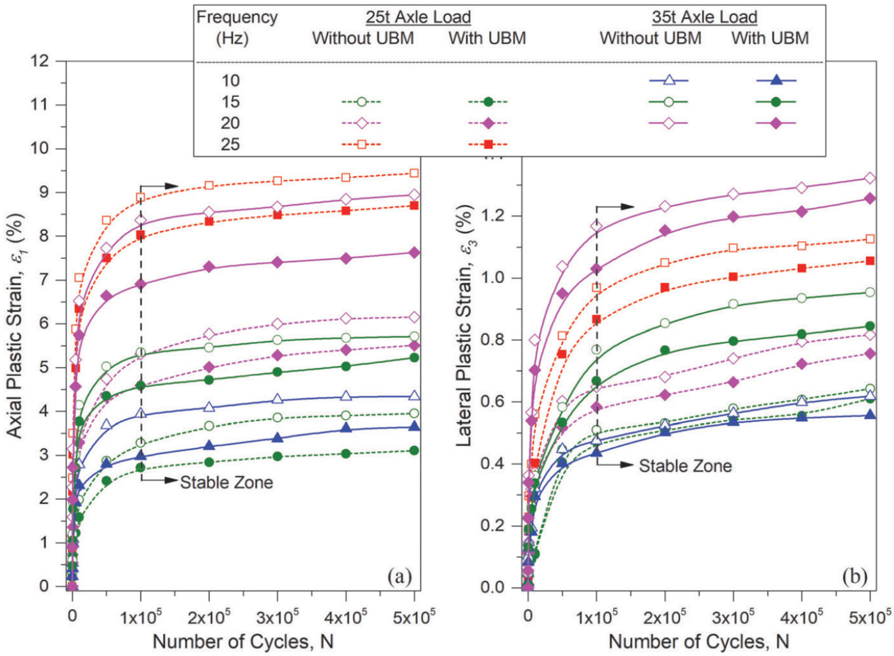

Figure 6 Plastic strain: a) Axial; b) Lateral with the number of load cycles (data sourced [32])

3.2.2 Ballast degradation and pressure variation

During the application of repetitive cyclic loading, ballast particle experiences continuous particle degradation making the ballast bed deteriorate and changing the ballast track geometry, which leads to uncomfortable rides and most importantly, causes safety issues such as derailment. During cyclic load testing, particle degradation was observed in the forms of grinding (abrasion), sharp corner breakage (attrition) and distinct splitting (fracture). This degradation contributes to increased ballast plastic strains leading to total and differential settlement in the actual rail track. The BBI calculated for each layer of the 12 cyclic load tests is presented in Figs. 7a and 7b for 25 t axle load and 35 t axle load, respectively. As expected, BBI is higher at the top layer, followed by the middle layer and bottom layer. It is also evident from the results, that the ballast degradation is increasing with the increase of axle load and loading frequency. However, the results show that ballast degradation is lessened significantly by the use of UBM placed on top of the concrete slab. The reduction in particle breakage is 20–25 % at the top layer, 30–50 % at the middle layer and the highest 50–60 % at the bottom layer due to the hard concrete base. When the overall ballast layer is considered, on average the reduction is more than 40 % when UBM was used to stabilise the stiffer base conditions.

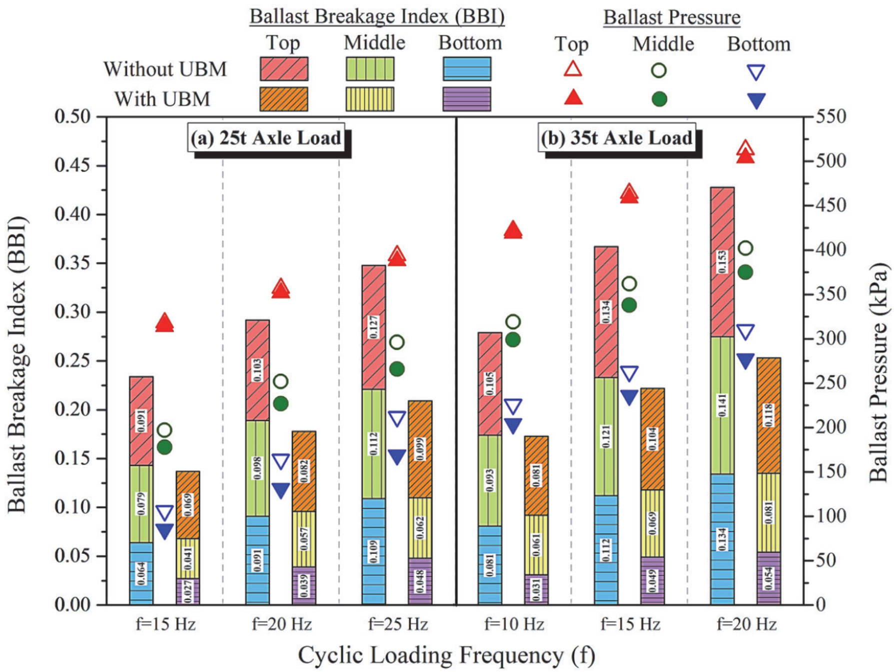

Figure 7 Variation of ballast breakage index (BBI) and ballast pressure with loading frequency and axle loads a) 25 t; b) 35 t (data sourced [32])

Granular soil type pressure cells were used at three locations to measure the variation of ballast pressure with depth. Top-level, the cell was placed underneath the sleeper, middle level, the cell was placed at the vertical centre of the ballast layer and bottom level, the cell was placed underneath the ballast layer to measure the ballast pressure variation along the depth of the ballast layer. Figs. 7a and 7b also illustrate the ballast pressure variation with the loading frequencies for axle loads 25 t and 35 t, respectively for ballast with and without UBM. The results clearly indicate that the pressure in the ballast layer increases with the axle load (changing from 25 t to 35 t) and loading frequency (varies from 10 Hz to 25 Hz). However, when a UBM is used to stabilise the hard concrete base, there is a substantial reduction in ballast pressure, especially at the bottom (ballast in direct contact with concrete slab) and the middle part of the ballast layer. The ballast-concrete interface intensifies the stresses, but due to the placement of UBM the pressure lessened by about 1–1.5 % at the top, 5–10 % at the middle and 10–20 % at the bottom.

4 Waste rubber tyres used in the subballast layer

In this method, waste rubber tyres with compacted infill materials are used to replace the standard subballast layer of a railroad track. This is done by removing a sidewall from the waste rubber tyre - the resulting part is called a “tyre cell”. The tyre cell is filled with granular material (preferably the recycled ballast) and the infill material is well compacted to make a unit cell. This unit cell is repeated in the subballast layer through the width and length of the railway track (Fig. 8).

Figure 8 Placement of tyre cells in a field project

In addition to the energy absorption characteristics of the rubber, this method also takes advantage of the 3D cylindrical geometry of the tyre cells. As a result, the infill material has additional confinement that increases the track's bearing capacity and reduces the track deformations. This technique of tyre cell reinforcement in the subballast layer of railway track is currently a pending international patent with the application number as PCT/AU2018/050074.
The following section presents the laboratory test results of the samples with unreinforced and tyre cell reinforced subballast layer subjected to plate loading.

4.1 Laboratory testing & results

In a test box (800 mm long, 600 mm wide, and 400 mm deep), the samples with and without tyre-cell reinforcement in the subballast layer were subjected to plate load tests [22]. The subgrade material (clayey sand) was compacted with a vibratory hammer to a 50 mm thick layer with a density of 17 kN/m^3 to the bottom of the test box. The subgrade layer was overlain by a 350 mm thick subballast with its particle size varying from 75 μm-19 mm. For the reinforced specimen, the subballast material was filled and then compacted to a layer of 200 mm over the subgrade. A thin geotextile (2 mm) was placed over this compacted material. The remaining 150 mm height was taken by the tyre cell placed on the geotextile. The same subballast material was filled both inside and outside the tyre cell and compacted to a density of 21 kN/m^3. The properties of the test materials are shown in Table 1, where ϕ is the friction angle, and γ_d is the dry density.

Table 1 Properties of the test materials

Test materials	**Properties**
Tyre infill (subballast)	D_{max} = 19 mm, D_{min} = 0.075 mm, C_u = 16.3, C_c = 1.3, ϕ = 39°, γ_d = 21 kN/m^3
Subgrade	D_{max} = 4.75 mm, D_{min} = 0.01 mm, Cu = 2.4, Cc = 1.1, γ_d = 17 kN/m^3
Tyre cell	diameter = 560 mm, width = 150 mm, ultimate tensile strength = 19.45 MPa
Geotextile	tensile strength = 16.8 kN/m, tensile elongation < 24 %

The deformation of the tyre cell in the axial and circumferential direction was recorded through the strain gauge. The biaxial strain gauge was attached with an industrial adhesive to the cleaned and degreased interior of the tyre cell wall. A schematic view of the test setup can be seen in Fig. 9.
In these tests, a circular loading plate having a 200 mm diameter was used. The centres of the loading plate and the tyre cell coincided with each other. The rate of displacement controlled loading was 0.2 mm/min. The readings of vertical load, displacement and strains in the tyre cell were recorded throughout these tests.
The load-displacement response of the unreinforced and reinforced samples is shown in Fig. 10a. The stiffness of the sample without tyre reinforcement is approximately 51.9 kPa/mm, however, for the test with tyre reinforcement, the stiffness of the sample is 78.4 kPa/mm. This reflects a 51 % gain in the sample stiffness because of the tyre cell reinforcement. This improvement is attributed to the additional confinement provided to the granular material by the tyre cell.
The strain readings in the tyre cell recorded by the strain gauge are extremely small (Fig. 10b). Under the vertical loading of 1610 kPa, the values of the axial compressive strain and the circumferential tensile strain are 0.0085 percent and 0.061 percent, respectively. This shows the ability of the rubber tyre cell to maintain its shape while providing confinement to the infill material. This is a great advantage over the other cell reinforcements such as geocells that tend to deform substantially on the load application.

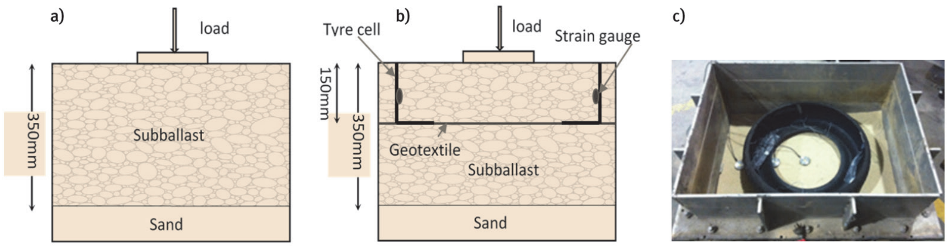

Figure 9 Schematic of the test setup for the: a) unreinforced sample, b) reinforced sample, c) photo showing the tyre cell in the test box (Modified after Indraratna et al., [22])

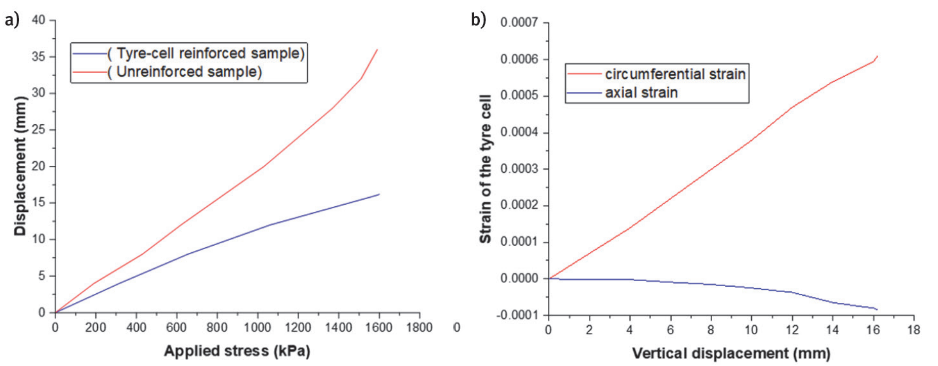

Figure 10 a) Load vs displacement curves of the unreinforced and reinforced samples; b) The change in circumferential and axial strain of the tyre cell with vertical displacement

5 Conclusions

This paper overviews three innovative recycled tyre inclusions in railway namely, rubber intermixed ballast system (RIBS), under ballast mats (UMB), and recycled tyre cell based on large-scale triaxial tests and physical modelling using the cylindrical static/cyclic triaxial facility, the PSPTA, and the plate load test facility. The remarkable findings can be concluded as below:

- The large-scale triaxial tests showed that under static loading RIBS with increased rubber content exhibited a lower peak strength but higher ductility and reduced dilation. Under cyclic loading, all the test specimens reached plastic shakedown, and increasing rubber contents in RIBS reduced the axial deformation and the ballast breakage up to 80 %.
- The results of the large-scale physical model using PSPTA showed that ballast on a stiffer foundation substructure stabilised with UBM experienced significantly less vertical and lateral plastic deformation (up to 20 %), reduced ballast stresses (up to 20 %) and degradation (up to 60 %).
- The plate load test results revealed that the reinforcement for subballast layer by the waste tyre cell increased the overall stiffness of the assembly by 51 % and efficiently maintain the axial and circumferential tensile strain of the reinforced section within a negligible level under a reasonable high vertical load (1610 kPa), hence mitigating the deformation of the track.

Acknowledgements

The authors would like to acknowledge the financial assistance provided by the Australian Research Council (ARC) Linkage Project (LP200200915) and ARC Industry Transformation Training Centre for Advanced Rail Track Technologies (ARC-ITTC-Rail: IC170100006). The financial and technical assistance provided by industry partners including Australasian Centre For Rail Innovation (ACRI), Transport for NSW, RMS, Sydney Trains, SMEC, Bestech, Douglas Partners, ASMS, South32, Ecoflex International and Tyre Crumbs Australia is gratefully acknowledged. Salient contents have been modified from research outcomes published earlier (e.g. ASCE-J. Geotechnical & Geoenvironmental Engineering, Transportation Geotechnics, and Acta Geotechnica), and reproduced with kind permission.

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