Advanced Geotechnical Solutions for Sustainable Transportation Infrastructure using Waste Materials

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Abstract: In view of worldwide national policies embracing the socio-economic and environmental perspectives of a circular economy, the Transport Research Centre at the University of Technology Sydney (UTS-TRC) has launched innovative measures of trialling recycled rubber derivatives in sustainable and innovative design of load-bearing substructure for railways in collaboration with industry. In this regard, this paper critically reviews two novel applications of recycled materials: (i) rubber intermixed ballast stratum (RIBS) to replace conventional rockfill, (ii) a hybrid track using recycled rubber tyre cells infilled with waste granular mixtures as an energy absorbing layer (REAL) which also provides additional confinement to the track substructure. Comprehensive laboratory tests using prototype cyclic triaxial testing rigs, the National Facility for High-speed Rail (NFHSR), and field tests have been conducted to examine the performance of these rubber inclusions. The tangible outcomes of laboratory and field tests reveal that the recycled rubber inclusions can act as energy reservoirs, thereby alleviating ballast breakage, deformation, and track acceleration, thus increasing the track stability.

Keywords: waste tyres, railway track, large-scale laboratory testing, field tests

1 INTRODUCTION

With the increasing demand for improved efficiency of transport networks, including new infrastructure developments, which are in contrast to the notable scarcity of quarried natural aggregates, more innovative design and construction methods for future transport corridors are urgently required. In particular, for ballasted rail tracks and highways, the use of recycled and marginal materials, including waste tyre products, demolished construction materials, and recycled crushed glass, has become an ideal practical option to replace traditional granular fills within an environmentally sustainable framework, without compromising the construction quality, performance, and longevity of transportation infrastructure (Indraratna et al., 2025).

Every year, there are around 1.5 billion waste tyres generated worldwide, and among them, over 50 million are produced in Australia, creating a significant issue due to improper disposal and inadequate recycling, leading to large stockpiles (Mountjoy et al., 2015). Recycling these waste tyres in railway foundations is promising due to their higher ductility and energy absorption properties than conventional aggregates (e.g. sand, crushed rock). Rubber granules/shreds/crumbs are the most popular waste tyres products, and they have been used: (i) in the railway capping/subballast layer by mixing with other rigid waste materials such as coalwash and steel slags (Hunt et al., 2022, Qi and Indraratna, 2022, Riyad et al., 2025), and (ii) in the ballast layer by mixing with fresh ballast materials (Guo et al., 2022, Arachchige et al., 2023b, Indraratna et al., 2024). Tyre cells, by removing one side wall of the waste tyre, have also been applied in the rail track capping layer to improve the track confinement. Comprehensive laboratory results have shown that adding granulated rubber or tyre cells can efficiently enhance the energy absorbing capacity, reduce the ballast breakage and mitigate the load propagation from the moving train loads (Malisetty et al., 2022, Qi et al., 2024, Riyad et al., 2024). While scrap passenger car tyres are the most common source for recycled tyre processing companies, handling the massive, heavy off-the-road (OTR) tyres from the mines adds to the challenge. Indraratna et al. (2022a) provided an innovative solution by cutting these giant OTR tyres into segments and installing them on the shoulder ballast to increase the confinement and reduce the dilation of ballast movement. While theories on confinement (e.g., hoop stress) and energy absorption are evolving, scientific evidence of using recycled tyres in tracks remains limited. Moreover, the practical application of rubber tyres, considering their 3D cylindrical shape for track performance, has not been tested. Recent studies have focused on static loading or cyclic loading with restricted boundary conditions (Indraratna et al., 2017, Indraratna et al., 2022b), but only within a unit cell framework.

This paper aims to introduce two novel applications of recycled tyre products in rail tracks: (i) rubber intermixed ballast stratum (RIBS) and (ii) a hybrid track using OTR tyre segments in shoulder ballast and tyre cells in the capping layer. Their performance (stress-strain response, vertical pressure along the track depth, and acceleration) was investigated through large-scale laboratory experiments, the prototype (1:1 scale) National Facility for High-speed Rail (NFHSR), as well as real-life field trials using 22-tonne freight locomotives for applying the cyclic loads.

2 RUBBER INTERMIXED BALLAST STRATUM (RIBS)

The RIBS integrates rubber granules sourced from waste tyres with traditional ballast materials to enhance railway track performance. This innovative approach aims to improve durability, reduce ballast degradation, and promote sustainability by utilising recycled rubber. Laboratory and field studies determined that an optimal rubber content of 10% by weight, with particle sizes between 9.5 mm and 19 mm (Fig. 1), would provide significant mechanical and environmental benefits (Arachchige et al., 2021, 2022). In this section, the mechanical behaviour of RIBS is investigated via large-scale cyclic triaxial tests. For this purpose, a full-scale field trial was also conducted near Sydney to validate the laboratory findings of RIBS in a real-world railway environment. For rail ballast, this study considered the most widely used latite basalt from a quarry located south of the city of Wollongong,NSW. Recycled rubber granules were obtained from Tyrecycle Australia. The rubber particles were chosen based on their angularity and size distribution to ensure compatibility with ballast aggregates. Since larger rubber particles exceeding 19 mm lack the necessary angularity for effective interlocking, the selected range of 9.5 mm to 19 mm ensures structural integrity. Similarly, smaller rubber crumbs (<9.5 mm) may contribute to ballast fouling and obstruct drainage. Figure 1 shows the gradation of the testing materials.

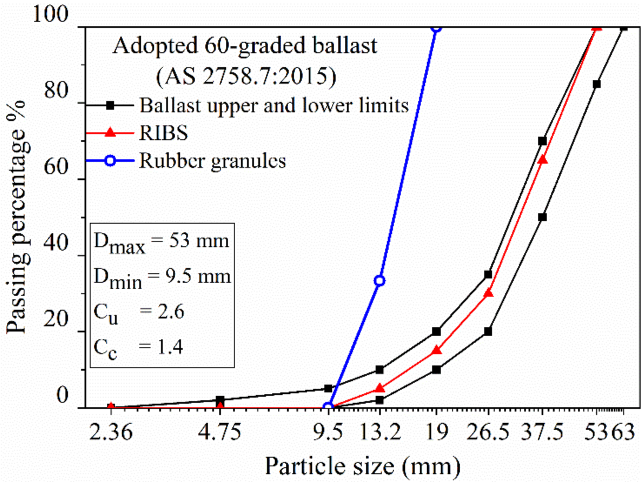


Figure 1. Particle size distribution of RIBS (After Arachchige et al. 2021 with permission from Springer)

2.1 Laboratory investigation of RIBS

Large-scale cylindrical triaxial tests were conducted to determine the geotechnical properties of RIBS specimens with varying rubber content ($R_b = 0$–15%). These tests were performed under confining pressures ranging from 10 to 60 kPa. Additionally, cyclic tests simulating a 22-tonne axle load train passing at a frequency of 20 Hz were carried out to assess the deformation and degradation of RIBS specimens.

Figure 2 illustrates the relationship between the deviator stress ratio ($\eta = q/p'$) and axial strain (ε_a) for both fresh ballast and RIBS material. The results indicate that pure ballast exhibits a higher peak stress ratio (η_{peak}) than RIBS, and that reflects the reduction in shear strength with the inclusion of rubber. It is also calculated that increasing the R_b from 0% to 10% results in a slight reduction of the effective friction angle by less than 3%, decreasing from 48.8° to 47.7°. Additionally, the inclusion of rubber particles delays the increase in the deviator stress ratio, a trend that becomes more pronounced as confining pressure (σ'_3) increases. When the confining pressure is relatively low ($\sigma'_3 \leq 30$ kPa) and the rubber content remains minimal ($R_b \leq 5\%$), the peak stress ratio of RIBS gradually decreases throughout the shearing process. However, at higher confining pressures ($\sigma'_3 > 30$ kPa) and with a greater rubber content ($R_b > 5\%$), the deviator stress ratio of RIBS stabilises at larger axial strains. Regarding stress ratio behavior, the influence of σ'_3 on RIBS with higher rubber contents ($R_b > 5\%$) is less pronounced compared to pure ballast. This is mainly attributed to the reduced dilatancy of RIBS, as evidenced in Figure 2(d), where higher rubber content leads to increased compressive strains at peak stress ratio, whereas pure ballast demonstrates dilation.

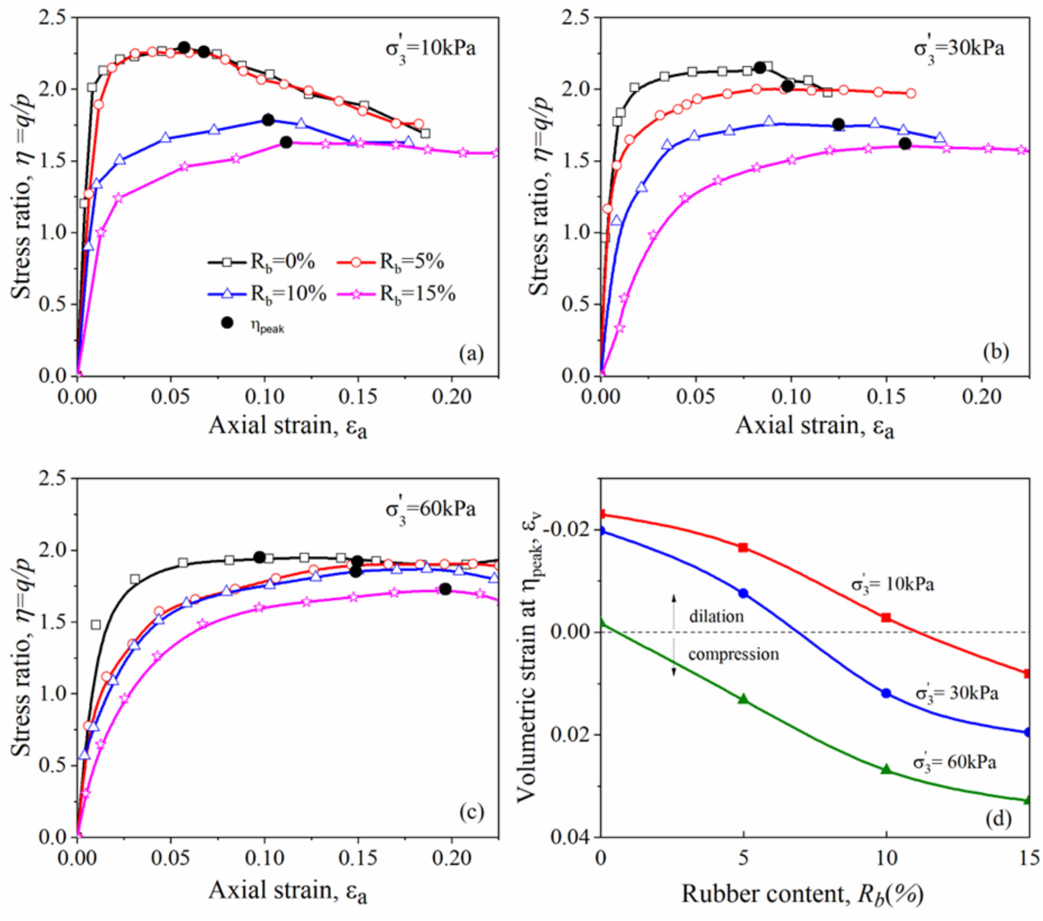


Figure 2. (a-c) Variation of deviatoric stress ratio with axial strain (d) Volumetric strain at η_{peak}.

Large-scale cyclic triaxial tests were also conducted under varying confining pressures (30 and 60 kPa) to evaluate the mechanical behaviour of RIBS. Cyclic loading was applied up to 400,000 cycles to monitor axial deformation and energy dissipation characteristics. Arachchige et al. (2021) observed significant initial compression strains with increasing rubber content under monotonic loading tests (Fig. 2). To account for this, an initial conditioning phase was introduced, as illustrated in the cyclic loading procedure as shown in Figure 3a. The axial strain (ε_a) measurements corresponding to this conditioning phase suggest that a higher rubber content promotes material rearrangement into a denser state (reduced void spaces). Consequently, there is reduction in axial strain during subsequent cyclic loading as observed in Fig. (3b). Similar to pure ballast, RIBS exhibits a decrease in ε_a with increasing σ'_3. However, ε_a continues to accumulate as the number of loading cycles increases and serves as an indicator of vertical deformation (settlement) under cyclic loading stress.

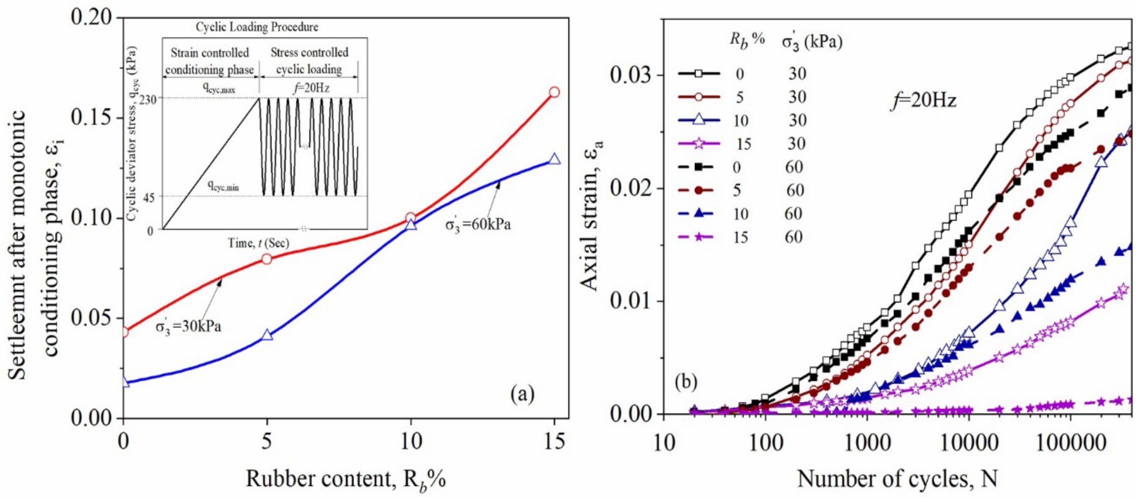


Figure 3. (a) Permanent axial deformation after the conditioning phase (b) Axial strain response against the number of cycles (after Arachchige et al. (2023a) with permission from ASCE)

2.2 Field testing of RIBS

A full-scale instrumented trial track was established in Chullora (a western suburb of Sydney), in collaboration with industry stakeholders, including Sydney Trains (now incorporated in the parent public organisation, Transport for NSW) and Bridgestone Corporation, to evaluate the field performance of RIBS. The trial included both RIBS integrated and conventional track sections to facilitate comparative analysis. The RIBS track formation was modified by replacing the conventional 150 mm thick bottom ballast layer with RIBS material as studied earlier using large scale laboratory testing. To assess the track performance, an 81-class locomotive with an axle load of 22 tonnes connected to two wagons was deployed along the trial track at speeds ranging from 10 to 13 km/h, representing the maximum allowable speed at the site.

Figure 4 presents the variations in vertical pressure caused by train movements over both the RIBS track and the standard track. The peaks in the graphs correspond to wheel passages, while each plot includes three curves representing pressure fluctuations of vertical pressure at distinct interfaces: (i) between the ballast and sleeper, (ii) between the capping and ballast, and (iii) between the subgrade and capping layers. In the RIBS section, the vertical stress at the bottom of the ballast layer was reduced by over 30% compared to the standard track. Notably, the maximum vertical pressure directly beneath the wheel contact point dropped by more than 35% in the RIBS track, signifying a lower impact load on the granular structure of the ballast layer compared to the standard track. This field test further validates the advantages of using RIBS, which could efficiently reduce the load propagation along the track depth, hence minimising the damage from the moving train loads.

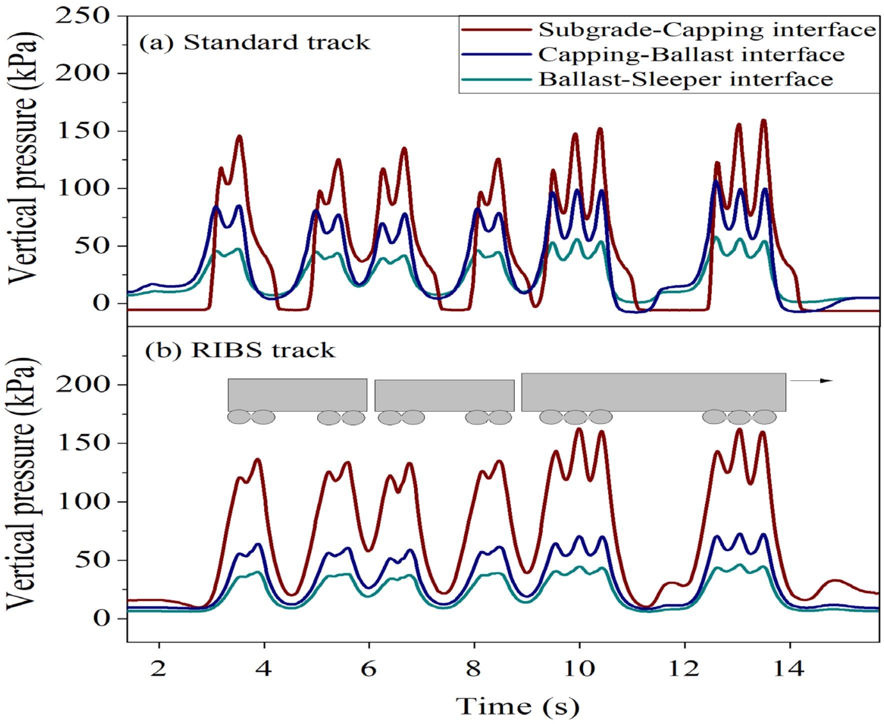


Figure 4. (a) Vertical pressure distribution (a) standard track, (b) RIBS track

3 APPLICATION OF RUBBER ELEMENTS IN TRACK

3.1 National Testing Facility for Heavy Haul Loading

This section developed a hybrid track using waste tyres, where OTR tyre segments were added to shoulder ballast to improve track confinement, and recycled rubber tyres were used as a capping layer (both awaiting international patents). In order to investigate the performance of this hybrid track, the National Facility for High-speed Rail (NFHSR) was used to conduct prototype testing by the Transport Research Center (TRC) at UTS, led by the first author. The facility specifications, test configuration and experimental outcomes of the hybrid track integrating rubber tyres are described in detail in Indraratna et al. (2021, 2022a). In summary, upto 25-tonne axle load was applied at 15 Hz for 500,000 cycles in the first test on an unreinforced track, which measured settlement, lateral deformation, stresses, accelerations, and ballast fracture. Some findings are re-used here to assess hybrid track performance after being compared with field data from tracks in Bulli and Singleton, NSW.

A hybrid track with (i) tyre cells in the capping layer (EcoFlex cell, Fig. 5a-c) and (ii) OTR elements in the shoulder ballast (Fig. 5b) was tested under cyclic loading. A cross-section of a test pit was built using layered track materials. A 795 mm fine-grained clayey sand layer compacted to 16.5 kN/m^3 was placed as the bottom layer to mimic the subgrade (natural soil foundation), and a structural fill of 650 mm in thickness was placed above the subgrade and compacted to 18.5 kN/m^3. The infilled tyre cell assembly was placed above the structural fill layer as a replacement to the traditional capping layer. For this trial, discarded spent ballast recycled from a nearby spoil tip was used as the infill material. Finally, a 300-mm thick ballast layer was placed and tamped to a unit weight of about 16 kN/m^3 above the infilled rubber tyre cells.

3.2 Measured settlement and lateral displacements

The hybrid track's vertical settlement was measured and compared with field measurements from Bulli track (Indraratna et al., 2010), laboratory testing (Indraratna et al., 2013), and unreinforced track results (Indraratna et al., 2021), as shown in Figure 6a. Up to N=100,000 cycles, all the results demonstrate rapid early settlement, beyond which there is a steady settlement until N=300,000 cycles and then eventual stabilisation (stable shakedown) after about N=500,000 cycles. The hybrid track settles more quickly at first than the unreinforced track, but it settles more slowly over time. It demonstrates quick ballast compression and rearrangement by stabilising at N=100,000 cycles, which is significantly earlier than the unreinforced track. This accelerated shakedown phase prolongs maintenance intervals and improves track stability.

The lateral displacement of unreinforced and reinforced tracks was measured by horizontal extensometers (Fig. 6a). It is seen that while the unreinforced track displaces about 9 mm, the reinforced hybrid track exhibits lateral displacement ranging from 3 to 6 mm, averaging 4.5 mm. The OTR shoulder reinforcement, which improves ballast confinement, primarily contributes to this decrease. In contrast to the unreinforced track, which has a lateral in situ pressure of 23 kPa, the hybrid track raises the effective confining stress to 55 kPa (Indraratna et al., 2021).

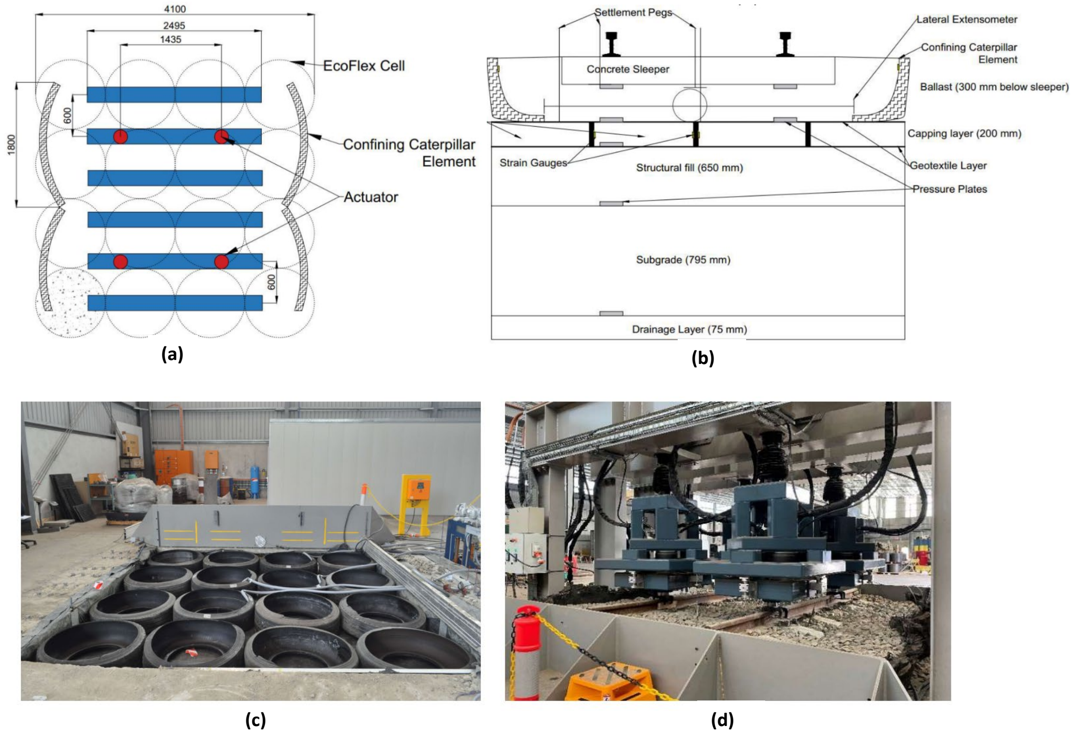


Figure 5. Diagram of test track: (a) top view; (b) cross-section; (c) tyre assembly as capping; (d) complete track with shoulder-confined tyre segments (after Indraratna et al., 2022a with permission from Elsevier)

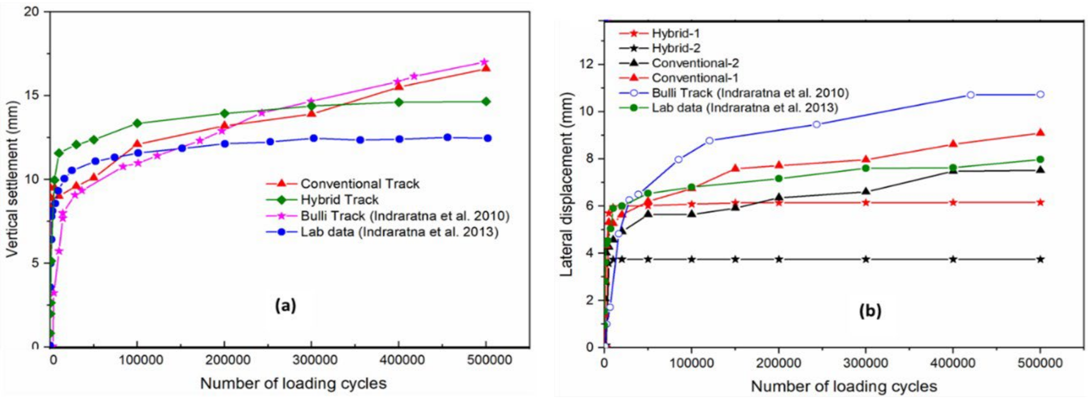
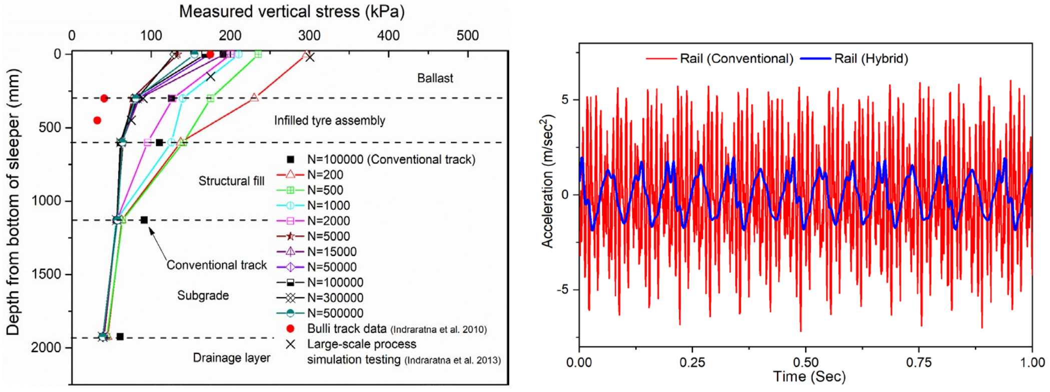


Figure 6. (a) Measured vertical settlement; (b) Lateral displacement (after Indraratna et al., 2022a with permission from Elsevier)

3.3 Stress distribution and accelerations of tracks

Figure 7a compares the vertical stress (σ_v) measured at various depths of the hybrid track with that of the unreinforced track at different loading cycles. In accordance with settlement tendencies, stress values stabilise at around N=100,000 after declining with loading cycles. The top ballast and capping layers could withstand significantly greater stress as a result of the reinforcement when compared to the unreinforced counterpart, while transfering less stress to the underlying layers, which is most beneficial in the case of soft subgrade (Indraratna et al., 2021). Rail accelerations at N=200,000 cycles are compared in Figure 7b, which demonstrates that the hybrid track accelerates less than half as fast as the conventional track. The hybrid track could reduce the vibrations by at least 50% at maximum accelerations of 2.47 m/s^2, as opposed to 5.60 m/s^2 on the conventional track. Comparing the hybrid track to the traditional section, ballast degradation tests showed a 33% and 42% decrease in breakage below the actuator and shoulder locations, respectively.



(a) (b)

Figure 7. (a) Measured stress distribution with depth; (b) Measure accelerations on the rail (after Indraratna et al., 2022a with permission from Elsevier)

4 CONCLUSIONS

In this Keynote paper, the recycled tyre products, including rubber granules, tyre cells, and off-the-road (OTR) tyre segments, were integrated in a track foundation to provide a rubber intermixed stratum (RIBS). This hybrid track section was constructed in which OTR tyre segments and tyre cells were installed as shoulder ballast and capping layer, respectively. Both laboratory and field tests were conducted to investigate their performance. The following conclusions can be drawn based on the results of this study.

- Large-scale monotonic and cyclic triaxial test results confirmed that during the conditioning phase, RIBS developed a denser granular structure as the rubber granules underwent compression. This process resulted in a reduction of permanent axial strains by 23% to 65%, as the rubber content increased from 10% to 15%.
- Real-time data from the field instruments indicated that the RIBS section of the track outperformed the standard track sections with a reduction in the vertical pressure on top of the structural fill and concrete sleeper by over 30% and 35%, respectively.
- As compared to an unreinforced track, the hybrid track was able to significantly decrease the ballast deformation, stresses at the capping-subgrade interface and the vibrations (by about 50%), with a corresponding reduction in ballast breakage by 30-40%.

These results suggest that using recycled rubber offers a sustainable and cutting-edge approach to rail track stability in addition to the environmental benefits of lowering carbon emissions and the need for quarrying, apart from reduced annual maintenance costs and extended lifespan of track. In the future, these impactful outcomes are guaranteed to facilitate revised technical standards for sustainable transport infrastructure, thereby effecting increased supply chain efficiency through higher freight loads and train speeds, as well as greater passenger comfort and increased safety on shared rail networks.

ACKNOWLEDGEMENTS

The authors would like to thank the financial support from the Australian Research Council (ARC) Linkage and Discovery projects, namely, ARC-LP200200915 and ARC-DP220102862. The authors would like to acknowledge the financial and technical support from industry partners including Sydney Trains, SMEC Australia, Bentley Systems, and Bestech Australia. Some figures

were reproduced from the authors' past articles published in journals such as Acta Geotechnica and Transportation Geotechnics, with kind permission from Springer and Elsevier, respectively.

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