

# INNOVATIVE USE OF RECYCLED RUBBER AND MINING BY-PRODUCTS FOR SUSTAINABLE RAIL AND ROAD INFRASTRUCTURE

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## ABSTRACT

Encouraging more real-life applications of circular economy perspectives in transportation infrastructure design and construction, this paper focuses on utilising granular wastes (i.e. coal wash and steel slag) from coal and steel mining for port reclamation, and recycled rubber elements including granulated rubber particles, rubber mats, tyre cells and truck tyre segments for stabilising track formations and reducing ballast degradation. The mixtures of coal wash and steel slag were optimised through a proposed novel customer-made selection criteria and verified through field trial. Moreover, the promising damping property of rubber (with respect to strain energy capacity) was fully exploited to design substructure energy retention layers to minimise deformation and degradation of track elements including impact damage caused by track irregularities such as rail corrugations. The large-scale laboratory testing results obtained using the large-scale triaxial, Process Simulation Prismatic Triaxial Apparatus, and the prototype National Facility for Cyclic Testing of High-speed Rail and the field trial verify that rail tracks altered with the above-mentioned rubber elements easily satisfy the specified standards and are even superior to conventional ballast tracks in terms of degradation, deformation, stress distribution, and track vibration. In addition, these environmentally friendly approaches promote the reuse of mining by-products and discarded tyres and conveyor belts in transportation infrastructure while providing long-term cost benefits that can save millions of dollars annually in track maintenance and quarrying natural rock aggregates.

## 1 INTRODUCTION

According to the Australian Infrastructure and Transport Statistics (2022), domestic freight transport in Australia has been experiencing significant growth over the past 40 years, with road, rail freight and coastal shipping activities dominating the sector. It is projected that the demand will continue to increase exponentially. Rail and road maintenance costs have been increasing due to the growing volume and intensity of freight transportation on existing infrastructure. The incorporation of waste and marginal materials in new rail and road construction projects as well as port reclamation projects, not only extends infrastructure longevity but also offers a sustainable approach to address the growing accumulation of waste materials, such as used tyres, industry by-products like coal wash (CW), and Basic Oxygen Steel furnace slag (BOS).

CW and BOS are two common granular by-products from coal mining and steel production, respectively. In Australia, millions of tons of these waste materials are generated every year (Malasavage et al., 2012, Indraratna et al., 2018). Rather than dumping them on useable lands, paying government levies, and causing environmental issues, both industries and the government expect novel solutions to reuse these materials in civil and geotechnical engineering. CW, albeit with a high particle breakage potential, has been proven to be a promising water-front embankment fill once compacted well (Rujikiatkamjorn et al., 2013). The volumetric instability (expansion) of BOS hinders its individual usage in civil/geotechnical engineering, but well-balanced mixtures by incorporating other materials such as CW, rubber crumbs, cement, asphalt, etc. have been investigated and verified their broad usage in roads, rail tracks, port reclamation and civil constructions (Wang, 2010, Malasavage et al., 2012, Indraratna et al., 2020, Qi and Indraratna, 2022a). For instance, a

blended mixture of CW and BOS, has been tested and applied in a real-life port expansion project located on the south coast of New South Wales (Port Kembla Reclamation project). This mixture has been proven to meet the expected requirements for bearing capacity, drainage, swelling potential, compaction, and shear strength properties through laboratory and field investigations and testing facilities (Chiaro et al., 2015).

Over 50 million waste rubber tyres are produced in Australia each year, posing a severe problem due to excessive dumping and uneconomical recycling techniques that result in massive stockpiles (Mountjoy et al., 2015). Additional challenges arise while handling enormously huge and heavy off-the-road (OTR) tyres produced by the mining industry. Due to the high energy-absorbing capacity and damping properties of recycled rubber materials, they have been recently brought to seismic-isolation projects and transportation infrastructure such as railways, roads, and airport runways (Tiwari et al., 2012, M Sol-Sánchez et al., 2015, Arachchige et al., 2022, Qi and Indranatna, 2022b). Given the need for faster and heavier rail lines, an innovative solution to reuse these tyres can provide promising outcomes to enhance railway substructures.

The typical products of recycled rubber used in rail tracks are granulated rubber (or rubber crumbs), rubber mats (e.g. under ballast mats, under sleeper pads), tyre cells, rubber geogrids, and arch-shaped rubber tyre segments. The granulation of used rubber tyres is a widely adopted practice, with tyre-derived aggregates commonly employed for energy recovery, rubberised asphalt, and concrete applications (Navarro and Gámez, 2012, Mohajerani et al., 2020). Moreover, recent research has highlighted the feasibility of incorporating rubber granules into conventional ballast for rail infrastructure. Rubber intermixed ballast system is an experimentally proven approach wherein the certain grain size of conventional ballast is partially substituted with rubber granules through the optimisation of the geotechnical characteristics of the ballast-rubber mixtures (Arachchige et al., 2021). Recent studies (e.g. Sinniah K Navaratnarajah and Indranatna, 2017, Ngo et al., 2019) found that the reuse of rubber sheets is worth considering in terms of track performance, sustainability, and economic perspective. For instance, rubber mats are placed under the ballast layer (under ballast mats; USB) to mitigate the degradation of ballasted railway tracks while reducing energy transferred into the subsequent track formation, including the subgrade. In addition, trial tracks were implemented as a real-life application, where waste tyre segments infilled with granular wastes served as the capping layer for railways (Indranatna et al., 2022b). These trials followed comprehensive experimental investigations, which involved large-scale laboratory physical simulations and testing using the process simulation prismoidal triaxial apparatus (PSPTA) and the National Facility for Cyclic Testing of High-speed Rail.

This paper describes four distinctly different innovative and cost-effective approaches including: (i) port reclamation using the optimal mixtures of CW and BOS, (ii) an alternative load-bearing granular mass, namely, Rubber Intermixed Ballast System (RIBS), developed by replacing a fraction of rock aggregates in the ballast matrix with similar size rubber granules (10% by weight), (iii) ballast mats (UBMs) installed on top of the concrete deck to reduce ballast deformation and degradation, and (iv) a hybrid track built using tyre cell assembly in tandem with giant off-the-road (OTR) arch-shaped tyre segments installed along the track shoulders to prevent the lateral movement of ballast, thus minimising ballast dilation and breakage. The optimal blends of CW and BOS from approach (i) were established to be used as structural fill based on comprehensive laboratory test results and then verified through a field trial for port reclamation. The novel rubber inclusions from approaches (ii)-(iv) aimed to provide an equivalent energy reservoir to reduce the dissipated energy from moving rollingstock to other track substructure elements such as ballast and concrete sleepers, thus minimising deformation and damage. Large-scale laboratory programs using the large-scale triaxial apparatus, the iconic Transport Process Simulation Triaxial Facility, and Australia's first and only National Facility for Cyclic Testing of High-speed Rail were conducted to verify these concepts. Recently, they were adopted as part of the track construction by Sydney Trains.

## **2 USE OF WASTE GRANULAR MIXTURES IN PORT RECLAMATION**

### **2.1 MATERIALS**

Port Kembla has been Wollongong's commercial harbour solely catering to the coal and steel export market. The coal mining and steel industry generates a massive volume of coal wash, and blast furnace slag up to 2.1 million tonnes per year. To attract new trades and increase the volume of existing berths, a new 45-hectare outer area was constructed via land reclamation. Due to the associated environmental concerns and the scarcity of natural fill, the Port Kembla Port Corporation considered using these locally abundant waste aggregates as the predominant reclamation fill. In-depth knowledge of the behaviour of heterogeneous waste materials through their geotechnical characterisation was acquired on the basis of load-bearing capacity and post-construction deformation. Based on the trace element concentration tests conducted by the Port Kembla Port Corporation (PKPC), both coal wash and furnace slag pose little or no contamination risk to the environment or public health (Coffey, 2009). Although numerous studies since the 1990's have reported on the geotechnical characterisation of heterogeneous coal wash, minimal information is still available to describe comprehensively their short and long-term behaviour on compaction due to particle breakage. Indranatna et al. (1994)

showed that the geotechnical properties of coal wash can be markedly improved with appropriate compaction. Applying steel slag alone can pose a severe problem of swelling (Chiaro et al., 2015). The optimum mixture of both materials can minimise the adverse effects and provide a suitable blend to be used as fill.

For compacted fill, shear strength and permeability are the main criteria where a friction angle greater than 30° or CBR of at least 10% (Davies and McIlquham, 2011) and the permeability within the range between  $1 \times 10^{-6}$  and  $1 \times 10^{-4}$  cm/sec (Look, 2007). The purposes of the criteria are to control post-compaction settlement and prevent the generation of excess pore water pressure and internal erosion. Under relatively low overburden pressure, the free swelling should be within 3%, whereas the breakage index of the waste mixture should be within 12%. Chiaro et al. (2015) showed that the optimum blend should contain 35-60% coal wash by weight (Figure 1).

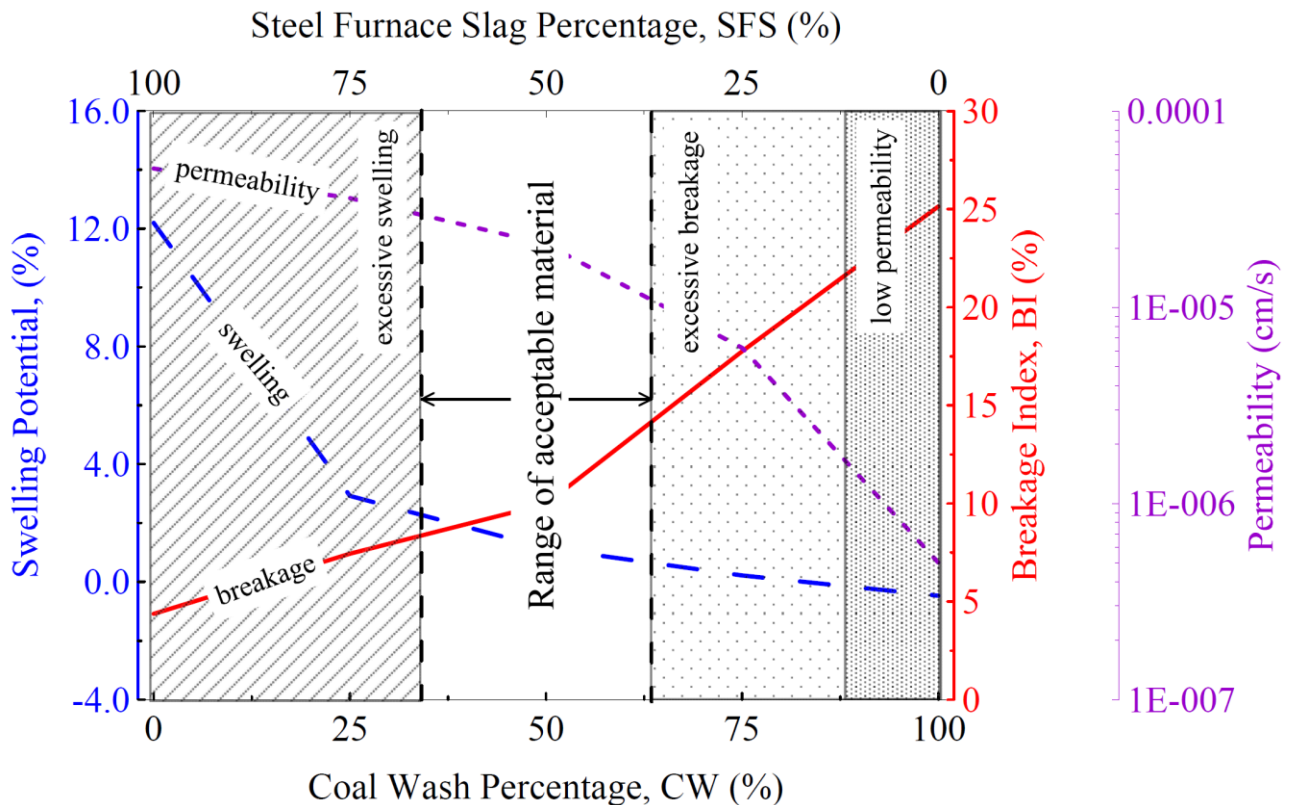


Figure 1: Determination of CW and BOS blend for port reclamation (modified after Chiaro et al., 2015)

## 2.2 FIELD TRIAL

The field verification was conducted at the Port Kembla Outer Harbor reclamation site with an area of  $55 \times 14\text{m}^2$  with 1.4 m below the ground level. The area was separated into two subsections for two mixtures (43% CW and 27% CW mixtures). The blending of the materials was carried out by an excavator and the materials with an initial layer thickness of 0.3 m were compacted using a 13-tonne smooth steel drum roller, as shown in Figure 2. The field density was determined using sand cone replacement and nuclear densitometer tests. The laboratory maximum dry unit weights for 27% and 43% CW are 21.1 and 20.2 kN/m<sup>3</sup>, respectively. Four roller passes provide sufficient energy to achieve a 90% relative compaction. Based on particle size distribution analyses, most of the large particles (>2cm) were degraded to smaller particles, and the overall gradation was similar to that of laboratory specimens.

To assess the shear strength of the mixtures with the depth, dynamic cone penetration tests (DCPTs) were conducted at 0.1 m intervals. The equivalent California bearing ratios are in the range of 25-50, similar to that of dense to very dense sand (Figure 3), confirming its suitability as structural fill in terms of shear strength.

Kindly take note that the outcomes of this investigation were constrained to a specific coal wash and steel furnace slag within the Illawarra region. Given the substantial alterations in the characteristics of these materials, there exists a valuable opportunity to delve into the examination of fluctuations in geotechnical properties. This examination would primarily centre around the impact of free lime content and the calibre of fines present in the coal wash.



Figure 2: Compaction trial (a) Coal wash and steel furnace slag and (b) Vibration roller

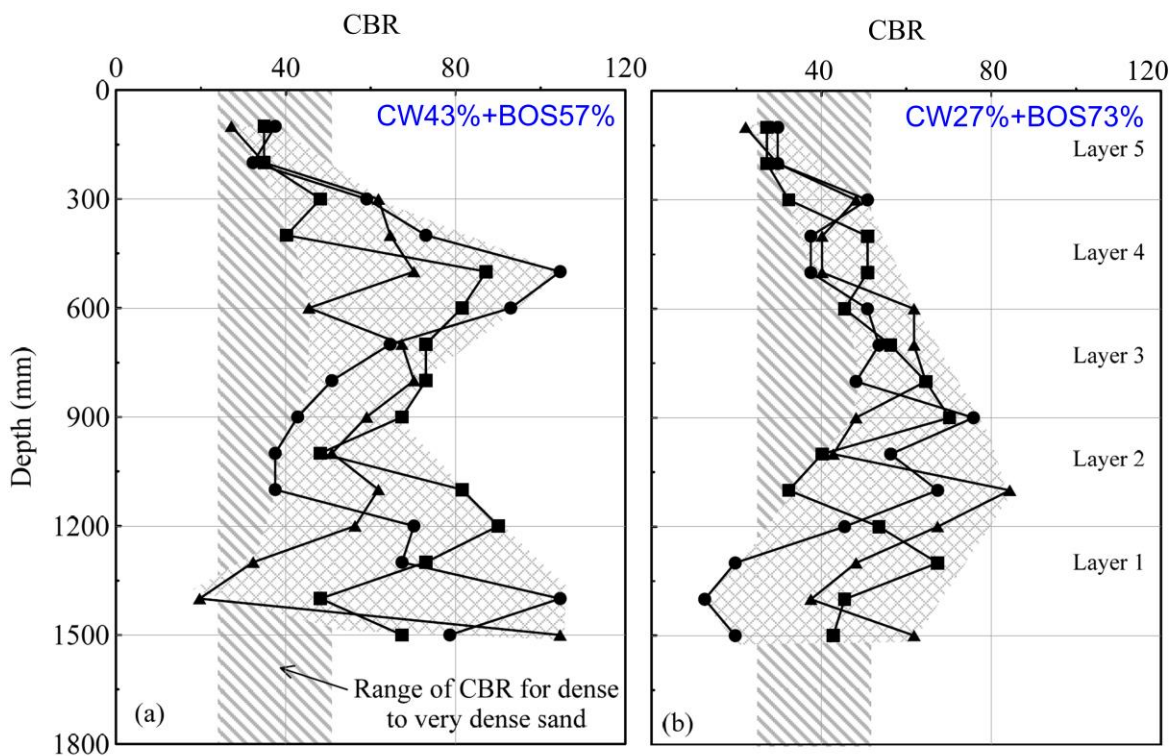


Figure 3: Equivalent CBR changing with depth for (a) 43% coal wash mixture and (b) 27% coal wash mixture (Tasalloti et al., 2015)

### 3 USE OF RECYCLED RUBBER GRANULATES WITH BALLAST IN RAIL CONSTRUCTION

Owing to restrictions in international shipping, transportation and storage limitations, and the lack of substantial domestic demand for products made from waste tyres, the Australian government's Department of Climate Change, Energy, the Environment, and Water included End of Life Tyres in the Minister's priority list for 2022-2023 (2022), marking the first instance in history. The utilisation of recycled rubber granulates in rail construction is one of the promising applications that can be developed as industry-led projects to elevate domestic consumption and enhance the onshore recovery rate of end-of-life tyres. Recently, a comprehensive study which involved large-scale laboratory simulations and field trials, was conducted to evaluate the potential applicability of rubber-mixed ballast as an alternative granular medium to the conventional ballast layer. The study used rubber granulates derived from discarded tyres, with sizes ranging from 9.5

mm to 19 mm (Arachchige et al., 2021, 2022). These granulates were mixed in varying proportions, from 0% to 15%, while ensuring compliance with Australian ballast standards (AS:2758.7, 2015) in the final mixture, the Rubber Intermixed Ballast System (RIBS).

### 3.1 PROPERTIES OF RUBBER INTERMIXED BALLAST SYSTEM

Shearing resistance is crucial in ballast, as the ballast layer in the track substructure serves as a load-bearing layer subjected to dynamic moving loads. At the same time, the dilation angle characterises the tendency of granular materials to dilate under applied loads. Figure 4a shows the effective friction angles ( $\varphi_{ef}$ ), the mobilised friction angles ( $\varphi_p$ ), and dilation angles ( $\psi_p$ ) at peak stress ratio ( $\eta_{peak}$ ) of RIBS mixtures with varying rubber percentages obtained from the large-scale consolidated drained triaxial tests. As the increased rubber content ( $R_b\%$ ) reduces the dilation, increasing effective confining pressures ( $\sigma_3'$ ) further contribute to the reduction in dilation, owing to a well-compressed particle arrangement. The  $\varphi_p$  at the peak stress ratio encapsulates the impact of both breakage and dilatancy within the sample; consequently,  $\varphi_p$  decreases with increased  $R_b\%$  due to the reduction in breakage and dilation.

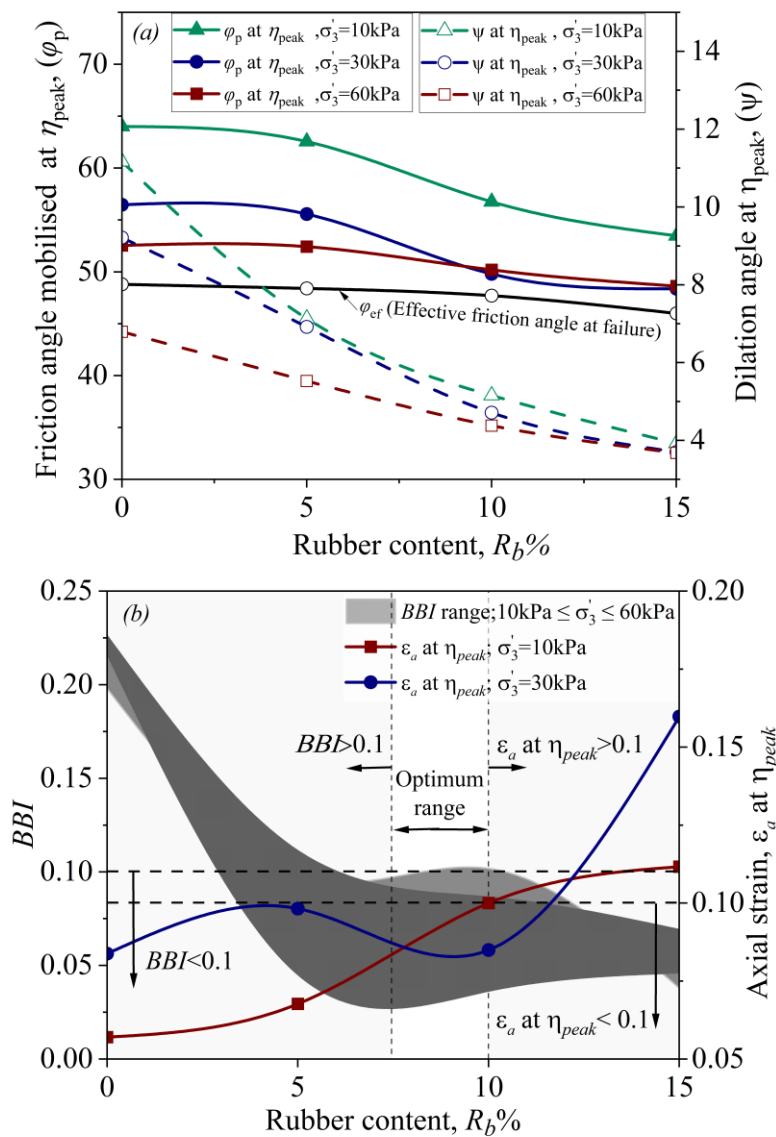


Figure 4: (a) Effect of the rubber on friction angle and dilation angle at the peak stress ratio (b) Effect of the rubber on ballast breakage and axial strain (modified after Arachchige et al., 2021)

The decrease in particle breakage with increased  $R_b\%$  is evident in Figure 4b. Note that an increase in  $R_b\%$  from 0 to 15% leads to a minor change ( $< 6\%$  reduction) in the effective friction angle for RIBS mixtures from  $48.8^\circ$  to  $46.0^\circ$ . The breakage of ballast during the tests is assessed by using the Ballast breakage Index (BBI) following the method outlined by Indraratna et al. (2005). As presented in Figure 4b, even a minor addition (5%) of rubber significantly reduces particle breakage, owing to the cushioning effect and the soft particle interaction within the mixture. Nevertheless, an increase in  $R_b\%$  beyond 5-10% does not yield a substantial improvement in controlling particle breakage. Moreover, according to Indraratna et al. (2015), the axial strain ( $\epsilon_a$ ) of conventional ballast remains below 0.1 under typical track conditions during laboratory testing conducted with large-scale apparatus. Hence, one of the other key factors considered when determining the optimal rubber content in RIBS is the maximum allowable axial strain of 0.1. As illustrated in Figure 4b, the introduction of rubber into the mixture leads to an increase in  $\epsilon_a$  with a substantial rise observed when  $R_b\%$  exceeds 10%. Based on the above, the optimal  $R_b\%$  added to RIBS is determined to be 10% by weight.

### 3.2 FIELD TESTS ON RIBS AT CHULLORA

Following a thorough analysis of laboratory test results, RIBS with an optimal rubber content of 10% was implemented in a 20-m instrumented trial track at Chullora, near Sydney. The conventional ballasted track construction methods could be adapted for RIBS tracks, except for placing RIBS from reduced heights ( $< 1\text{m}$ ). Figure 5 (a-b) illustrates the onsite blended RIBS and placement of RIBS in a 20 m stretch atop the geotextile positioned on the capping layer. This adjustment was made to manage the segregation of rubber particles caused by their lower specific gravity in comparison to natural rock aggregates. The RIBS material was laid on top of the prepared capping layer, effectively substituting a 150 mm bottom ballast layer in conventional ballasted tracks. To mitigate vertical deformations over the service period, RIBS tracks were densely compacted using an augmented number of roller passes. It is noteworthy that visual observations indicated a comparably minimal particle breakage under roller compaction of RIBS, as opposed to the ballast breakage observed during the compaction of conventional ballast. Instrumentation was employed on both the RIBS track and the conventional track stretch to gather data for a comparative assessment of performance and lifespan. The instruments have been configured to capture data essential for analysing key track parameters, including vertical pressure distribution, settlement, ballast dilation, ballast breakage, vibration, and noise.



Figure 5: (a) Onsite blended RIBS (b) Placement of RIBS on track at reduced height ( $1 < \text{m}$ )

## 4 USE OF WASTE RUBBER SHEETS FOR ENHANCED TRACK PERFORMANCE

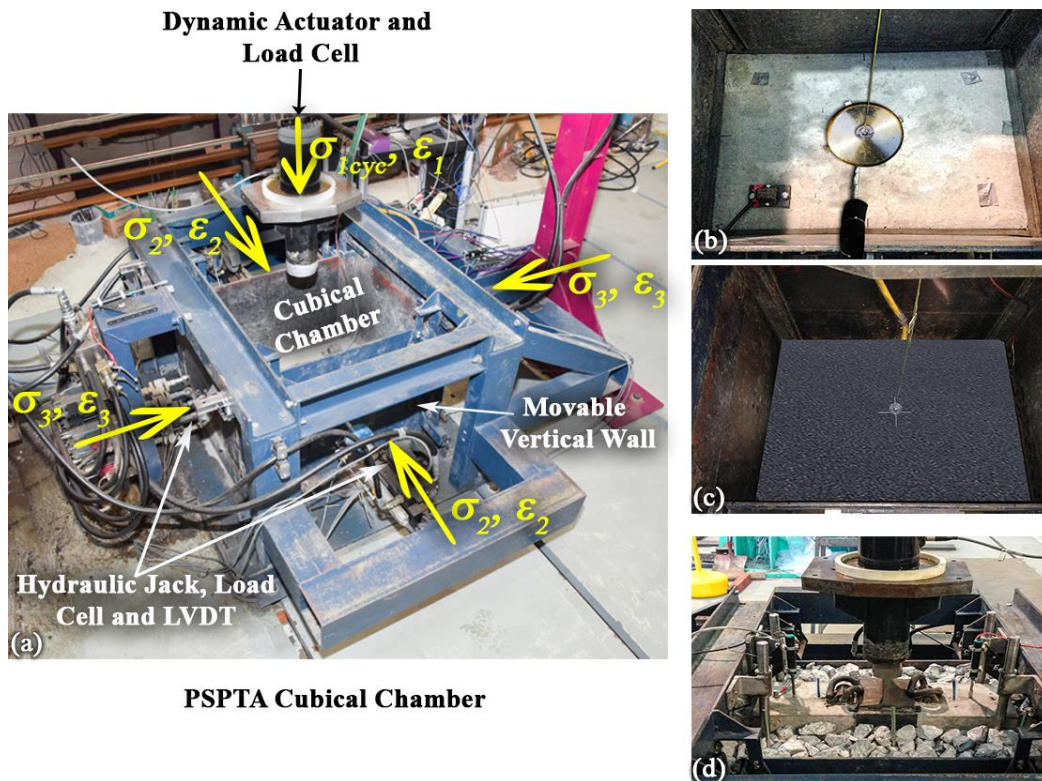
Incorporating artificial inclusions like rubber sheets into rail track foundations absorbs energy and improves the soil-structure interaction, while reducing particle deterioration, offering an economically viable approach to enhancing track efficiency and prolonging maintenance intervals. The implementation of these rubber sheets within rail tracks can effectively dampen the impacts of dynamic stresses caused by moving wheels, thereby curbing track wear. These flexible components are typically made from materials such as rubber, high-density polyethylene (HDPE), polyurethane elastomers (PU), thermoplastic polyester elastomer (TPE), and ethylene vinyl acetate (EVA) (Kaewunruen and Remennikov, 2006, SK Navaratnarajah and Indraratna, 2020). In recent times, elastic components have been produced by recycling discarded materials like worn-out tires, with the aim of stabilising the ground for constructing various infrastructures (Tiwari et al.,

2012, Miguel Sol-Sánchez et al., 2014, Sinniah K Navaratnarajah and Indrarnatna, 2017). A track composed of concrete sleepers placed on a ballasted bridge deck demonstrated elevated rigidity and insufficient track damping, resulting in pronounced dynamic stresses within the substructure. Hence, careful attention to track damping is essential when exploring strategies to alleviate dynamic stresses and adverse vibrations (Sasaoka, 2006).

Enhancing the damping characteristics of the track structure involves incorporating a shock-absorbing pad into the ballasted track structure at an appropriate location. While elastic components closer to the track surface (such as rail pads and under sleeper pads) contribute to increased track elasticity, Under Ballast Mats (UBMs) prove more effective in mitigating rapid ballast deterioration in situations involving inflexible substructures like bridges and tunnels. Notably, areas with reduced ballast thickness or the substitution of lightweight timber sleepers with heavier concrete sleepers experience amplified stresses and accelerated deterioration in ballasted tracks. Implementing UBMs in these specific areas counteracts excessive degradation of ballast and counterbalances the adverse impacts linked to shallow ballast depths (Potocan, 2010).

**4.1 LARGE-SCALE LABORATORY TESTING**

A laboratory simulation was conducted by mimicking a track on a concrete bridge deck using the large-scale Process Simulation Prismoidal Triaxial Apparatus (PSPTA) to study the effect of a ballasted track stabilised with UBM made from discarded tyres. This facilitated the study of the performance of UBM when placed atop a concrete foundation. In this study, 10 mm in thick dense rubber mats (with a static stiffness of 0.2 N/mm<sup>3</sup>) were employed on the surface of the concrete. The laboratory tests involved using two different axle loads (25t and 35t) and frequency of cyclic loading ranging from 10 to 25 Hz. The process included various steps as depicted in photographs, such as setting up the PSPTA cubical triaxial chamber (Figure 6a), creating the concrete base (Figure 6b), placing UBM on the concrete base (Figure 6c), and the final test sample (Figure 6d). The study collected information on both vertical and lateral deformations, as well as the degradation of ballast, under conditions with and without placing UBM on the surface of the concrete foundation. Additionally, an empirical model for energy dissipation characteristics of ballast was proposed to predict the performance of the ballast layer integrated using UBM.



**Figure 6: (a) PSPTA cubical triaxial chamber; (b) concrete base; (c) UBM on top of the concrete base and (d) final test sample (Modified after Navaratnarajah and Indrarnatna, 2017)**

**4.2 DEFORMATION AND DEGRADATION**

Figures 7a and 7b illustrate the cumulative plastic deformations in the vertical and lateral directions, both with and without UBM, for axle loads of 25t and 35t. In each load, under various frequencies and UBM conditions, the plastic deformation

of the ballast exhibited swift progression until around 10,000 cycles. Afterwards, the rate of settlement gradually decreased, maintaining stability with a nearly constant settlement as the loading reached around 100,000 load cycles. This initial rapid plastic deformation emerged from the rearrangements of differently sized ballast aggregates within the ballast mass, coupled with the abrasion of the surface and attrition of sharp-angular fresh ballast particles. Throughout this rapid deformation phase, the ballast particles compacted further, progressively reducing the potential for particle rearrangement until reaching a stable state.

Subsequent minimal plastic deformation was attributed to the continued degradation of well-contained particles due to repeated loading. To evaluate particle degradation, the study employed the BBI as recommended for ballast materials by Indraratna et al (2005). The quantified BBI are depicted in Figure 7c for axle loads of 25t and 35t under cyclic loading frequencies ranging from 10 to 25 Hz for ballast with/without UBM atop the solid concrete base.

The outcomes reveal that the application of UBM atop a rigid base can effectively diminish the overall plastic deformation of the ballast. This study also indicates the potential for a reduction of around a 10-20% decrease in vertical plastic deformation and roughly a 5-10% decrease in lateral plastic deformation. As anticipated, ballast degradation escalates with higher loads and frequencies of cyclic loading. Notably, the introduction of UBM yields a significant decline in ballast degradation atop the robust concrete base. The present investigation demonstrates an average reduction of 35-45% in breakage, highlighting the positive impact of UBM integration. Additionally, UBMs utilized in this research were produced locally using recycling discarded tyre waste. From a national perspective, crafting these rubber sheets from recycled rubber tyres would not only decrease the accumulation of tyre waste at disposal sites but also enhance land utilization, particularly in high-cost urban regions. Additionally, the resultant savings resulting from reduced demand for new aggregates through quarrying would present a direct environmental advantage, mitigating undue disruption of landscapes.

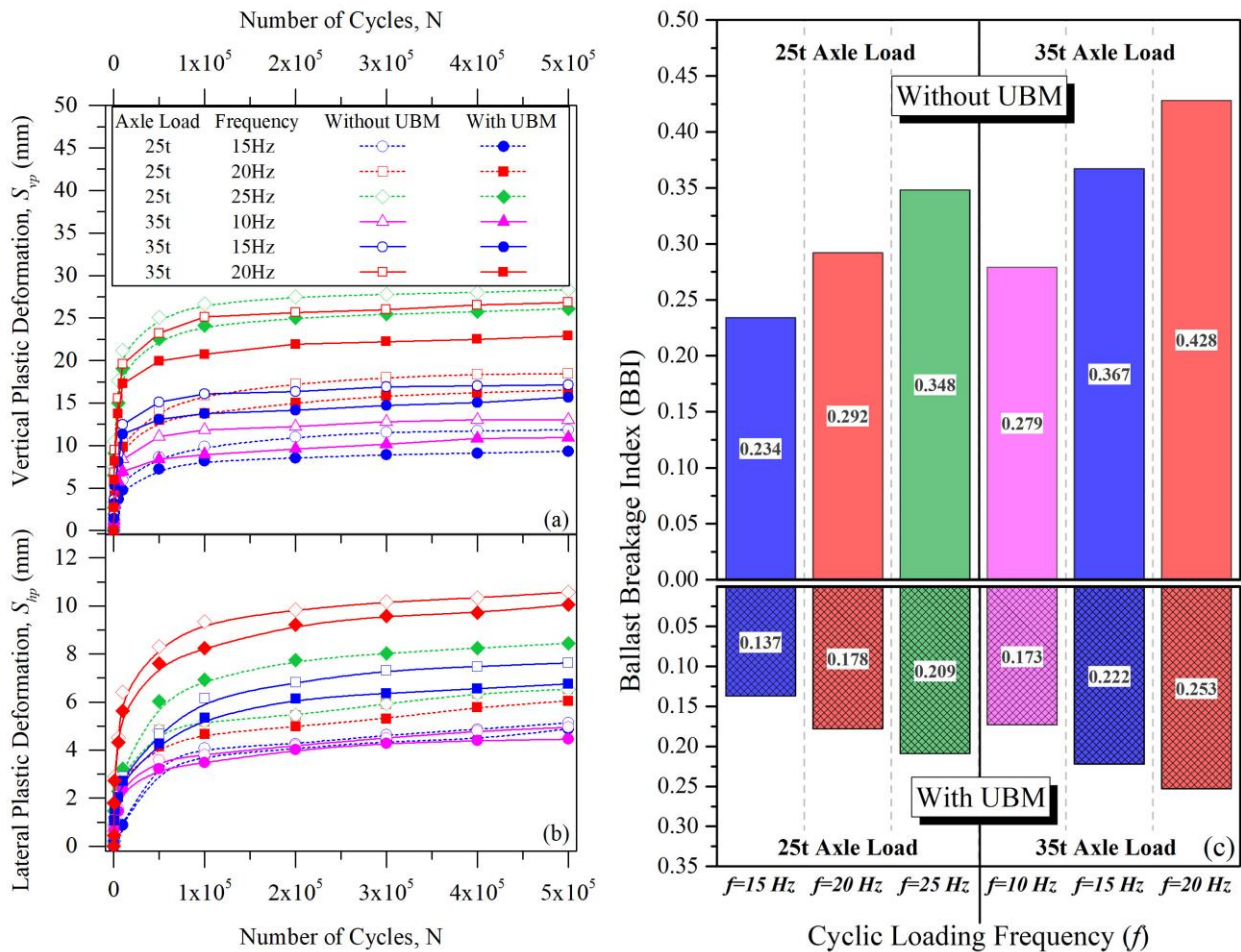


Figure 7: Ballast plastic deformation (a) vertical, (b) lateral; and (c) Ballast Breakage Index (Sinniah K Navaratnarajah and Indraratna, 2017)

4.3 ENERGY DISSIPATION

In this investigation, an empirical equation has been developed to quantify the overall dissipation of energy ( $E_D$ ) per unit volume of ballast. This is achieved by incorporating separate dissipation components associated with plastic sliding of ballast particles ( $E_S$ ) and the breakage of ballast ( $E_B$ ). The initial component,  $E_S$ , represents frictional sliding and is intricately linked to the imposed deviator stress ( $q_d$ ) and the cumulative shear strain ( $\epsilon_s$ ). This factor considers the energy necessary to surpass the shear resistance originating from inter-particle friction. The subsequent term,  $E_B$ , correlates with the progression of particle breakage as determined by the BBI. Considering these factors, the subsequent empirical relationship is derived.:

$$E_S = a(q_d \epsilon_s) \tag{1}$$

$$E_B = b(\kappa \times BBI)^c \tag{2}$$

where a, b, and c represent the parameters of the empirical model, a and c are dimensionless parameters, while parameter b is expressed in energy units.  $\kappa = \sqrt{L_a / L_m}$  is the axle load factor normalized to the minimum axle load ( $L_m$ ), as per the Australian standard for heavy haul operations,  $L_m = 20t$ , and  $L_a$  represents the simulated axle load in this study. For a standard 20t axle load (i.e.  $L_a = 20t$ ,  $\kappa = 1$ ),  $b = 1 \text{ MJ/m}^3$  is associated with complete breakage (i.e.  $BBI = 1$ ) as indicated by Equation (2).

This energy dissipation model has been validated for up to 500,000 loading cycles. This value corresponds to approximately one year of typical heavy haul service in the State of New South Wales (NSW), involving an annual traffic tonnage of 50 million gross tons (MGT). Through non-linear regression, the model parameters have been calculated and are displayed in Figure 8, illustrating a strong correlation ( $R^2 > 0.98$ ) between the predicted and observed energy dissipation.

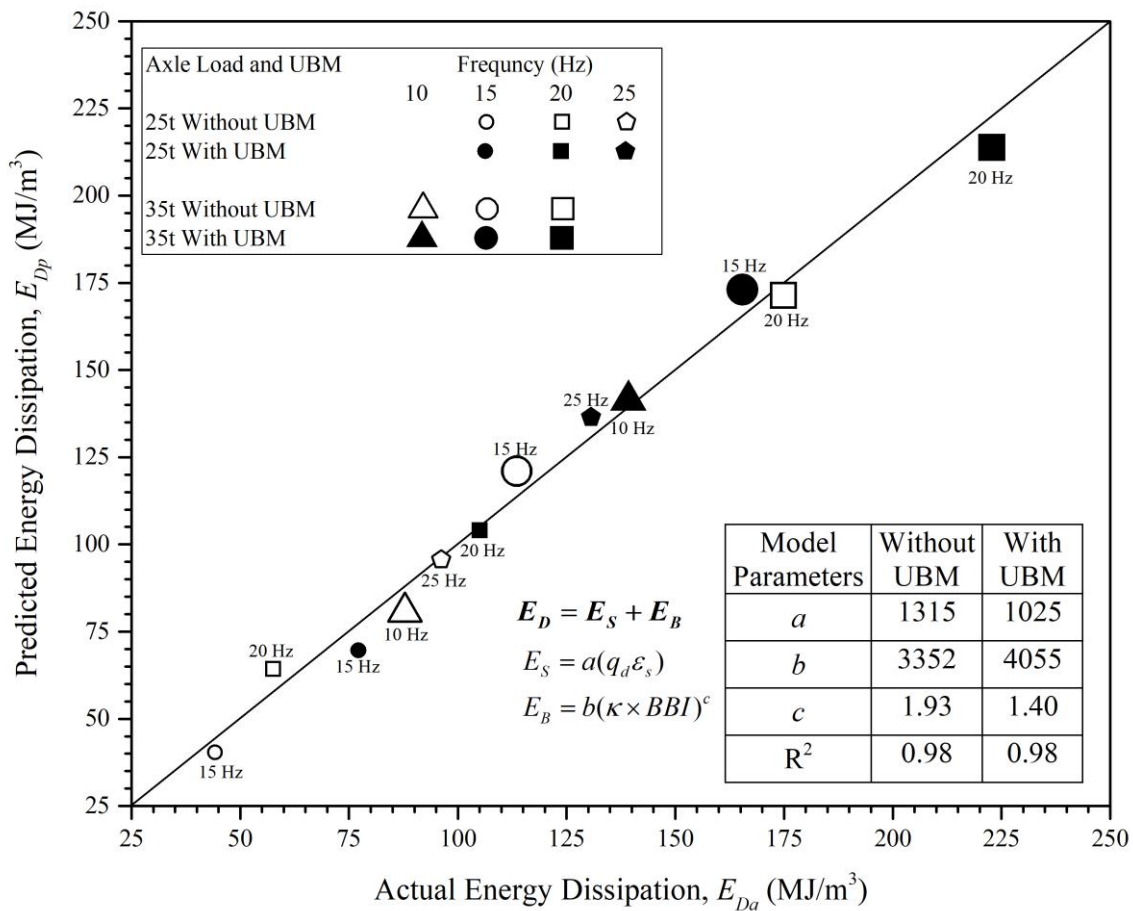


Figure 8: Energy dissipation model (modified after Navaratnarajah and Indraratna, 2017)

## 5 USE OF RUBBER TYRES AND TYRE SEGMENTS IN TRACK STABILISATION

This section introduces a hybrid track by combining two types of recycled tyre products consisting of (1) recycled tyre cells infilled with compacted recycled ballast to replace the usual capping layer of the railroad and (2) arch-shaped tyre segments from off-the-road (OTR) truck tyres installed in the shoulder ballast to reduce ballast lateral movement (Figure 9a) (Indraratna et al., 2022a). This technology results in tightly contained infill material and higher track-carrying capacity by utilising the 3D cylindrical form of the tyre cells and the damping property of rubber. In addition, the reinforced shoulder ballast using the OTR elements increases the track stiffness, reduces ballast layer deformations, and improves the load-bearing capacity of the track substructure (Sun et al., 2020).

### 5.1 TEST SETUP AND LOADING PROGRAM

The performance of the hybrid track was examined through the National Facility for Cyclic Testing of High-speed Rail. The trial track has a 4.1 x 4.1 m<sup>2</sup> cross-section and was made up of layers of various materials and depths (Figure 9b). Totally 16 waste rubber tyre cells (1 m in diameter and 275–300 mm deep) that had been filled with recyclable ballast were used to build the capping layer (Figure 9c) and a 300 mm-thick ballast layer was placed on top. To keep the material in the shoulder ballast contained, 4 arch-shaped OTR segments were also used. A complete track is shown in Figure 9d. More details about the test set-up and materials used can be found in Indraratna et al. (2022a).

Several sensors and instrumentation were installed on the test track to record data during the test. Settlement pegs and extensometers were used to measure the track's settlement and lateral displacement. Pressure plates were installed at different depths to record stress at various interfaces. Strain gauges were used to measure mobilised strain in tyre cells. Track accelerations at the sleeper and rail levels were measured using accelerometers. Ballast breakage was assessed using BBI by sieving it before and after the test. The test was conducted under a 25-tonne axle load, simulating a typical Australian freight train (vertical load of  $P_{max}=125$  kN,  $P_{min}=15$  kN, and  $P_{mean}=70$  kN). A realistic range of heavy freight train speeds of 60–80 km/h on standard gauge lines was covered by the applied frequency of  $f=15$  Hz. The test concluded after 500,000 cycles of load application.

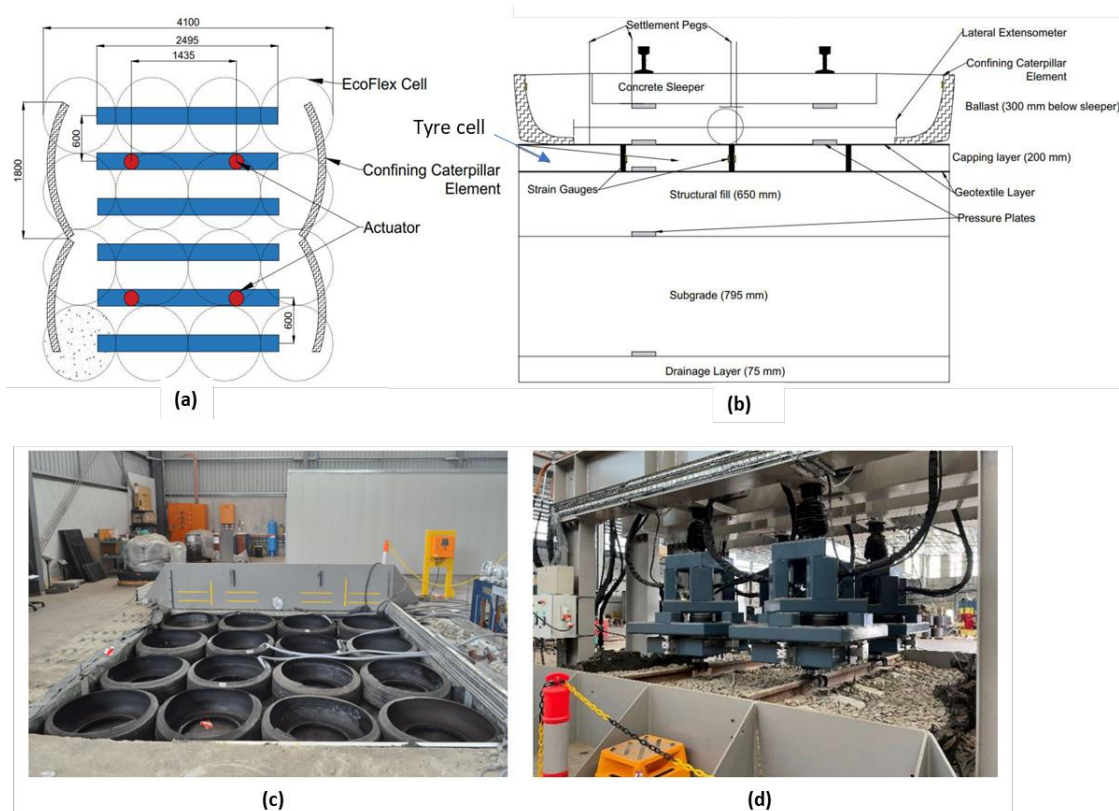


Figure 9: Schematic diagram of test track: (a) top view; (b) cross-section; (c) tyre assembly as capping; (d) complete track with shoulder-confined tyre segments (modified after Indraratna et al., 2022a)

### 5.2 MEASURED VERTICAL AND LATERAL DISPLACEMENT

Figure 10 shows the measured vertical and lateral displacement from this hybrid track and results obtained from a conventional track (Indraratna et al., 2021), laboratory test (Indraratna et al., 2013) and field measurements (Indraratna et al., 2010) are also included for comparison. It reveals that although the reinforced track initially settles more quickly than the unreinforced track, overall settlement on the reinforced way is lower. The reinforced track achieves stability significantly more rapidly than the unreinforced track, approximately N=100,000. The lateral displacement for both the unreinforced and reinforced track, as determined using lateral extensometers, is shown in Figure 10b. The lateral displacement in the strengthened track ranges from 3 to 6 mm, with an average displacement of 4 mm. In contrast, the unreinforced track displays a more significant lateral displacement reaching up to 9 mm. It can be concluded that the presence of shoulder reinforcement (OTR elements) in the reinforced track is responsible for the decrease in lateral displacement.

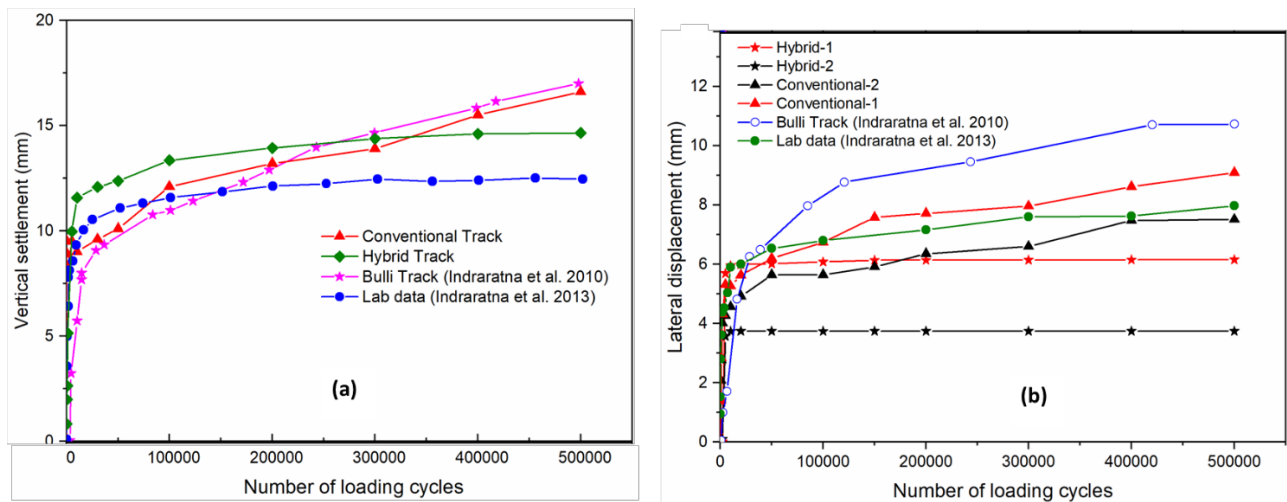


Figure 10: (a) Measured vertical settlement; (b) Lateral displacement of the hybrid track compared to a conventional track (modified after Indraratna et al., 2022a)

### 5.3 MEASURED STRESS DISTRIBUTION AND ACCELERATION

Figure 11 shows the measured stress distribution changing with depth for the hybrid track at different loading cycles and in comparison with results measured from the conventional track, laboratory and field tests. It is seen that as the number of loading cycles increases, the stress values at various depths decrease until N=100,000 loading cycles, at which point the stress values practically stabilise. The top ballast and capping layers take on more significant stress as a result of the reinforcement when compared to the unreinforced track stresses, and they transfer less stress to the underlying layers, which is highly advantageous in the case of soft subgrades (Indraratna et al., 2022a).

Figure 11b compares the rail accelerations of a hybrid track with those of a conventional track at N=200,000 cycles, as reported by Indraratna et al. (2021). The accelerations on the hybrid track are much lower, less than half of those on the regular track. Maximum accelerations observed on the hybrid track's rail were about 2.47 m/s<sup>2</sup>, compared to 5.60 m/s<sup>2</sup> on the conventional track, demonstrating that incorporating recycled rubber elements in the track substructure can reduce vibration by at least 50%. At the end of the test, samples of ballast were collected and sieved to determine the amount of breakage. Measured results demonstrated that the hybrid track shows 33% and 42% reductions in ballast breakage below the actuator and shoulder locations compared to a standard track.

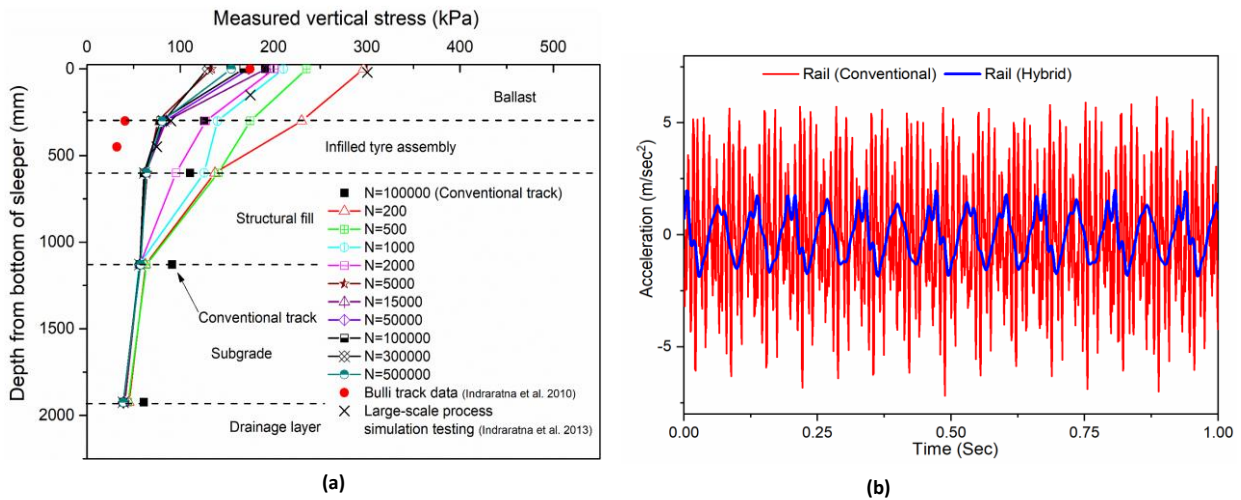


Figure 11: (a) Measured stress distribution with depth; (b) Measure accelerations on the rail (modified after Indraratna et al., 2022a)

## 6 CONCLUSIONS AND RECOMMENDATIONS

This paper reviews four state-of-the-art approaches to using recycled materials in transportation infrastructure including (1) using mining by-products coal wash and steel slag for port reclamation, (2) using rubber intermixed ballast system (RIBS) for minimising ballast breakage, (3) installing under ballast mats (UBMs) for reduced ballast deformation and degradation, and (4) employing a hybrid track of using recycled tyre cell infilled with recycled ballast in tandem with OTR segments for enhanced track performance. Large-scale laboratory tests and field trials were conducted to investigate their performance, and the following findings can be drawn from the above research:

- The coal wash and steel furnace slag blends were optimised using geotechnical testing, where the optimal blends should contain 35-60% coal wash by weight. A field test confirmed that average equivalent in-situ CBR values were between 25 and 60, similar to medium to dense sandy fills.
- The large-scale triaxial tests revealed that increasing rubber content in RIBS reduced the ballast dilation and shear strength and significantly mitigated the ballast breakage but caused the axial strain to increase. An optimal rubber content in RIBS was determined as 10% by weight as with this amount of rubber, RIBS had a substantial reduction (around 70%) in particle breakage while a minor reduction (<6%) in shear strength and acceptable axial strain compared to pure ballast.
- The hard interface beneath the ballast layer exerts a noteworthy impact on the overall deformation and breakage of the ballast. The incorporation of UBM on the surface of a concrete base plays a substantial role in diminishing both deformation and degradation. The test results obtained from large-scale cubic triaxial tests indicated that placing the UBM atop a concrete base (hard subgrade condition) could help to reduce the vertical deformation by approximately 10-20%, lateral dilation by around 5-10%, and ballast breakage by 35-45%. The impact of the incorporation of UBMs was also calibrated and verified by the proposed energy dissipation model.
- The overall accumulated lateral displacement and settlement of the hybrid track over a large number of loading cycles (N = 500,000) was smaller than the standard track. This finding implies that the use of recycled tyres in the track can provide immense benefits in relation to increased track stability and extended longevity of the hybrid track.
- Compared to an unreinforced track, the hybrid track significantly reduced the vertical stress distribution in track substructure layers, and reduced vibrations and this resulted in lesser ballast breakage. The results from this hybrid track test can lead to a conclusion that the use of recycled rubber in track not only reduces quarrying, and carbon emissions but also offers eco-friendly track stabilisation with an extended life cycle, and lower maintenance costs.

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