Assessment of initial compaction characteristics of Rubber Intermixed Ballast System

Chathuri Arachchige
Research Associate, Transport Research Centre, School of Civil and Environmental Engineering, University of Technology Sydney, NSW 2007. Australia. Email: chathuri.arachchige@uts.edu.au

Buddhima Indraratna
Distinguished Professor of Civil Engineering, Director of Transport Research Centre, School of Civil and Environmental Engineering, University of Technology Sydney, NSW 2007, Australia. *Email: buddhima.indraratna@uts.edu.au*

Yujie Qi
Lecturer, and Program Co-leader of Transport Research Centre, School of Civil and Environmental Engineering, University of Technology Sydney, NSW 2007, Australia. Email: yujie.qi@uts.edu.au

Cholachat Rujikiatkamjorn
Professor, Transport Research Centre, School of Civil and Environmental Engineering, University of Technology Sydney, NSW 2007, Australia. Email: cholachat.rujikiatkamjorn@uts.edu.au

ABSTRACT: Experimental results indicate that angular rubber granules between 9.5 and 19 mm can be strategically exploited to replace a 10% weight fraction of the same-sized ballast particles, namely Rubber Intermixed Ballast System (RIBS). The rubber elements can reduce the breakage of stiffer coarse aggregates, which are most vulnerable to breakage under typical train loading. The study further evaluated the initial compaction characteristics of RIBS, and its influence on the deformations of the ballast layer under repeated loads using large-scale triaxial apparatus. All the samples were subjected to a strain-controlled monotonic conditioning phase to simulate the initial compactions (conditioning phase) before applying the cyclic loads. It was found that increased initial settlements observed for RIBS during the conditioning phase reduced the plastic deformations under long-term cyclic loads. RIBS is worth considering as a sustainable material for long-lasting rail transport infrastructures that rely on fewer raw materials and reduced carbon footprint.

KEYWORDS: Compaction Characteristics, Recycled Tyres, Rubber Intermixed Ballast

1 INTRODUCTION

Railway's compacted granular layers below sleepers usually consist of a capping layer overlaid by ballast. Compacted layer thickness, particle gradation, relative density, and other technical requirements are implemented differently in various territories in Australia following relevant technical standards. Initial compaction of granular materials reduces the voids between gains by particle rearrangement. However, care should be taken when applying compaction efforts on granular materials to avoid grain breakage. The ballast compaction, either by roller compaction or tamping, occurs during new track construction and the ballast replenishment. Aursudkij (2007) showed that the tamping tine vibration and the rate of lowering the tamping tine into ballast cause breakage of ballast rock particles, and the effect is significant when tamping is conducted in compacted ballast and used tracks because of the resistance to penetration.

During the construction, the ballast layer is compacted to satisfy the density requirements using a roller machine, but the initial densification of the completed track happens during the stabilizing process via low-speed trains under relatively low confinement (Sussmann et al. 2003). It is identified that substantial ballast breakage before commencing the actual service is one of the significant concerns of railway asset owners, compromising the performance of ballasted rail tracks.

In addition, over the service period, ballast undergoes further compaction due to the heavy cyclic loads with an increase in particle breakage, especially the load-bearing rock aggregates. In general, the loss of angularity of ballast particles decreases the shearing resistance of the ballast assembly. Moreover, the crushed fines cause ballast fouling and reduce the overall permeability of the ballast layer.

The properties of tyre-derived rubber granules can vary from natural rock aggregates due to two main components, i.e., natural rubber and polymer (synthetic rubber). The granules exhibit elastic properties upon deformations under applied loads, so the particle-to-particle contact area varies due to the resulting particle interaction between rubber and ballast.

Recycling waste tyres to create rubber granules for railway substructure make an enormous impression, decreasing the need for raw materials and minimizing the carbon footprint. Moreover, granulation of rubber is a well-established and straightforward process, and there are no significant or scientifically justified risks associated with using rubber granules made from end-of-life tyres (ETRMA 2016).

Rubber-blended ballast is considered as an efficient, sustainable, and cost-effective solution for ballasted rail tracks. Numerous experimental studies (Sol-Sanchez et al. 2015, Esmaeili et al. 2016, Gong et al. 2019) demonstrated the positive outcomes of rubber intermixed ballast, such as reduced particle breakage, increased damping properties and energy absorption. Koohmishi & Azarhoosh (2020) confirmed that improved drainage characteristics could be obtained when mixed properly. Arachchige et al. (2022) conducted triaxial tests for Rubber Intermixed Ballast System (RIBS) under cyclic loads followed by the initial conditioning phase. It is shown that even a small percentage of rubber (R_b > 5%) is beneficial in terms of performance and longevity. This paper discusses the role of rubber in relation to compaction and initial densification of RIBS and its contribution to the enhancement of conventional ballasted rail tracks.

2 MATERIALS AND TESTING PROGRAM

2.1 *Rubber Intermixed Ballast System (RIBS)*

Rubber Intermixed Ballast System (RIBS) is an alternative railway ballast material incorporating rubber granules into traditional track ballast (Arachchige et al. 2021). Rubber particles derived from waste tyres in size ranging from 9.5 to 19 mm and at 10% by weight is recommended to replace the same fraction of ballast gradation for the optimum result. The particle size distribution of RIBS satisfies the Australian nominal 60 - graded ballast specified in AS 2758.7:2015. Rubber granules and fresh ballast used in the study are shown in Figure 1, and the basic geotechnical properties of RIBS and fresh ballast are shown in Table 1. Tyrecycle Australia supplied rubber granules, and the fresh ballast for the study was obtained from Bombo Quarry, located in New South Wales, Australia.

Figure 1. Granular materials (a) Rubber granules (9.5 -19 mm) (b) fresh ballast (9.5 -53 mm).

Table 1. Basic properties of RIBS and fresh ballast

R_b (%) in RIBS	*0*	*5*	*10*	*15*
Initial specific gravity	2.8	2.61	2.45	2.3
Density (kg/m^3)	1535	1432	1342	1263
Effective friction angle ($^\circ$)	48.8	48.4	47.7	46

2.2 *Testing procedures*

Large-scale triaxial tests were conducted for both pure ballast and RIBS specimens (300 mm in diameter and 600 mm in height) with different percentages of rubber (R_b= 0-15%) under two confining pressures (σ_3), 30 kPa and 60 kPa. Cyclic loads were applied at the frequency of 20 Hz, simulating a 25-tonne axle load train travelling at 150 km/hr. As shown in Figure 2, frequent cyclic loading was applied after a strain-controlled monotonic conditioning phase up to the maximum cyclic load ($q_{cyc,max}$) of 230 kPa. The minimum cyclic load was 45 kPa, and the tests were continued up to 400,000 cycles. According to Technical Note - TN 028: 2017 (Transport Standards: August 2017), freight siding under unlimited operation should consider a total traffic volume of 5 million gross tons per year (5 MGT/Year). The traffic volume considered for the study can be calculated using Eq. 1.

$$MGT = \frac{F \times (T \times f)}{10^6} \tag{1}$$

where F is static axle load (in tonnes), T is the total testing duration (in seconds), and f is cyclic loading frequency.

According to the test condition, total traffic of 10 MGT was adopted to assess the impact of a freight sliding track under unlimited operation over two years. The sequences of cyclic loading are shown in Figure 2.

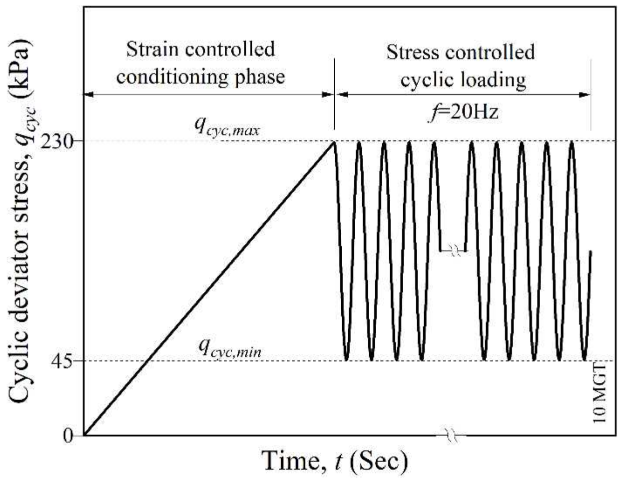

Figure 2. Loading phases adopted in this study. (Modified after Arachchige (2022))

3 LABORATORY TEST RESULTS

3.1 *Void ratio*

The void ratio of the specimens was calculated before the test (e_i), after the conditioning phase (e_0), and at the end of the test (e_f). During the conditioning process, the materials became more densely packed, resulting in a marked decrease in void ratios, as shown in Figure 3. The percentage of reduction in void ratio during the conditioning phase $(e_i - e_0)$ is denoted as $\%\Delta e_1$.

The reduction of void ratio (%Δe_1) is significant in RIBS mixtures compared to the pure ballast and, with increased rubber further, helps to lower the void ratio during the conditioning phase. For pure ballast, %Δe_1 decreases with the increased confining pressure from 30 kPa to 60 kPa, whereas the reduction of the void ratio in RIBS increases.

Possible reasons for the reduction of void ratio under applied loads could be particle movement, particle breakage, and compression and distortion of rubber in RIBS. At the beginning of the tests, samples were prepared to the same initial void ratio (e_i), of 0.824 for all the specimens. Therefore, the particle assembly (if there is no breakage and no rubber compression) should be similar in all specimens. The marked difference in the (%Δe_1) between RIBS and fresh ballast is attributed to the compression of rubber particles that suppress the effect of common particle breakage in pure ballast. Notably, the particle rearrangement at this initial stage in RIBS is permanent; hence, densified particle formation was obtained at the end of the conditioning phase.

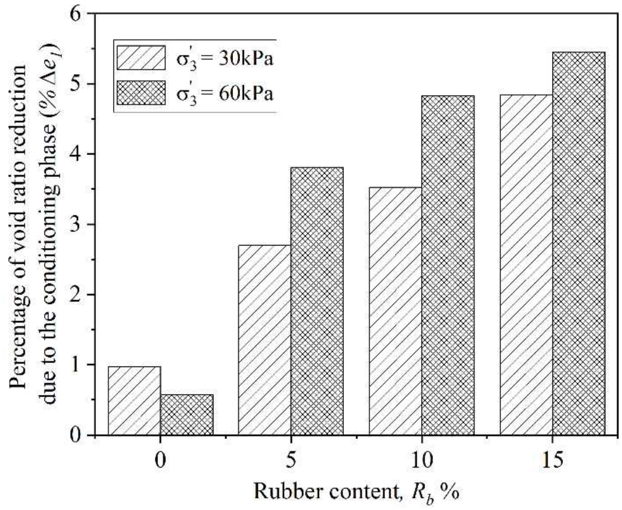

Figure 3. Reduction of void ratio due to the conditioning phase (% Δe_1).

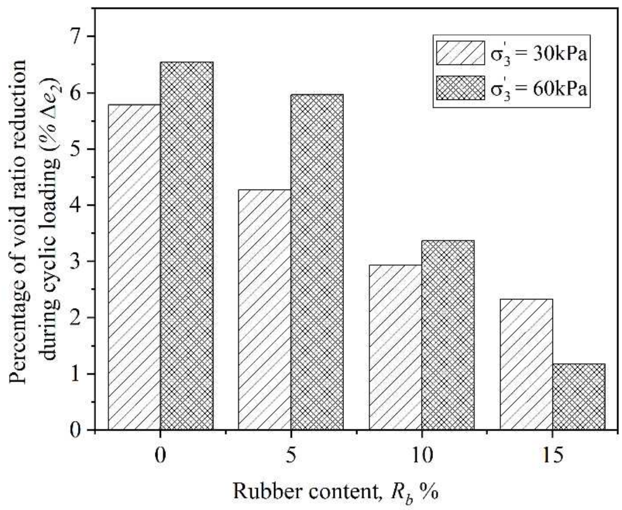

Figure 4. Reduction of void ratio during cyclic loading (% Δe_2).

The conditioning phase represents the initial compaction stage of the field before commencing train operations. As mentioned in the loading procedure, cyclic loads were applied to the samples after the conditioning phase, in which the specimens were further densified. Reduction of void ratio during the cyclic loading (Δe_2) calculated between the end of the conditioning phase and after 400,000 loading cycles (N=400,000). It is already explained that N = 400,000 simulates unlimited freight train service for approximately two years. The reduction percentage of the void ratio under long-term loading (% Δe_2) is shown in Figure 4.

Unlike the conditioning phase, during the cyclic loading phase, the maximum reduction of void ratio was observed in fresh ballast. Similar to the conditioning phase, with increased confining pressure from 30 kPa to 60 kPa, pure ballast showed a decrease in change of void ratio, whereas RIBS demonstrated an increase in % Δe_2. In addition, RIBS with increased rubber demonstrates a minor reduction in void ratio, indicating less densification under long-term cyclic loads. In other words, enhanced compaction of RIBS (R_b > 0%) in the conditioning phase tends to decrease the likelihood of settlements under cyclic loads. Diminished settlements of RIBS under cyclic loads are further explained in Section 3.2.

3.2 *Axial strain*

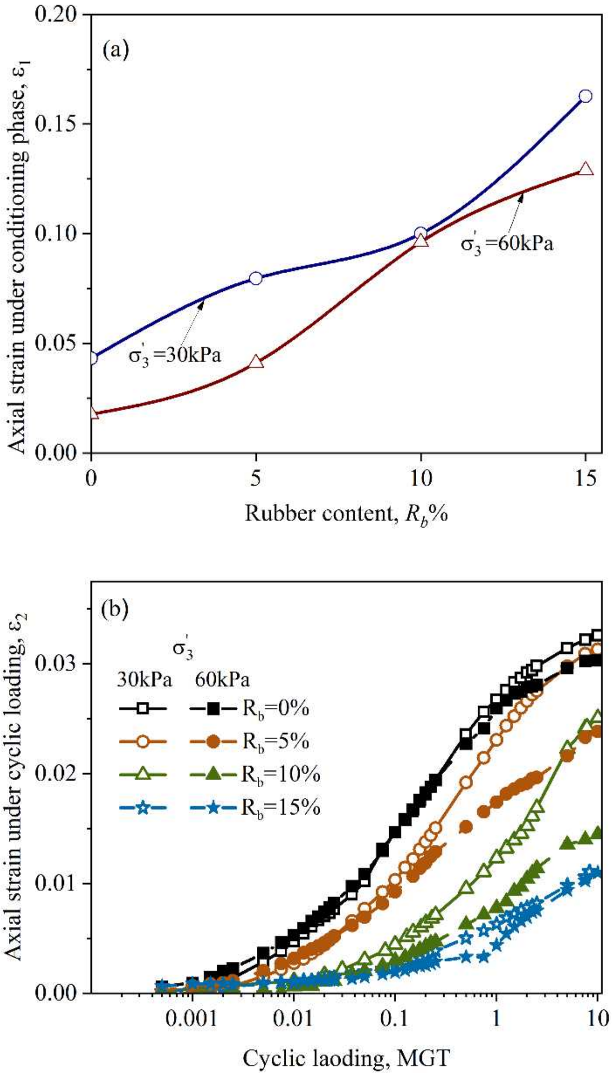

Figure 5. Axial strain (a) after conditioning phase (b) under cyclic loading. (Modified after Arachchige (2022))

Axial strain is an indication of vertical deformation (settlement) of the samples subjected to axial stresses. Figures 5a-b present the axial strains of specimens under the monotonic conditioning and cyclic loading phase, respectively. It is evident that a considerable reduction in the void ratio in RIBS during the conditioning phase resulted in increased initial axial strains (ε_1). Moreover, an increase of $R_b\%$ in RIBS further increases ε_1.

For instance, $R_b = 10\%$ increased the deformation during the initial conditioning phase by approximately three times compared to pure ballast.

On the other hand, as shown in Figure 5b, an increase of $R_b\%$ in RIBS decreases axial strain under cyclic loads applied after the conditioning phase (ε_2). It is interesting to observe RIBS could reduce settlements compared to the pure ballast under cyclic loads. It is known that an increase in confining pressure decreases axial strains of granular materials. However, the effect of rubber in RIBS suppresses the influence of confining pressure (Fig. 5b). The primary reason for this observation is the improved initial compaction of RIBS caused by the conditioning phase. Including 5% rubber does not significantly differ from pure ballast in terms of settlements. Notably, 10% rubber reduces settlement under repeated loads and considerably decreases the usage of natural rock aggregates by replacing the same fraction with recycled rubber granules. It is calculated that the reduction of settlement in RIBS with 10% rubber at confining pressure 30 kPa and 60 kPa are around 23% and 52%, respectively. Moreover, incorporating rubber granules in the ballast is intended to improve the deformation behaviour of the track, as well as reduce ballast degradation.

3.3 *Rate of axial strain*

From Figure. 6 it is also clear that when $R_b\%$ increases, the permanent axial strain rate ($\delta\varepsilon_2/\delta N$) progressively decreases to a fairly small plastic axial strain rate (up to around 10^{-7}) and attains a stable rate at a reduced axial strain. Hence the behaviour of RIBS also can be categorised into the plastic shakedown state (no more accumulation of plastic strain) irrespective of the rubber content. The approximate cycle numbers where the RIBS reach the plastic shakedown (no more accumulation of plastic strain) are marked in Figure 6 as solid circles. This is mainly attributed to the quick irrecoverable particle rearrangement occurs during the initial loading, after which further cyclic loading cannot generate significant compression. It is clear that RIBS with $R_b \geq 10\%$, reaches the plastic shakedown at a slower rate, and it is favourable in practice to reduce track maintenance cycles which are required when track settlements are higher than the tolerable levels.

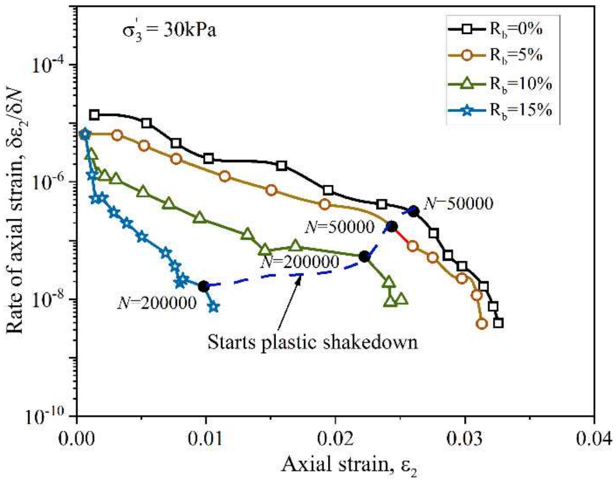

Figure 6. Rate of axial strain variation during the cyclic loading phase. (Modified after Arachchige (2022))

3.3 *Particle breakage*

When a confined assembly of granular materials is subject to axial compression, the void ratio decreases with increasing applied stress. In the beginning, the behaviour is quasi-elastic because loose particles rearrange to a denser assembly, and then the plastic deformation becomes predominant. The triaxial testing specimens were prepared in layers by applying slight tamping with vibration using a rubber-padded lightweight compacter. Therefore, comparatively minor deformations were observed in pure ballast specimens during the conditioning phase, and the particle breakage was also negligible before applying repeated cyclic loading. However, significant compression of rubber and reduced void ratio were demonstrated in RIBS specimens during the conditioning phase, but the breakage was negligible. At the end of the cyclic loading ($N = 400{,}000$), all specimens were sieved in order to quantify the ballast breakage according to the method proposed by Indraratna et al. (2005). The definition of the Ballast Breakage Index (BBI) proposed by Indraratna et al. (2005) and the BBI of specimens after the completion of tests are shown in Figure 7.

It is clear that BBIs significantly decrease with the increased rubber content in RIBS (even with 5% of rubber) during the compaction, conditioning, and cyclic loading stages. In practice, ballast breakage occurs due to repeated service loads and ballast tamping. Ballast tamping generally occurs in new track construction and existing tracks during ballast replenishment. During the tamping process, the tamping tines of the machine penetrate the ballast layer and vibrate particles to rearrange into a compacted state. If the ballast layer replaces with RIBS ($R_b >$ 10%), the breakage (especially the corner breakage and attrition) would be minimal due to relatively low-stress concentration at the corners of angular particles.

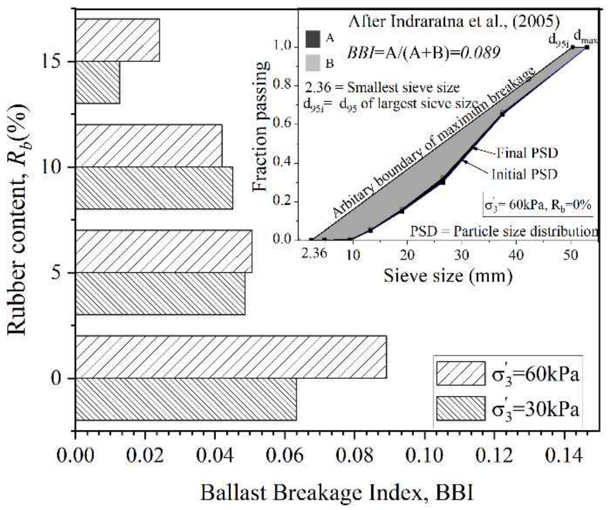

Figure 7. Quantified ballast particle breakage at the end of the tests.

4 FIELD OBSERVATIONS

4.1 *Trial track at Chullora Technology Precinct*

A trail track was constructed at Chullora Technology Precinct, New South Wales, Australia, in which a 20-m long section was constructed by replacing the 150 mm thick bottom fresh ballast layer with RIBS conforming specification for ballast by Transport for New South Wales, Australia (T HR TR 00192 ST:2018-TfNSW). Arachchige et al. (2021) suggested an optimum amount of 10% rubber by weight with a particle size range of 9.5 to 19 mm. However, slightly deviating from the laboratory recommendation, commercially available recycled rubber granules (8 to 15 mm) were added to the standard fresh ballast due to a larger quantity of rubber granules.

4.2 *Compaction of Ballast and RIBS layers in the field*

The same compaction rollers (6T and 10T) were used for the compaction of RIBS and conventional ballast layers in both track sections. To ensure uniform rearrangement of particles in the RIBS section, the number of roller passes was increased as no or limited risk of particle breakage was observed during compaction. The visual observation of the compacted RIBS surface confirmed that particle configuration was closely intertwined, compared to the compacted conventional ballast layer (see Fig. 8). During compaction of the conventional ballast layer, splitting and corner breakage of rock particles were observed. Conversely, no considerable particle breakage occurred while compacting the RIBS section. It is worth mentioning that particle rearrangement of the RIBS layer during the compaction can be considered irreversible since the bounce back of particles after the rollers passed over the layer was negligible. Furthermore, before the service and during maintenance, general ballast tamping procedure can also be applied for RIBS tracks.

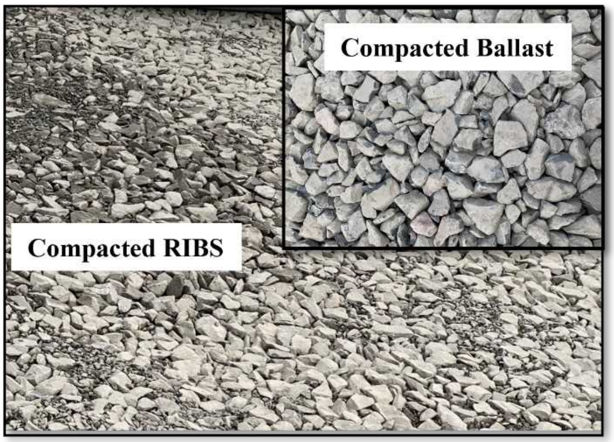

Figure 8. Compacted ballast and RIBS at Chullora technological precinct (near Sydney).

5 CONCLUSIONS

Ballast compaction plays a significant role in track construction and maintenance. Generally, ballasted tracks require further densification, even after track completion, by stabilizing or initial service loading cycles. This study presents the initial compaction characteristics of the RIBS mixture, which can induce particle densification to control long-term track deformations and reduce frequent track maintenance. Based on the large-scale laboratory tests and a field trial, the following salient findings can be concluded from the study.

1. Attributed to the compression of rubber, RIBS mixtures tend to densify more by reducing the void ratio during the conditioning phase (strain-controlled static loading up to the maximum cyclic stress). As a result, increased initial settlements are expected in RIBS tracks. RIBS $(with\, R_b = 10\%)$ specimens demonstrated increased deformation during the initial conditioning phase by approximately three times compared to pure ballast.
2. Significant reduction in the void ratio during the conditioning phase leads to minimal variation in void ratio under repeated cyclic loads and therefore reduced settlements. The reduction of settlement in RIBS with 10% rubber under repeated cyclic loads at confining pressure 30 kPa and 60 kPa is around 23% and 52%, respectively.
3. Based on reduced accumulated permanent stains at the increased number of cycles and the reduced rate of rate of axial strais, study confirms that the RIBS increase track longevity compared to the conventional ballast material.
4. During the conditioning phase, increased confining pressures increase the void ratio reduction in RIBS, whereas a decrease in pure ballast. For example, the increase in confinement pressure from 30 to 60 kPa increased the reduction percentage of the void ratio of RIBS $(with\, R_b = 10\%)$ from 3.5 % to 4.8 %.
5. Compaction rollers, which are typically used for the compaction of the ballast layer (i.e., 10 T, 12 T rollers), can be employed for the compaction of the RIBS layer. It is noted that there is no or limited risk of increased particle breakage due to the increased number of roller passes (if required). Furthermore, it is proven that particle breakage of RIBS under compaction and service loads is well controlled compared to the conventional ballast material.
6. The typical ballast tamping procedure can be employed for the RIBS track for the new tracks and during track reconstruction.

6 ACKNOWLEDGEMENTS

The authors would like to express their appreciation to the Australian Research Council (ARC) for providing funding to this Discovery Project (ARC DP220102862) and ARC Industry Transformation Training Centre for Advanced Rail Track Technologies (ITTC-Rail IC170100006). The assistance provided by industry partners (Sydney Trains, Australasian Centre For Rail Innovation (ACRI), Transport for NSW, Bridgestone) is gratefully acknowledged.

7 REFERENCES

Arachchige C.M.K. 2022. Experimental and numerical study of Rubber Intermixed Ballast System subjected to monotonic and cyclic loading. Doctoral dissertation. Univ of Tech Sydney, Australia.

Arachchige, C.M.K., Indraratna, B., Qi, Y., Vinod, J. S. and Rujikiatkamjorn, C. 2021. Geotechnical characteristics of a Rubber Intermixed Ballast System, *Acta Geotechnica* 17 (5), 1847-1858.

Arachchige, C.M.K., Indraratna, B., Qi, Y., Vinod, J. S. and Rujikiatkamjorn, C. 2022. Deformation and degradation behaviour of Rubber Intermixed Ballast System under cyclic loading. *Eng Geol* 307, 106786.

AS (Australian Standards), 2015. Aggregates and rock for engineering purposes. Part 7: Railway ballast AS 2758.7, Standards Australia. In:

Aursudkij B. 2007. A Laboratory study of railway ballast behaviour under traffic loading and tamping maintenance. Doctoral dissertation. Univ of Nottingham, England.

Esmaeili, M., Zakeri, J.A., Ebrahimi, H., and Sameni, M.K. 2016. Experimental study on dynamic properties of railway ballast mixed with tire derived aggregate by modal shaker test. *Adv. Mech Eng* 8 (5), 1687814016640245.

ETRMA 2016. Safety of recycled rubber infill material, European Tyre and Rubber Manufacturers' Association, Belgium.

Indraratna, B., Lackenby, J. and Christie, D. 2005. Effect of confining pressure on the degradation of ballast under cyclic loading. *Geotechnique* 55 (4), 325-328.

Koohmishi, M. and Azarhoosh, A. 2020. Hydraulic conductivity of fresh railway ballast mixed with crumb rubber considering size and percentage of crumb rubber as well as aggregate gradation. *Constr Build Mater* 241, 118133.

Sol-Sanchez, M. Moreno-Navarro, F. and Rubio-G´amez, M.C. 2015. A study into the use of crumb rubber in railway ballast. *Constr Build Mater* 75, 19–24.

Sussmann, T. Kish, A. and Trosino, M. 2003. Influence of track maintenance on lateral resistance of concrete-tie track. *Transp Res Rec* 1825, 56–63.

Technical Note - TN 028. 2017. Update to ESC 200 Track System, version 4.3 - Replacement of components in existing track. Asset Standards Authority (ASA), Transport for New South Wales, Australia.

T HR CI 12111 SP:2018-TfNSW. 2018. Earthwork materials, Transport for New South Wales, Australia.