**Experimental Study of Rubber Intermixed Ballast Stratum**

**Subjected to Monotonic and Cyclic Loads**

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**ABSTRACT**

The study sets out to investigate the use of rubber granules from used tires as solid (elastic) particles (without steel wires) mixed with conventional ballast aggregates for enhanced track performance (i.e. a Rubber Intermixed Ballast Stratum, or RIBS). The study evaluates the performance of RIBS subjected to both monotonic and cyclic loads by conducting large-scale triaxial tests for a range of rubber contents (0-15%) under different confining pressures (). It is evident from the results that rubber particles ranging from 9.5 to 19 mm with similar angularity to ballast aggregates are advantageous because they reduce the breakage of load-bearing larger aggregates, thus effectively controlling ballast fouling within the granular matrix while providing adequate resiliency. This project also demonstrated that particle densification at the conditioning phase can cause a reduction in permanent strains during the cyclic loads, thereby increasing track longevity.

**INTRODUCTION**

Subjected to heavy dynamic loads, crushed aggregate is one of the most popular materials used in ballasted railways across the world. The mechanical properties of ballast play a major role in contributing to track stability and drainage to provide a safe, reliable, and continuous operation. After a certain period of operation and fatigue under repeated loading, degraded ballast requires replenishment with freshly quarried ballast, which is one of the most expensive items in track maintenance schemes (e.g. Abadi et al., 2016, Indraratna et al., 2018). Given the current environmental issues and reservations of quarrying in various parts of the world, as well as the challenges in obtaining very large quantities of high-quality ballast, railway authorities have now looked for other alternatives.

A study on end-of-life tire (ELT) management (Deloitte, 2019) reveals that globally over 30 million tons of tires reach the end of life every year but sufficient cost-effective and environmentally friendly approaches for the management of ELT have not been developed in many countries. For instance, globally around 29% (even more than 60% in China) of ELT are collected with undetermined end-use and another 12% of ELT are landfilled, stockpiled, or not even collected. There have been a considerable number of investigations into the utilization of unbounded shredded or crumbed used tires in railway substructures as alternatives to the traditional ballast and sub-ballast material. Qi et al. (2018) proposed the use of waste materials (i.e. crumbed rubber, steel furnace slag, and coal wash) in sub-ballast, and [Fathali et al. (2016](#_ENREF_15)), [Esmaeili et al. (2016](#_ENREF_14)) and Sol Sanchez et al. (2015) tested ballast mixed with tire-derived aggregates. Although several studies have been carried out on ballast with tire-derived aggregates, there is a knowledge gap in the area of performance of the material under controlled confining pressures representing typical rail tracks.

Therefore, the current research involves the study of the physical and mechanical characteristics of RIBS and the effect on stiffness and damping properties by conducting large-scale laboratory triaxial tests for static and cyclic loading under changing confining pressures It is understood that even though the isotropic confining stresses are used in the laboratory, in the field an anisotropic stress state is present. Therefore, for the laboratory tests, the cell pressures were selected considering the lateral confining stresses of real tracks, because the lowest confining is monitored in the lateral direction of the loaded track. The optimal amount and the size of rubber particles to be utilized in the RIBS mixture are determined through a comprehensive approach considering the material response under both quasi-static and cyclic loads.

**MATERIALS AND TESTING PROGRAMME**

This section explains the material preparation and laboratory test plan, including selecting particle size range for rubber granules derived from waste tires by optimizing the benefits and limitations.

**Particle size range for rubber granules.** Generally, in previous studies, the particle size distribution similar to the ballast gradation is used for rubber granules ([Esmaeili et al., 2016](#_ENREF_3), [Fathali et al., 2016](#_ENREF_4), [Gong et al., 2019](#_ENREF_5)), whereas a few studies considered adding rubber granules in a selected size range from the specified ballast gradation ([Sol-Sanchez et al., 2015](#_ENREF_15), Koohmishi and Azarhoosh, 2021). The amount and the size of rubber granules in the ballast matrix control the material stiffness and effects the drainage capacity of the granular mix. Therefore, selecting rubber granules in a particular size range is essential, nevertheless, the subsequent particle size distribution of granular assembly should satisfy specified ballast gradation.

According to past experimental studies ([Indraratna et al., 1998](#_ENREF_7), [Indraratna and Salim, 2002](#_ENREF_9)) conducted for the most commonly used railway ballast rock aggregate in the state of New South Wales in Australia, particles that are vulnerable to break have been identified in the range of 19–53 mm. In the current study, large-scale triaxial tests were conducted under monotonic and cyclic loads for pure ballast and the particle breakage was quantified according to Marsal’s breakage index (. is the percentage difference of particle weights before and after the test, i.e., = = -, where and represent the percentages of weight of the particles retained on sieve size before and after the test, respectively (Marsal 1967). is expressed as a percentage and the is positive when the weight of particles retained in the sieve after the test is lesser due to the breakage into smaller particles. Figure 1 shows the particle breakage from the preliminary tests conducted for this study.

It is observed that 19-53 mm particles are subjected to higher particle breakage than the smaller particles indicating the highest positive . The plots are starting from zero as the largest particle used in the study was 53 mm. This is in line with previous studies (i.e. [Indraratna et al. (1998)](#_ENREF_7), [Indraratna and Salim (2002)](#_ENREF_9), and [Fathali et al. (2016)](#_ENREF_4)), although the complying standards for the particle distribution curves are different. The reason is larger particles in the granular assembly transfer much of the loads safely into the below layers. Therefore, the stiffer bigger rock particles should not replace with rubber as the stiffness and the bearing capacity can be compromised.



**Figure 1. Marsal’s breakage index, for pure ballast (latite basalt).**

The larger particles derived from waste tires are planar and elongated due to the tire thickness and the shredding process (Figure 2). The reduction of angularity of the larger rubber particles (>19 mm) reduces the effective interlocking with the rock particles. On the other hand, the particles between 9.5-19 mm have a similar angular shape to rock aggregates used in conventional ballast layers. Also, considering the findings from [Tennakoon (2012](#_ENREF_19)), particles other than rock aggregates that are smaller than 9.5 mm in size can be considered fouling material.



**Figure 2. Different size rubber granules**

Taking together the factors mentioned above, the optimum sizes for the rubber granules are evaluated as shown in Figure 3. To ensure less particle breakage and better particle interlocking while controlling ballast fouling, rubber granules from 9.5 to 19 mm were used for the current study as a replacement for a percentage of same-size rock aggregates in the gradation curve. Moreover, replacing a fraction of ballast with rubber granules has not been considered in previous studies ([Esmaeili et al., 2016](#_ENREF_3), [Fathali et al., 2016](#_ENREF_4), [Gong et al., 2019](#_ENREF_5)).



**Figure 3. Evaluation of best particle size for rubber granules.**

**Test materials and laboratory test plan.** Ballast rock type is latite basalt composed of feldspar, plagioclase and augite from Bombo quarry (New South Wales, Australia). Characteristics of latite basalt from the Bombo quarry can be found elsewhere ([Indraratna et al., 1998](#_ENREF_8)). Table 1 shows the gradation of RIBS with changing rubber contents ( following the nominal 60 graded Australian ballast specification (AS 2758.7:2015). The values of uniformity coefficient and coefficient of curvature are 2.6 and1.4 respectively. The specific gravities of rubber and ballast are 1.15 and 2.8 respectively.

**Table 1. RIBS gradation**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Sieve size (mm) | Particles, % passing | | | | | | |
| Pure Ballast | RIBS | | RIBS | | RIBS | |
| Ballast |  | Ballast |  | Ballast |  |
| 53 | 100 | 100 | - | 100 | - | 100 | - |
| 37.5 | 65 | 65 | - | 65 | - | 65 | - |
| 26.5 | 30 | 30 | - | 30 | - | 30 | - |
| 19 | 15 | 15 | - | 10 | 5 | 5 | 10 |
| 13.2 | 5 | - | 5 | - | 5 | - | 5 |
| 9.5 | - | - | - | - | - | - | - |

Prepared specimens with different percentages of rubber (by weight) were tested in large-scale triaxial test apparatus under static and cyclic loads at changing confining pressures . The sample size of the test apparatus was 600 mm in height and 300 mm in diameter. A picture of the apparatus is shown in Figure 4. More details regarding the triaxial apparatus can be found in ([Indraratna et al., 1998](#_ENREF_8)). Monotonic tests for the specimens were conducted under the confining pressures of and at a shearing rate of 1.5 mm/min. Cyclic loading was applied after a monotonic conditioning phase simulating a 25-tonne train axle load at a frequency of 20 Hz resembling a train speed (V) of about 150 km/h ([Hussaini et al., 2015](#_ENREF_6)). The details of the cyclic loading are presented later in the paper. The initial void ratio was maintained at around 0.824 for all the samples and the tests were conducted as per the ASTM D7181 ([ASTM, 20](#_ENREF_2)20) under drained conditions.



**Volume change unit**

**Servo control unit**

**Data logger**

**Computer**

**Loading**

**actuator**

**Triaxial chamber**

**Pressure**

**Control**

**unit**

**Figure 4. A picture illustration of the large-scale triaxial testing system.**

**BEHAVIOUR UNDER MONOTONIC LOADING**

**Stress ratio and volumetric strain.** Figure 5(a-c) shows the variation of deviator stress ratio (= *q*/*p*′) with the increasing axial strain () for the fresh ballast and RIBS material. It is clear that pure ballast exhibits a higher peak stress ratio () compared to RIBS, especially at low confining pressures (i.e. ). It also reveals that the attaining peak stress ratio () is delayed by adding rubber and that is predominant at increased confining pressures. At low confining pressures () and with lower rubber contentsthe peak stress ratio of the RIBS decreases gradually along with the shearing progress. At increased confining pressures () and with increased rubber , however, the deviator stress ratio of RIBS reaches a stable value at higher axial strains. In terms of stress ratio, an increase in confining pressure does not make a significant effect on RIBS compared to pure ballast primarily due to the absence of dilatancy. This is reflected in Figure 5(d), where the RIBS with increased rubber shows increased compression volumetric strains at peak stress ratio whereas pure ballast shows dilation.



**Figure 5. (a-c) Variation of deviatoric stress ratio with axial strain**

**(d) Volumetric strain at .**

**Friction angle and dilation angle.** It is observed that the increase in in RIBS mixtures from 0 to 10% slightly (< 3%) changes the effective friction angle () from 48.8 to 47.7 The relationship between the effective friction angle at a certain confining pressure and the rubber content can be correlated by a linear function for the range of rubber contents considered in this study (i.e. 0-15%). As shown in Figure 6(a) the equation for the effective friction angle can be written as;

|  |  |
| --- | --- |
| (%) + 49 | (Eq. 1) |

The effective friction angle and the mobilized friction angle at the peak stress ratio against the rubber content are shown in Figure 6a. [Indraratna and Salim, (2002](https://studentutsedu-my.sharepoint.com/personal/chathuri_arachchige_student_uts_edu_au/Documents/PhD/Phd%20thesis/My%20thesis/Chapters%20after%20Yujie%20comments/Chapter%204.docx#_ENREF_6)) demonstrated that included the effect of particle breakage and dilatancy, whereas the effective friction angle does not. Therefore, the reduction of the difference between the and the with the increased represents reduced dilation and breakage. Equation 2 is used to calculate the dilation angle (, where and represent the increments of volumetric strain, and the axial strain respectively.

|  |  |
| --- | --- |
|  | (Eq. 2) |

As also shown in Figure 6(b), increased rubber content decreases the dilation angle at peak deviator stress ratio ( at and when 5%, reduction of in RIBS is pronounced due to the increased rubber compared to the increased confining pressure.



**Figure 6. Effect of the rubber on (a) , (b) at .**

**BEHAVIOUR UNDER CYCLIC LOADING**

As considerable initial compression strains can be observed (Arachchige et al. (2021)) with increased under monotonic loading tests, initial conditioning phase was introduced as shown in cyclic loading procedure in Figure 7(a). In the field, it is possible that sufficient compaction and tamping could reduce any undue initial settlements during the cyclic loading to an admissible limit. Axial strains corresponding to the conditioning phase shown in Figure 7(a), imply that the material with increased rubber content rearranges into a more densified state which intern reduces the axial strains during the cyclic loading (Figure 7(b)) under the confining pressures of and . It is found that under the confining pressure of RIBS with increased rubber (10%) demonstrated reduced peak deviator stress compared to the maximum cyclic stress considered in the study. Similar to the pure ballast, axial strains of RIBS decrease with the increased confining pressure. The axial strain increases with the increased number of cycles. Further information on the performance of RIBS under cyclic loading can be found in Arachchige et al, 2022.



**Figure 7. (a) Permanent axial deformation after monotonic conditioning phase (b) Axial strain response against the number of cycles.**

Figure 8 presents the resilient modulus ( and the dissipated energy ( of the cycle number N=200000. Note that at N=200000, the resilient modulus and the energy dissipation of all the specimens were attained to a stable stage. As shown in Figure 8, decreases with the increased rubber whereas dissipated energy per cycle is increased. An increase in confining pressures increases the resilient modulus but decreases the dissipated energy per cycle. =15% can be considered as the threshold because curves for and attains a steady behavior and , is generally the minimum recorded for pure ballast. The reason can be that the increased changes the mixture into a more rubber-like material.



**Figure 8. Influence of rubber content %** **on (a) resilient modulus (b) dissipated energy corresponds to the cycle 200000.**

Particle breakage due to the cyclic loads was calculated according to the method introduced by Indraratna et al. (2005), namely , where, is the difference in particle size distribution curves before and after the test, and B is the area between the final gradation curve and the arbitrary boundary. Table 2 represents the quantified values of RIBS specimens tested under the confining pressures of 30 and 60. As shown in table 2, the particle breakage decreases with the increased and generally the increased confining pressures increase the regardless of the rubber content. Increase in up to 10% reduces the particle breakage by 28% and 53% under 30 and respectively.

**Table 2. Particle breakage based on values**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Specimen | Confining pressure, | | | | Confining pressure, | | | |
| Rubber content | | | | Rubber content | | | |
| 0% | 5% | 10% | 15% | 0% | 5% | 10% | 15% |
|  | 0.0632 | 0.0486 | 0.0451 | 0.0127 | 0.0892 | 0.0506 | 0.042 | 0.0241 |

**CONCLUSION**

RIBS, a blend of ballast particles with rubber granules derived from end-of-life tires was tested as an alternative ballast material in large-scale triaxial apparatus under static and cyclic loading conditions. This study identified that the 9.5-19 mm size rubber granules substituting a fraction of same size ballast particles assure less ballast breakage, better particle interlocking, and reduced dilation while preventing the ballast fouling.

An increased amount of rubber (> 5%) in RIBS demonstrated increased compressive volumetric strains under shearing, especially at larger confining pressures ( Similar behavior was observed during the conditioning phase of the cyclic loading tests so that the axial and volumetric strains of RIBS during the cyclic loading were lesser compared to the pure ballast. An increased rubber reduced the dilation angle at peak stress ratio significantly compared to that of pure ballast (49% reduction with 10% rubber at= ). Increase in from 0 to 15% caused a minor change (< 6%) in the effective friction angle by reducing the from 48.8 to 46.0. This project also demonstrated that the increased rubber content in RIBS would enhance the energy absorption capacity, thus reducing the breakage of ballast and its resilient modulus.

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