

Shakedown Response of a Recycled Rubber and Coal Wash Mixture for Sustainable Rail Substructure

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ABSTRACT: The practical application of waste granular materials such as steel furnace slag (SFS) and coal wash (CW) is becoming more prevalent in many geotechnical engineering projects. Mixing rubber crumbs (RC) from recycled tyres with granular mining wastes to produce a construction material not only contributes to alleviating the accumulation of waste tips, a rubber-mixed granular layer can also provide an energy-absorbing medium to reduce vibration and degradation of rail corridors, attributed to its high damping properties. Understanding and quantifying the long-term deformation of granular materials under repeated loads is imperative for ensuring the longevity of rail tracks. One of the most relevant characteristics of granular materials under repeated cycles of loading and unloading is their ability to achieve a relatively stable state (shakedown) after being subjected to initial compression. In this study, the influence of rubber crumbs (RC) contents, cyclic vertical stress, and the static shear strength on the cyclic loading behavior of these rubber-mining waste mixtures (SFS+CW+RC) with special respect to shakedown was investigated based on small-scale cyclic triaxial tests. The results reveal that when rubber content is less than 20% or when the cyclic load is lower (<64 kPa), the waste mixture can easily achieve plastic shakedown, while adding more rubber or increasing the cyclic load can result in plastic creep or collapse. On this basis, an empirical model was developed to predict the permanent deformation mechanism for higher rubber contents and loading conditions. Moreover, it is observed that the variation of static shear strength with rubber contents is found to affect the shakedown response. Therefore, a unified method of estimating the shakedown limit is proposed by analysing permanent axial strains with normalised cyclic stress ratio at different loading cycles.

KEYWORDS: cyclic loading, recycled rubber, plastic shakedown, empirical model, sub-ballast.

1 INTRODUCTION

The use of recycled materials in transport infrastructure construction, particularly in railway substructures, holds significant environmental and economic benefits. Incorporating materials such as recycled rubber, glass, and construction waste helps reduce landfill demand, lower greenhouse gas emissions, and conserve natural resources (e.g. sand and crushed rock aggregates) (Arulrajah et al, 2020; Disfani et al, 2011; Indraratna et al, 2021; Indraratna et al, 2025c; Saberian et al, 2018; Taha & Nounu, 2009). In railway substructures, these materials can enhance drainage, reduce vibration, and improve load-bearing capacity, contributing to longer-lasting and more sustainable track systems (Indraratna et al, 2025b), hence minimising costly and frequent rail track maintenance. Additionally, utilising recycled materials supports circular economy principles and reduces construction costs. As Australia moves toward greener infrastructure, integrating recycled components into transport networks is a practical and impactful step toward achieving climate resilience and sustainable development goals.

In recent years, recycled rubber products (e.g. rubber granules, tyre cells, rubber geogrid, rubber mats/pads) have been increasingly adopted in rail track construction due to their superior damping and energy-absorbing properties (Guo et al, 2022; Indraratna et al, 2024b; Ngo et al, 2023; Qi et al, 2024). For example, recycled conveyor belts from the mining industry have been made into rubber geogrids by combining the advantages of under-ballast mats and conventional polymer geogrids to increase the confinement, energy absorption, and reduce ballast degradation (Hettiyahandi et al, 2025). Under sleeper pads and under ballast mats made of recycled rubber have been found to effectively mitigate ground vibration and noise, ballast breakage and track deformation (Indraratna et al, 2022; Jayasuriya et al, 2019; Kraśkiewicz et al, 2021; Sol-Sánchez et al, 2014). Tyre-derived aggregates (TDA) or rubber granules have been blended with fresh ballast or soil/waste

materials and incorporated into ballast or subballast layers (Arachchige et al, 2022; Ding et al, 2021; Hunt et al, 2022; Koozmishi & Azarhoosh, 2020; Riyad et al, 2025). Extensive laboratory testing and field trials have demonstrated that the inclusion of rubber materials can significantly mitigate track degradation, such as ballast breakage, excessive vibration, and lateral spreading (Indraratna et al, 2025a; Indraratna et al, 2024a, Indraratna et al, 2024c). However, unlike conventional rigid geotechnical aggregates, rubber particles are deformable, potentially introducing distinct deformation mechanisms that remain insufficiently explored in current research. Furthermore, understanding and quantifying the long-term deformation behaviour of rubber-enhanced granular mixtures under repeated loading is crucial for ensuring the durability and performance of railway tracks. A key characteristic of granular materials under cyclic loading is their tendency to reach a relatively stable deformation state, known as shakedown, after undergoing initial compression, which is essential for predicting long-term track stability and maintenance needs.

This paper aims to investigate the permanent cyclic deformation behaviour of the rubber-included mixtures, i.e. rubber crumbs (RC) mixed with coalwash (CW) and steel furnace slag (SFS), which is a promising alternative to traditional railway subballast material. The influence of the amount of rubber in the mixture and applied loading conditions on the shakedown response of the SFS+CW+RC mixtures will be explored and captured via empirical models.

2 MATERIALS AND DATA SOURCE

The SFS+CW+RC mixture comprises three distinct recycled components, each with unique engineering properties. Steel furnace slag (SFS), with a specific gravity of 3.43, is a coarse, granulated by-product of the steel industry known for its high shear strength and superior resistance to abrasion and impact. Coalwash (CW), possessing a specific gravity of 2.11, is the most common form of coal mining refuse. Compared to

conventional rockfill materials, CW exhibits lower shear strength and typically contains a mix of angular and flaky particles, making it more prone to degradation. Recycled rubber crumbs (RC), with a specific gravity of 1.15, are granular fragments derived from waste tyres. They are highly elastic and significantly deformable, contributing to improved energy absorption when blended into soil mixtures.

This study considers data from a series of consolidated drained cyclic triaxial tests conducted by Qi et al (2018) on saturated SFS+CW+RC blends. The mix ratio of SFS to CW was maintained at 7:3 to ensure the mixture has an ignorable swelling potential while maintaining acceptable shear strength (Qi et al, 2019). The amount of rubber ($R_b\%$) within the mixture was varied by weight across five levels: 0%, 10%, 20%, 30%, and 40%. To ensure consistency and eliminate any size-related bias in geotechnical performance, all components (SFS, CW, and RC) were sieved and mixed with the same gradation (Figure 1) to match the particle size distribution standards for subballast materials used in Australian railways. A photo of the mixture with 10% rubber is also shown in Figure 1. Test specimens were compacted to 95% of their maximum dry density at optimum moisture content. Cyclic triaxial tests were performed under effective confining pressures of 10, 40, and 70 kPa, using cyclic stress ratios ($CSR = q_{cyc,max}/2\sigma'_v$) of 0.4 and 0.8. Further details on sample preparation and testing protocols can be found in Indraratna et al (2018) and Qi et al (2018).

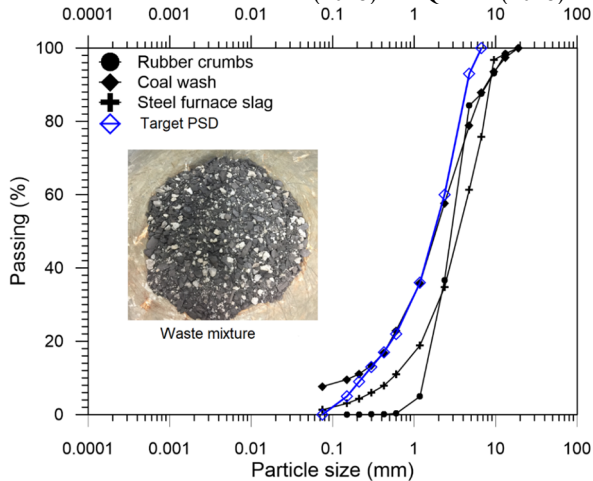


Figure 1. Particle size distribution curves of the tested materials (modified after Indraratna et al, 2018)

3 PERMANENT AXIAL STRAIN

Figure 2(a–c) illustrates the variation in permanent axial strain with respect to loading cycles, rubber content, and maximum cyclic deviator stress. As anticipated, increasing the rubber content in the mixtures leads to greater axial deformation, attributed to the higher compressibility of rubber-modified blends. With an increasing number of loading cycles, permanent axial strain continues to accumulate, though the rate of accumulation gradually decreases. This evolving axial strain behaviour aligns with the principles of shakedown theory, which classifies the deformation response into three distinct regimes: plastic shakedown, plastic creep, and incremental collapse.

Unlike static loading conditions, where failure in granular materials typically manifests as a well-defined shear plane following the peak deviator stress, cyclic loading involves deviator stress levels that are generally lower than the material's peak shear strength. Consequently, the long-term accumulation of vertical strain and its strain rate becomes a more critical indicator of material performance under repeated loading.

Understanding this behaviour is essential for assessing the durability and deformation characteristics of rubber–granular mixtures in railway applications.

For SFS+CW+RC mixtures with $R_b \leq 40\%$ tested under $q_{cyc,max} = 16, 64 \text{ \& } 112 \text{ kPa}$, only two distinct zones were observed as below, as per the shakedown theory:

- **Range A: Plastic shakedown.** This applies to SFS+CW+RC mixtures with $R_b \leq 40\%$ under $q_{cyc,max} = 16 \text{ kPa}$, and $R_b \leq 10\%$ under $q_{cyc,max} = 64 \text{ \& } 112 \text{ kPa}$. The axial strain of the materials in this range stabilises quickly with the loading cycles and ends with a strain rate $< 10^{-8}$ (Figure 2d-f), indicating ignorable deformation accumulation. The mixtures in this range will be very promising to be used for railway subballast, given their stable strain response subjected to long-term loading conditions.
- **Range B: Plastic creep.** Under a higher $q_{cyc,max}$ (i.e. 64 & 112 kPa), the mixtures having $R_b \geq 20\%$ exhibit a continuous evolving axial strain, albeit with a reduced strain rate between 10^{-7} and 10^{-8} by 50,000 cycles. Materials within this range require careful consideration, as the continued accumulation of vertical deformation can lead to internal particle damage and fatigue, potentially resulting in excessive settlement or even structural failure. While none of the tested mixtures exhibited incremental collapse (Range C) within the test parameters, increasing either the rubber content or the applied maximum deviator stress may trigger such collapse. This is typically indicated by a significantly higher strain rate (greater than 10^{-6}) after 50,000 loading cycles.

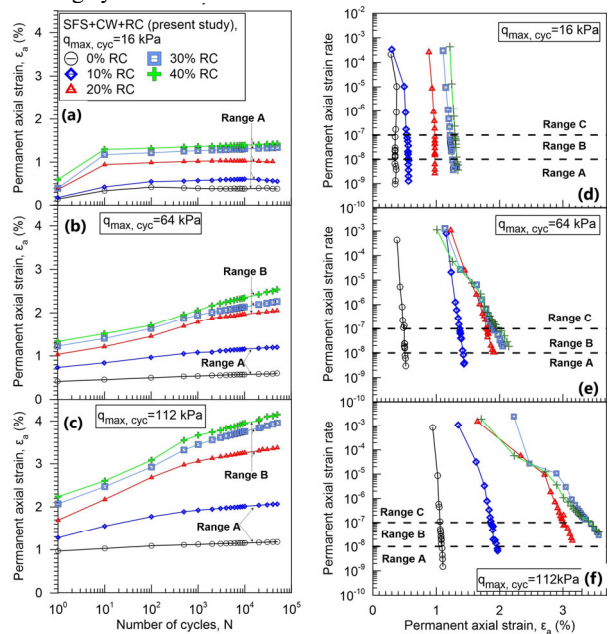


Figure 2. Permanent axial strain and its rate of SFS+CW+RC mixtures changing with loading cycles under different loading conditions (modified after Qi & Indraratna, 2022).

4 SHAKEDOWN LIMIT

It has been reported that the addition of rubber crumbs into granular materials reduces the shear strength of the overall mixture (Hunt et al, 2022; Qi et al, 2024). This indicates that if applying the same $q_{cyc,max}$, the waste mixtures with varying amounts of rubber will be subject to different levels of stress compared to their internal strength. Therefore, it is imperative to identify how the static shear strength influences the permanent axial strain and the shakedown response of the waste mixtures. For this purpose, the maximum deviator stress

$q_{cyc,max}$ is normalized by the peak shear strength q_{peak} of each mixture obtained under static loading:

$$\Psi = \frac{q_{cyc,max}}{q_{peak}} \quad (1)$$

Figure 3 shows the peak shear strength and normalized cyclic stress ratio (Ψ) of SFS+CW+RC mixtures under different confining conditions. It is noted that q_{peak} reduces with the addition of rubber in the mixtures and correspondingly causes an increase in Ψ . This means the waste mixtures with higher rubber inclusions were subject to a higher ratio of loading towards its internal shear strength and may have a higher chance of failure.

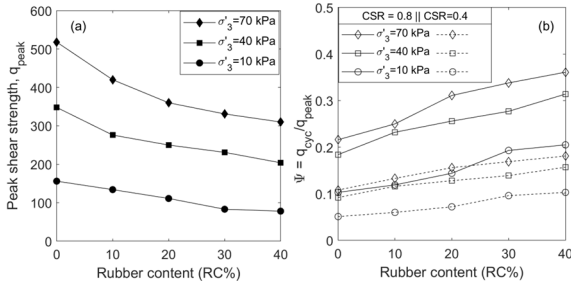


Figure 3. (a) Peak shear strength and (b) Ψ plotted with RC of SFS+CW+RC mixtures (modified after Malisetty et al, 2022).

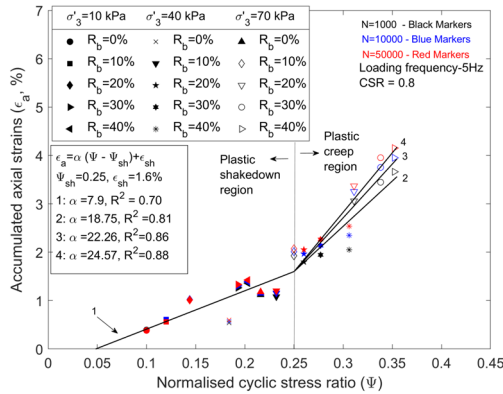


Figure 4. Permanent axial strain varies with the normalized cyclic stress ratio (modified after Malisetty et al, 2022).

The influence of Ψ on the permanent axial deformation is shown in Figure 4, where the accumulated axial strain at loading cycles $N=1000$, 10,000 and 50,000 of the waste mixtures having different rubber amounts under different loading conditions are plotted. It is worthwhile to note that when $\Psi \leq 0.25$, the accumulated axial strain of the same sample converges closer to almost one point at three different loading cycles. This indicates that ignorable increment of axial strains is generated under relatively lower cyclic vertical stress compared to their peak shear strength, and therefore, they are able to reach plastic shakedown easily. When $\Psi > 0.25$, the accumulated axial strain of the waste mixtures is scattered at the three distinct loading cycles showing obvious strain accumulation as loading cycles increases, and this becomes more pronounced with the increase of the rubber content in the mixture. This indicates that with a higher Ψ , the SFS+CW+RC mixtures with a higher rubber content ($\geq 20\%$) are subjected to a relatively higher load ratio towards their peak shear strength, hence generating more particle damage, friction and rearrangement with continuous deformation, so they cannot reach plastic shakedown but end with plastic creep. On this basis, $\Psi = 0.25$ is taken as an arbitrary shakedown threshold for SFS+CW+RC mixtures.

The best-fit regression lines are drawn for the relationship between the accumulated axial strain and Ψ (Figure 4).

$$\epsilon_a = \alpha(\Psi - \Psi_{sh}) + \epsilon_{sh} \quad (2)$$

where α is the slope of the regression line, $\Psi_{sh} = 0.25$ is the shakedown limit for SFS+CW+RC mixtures, and ϵ_{sh} is the accumulated axial strain when $\Psi_{sh} = 0.25$. It is noted that when $\Psi \leq 0.25$, the accumulated axial strain converges to one line, which is due to the relatively small Ψ that ignorable plastic deformation is generated after the initial cyclic densification stage ($N < 1000$ cycles). In contrast, three regression lines are plotted for the plastic creep region as the accumulated strain at different loading cycles are scattered. The regression parameters are shown in Figure 4.

5 PREDICTED SHAKEDOWN RESPONSE UNDER HIGHER LOADING CONDITIONS

To predict the deformation responses (Range A: plastic shakedown; Range B: Plastic creep; Range C: collapse) of the SFS+CW+RC mixture having higher rubber contents under higher train loading, Qi & Indraratna (2022) proposed the below empirical model of the permanent axial strain rate ($\dot{\epsilon}_p$) of the waste composite by capturing the effect of the amount of rubber (R_b , %), the applied vertical deviator stress ($q_{cyc,max}$) and loading cycles (N) (Figure 5):

$$\dot{\epsilon}_p = [(\beta_1 q_{cyc,max} + \beta_2) \ln(R_b + 1) + (\beta_3 q_{cyc,max} + \beta_4)] \cdot N^m R_b^n \quad (3)$$

where β_{1-4} , m and n are the material constants with values of 3.69×10^{-5} , -2.4×10^{-4} , 5.4×10^{-5} , 0.004, 0.0042, and -1.448, respectively.

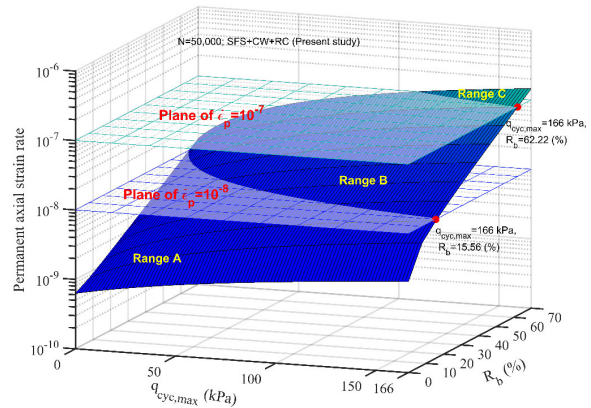


Figure 5. Predicted shakedown response of the waste mixture (Qi & Indraratna, 2022)

Figure 5 illustrates that under a simulated heavy haul loading condition, equivalent to a 30-tonne axle load or approximately 166 kPa applied on top of the subballast layer (Indraratna et al, 2023), the SFS+CW+RC composite containing more than 60% rubber content experiences failure (incremental collapse) within 50,000 load cycles. Mixtures with rubber content between 15% and 60% enter a plastic creep phase, where axial strain continues to accumulate throughout the test duration. In contrast, mixtures containing less than 15% rubber rapidly reach a plastic shakedown state, exhibiting stable deformation behaviour. Based on these findings, it is recommended that the rubber content in the composite mixture not exceed 15% when used as a railway subballast layer, to ensure stable long-term performance under high-intensity cyclic train loads.

6 CONCLUSIONS

This paper investigates the accumulated axial strain response under cyclic loading of the SFS+CW+RC mixtures which is expected to replace traditional railway subballast materials. Some of the important findings can be concluded below:

- The waste mixtures easily achieved plastic shakedown with a smaller Rb% (<20%) or under very low $q_{cyc,max}$ (e.g. 16 kPa), whereas having a greater value of Rb% (30–40%) and under higher $q_{cyc,max}$ (64–112 kPa) the waste mixtures fell with the plastic creep region.
- The influence of the internal shear strength of the waste mixtures with varying rubber content was investigated via the introduction of the normalised cyclic stress ratio Ψ . $\Psi = 0.25$ was found to be the shakedown limit for SFS+CW+RC mixtures. A linear relationship was found between the accumulated strain with Ψ .
- Using the proposed empirical model for the permanent axial strain rate for heavy haul loading revealed that the optimal rubber content in the waste mixtures should be less than 15% to ensure the mixtures, serving as subballast can reach plastic shakedown with 50,000 loading cycles.

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