

# Performance comparison of Geosynthetic-embedded capping layers on soft subgrade constructed with RCA and crushed rock

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**ABSTRACT:** Unbound granular pavements dominate the Australian road network, accounting for over 80% of its total length. Commonly, natural aggregates are used as base and subbase materials in these pavements. However, the depletion of high-quality natural aggregates has created significant challenges for road construction and maintenance, particularly in the context of achieving net-zero carbon emissions. As a response, road authorities are turning to sustainable alternatives, including Recycled Concrete Aggregate (RCA) derived from Construction and Demolition (C&D) waste, as potential substitutes. RCA quality and performance are mainly based on the source and the manufacturing process. Despite the increasing demand for RCA, there is a significant lack of comprehensive studies evaluating RCA's performance incorporated with geosynthetic compared to crushed rocks. This study addresses this research gap by conducting large-scale cyclic loading model box tests to investigate the performance of RCA when geosynthetics are incorporated within capping layers placed over soft subgrade conditions. The integration of geosynthetics is evaluated for its ability to enhance the structural performance and deformation resistance of RCA-based pavements. This research advances sustainable pavement material development by validating RCA as a viable alternative to natural aggregates. The experimental results demonstrated that the inclusion of geocomposites significantly improved the rutting resistance of RCA and high-quality crushed rock (SM01), with respective Traffic Benefit Ratios (TBR) of 23.68 and 24.96. The outcomes of this study provide practical recommendations for the design and construction of RCA-based unbound granular pavements, supporting the adoption of recycled materials in road infrastructure.

**KEYWORDS:** Recycled Concrete Aggregates, Geosynthetics, Cyclic Loading, Crushed rocks.

## 1 INTRODUCTION

Approximately 80% of the Australian road network consists of unbound granular pavements. (ARRB 2023; Dushmantha & Gallage 2025). Hence, there exists a significant demand for pavement materials, particularly granular materials, due to the high usage of low-volume (rural) roads. (Korkiala-Tanttu & Dawson 2007; Behak 2011; Ishikawa 2021). Given the limited availability of natural aggregates, substitute materials such as Reclaimed Asphalt Pavement (RAP), and RCA are currently under investigation. Concrete, being one of the most prevalent C&D waste streams globally. (Akhtar & Sarmah 2018; Salehi, Arashpour, Kodikara, & Guppy 2021; Ranasinghe, Pelden, Dushmantha, & Jayakodi 2025) Research has demonstrated that incorporating waste byproducts from C&D into pavement construction yields beneficial outcomes. (Correia, Roque, Ferreira, & Fortunato 2012). The mechanical and durability characteristics of RCA depend largely on the quality of the source concrete and the specific methods of processing. Several studies have evaluated and concluded that RCA's material characterisation aligns with the traditional Unbound Granular Materials (UGMs) (Safiuddin, Alengaram, Rahman, Salam, & Jumaat 2013; Wang, Yan, Fu, & Kasal 2021; Aytekin & Mardani-Aghabaglou 2021; Hung, Egodawatta, Gallage, & Dawes 2024).

In Queensland, according to Queensland Department of Transport and Main Roads (QDTMR), there are five main types of UGMs based on their quality. Type 2.1 is the highest quality material, and Type 2.5 is the lowest quality material. (Roads 2022; Clark, Piacere, & Gallage 2018; Cheah, Gallage, & Dawes 2017). It is important to evaluate the mechanical performance of RCA under the in-situ conditions. Such as incorporating RCA for pavement construction under weak subgrade conditions. However, to promote the widespread application of RCA as a granular layer in pavements, it is imperative to develop robust design criteria, which necessitates a comprehensive investigation of laboratory experiments to compare its performance with the traditional UGMs. Roads in

Queensland are frequently constructed over subgrades exhibiting low bearing capacity, typically characterised by expansive clay soils with California Bearing Ratios (CBR) below 3% (Dushmantha, Jayakody, Gui, & Gallage 2025; Dushmantha, Jayakody, Gui, Zhong, Southon, FitzChance, & Gallage 2025; Dushmantha, Zhang, Gui, Zhong, & Gallage 2025; Ranasinghe, Barnes, & Rajapakse 2025). Traditional ground improvement methods in the region often involve chemical stabilisation using cement or lime. (Austroads 2019; Chaminda Gallage, Cochrane, & Ramanujam 2012; Souliyavong, Gallage, Egodawatta, & Maher 2012; C. Jayalath, Gallage, & Wimalasena 2024). Alternatively, the incorporation of geosynthetics has been investigated as a method for improving subgrade conditions.

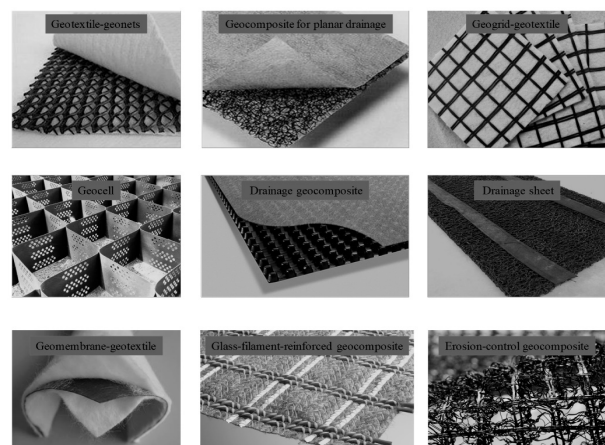


Figure 1. Different types of geosynthetics.

Geosynthetics encompass several categories, including geotextiles, geogrids, geocomposites, and geocells (See Figure 1). Their functional properties primarily differ in terms of aperture size and tensile strength (Xue, Gallage, Qiu, Zhong, & Southon 2023; Klompaker, Shahkolahi, & Gallage 2024;

C. Jayalath, Gallage, Wimalasena, Lee, & Ramanujam 2021). The main roles of geosynthetics are filtration, separation, and reinforcement. Various studies have indicated that the incorporation of geosynthetics results in the formation of stiffened layers immediately above and below their installation position (C. Gallage & Jayakody 2023; Jayakody Arachchige, Gallage, & Kumar 2012). Consequently, the optimal placement for geosynthetics is typically at the interface between the base layer and weak subgrade in unbound pavement structures. However, limited research has been conducted to clearly identify the thickness of these stiffened zones and the ideal spacing for double-layer reinforcement configurations. Geocomposites can function effectively as tension membranes, enhancing structural performance through tensile resistance (C.P.G. Jayalath, Gallage, & Wimalasena 2022; Shahkolahi & Gallage 2025; Gedara, Jayakody & Nayanathara 2025).

Previous research has demonstrated that geosynthetic reinforcement within pavement systems can enhance structural performance by increasing service life, reducing maintenance requirements, and permitting a reduction in the thickness of base layers. (Zornberg 2017; Cheah, Gallage, Dawes, & Kendall 2016; C.P.G. Jayalath, Wimalasena, & Gallage 2024; C. Gallage, Wimalasena, & Pathirana 2024; Hung, Egodawatta, Gallage, & Dawes 2024). While numerous studies have examined the performance of RCA in base and subbase layers. Despite numerous studies investigating RCA's use in base and subbase layers, limited research explicitly addresses the combined reinforcement effects of RCA with geosynthetics, particularly over weak subgrades.

This study addresses the existing knowledge gap by investigating the performance of capping layers reinforced with geosynthetics and constructed using RCA over weak subgrades. Large-scale model box testing is employed to assess the rutting behavior of these layers under repeated loading, simulating standard tyre pressures through a cyclic loading system. Additionally, monotonic plate load tests are conducted to assess the load-bearing capacity of the reinforced configurations. The results enable a comparative assessment of the structural response of RCA against conventional UGMs when integrated with geosynthetics.

## 2 MATERIALS AND METHODS

### 2.1 Materials

In this investigation, expansive black soil was selected as the subgrade material, which is common in Australia. Three types of UGM were used: a standard high-quality granular material (SM01), a standard low-quality granular material (SM02), and RCA. A geocomposite was also used as a reinforcement layer at the interface of the subgrade and the granular layer. Geocomposites' properties were mentioned in Table 1. Figure 2 (a–d) presents the physical appearance of the SM01, SM02, RCA, and the geocomposite employed in the experimental program, respectively.

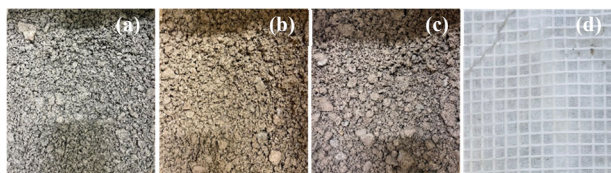


Figure 2. Test materials: (a) SM01; (b) SM02; (c) RCA; (d) Geocomposite.

Table 1. Geocomposite properties.

Property	MD/CMD	MTRS58 Specification	Complaint/Non-compliant
Nominal Strength (kN/m)	30/30	-	-
Maximum Tensile Strength (kN/m)	32/32	-	-
Tensile Strength at 2% Elongation (kN/m)	11/12	≥ 10.5	Compliant
Aperture Size (mm)	32/32	Min ≥ D <sub>50</sub> ≈ 9.5mm Max ≥ 2×D <sub>85</sub> ≈ 38mm	Compliant
Thickness (mm)	1.4/1.4	-	-

### 2.2 Methodology

In this study, cyclic loading tests were performed on three material types: RCA, SM01, and SM02 under conditions with and without geocomposite reinforcement. The cyclic loading tests were conducted to assess the accumulation of Permanent Deformation (PD) over time, while the monotonic loading tests were used to evaluate the ultimate bearing capacity of each configuration.

#### 2.2.1 Pavement Model Box Preparation

The subgrade soil was oven-dried at 105 °C for 48 h, pulverised in a mechanical crusher, and mixed with water in a pot mixer to reach a moisture content of 47 ± 1 % and a dry density of 1.12 g cm<sup>-3</sup>. Subgrade compaction for each model test was carried out up to 500 mm height of the box using a 20 kg tamper with a 200 mm × 200 mm base, applied in 50 mm lifts by dropping from 150 mm. After the subgrade was prepared, the geocomposite was placed directly on its surface.

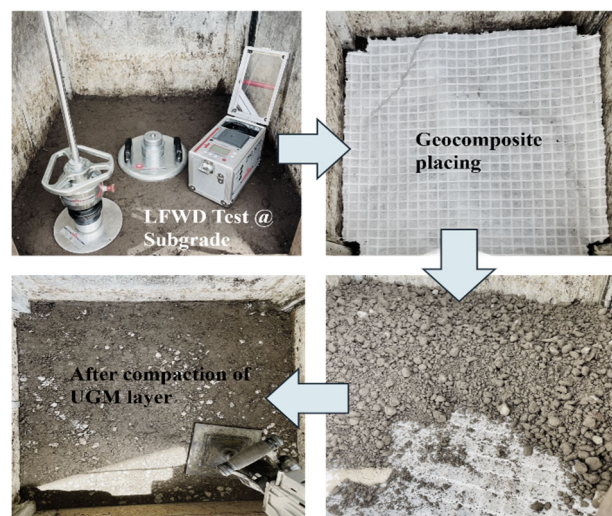


Figure 3. Different construction stages of large-scale model test specimen.

UGM layers: RCA, SM01, and SM02 underwent the same moisture conditioning procedure (without crushing). Target moisture contents were 9.5 % for RCA, 5.5 % for SM01, and 7 % for SM02, with corresponding dry densities of 2.05, 2.21, and 2.11 g cm<sup>-3</sup>, respectively. Quality control was performed during the compaction of each layer using a Light Weight Falling Weight Deflectometer (LWFD) (See Figure 3), ensuring that the target stiffness values were achieved for each layer. The dynamic deformation modulus ( $E_{vd}$ ), as measured using the LWFD, was consistently maintained within the ranges of 7–10 MN/m<sup>2</sup> for the compacted 500 mm subgrade layer, 10–12 MN/m<sup>2</sup> for the 100 mm-thick UGM layer, and 12–20 MN/m<sup>2</sup>

for the 200 mm UGM layer, ensuring compliance with target stiffness criteria during layer-wise compaction.

### 2.2.2 Loading and data analysis

In this experimental series, cyclic loading was generated through a hydraulic actuator with a rated capacity of 500 kN. A peak deviator stress ( $\sigma_d$ ) of 17.3 kN was applied to the test section via a vertically loaded shaft connected to a 200 mm diameter circular steel loading plate, simulating a typical tyre contact pressure of 550 kPa. The loading was applied at a frequency of 0.33 Hz to replicate repeated traffic loads. A schematic representation of the large-scale model box setup, including the layered pavement structure and loading system, is presented in Figure 4.

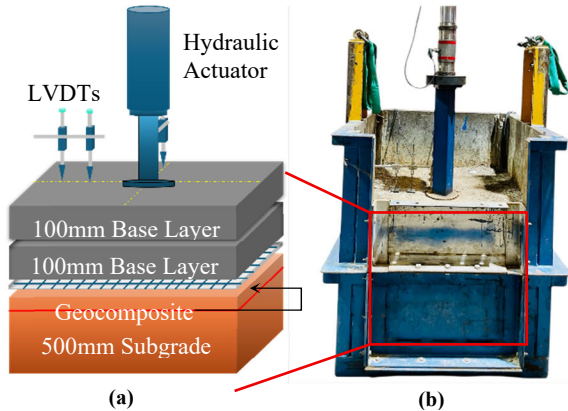


Figure 4. Model box test setup (a) schematic diagram; (b) actual setup.

## 3 RESULTS AND DISCUSSION

### 3.1 Material Characterisation

The upper and lower gradation limits for the granular materials were established according to the QDTMR MRTS05 specification. SM01 conforms to the high-quality material gradation envelope, whereas SM02 aligns with the lower-quality envelope. RCA samples fall within the gradation envelope specified by the manufacturer. According to the Unified Soil Classification System (USCS), all three materials are categorised as well-graded gravel with sand. Figure 5 illustrates the particle size distributions of the three materials alongside their respective specification envelopes and includes a backlight microscopic image analysis to qualitatively assess the particle shape characteristics of RCA.

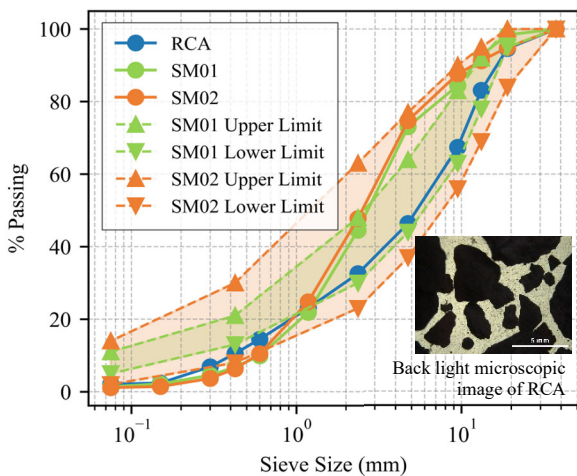


Figure 5. Particle size distribution of the test materials.

RCA consist of remaining mortar particles, which create the porous nature, and it will affect the moisture absorption, which is most challenging in the pavement construction under the compaction stage. But it can be managed with the novel mechanical compaction methods with high energy levels. As shown in Figure 6, RCA requires higher moisture content than the other two materials to achieve its maximum dry density of  $2.01\text{g/cm}^3$ . Additionally, Specific gravity values for SM01, SM02 and RCA are 2.83, 2.64, and 2.62 respectively.

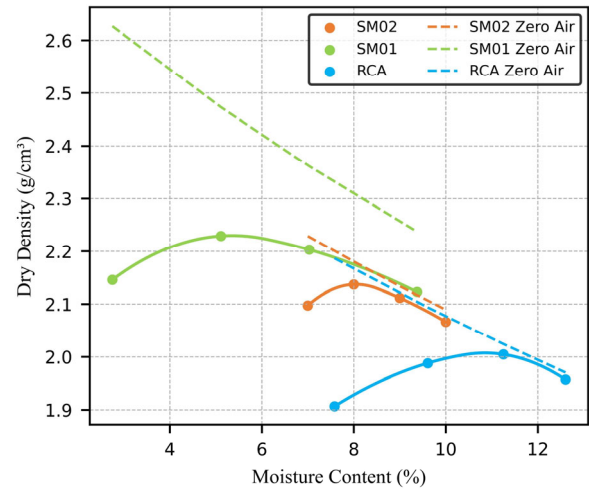


Figure 6. Compaction results of all three UGMs.

### 3.2 Large-Scale Cyclic Model Box Testing

Large-scale model tests were carried out to assess the rutting behavior of each material. Figure 7 represents the observed test results of PD changes with the different loading cycles for without (Control test) geocomposites. SM02 test terminates when the Number of Cycles (N) reaches 60000 because it achieves 80mm of PD.

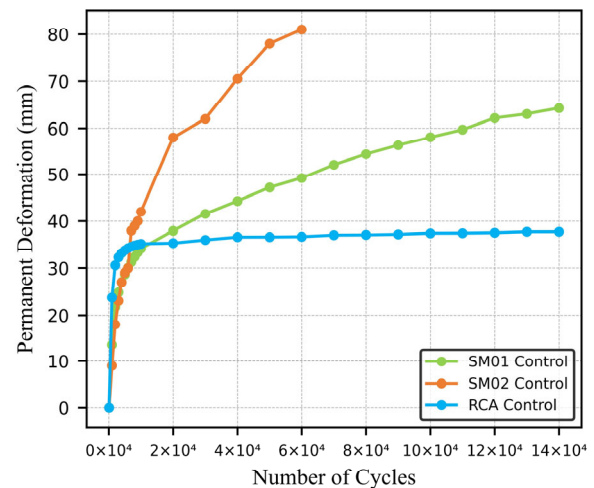


Figure 7. Permanent deformation results of the Control Cyclic Model box test.

In control test results (without geocomposites), SM02 has the highest PD, and RCA has the lowest PD. Mainly SM02 shows poor gradation than the RCA and SM01. RCA shows the shakedown behavior at the end of the test, which has a lower accumulation of PD. However, the observed initial loading phase elevated rutting is primarily attributed to particle degradation caused by the presence of residual mortar. The final PD values recorded for RCA, SM01, and SM02 were 37.74

mm, 64.28 mm, and 81 mm, respectively. Notably, these PD vs N curves show three distinct natures.

These different PD accumulation stages (load cycle ranges) were identified through the analysis of the results of PD changes with the load cycles. The central difference method was used to calculate the rate of rutting accumulation with respect to load cycles (see Equation (1)).

$$\left(\frac{d(PD)}{dN}\right)_i \approx \frac{PD_{i+1} - PD_{i-1}}{N_{i+1} - N_{i-1}} \quad (1)$$

Figure 8 represents the rate of rutting changes with the load cycle for the control test, which is used to identify the segmentation points. Stage I has higher rate of change of PD below the 5000 number of cycles. And stage II is the transition phase it takes place in between 5000-10000 cycles. And beyond 10000 cycles stage III determined with the stabilised rutting.

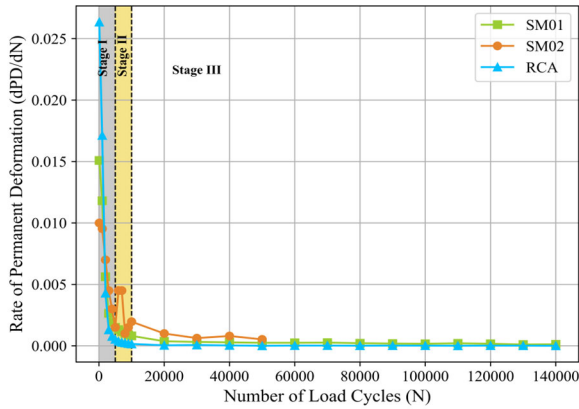


Figure 8. Rate of Change of PD with the Load Cycles for Control Tests

**Note:** Stage I (Early Rutting,  $N \leq 5000$ ), Stage II (Transition Phase,  $5000 < N \leq 10000$ ), Stage III (Stabilised Rutting,  $N > 10000$ )

Furthermore, a dimensionless parameter, referred to as the Material Response Factor (MRF) (See Equation (2)), was introduced to quantify the proportion of total PD that develops during the early stage of loading. This metric facilitates a direct comparison of rutting performance among different material types.

$$MRF = \frac{\overline{PD}_{Stage I}}{PD_{final}} \quad (2)$$

The MRF serves as an effective metric for evaluating and comparing the rutting behavior of different UGMs. The term  $\overline{PD}_{Stage I}$  denotes the average PD observed during the early loading phase (Stage I), where rutting accumulation tends to occur at an accelerated rate. This elevated deformation rate is primarily attributed to the initial particle rearrangement, interlocking, and crushing mechanisms. In Stage I, rutting is strongly influenced by particle morphology and gradation characteristics. The computed MRF values for RCA, SM01, and SM02 are 0.678, 0.311, and 0.218, respectively. Table 2 presents a summary of the MRF values and corresponding Stage I average rut depths for all three unreinforced (control) test sections.

Table 2. MRF for control cyclic tests.

Test Material	$\overline{PD}_{Stage I}$ (mm)	Total PD (mm)	MRF
RCA	25.57	37.74	0.678
SM01	19.97	64.29	0.311
SM02	17.67	81.00	0.218

The primary objective of this study is to assess the improvement in performance resulting from the incorporation of geocomposites. Figure 9 presents the results of cyclic loading tests conducted with geocomposite reinforcement. Among the tested materials, RCA exhibited the least PD, outperforming both SM01 and SM02. The final PD measured after 140,000 load cycles was 26.41 mm for RCA, 29.74 mm for SM01, and 51.80 mm for SM02, respectively.

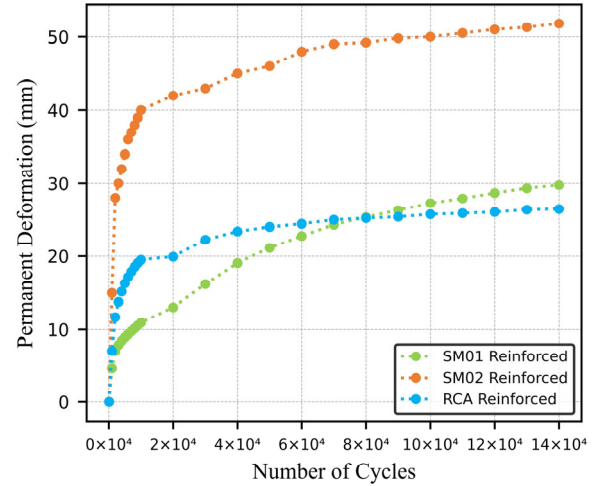


Figure 9. Permanent deformation results of the with geocomposite Cyclic Model box test.

The TBR (See Equation (3)) was calculated in order to assess the efficacy of geocomposite reinforcement (Baadiga, Balunaini, Saride, & Madhav 2023). TBR measures the increase in service life that the reinforcement offers by postponing the onset of critical rut depths. The number of load cycles needed for both reinforced and unreinforced conditions was taken from the cyclic test results for a target rut depth of 20 mm ( $N_{20}$ ; number of load cycle at 20mm rut depth).

$$TBR = \frac{N_{20, reinforced}}{N_{20, Control}} \quad (3)$$

The calculated TBR values for RCA and SM01 were 23.68 and 24.96, respectively. SM01, classified as a high-quality granular material, demonstrated inherently strong rutting resistance under unreinforced (control) conditions. The integration of geocomposite reinforcement further improved its structural response by substantially increasing its resistance to PD. For RCA, which exhibits moderate stiffness but is susceptible to early-stage rutting due to residual mortar content and particle fragmentation, the application of geocomposites proved effective in mitigating deformation. This improvement is primarily attributed to the reinforcement's ability to constrain lateral movement and engage tensile resistance. The relatively high TBR value observed for RCA indicates strong compatibility with geosynthetic reinforcement strategies. Conversely, SM02 recorded a markedly lower TBR of 0.57, indicating limited benefit from reinforcement, likely due to its inferior mechanical properties and weak particle interlocking capacity.

In addition, when comparing the rutting reductions at the 60,000-cycle mark (noting that SM02 failed at this point), RCA, SM01, and SM02 exhibited rut depth reductions of 33.48%, 53.76%, and 40.74%, respectively. By the end of the test, SM01 and RCA achieved total rutting reductions of 53.73% and 30.05%, respectively. The relatively smaller additional rut accumulation observed above 60,000 cycles resulted in similar overall reduction percentages for SM01 and RCA, indicating

that most performance gains from reinforcement occurred during the earlier stages of loading.

This comparative investigation has comprehensively evaluated the mechanical response of geocomposite-reinforced RCA and conventional crushed rock materials (SM01 and SM02) when constructed over soft expansive subgrades. The findings provide clear insights into rutting behavior across different loading stages, quantify the contribution of geosynthetic reinforcement through TBR, and introduce material-specific metrics such as the MRF to assess early-stage deformation characteristics. These results form a foundation for the subsequent conclusions and implications for pavement design using alternative materials.

#### 4 CONCLUSIONS

A comprehensive large-scale model testing program was undertaken to evaluate the performance of geocomposite-reinforced capping layers constructed over expansive soft subgrade soils (black soils), using Recycled Concrete Aggregate (RCA) and two conventional Unbound Granular Materials (UGMs): the highest quality (SM01) and the lowest quality (SM02) per Queensland Department of Transport and Main Roads (QDTMR) specifications. The key findings are summarised below:

- The particle size distribution of RCA closely aligned with the grading envelopes of SM01 and SM02, indicating its compliance with standard gradation criteria for unbound materials.
- In the unreinforced cyclic loading tests, RCA exhibited elevated rut accumulation during Stage I (initial 5,000 cycles), which was attributed to early particle rearrangement and potential crushing of residual mortar. However, in Stage III ( $N > 10,000$ ), RCA demonstrated a stabilised rutting trend indicative of a post-compaction shakedown response. Comparatively, SM01 exhibited moderate rutting, while SM02 experienced the highest Permanent Deformation (PD).
- The evolution of PD with increasing load cycles revealed three distinct deformation phases: Stage I ( $N \leq 5,000$ ), Stage II ( $5,000 < N \leq 10,000$ ), and Stage III ( $N > 10,000$ ). These transition points were determined using the central difference method. To quantitatively assess early-stage deformation, a Material Response Factor (MRF) was introduced. The computed MRF values for RCA, SM01, and SM02 were 0.678, 0.311, and 0.218, respectively, indicating RCA's pronounced early rutting response.
- The influence of geocomposite reinforcement was evaluated using the TBR. The TBR values for RCA, SM01, and SM02 were calculated as 23.68, 24.96, and 0.57, respectively. These results confirm that geocomposite inclusion substantially enhanced the deformation resistance of SM01 and RCA. In contrast, SM02 showed minimal benefit, likely due to its inferior material quality and limited ability to mobilize reinforcement mechanisms.

#### 5 ACKNOWLEDGEMENTS

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