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Laboratory evaluation of the performance of blended recycled glass and natural aggregates composite for flexible pavements

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ABSTRACT: Reusing waste in road infrastructure presents an effective solution to minimize waste accumulation and conserve natural resources amid rapid population growth and urbanization. Although the utilization of recycled crushed glass (RCG) in road infrastructure is being investigated throughout the world, limited studies have evaluated the performance of RCG blended with natural gravel (NGA) for potential application in the base and subbase layers of the flexible pavement. This paper investigates the performance of 20% RCG blended with 80% NGA as an unbound pavement base or subbase material. Basic geotechnical properties of NGA, RCG, and their blend were evaluated, including particle size distribution, compaction, and soaked California Bearing Ratio (CBR). Monotonic drained triaxial tests were performed to evaluate the effect of RCG on the shear behavior of the blends. The results showed that 20% replacement of NGA by RCG increased the CBR value and peak effective friction angle by 9.6% and 6%, respectively. Hence, this blend can be effectively used for pavement substructure applications.

KEYWORDS: Recycled glass, flexible pavement, laboratory tests, monotonic loading, shear strength.

1 INTRODUCTION

The rapid rise in population and urbanization has led to massive solid waste generation and increased consumption of natural resources, causing environmental concerns such as resource depletion, greenhouse gas emissions, and biodiversity loss. The road construction industry contributes significantly to these issues, using about 25% of fossil fuel and accounting for 30% of greenhouse gas emissions worldwide, respectively, due to its reliance on quarry-based materials (Azam et al., 2015, AzariJafari et al., 2019). Intuitively, repurposing waste for road construction presents an effective strategy to not only reduce waste accumulation but also conserve natural resources.

About 130 million tons of waste glass is generated annually, with around 79% being disposed of in landfills (Kazmi et al., 2020). This waste is typically derived from construction and demolition (C&D) activities, as well as commercial and municipal waste. Although recycling into new glass products is possible, challenges like contamination and color sorting limit its use (Disfani et al., 2011). Alternatively, waste glass pieces can be crushed into small-sized particles to form recycled crushed glass (RCG), which can be used in road substructure layers.

Several researchers have explored the potential of RCG for geotechnical applications. Disfani et al. (2011) reported that the medium (4.75-9.5 mm) and fine (0-4.75 mm) sized RCG fractions are suitable for use in civil applications. Previous studies have revealed that RCG typically exhibits low water absorption (~1%) due to its negligible porosity, although the presence of debris may contribute to minor moisture retention (Mohsenian Hadad Amlashi et al., 2020). Its specific gravity ranges from 1.96 to 2.54, approximately 10–15% lower than that of natural aggregates, which contributes to its relatively low maximum dry density (MDD) (1451–1990 kg/m^3) and optimum moisture content (OMC) (8–13.6%) (Punetha and Nimbalkar, 2025). The California Bearing Ratio (CBR) of RCG ranges between 18–76%, with values influenced by factors such as particle size distribution (PSD), compaction effort (standard or modified), and soaked or unsoaked condition (Punetha and Nimbalkar, 2025). In addition, it exhibits internal friction angles ranging from 37° to 48°, which are comparable to those of conventional granular materials. The gradation of RCG often falls outside the acceptable range for use as a standalone base or subbase material (Disfani et al., 2012). Consequently, it requires blending with other aggregates to comply with industry specifications.

Several studies have investigated the behavior of RCG when mixed with natural or recycled aggregates. For instance, Arulrajah et al. (2014) reported that the addition of RCG to waste rock (WR) reduced its MDD and CBR values, while increasing the OMC. Similarly, blending recycled concrete aggregates (RCA) with RCG resulted in reduced MDD, OMC, and CBR values (Ghorbani et al., 2021). However, Chen et al. (2021) reported that by adding RCG to natural aggregates and C&D waste, both CBR and MDD of the blends increase. Previous studies have also shown that with increasing RCG content, both cohesion and friction angle decrease in blends with RCA and WR (Arulrajah et al., 2014). However, Naeini et al. (2021) found that by increasing RCG content in RCA&RCG blends, the peak deviatoric stress at all confining stresses, the magnitude of dilation, and cohesion decrease, while axial strain corresponding to the peak and friction angle (in up to 30% RCG) was higher than that for pure RCA.

Thus, several studies have examined the suitability of RCG and its blends for geotechnical applications. However, the reported outcomes are often inconsistent, primarily due to variations in the gradation of both RCG and the base materials used. These variations result in blended materials with differing PSDs, making it difficult to isolate the influence of RCG on the mechanical behavior of the blends (i.e., eliminate the effect of gradation).

This paper investigates the effect of replacing NGA with RCG on its physical characteristics and shear behavior when a constant target gradation is considered for the blend. The suitability of this blend for pavement base/subbase application is also explored through comprehensive laboratory experiments, including standard compaction tests, 4-day soaked CBR tests, and static triaxial tests.

2 MATERIALS AND METHODOLOGY

2.1 *Materials*

In this research, two types of materials are selected for testing: NGA and RCG. NGA is the natural base course material, which was procured from a quarry in New South Wales, Australia. It is classified as GW-GM as per ASTM D2487 (2000). RCG was sourced from a glass recycling plant in New South Wales, Australia. It has a $D_{\max}$ of 4.75 mm and is classified as SW according to ASTM D2487 (2000). Figure 1 shows the PSD curve for NGA and RCG along with the gradation limits according to current industry practice in Australia. It is apparent that NGA satisfies the grading requirements of both Type 2.3 (used in subbase course of sealed roads) and Type 4.5 materials (used in base course of unsealed roads) specified in DTMR MRTS05 (2022) with a $D_{\max}$ of 26.5 mm.

In this study, RCG is blended with NGA at 20% replacement level by weight (termed NGA80&RCG20 henceforth). The NGA&RCG composite is prepared using a controlled blending approach, in which the gradation of the blend is adjusted to match a predefined target gradation identical to that of NGA. This method is adopted to eliminate the effect of gradation on the performance of the blend.

2.2 *Experimental methodology*

A series of laboratory experiments were conducted on NGA and RCG to obtain their basic geotechnical properties, such as PSD, particle density and water absorption, Atterberg's limits, and organic content. Standard compaction, soaked CBR, and static triaxial tests were subsequently carried out on NGA, RCG, and NGA80&RCG20 blend.

Particle density and water absorption were assessed in accordance with AS 1141.6.1 (2020) and AS 1141.5 (2018) for both NGA and RCG. The results showed that RCG has a particle density approximately 11% lower than NGA and exhibits substantially lower water absorption (<1%) compared to NGA (~4.4%).

The organic content of the materials, which can impact stability, decomposition potential, and long-term performance, was determined using the loss on ignition method according to DTMR Q120B (2023e). Both NGA and RCG were found to contain less than 1% organic matter, confirming their suitability for use in unbound pavement layers.

Atterberg limit tests were conducted following DTMR Q104A (2023a), DTMR Q105 (2023b), and DTMR Q106 (2023c) to assess the plasticity characteristics of fine fractions. NGA exhibited low plasticity with a plasticity index of 3.59, while RCG was classified as non-plastic due to its non-cohesive nature. Table 1 shows the index properties of NGA and RCG.

Compaction testing is essential for identifying the OMC and MDD of pavement materials, which are critical for achieving desired strength and durability. In this study, standard proctor compaction tests were conducted in accordance with DTMR Q142A (2023f) on NGA, RCG, and their blend. The materials were first oven-dried, mixed with water, and cured appropriately. Each sample was compacted in three layers using a standard effort. The compacted specimens were then trimmed, weighed, and their moisture contents measured to calculate dry densities.

The CBR test evaluates the bearing capacity and penetration resistance of pavement base/subbase materials under soaked and unsoaked conditions. This test was performed according to DTMR Q113C (2023d) on NGA, RCG, and NGA80&RCG20 in soaked condition (to simulate the worst-case scenario). Specimens were compacted at their respective OMC and MDD in three layers inside a 152×178 mm mold. Samples were submerged in water for 96 hours, and swelling was measured before and after soaking. A steel piston (49.6 mm diameter) was then driven into the specimen at a rate of 1 mm/min with a 4.5 kg surcharge, and the applied force at 2.5 mm and 5.0 mm penetration was used to calculate the CBR value.

Consolidated drained (CD) static triaxial tests were conducted on NGA, RCG, and NGA80&RCG20 blend as per ASTM D7181(2020). Samples were compacted in five layers inside a 100×200 mm mold at their OMC to achieve a target of 100% MDD. The specimens were saturated using de-aired water and subsequently consolidated under 15, 50, and 150 kPa effective confining pressures (σ'_3). The shearing phase was performed in drained conditions at a rate of 0.05 mm/min. The shearing rate is derived based on the consolidation-time criteria as specified in ASTM D7181(2020) to prevent excess pore water pressure development.

Static triaxial testing conducted in this study provides insight into the material stability governed by its resistance to shear-induced deformation. The deviatoric stress and volumetric strain responses reflect the moduli and stiffness evolution as well as dilatancy and deformation behaviour. In conjunction with the soaked CBR tests, these mechanical evaluations support the growing emphasis on plasticity-based assessment of unbound granular pavement materials, rather than relying solely on elasticity-based design approaches.

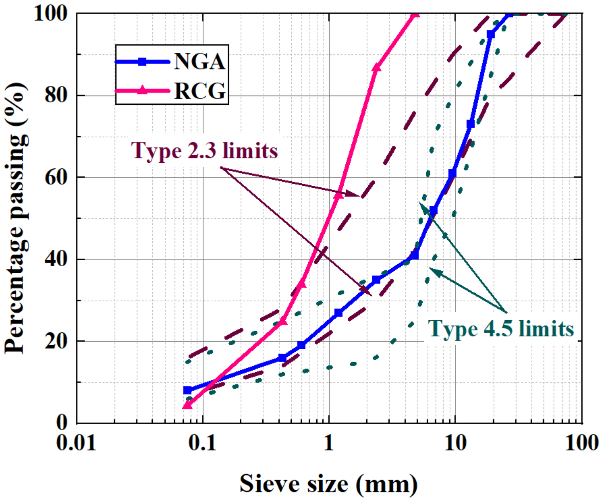

Figure 1. Particle size distribution of NGA and RCG.

Table 1. Index properties of NGA and RCG.

Property	Unit	Test method	NGA	RCG
Gravel content	%	Q103A	59	0
Sand content	%	Q103A	33	95.66
Fine content	%	Q103A	8	4.34
D_{50}	mm	Q103A	6.34	1.02
Coefficient of curvature, C_c	-	Q103A	1.78	1.19
Coefficient of uniformity, C_u	-	Q103A	56.54	7.82
Liquid limit, LL	%	Q104A	23.64	22.84
Plasticity index, PI	%	Q105	3.59	-
Linear shrinkage, LS	%	Q106	0.59	0
Organic content	%	Q120B	0.5	0.61
Particle density (coarse fraction)	kg/m^3	AS1141.5	2690	-
Particle density (fine fraction)	kg/m^3	AS1141.6.1	2670	2380
Water absorption	%	AS1141.6.1	4.4	0.28

3 RESULTS AND DISCUSSION

3.1 *Compaction*

Table 2 shows the values of MDD and OMC for NGA, RCG, and NGA80&RCG20 blend. It is apparent that NGA has a higher MDD of 2073 kg/m^3 compared to RCG, likely due to the lower specific gravity of RCG and its finer gradation, leading to less efficient particle packing. The NGA80&RCG20 blend has MDD of 2074 kg/m^3, which is nearly identical to that of NGA, indicating that partial replacement of NGA with 20% RCG does not significantly affect the compaction characteristics. The OMC values are also similar across all samples (10.3–10.5%), implying that RCG inclusion at this level does not substantially alter the moisture requirement for maximum compaction. These results suggest that the inclusion of 20% RCG maintains comparable density to that of NGA while offering the benefit of waste utilization.

Table 2. Compaction properties of NGA, RCG, and their blend.

Property	Unit	NGA	RCG	NGA80&RCG20
MDD	kg/m^3	2073	1869	2074
OMC	%	10.5	10.3	10.3

3.2 *CBR*

Table 3 shows 4-day soaked CBR values for NGA, RCG, and NGA80&RCG20 blend. It is evident that all the samples meet the minimum requirements specified for type 2.3 unbound material (CBR ≥ 45) and type 4.5 unbound materials (CBR ≥ 15) by DTMR MRTS05 (2022). Among the materials tested, RCG exhibits the lowest CBR value (45%), attributed to its sand-sized particles and comparatively weaker structure. Notably, the NGA80/RCG20 blend shows a higher CBR value (165%) than NGA (150.5%), suggesting that the inclusion of 20% RCG enhances the load-bearing capacity of NGA. This increment in CBR value can be attributed to a reduction in porosity of the blend with RCG particles filling the voids between the coarser NGA particles. Additionally, the enhanced compactability of the blend, resulting from the higher particle mobility associated with the less angular shape of RCG, further contributes to this improvement. This trend is also in line with the results reported by Chen et al. (2021). It must be noted that all samples exhibited insignificant swelling during the 4-day soaking, with values approaching 0.

Table 3. CBR value of NGA, RCG, and their blend.

Property	Unit	NGA	RCG	NGA80&RCG20
4-day soaked CBR	%	150.5	45	165

3.3 *Stress-strain behavior*

Figure 2 shows the variation of deviatoric stress with axial strain for NGA, RCG, and NGA80&RCG20 blend under 15 and 50 kPa σ'_3. The NGA sample exhibits a typical strain-softening behavior, characterized by a rapid increase in deviatoric stress followed by a gradual reduction as strain increases. This pattern reflects the dense packing and high interparticle friction of natural aggregates, which enables strong resistance to deformation, followed by particle rearrangement and reduction in strength beyond a strain level. In contrast, RCG shows a noticeable reduction in the degree of strain-softening compared to that of NGA with a flatter post-peak stress response. This behavior can be attributed to the gradation and smooth surface of RCG, which limits the development of strong interlocking and dilation. The inclusion of RCG in the blend exhibits a similar stress-strain trend to NGA with a small reduction in the magnitude of strain softening, indicating that 20% replacement of RCG does not significantly alter the overall mechanical behavior, possibly due to the limited contribution of the smaller, less angular RCG particles to shear strength. It is also apparent that the peak deviatoric stress and axial strain corresponding to peak increases with increasing σ'_3 for all samples.

Figure 3 illustrates the variation of volumetric strain with axial strain for NGA, RCG, and NGA80&RCG20 blend under 50 kPa σ'_3. All the samples initially undergo a small amount of volumetric contraction up to about 1-2% axial strain, followed by a continuous volumetric dilation as axial strain increases. This behavior is typical of dense granular materials subjected to shearing, where the initial contraction corresponds to particle rearrangement and the subsequent dilation reflects the development of shear-induced particle separation. Among the tested materials, NGA exhibits the lowest volumetric contraction and highest volumetric dilation, reaching approximately 7% at the end of the test. This can be attributed to its well-graded nature and high interparticle friction and dilative tendencies. In contrast, RCG shows the least volumetric dilation, which may be due to its gradation and smooth surface, limiting particle rearrangement and the tendency for dilation.

Adding RCG to NGA increases the initial volumetric contraction and suppresses the dilation. Therefore, the NGA80&RCG20 blend shows intermediate dilative behavior to NGA and RCG due to less angular RCG particles. This constrained dilation helps explain the reduced rate of stress drop after peak strength. Thus, the integration of RCG appears to modify the dilative capacity of the blend, leading to a more gradual and controlled stress degradation beyond the peak.

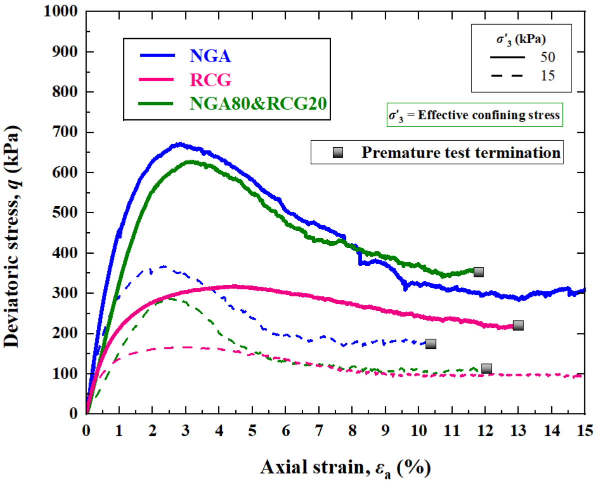

Figure 2. Variation of deviatoric stress with axial strain for NGA, RCG, and their blend.

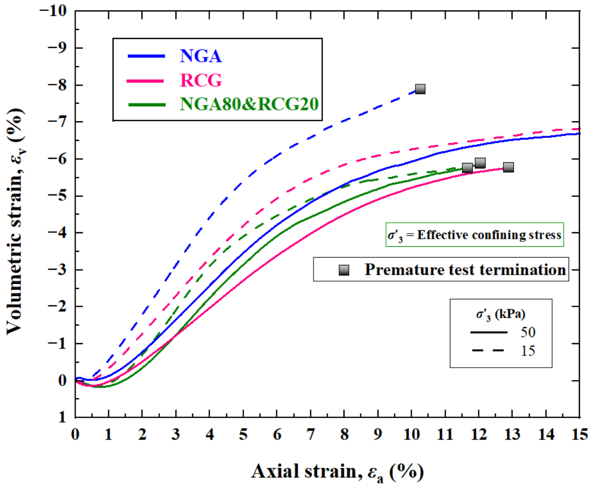

Figure 3. Variation of volumetric strain with axial strain for NGA, RCG, and their blend.

3.4 *Peak friction angle and cohesion*

Table 4 summarizes the peak effective friction angle (φ'_{p}) and peak apparent cohesion (c'_{p}) for NGA, RCG, and NGA80&RCG20 blend. Among the three materials, NGA shows a relatively high φ'_{p} of 48.7 and c'_{p} of 57.9 kPa, indicating strong interparticle friction and bonding within the natural aggregates. However, RCG exhibits the lowest φ'_p of 43.4° with zero c'_p, likely due to the smoother surface of RCG particles. Interestingly, by adding 20% RCG to NGA, the NGA80&RCG20 blend exhibits an increase in φ'_p by 5.74%, while c'_p reduces to 36.7 kPa compared to that of NGA. These observations are in line with the behavior observed in Naeini et al. (2021) for RCA&RCG blends. The increase in φ'_p may be due to improved particle interlock and better packing structure created by the inclusion of finer RCG particles, which enhances the frictional resistance of the matrix. Hence, adding RCG can enhance frictional strength by improving interparticle friction while retaining a reasonable level of cohesion.

Table 4. Peak shear strength parameters of NGA, RCG, and their blend.

Property	Unit	NGA	RCG	NGA80&RCG20
φ'_p	°	48.7	43.4	51.6
c'_p	kPa	57.9	0	36.7

4 CONCLUSIONS

This study investigated the geotechnical behavior of NGA, RCG, and their blend by considering a constant PSD, through a series of laboratory tests, including compaction, CBR, and static triaxial tests, to evaluate the feasibility of using RCG as a partial replacement for natural aggregates in pavement base/subbase applications. Compaction test results showed that the inclusion of 20% RCG had a minor impact on the MDD and OMC, indicating that the blend maintains similar compaction behavior to NGA. The NGA80&RCG20 blend outperformed NGA in terms of soaked CBR value, confirming that the blend increased load-bearing capacity for pavement base or subbase applications. Static triaxial test results revealed that the addition of RCG to NGA leads to a mechanical response closely resembling that of NGA, with only a slight reduction in the amount of strain-softening. Volumetric strain analysis supported these findings, showing that the blend retained a dilation-dominated response, though the extent of dilation was lower than NGA. Furthermore, shear strength parameters indicated that the inclusion of 20% RCG increased the peak effective friction angle while slightly reducing the apparent cohesion.

Overall, the results highlight that incorporating 20% RCG into NGA enhances bearing capacity and offers favorable strength and deformation behavior, justifying its suitability for pavement base/subbase applications while contributing to sustainable resource use by diverting glass waste away from landfills.

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