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Performance assessment of construction and demolition waste as a sustainable alternative material in unbound granular pavements

Nariman Khorsandiardebili, Sanjay Nimbalkar, Piyush Punetha
School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, Australia,
Sanjay.Nimbalkar@uts.edu.au

ABSTRACT: The utilisation of construction and demolition waste (CDW) materials for pavement applications is essential for reducing dependence on virgin quarried materials and minimising the waste directed to landfills. Recycled concrete aggregate (RCA), the main component of CDW, is identified as a prominent material in this context, gaining traction for use in the foundational layers of pavements. This research evaluates the performance of pure CDW (CDW100), natural gravel aggregate (NGA100), and their 50/50 mixture (NGA50/CDW50) for pavement applications, following a consistent single gradation. A series of laboratory tests, including basic characterisation, compaction, California Bearing Ratio (CBR), and static triaxial testing, were conducted to assess NGA/CDW mixtures' characteristics and shear behaviour. The results indicate that CDW possesses higher water absorption and lower apparent density compared to NGA. While NGA demonstrates superior packing ability compared to CDW, the incorporation of CDW into NGA improves the soaked CBR values. Furthermore, static triaxial testing indicates that CDW100 achieved the highest peak deviatoric stress, with NGA50/CDW50 performing comparably to NGA100, thereby confirming enhanced shear strength parameters in mixtures containing CDW due to the presence of RCA. Overall, the findings support the hypothesis that CDW is an effective modifier for improving the durability and structural stability of pavement layers, whether used alone or in combination with NGA.

KEYWORDS: Construction and demolition waste, natural granular aggregates, experimental program, shear strength.

1 INTRODUCTION

The surge in construction activities worldwide has led to a substantial increase in construction waste, with environmental consequences manifesting at every stage of the process. These stages encompass raw material extraction and processing, manufacturing, transportation, on-site construction, and demolition. Reliance on conventional waste management approaches, predominantly landfill disposal, has exacerbated ecological problems such as climate change, resource depletion, and diminished biodiversity.

Research has shown that while the physical properties of recycled construction and demolition waste (CDW) aggregates (with the exception of water absorption) may be slightly inferior to those of natural gravel aggregates (NGA), they exhibit fair performance in terms of key characteristics, namely gradation, flakiness index, specific gravity, and Los Angeles abrasion (LAA) loss values, which affirm their suitability for use in road base and subbase layers in pavement applications. In this regard, Ok et al. (2020) demonstrated that these materials meet the minimum requirements outlined by highway standards, supporting their potential in sustainable pavement applications.

Further investigations, including those by Nataatmadja & Tan (2001), have indicated that the resilience of sub-base materials made from CDW closely matches that of NGA, the performance of which is influenced by factors such as original compressive strength and the flakiness index of the aggregates. This aligns with findings from Barbudo et al. (2012), who noted that the mechanical performance of mixed masonry and recycled concrete aggregates (RCA), the main component of CDW, performs well mechanically, particularly in roads with low traffic, due to their substantial bearing capacity as measured by the California Bearing Ratio (CBR) index.

Moreover, it is found that the moisture sensitivity is a crucial factor in the performance of CDW materials, as noted by Arulrajah et al. (2011), who recommended maintaining specific moisture ratios to mitigate adverse effects on resilient modulus. This consideration is further supported by Ji et al. (2021), who found that the endurance properties of CDW vary significantly based on sourcing and processing, with increased porosity leading to lower apparent relative density and higher water absorption rates compared to NGA.

Among various CDW materials, RCA and crushed brick (CB), derived from CDW, have established themselves as critical materials in pavement construction, particularly within foundational layers (Ghorbani et al. 2020; Jayakody, Gallage & Ramanujam 2019; Poon & Chan 2006). RCA frequently demonstrated enhanced structural strength and mechanical performance compared to other forms of CDW, fulfilling durability criteria defined by CBR and repeated load triaxial (RLT) tests, with certain evaluations indicating resilient modulus values up to 229% higher than those of natural aggregates (Arulrajah et al. 2012).

While these attributes make RCA an attractive alternative, challenges remain. RCA typically exhibits higher water absorption and lower density compared to NGA, primarily due to increased porosity and attached mortar (Ahmed et al. 2024; Ji et al. 2021). This heightened porosity can elevate permeability and moisture sensitivity, particularly for RCA, potentially complicating sub-base design in wet climates. Such factors necessitate careful moisture management, as inconsistent mechanical properties can arise from variations in source material and processing techniques. Furthermore, the presence of flaky aggregate morphologies influences long-term performance, increasing susceptibility to breakage under repeated loading conditions (Oskooei et al. 2021).

Studies conducted on the mixture of NGA with RCA, the main component of CDW, highlight how these blends can significantly enhance the performance of granular road base and sub-base. Laboratory tests have shown that mixtures with about 50% RCA yield optimal results regarding permanent deformation and CBR values (Toka & Olgun 2022).

Exploring the monotonic shear behaviour of binary mixtures is of great importance, as these materials exhibit highly variable and often complicated responses under shearing (Farooq & Nimbalkar 2024a, 2024b, 2024c; Naeini et al. 2021). Their mechanical performance depends on multiple interacting factors, including particle size ratio, fines content, gradation, relative density, and particle morphology, which together govern fabric development, load transfer mechanisms, and dilatancy behaviour. Static shear behaviour assessments of NGA/RCA blends indicated that these mixtures can maintain favourable mechanical properties, including friction angle and cohesion, supporting the idea that RCA can effectively achieve performance standards akin to those of NGA (Toka & Olgun

2022; Wang et al. 2024; Zhi et al. 2023). Limited studies in the existing literature reported the friction and cohesion of such mixtures (Wang et al. 2024; Zhi et al. 2023), and thus a significant research gap remains concerning the stress-strain and shear strength characteristics of CDW materials blended with NGA. This analysis is critical for accurately assessing the engineering properties and performance of NGA/CDW mixtures.

This study investigated the behaviour of NGA, CDW and their 50% mixture. A comprehensive laboratory testing program was conducted, including material characterisation, standard Proctor compaction, CBR, and static triaxial tests to evaluate compaction properties and shear strength characteristics of these mixtures.

2 METHODOLOGY

2.1 *Basic characterisation*

For pavement applications, the particle size distribution (PSD) of base/subbase materials is a crucial factor necessitating a continuous and evenly distributed gradation curve encompassing a broad range of particle sizes, from coarse to fine. A suitable material for pavement application is characterised by a well-graded curve that adheres to stringent standards established by local road authorities. These specifications provide the lower and upper bound PSD based on the type of materials used and maximum particle size. Figure 1 shows the lower and upper limits for granular material type 2.3 and 4.5, respectively, for pavement base and subbase layers, employed in the present study. Based on these margins, a target PSD is selected to meet the requirements of both the Department of Transport and Main Roads (DTMR) and Scenic Rim Regional Council (SRRC) standards for type 2.3 and 4.5 materials, respectively. This selective PSD curve is employed as a single target gradation to be used for NGA, CDW and their mixture (NGA50/CDW50). This approach was adopted to ensure consistency of materials and elimination of gradation effect on the results, facilitating a more accurate comparison of the results obtained from each material, including NGA100, CDW100 and NGA50/CDW50 with varying structures. In the present study, both NGA and CDW materials were procured from local suppliers in New South Wales. CDW comprised primarily RCA, with CB as a secondary component, constituting less than 15% of CDW.

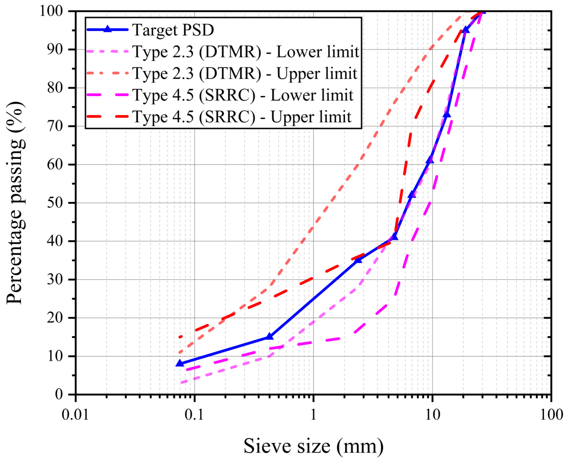

Figure 1. Target PSD curve satisfying both DTMR and SRRC criteria.

The flakiness index (FI) of aggregates was explored according to DTMR Q201 (2023c), evaluating the shape and angularity of particles. This parameter influences the workability and compaction of the aggregates. NGA and CDW were subsequently evaluated for density and water absorption as per AS 1141.5 (2018) and AS 1141.6.1 (2020).

In this study, three material types were evaluated in compaction, CBR, and static triaxial tests: pure NGA (NGA100), pure CDW (CDW100), and a 50/50 blend of NGA and CDW (NGA50/CDW50). The standard compaction test, based on DTMR Q142A (2023b), is carried out to determine the optimum moisture content (OMC) at which the soil sample becomes most dense and achieves its maximum dry density (MDD). The 4-day soaked CBR test based on DTMR Q113C (2023a) was performed to measure the strength of materials under simulated loading conditions.

2.2 *Static triaxial test*

A triaxial testing system capable of applying up to 2 MPa confining pressure and 2.5 MPa axial stress was utilised in this study to perform a set of consolidated drained (CD) triaxial tests on NGA/CDW mixtures. First, the soil samples were carefully graded to the target PSD [see Figure 2(a)], as established earlier in Figure 1. Then, a cylindrical specimen (100 mm in diameter and 200 mm in height) was compacted with a standard effort at their corresponding MDD and OMC in 5 layers to prepare a homogeneous sample, as shown in Figure 2(b).

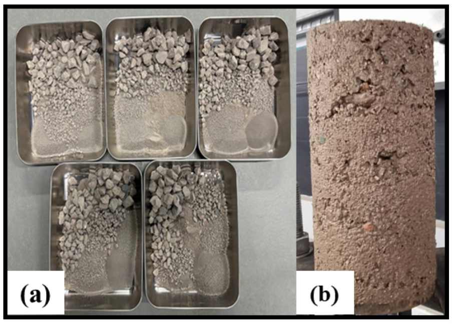

Figure 2. (a) Typical sample during preparation; (b) cylindrical sample after compaction.

A 1-mm thick latex rubber membrane encased the specimen to isolate it from the surrounding fluid in the triaxial chamber. Saturation is achieved by increasing cell pressure and back pressure until Skempton's pore pressure parameter (B value) reaches 0.95 or higher, indicating full saturation. The specimen is then isotropically consolidated under the target confining pressure, followed by sensor calibration before the shearing stage. The actual shearing is conducted at a slow rate of 0.05 mm/min until failure while letting the sample drain. The test is terminated at an axial strain of 15%. Figure 3 illustrates the evolution of a typical sample before and after shearing in static triaxial test.

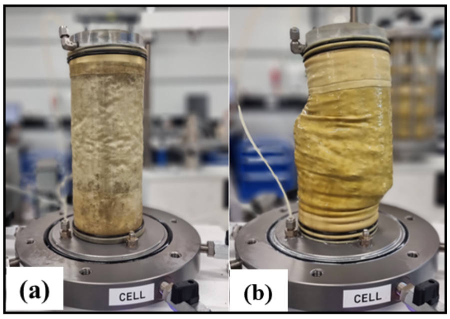

Figure 3. Evolution of a typical sample: (b) a compacted sample before shearing; (c) a tested sample after shearing.

3 RESULTS AND DISCUSSION

3.1 *Material properties*

Table 1 provides the values of the FI for NGA and CDW. It can be observed that FI of both materials is within the limits (≤ 40%) specified for type 2.3 unbound material by DTMR MRTS05 (2022). It is also apparent from Table 1 that CDW comprised fewer flaky particles with the FI of 5.8% compared to NGA with the FI of 11.7%. Figure 4 shows flaky and non-flaky particles in a typical CDW sample.

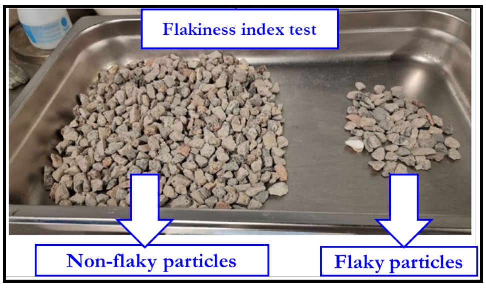

Figure 4. Flakiness index test and separation of flaky and non-flaky particles of CDW material.

It is also observed from Table 1 that the apparent particle density of CDW is lower than NGA. Furthermore, the water absorption of CDW (6.3%) is greater than that of NGA (4.40%). These results may be attributed to the higher porosity of RCA and CB present in CDW, leading to lower density and higher water absorption.

Table 1. Material characteristics of NGA and CDW.

Property	Test method	NGA	CDW
Flakiness index (%)	DTMR Q201 (2023c)	11.7	5.8
Apparent particle density (kg/m^3)	AS 1141.5 (2018)	2,670	2,610
Water absorption (%)	AS 1141.6.1 (2020)	4.4	6.3

Standard compaction tests were carried out on NGA100, CDW100 and NGA50/CDW50. These samples were prepared in a way that the target gradation (see Figure 1) is achieved, which satisfies the grading requirements of both type 2.3 and type 4.5 materials set by DTMR and SRRC, respectively. Table 2 lists the MDD and OMC values for NGA100, CDW100 and NGA50/CDW50. It is apparent that NGA100 possesses the highest packing ability among all the materials tested, with the MDD of 2,073 kg/m^3 and the lowest required moisture with OMC of 10.5%. CDW100 shows the lowest MDD (1,908 kg/m^3) and the highest OMC (14.1%).

Table 2. Standard compaction and 4-day soaked CBR test results.

Property	Unit	NGA100	NGA50/CDW50	CDW100
OMC	%	10.5	12	14.1
OMC range	%	10.4–10.55	11.8–12.2	13.8–14.2
MDD	kg/m^3	2,073	2,002	1,908
MDD range	kg/m^3	2040–2085	1993–2005	1900–1917
Soaked CBR	%	151.4	153.2	172.1

It can be observed that the OMC increases with an increase in the percentage of CDW. This is attributed to the fact that the RCA material, as well as CB, in CDW features higher water absorption compared to NGA (see Table 1). Furthermore, with increasing CDW percentage, MDD decreases. This shows the lower packability potential of the samples, which include CDW, as compared to NGA100. In order to establish a reliable correlation between dry density and moisture content for each mix composition, a minimum of eight specimens were tested across different water contents. This approach ensured sufficient data to accurately determine the OMC and MDD. The corresponding ranges, encompassing both the lower and upper limits for each mixture, are presented in Table 2.

Table 2 also depicts the 4-day soaked CBR values for NGA100, NGA50/CDW50 and CDW100. It is apparent that CDW100 exhibits the highest 4-day soaked CBR value of 172.1%, while NGA100 shows the lowest value of 151.4%. When CDW is added to NGA at proportions of 50%, the soaked CBR values increase to 153.2%. It is worth noting that all the blends of NGA and CDW satisfy the minimum requirements specified by DTMR MRTS05 (2022) for type 2.3 unbound material (soaked CBR ≥ 45). It was also observed that all the blends exhibited negligible swelling values during soaking.

3.2 *Stress-strain analysis*

Figure 5 shows the results of the static triaxial tests conducted on NGA100, CDW100 and their 50% mixture under effective confining pressure (σ'_3) of 50 kPa. It can be observed from Figure 5 that deviatoric stress increases nonlinearly up to a peak value, beyond which a reduction in stress occurs, and it becomes constant after reaching the residual state. The peak deviatoric stress under σ'_3 of 50 is 751 kPa for CDW100, which exhibits the highest value among all samples tested. NGA100 and NGA50/CDW50 showed comparable peak stress values of around 670 and 675 kPa, respectively. Overall, mixtures incorporating CDW exhibit comparable or improved peak strength relative to pure NGA. However, CDW100 reached the constant residual state at a lower axial strain, with the lowest residual strength of approximately 270 kPa. Whereas NGA50/CDW50 and NGA100 reached residual strength at higher axial strains, with greater residual strengths of about 295 kPa and 310 kPa, respectively.

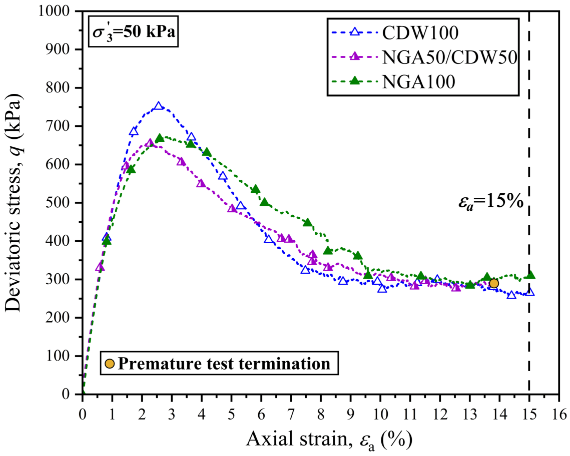

Figure 5. Variation of deviatoric stress with axial strain for NGA100 and CDW100, and their 50% mixture (NGA50/CDW50).

3.3 *Peak shear strength properties*

Table 3 illustrates peak apparent cohesion (c'_p) and peak effective friction angle (φ'_p) parameters obtained for NGA100, CDW100 and NGA50/CDW50. It is observed that CDW100 exhibits the highest apparent cohesion, 74.6 kPa, among all mixtures. This may be attributed to the presence of RCA and the cementation bonds formed during saturation and exposure of the sample to water (Amin et al. 2016; Poon, Qiao & Chan 2006; Wang et al. 2023). The incorporation of NGA fines appears to disrupt the cementitious bonding within the RCA particles in CDW, leading to reduced soaked CBR value for the blended mix. Mixtures that included CDW material also showed higher peak effective friction angles compared to NGA100. In general, NGA100 demonstrated lower strength parameters compared to CDW100 and their 50% mixture. This observation suggests that the addition of CDW enhances the shear strength parameters, likely due to the synergistic effects of RCA along with the hydration and cementation processes occurring within the mixture samples of CDW.

Table 3. Effective friction and apparent cohesion corresponding to the peak for NGA and CDW mixtures.

Material	φ'_{P} (°)	c'_{P} (kPa)
NGA100	48.7	57.9
NGA50/CDW50	51	46
CDW100	50.1	74.6

4 CONCLUSIONS

This research evaluated the performance of CDW100, NGA100, and NGA50/CDW50 for pavement applications, adopting a consistent gradation throughout the analysis. A thorough series of laboratory tests, viz. basic characterisation, compaction assessment, CBR evaluation, and static triaxial testing, was conducted to explore the performance of CDW100, NGA100 and NGA50/CDW50.

It was demonstrated that CDW100 exhibits higher water absorption due to its increased porosity, which is related to the intrinsic nature of RCA and CB. Although NGA100 exhibited superior packing ability, resulting in the highest MDD and the lowest OMC, samples with higher CDW content showed improved soaked CBR values, with CDW100 achieving a peak value of 172.1%. Furthermore, static triaxial tests revealed that CDW100 exhibited the highest peak deviatoric stress, confirming its enhanced shear strength parameters. This highlights the potential of CDW as a sustainable alternative material for unbound base and subbase layers.

CDW100 and the NGA50/CDW50 mixture exhibited superior shear strength characteristics relative to NGA100. Consequently, the integration of CDW into NGA yielded substantial enhancements in both shear strength and soaked CBR, thereby substantiating the hypothesis that CDW can serve as an effective modifier to augment the durability and structural stability of pavement construction. This underscores the potential for utilising CDW as a technically viable alternative in unbound base and subbase applications.

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