# Recycled concrete aggregate and cinder gravel as base course construction materials

**Atnafu Sahile[1], Elmer C. Agon[2], Anteneh Geremew[2] and Oluma Gudina[2]**

[1] *Kaffa Zone Transport & Road Building Department, Kaffa, Bonga, Ethiopia*

[2] *Jimma University; Faculty of Civil and Environmental Engineering, Jimma, Ethiopia*

**Corresponding author:**
Anteneh Geremew
antjiren@gmail.com

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Faculty of Civil Engineering and Architecture Osijek
Josip Juraj Strossmayer University of Osijek
Vladimira Preloga 3
31000 Osijek
CROATIA



**Abstract:**
In this research, the potential use of recycled concrete aggregate (RCA) and CG as a base course construction material was investigated. A laboratory test involving the mechanical stabilization of RCA and CG was conducted to examine their physical properties. Eight samples of RCA blended with CG in varying proportions from 0% to 100 % with 10 % variation were studied. The laboratory test results indicate that 100 % CG yields specific gravity (SG), aggregate crushing value (ACV), aggregate impact value (AIV), Los Angeles abrasion (LAA), flakiness index (FI), elongation index (EI), plasticity index (PI), water absorption, soundness, and California bearing ratio (CBR) values of 2,54 %, 38,37 %, 20,10 %, 33,17 %, 5,59 %, 12,09 %, 0,90 %, 3,52 %, 10,60 %, and 38,08 %, respectively. The results for 100% RCA show SG, ACV, AIV, LAA, FI, EI, PI, water absorption, soundness, and CBR values of 2,70 %, 9,56 %, 5,30 %, 9,20 %, 15,30 %, 15,84 %, NP, 0,23 %, 1,49 %, and 105,87 %, respectively. These results also fail to meet the gradation requirements based on ERA standard specifications. Therefore, mechanical stabilization was adopted to improve the physical properties of the samples. Blending 60 % RCA with 40 % CG resulted in SG, ACV, AIV, LAA, FI, EI, PI, water absorption, soundness, and CBR values of 2,65 %, 19,46 %, 10,70 %, 10,88 %, 16,15 %, 22,01 %, NP, 0,26 %, 2,09 %, and 101,98 %, respectively. At this proportion, the gradation aligns with the required ERA standard specifications for GB2 and GB3 materials. Therefore, CG up to 40 % by weight with 60 % RCA is viable for road base course construction, especially when readily available or nearby.

**Keywords:**
recycled concrete aggregate; cinder gravel; marginal materials; natural aggregate; base course; CBR

## 1 Introduction

Road construction is a key focus area for any country seeking to initiate rapid industrial development and increase socioeconomic interactions. Transportation infrastructure allows rapid movement of people and supplies from one location to another, thereby enhancing mutual social interactions [1]. Road pavements provide safe, comfortable, convenient, and economical running surfaces for passages to accommodate fast-moving traffic [2]. Asphalt pavements are lasting surface structures laid down to allow the passage of traffic and are usually set up with three layers: an asphalt or hot mix asphalt (HMA) layer, a base or aggregate layer, and a subgrade layer. Each layer contributes to the durability of the pavement and distributes the forces and pressure exerted by vehicles [3]. As each layer has a specific function, appropriate materials and layer thicknesses must be selected for each layer to ensure efficiency and economy.

Pavement base courses are generally desired to be densely graded to achieve the maximum density and strength. The quality of the base depends on factors such as gradation, angularity and shape of the particles (flat and elongated particles should be avoided), soundness of the aggregate particles, and resistance to weathering [4]. The global demand for construction aggregates exceeds 26,8 billion tons annually, and many countries, including Egypt, are experiencing a notable increase in natural aggregate use owing to infrastructure and construction development. The utilisation of recycled aggregates in construction, a practice initiated at the end of World War II, offers environmental and economic benefits. This is particularly relevant for Egypt, given the 4.0 million tons of construction and demolition waste generated annually in the country, which highlights the need for sustainable waste management solutions and the potential of recycling concrete waste for base-course construction in various developing countries [5].

The demand for non-renewable natural resources, such as mineral aggregates, for highway construction is high. A common approach to enhance pavement sustainability is to reduce the use of virgin aggregates by substituting them with alternative aggregates. Recycled concrete aggregates (RCA) have emerged as promising alternatives, exhibiting equivalence to conventional aggregates in pavement production. In particular, field investigations suggest that substituting up to 40 % of the coarse RCA with natural aggregates yield pavements with comparable performances [6].

Researchers have extensively explored the use of recycled concrete in various construction applications such as pavements, drainages, embankments, bases, and sub-bases. However, the successful substitution of recycled aggregates for normal aggregates remains limited owing to challenges such as insufficient laws, guidelines, utilisation experience, and low-quality materials. The limited or no use of demolished concrete presents an environmental hazard due to the space required for disposal, while incorporating such materials into construction faces challenges related to the diverse sources of demolished aggregates. [7]. In the 1970s, the United States reintroduced RCA in non-structural uses, such as fill material, foundations, and base course material [8]. Since then, research has been conducted on the viability of RCA as an alternative to unused natural aggregates (NA) in structural concrete [9].

In Ethiopia, base-course construction materials are typically specified to include unbound granular materials, such as crushed stone, natural river gravel, and chemically stabilised materials, such as lime, cement, or pozzolana-lime. However, obtaining high-quality aggregates often requires the transportation of alternative materials over long distances, prompting the exploration of locally available marginal materials. These materials are considered marginal owing to factors such as gradation, particle shape, strength, or plasticity behaviour, with coarse materials impacting stability and compaction, and gap-grade materials causing difficulties in compaction, moisture susceptibility, and fine dispersion [4].

The research revealed that cinder cones are concentrated in the rift valley, extending southwards into Kenya and Tanzania. Laboratory studies on cinder materials from various locations in the country demonstrated dry modified aggregate impact values ranging from 46 to 100, with no loss in strength upon soaking. However, challenges such as undefined optimum

moisture content and issues with gradation and weak particles make cinder gravel (CG), which is abundant in Ethiopia's rift valley areas and shows potential for improvement through repeated compaction tests, unsuitable for base course construction [4]. Marginal aggregates, such as lateritic, calcareous, and volcanic gravels, deviate from standard base course material specifications but have been used successfully in lower traffic categories (i.e., T1 and T2).
This study focuses on assessing the potential utilization of RCA and CG as base course materials. Based on the study findings, the use of locally available marginal materials is advocated to address material scarcity and environmental degradation in the study area.
The laboratory investigations performed at the Jimma Institute of Technology (JIT), including tests on gradations, aggregate properties, and compaction, reveal that the construction industry is benefiting from the use of abundant local resources over expensive virgin materials, contributing to the conservation of natural resources.
Road construction is vital for industrial development and socioeconomic interactions. However, the increasing demand for conventional aggregates increases construction costs, depletes natural resources, and contributes to surface degradation. The scarcity of high-quality aggregates at some locations necessitates the transportation of alternative materials over longer distances.
In road infrastructure projects, the quality and grain-size distribution of base-course materials are crucial, and the unavailability of suitable materials nearby can lead to high costs, delays, and compromised road quality. This is particularly relevant when working with low-quality materials, which can affect road durability and result in significant losses over time, particularly if the material faces compaction challenges owing to its light weight, rough circular surface, and high porosity [10]. The shortage of quality base-course materials such as natural gravel or crushed rock in certain regions of Ethiopia leads to increased transportation costs and project delays.
The annual disposal of millions of tons of concrete fragments and blocks as construction waste poses environmental and land fertility concerns, thus exacerbating the need for sustainable alternatives in construction practices.

## 2 Methodology

### 2.1 Materials required

Demolished RCA and CG samples were collected using purposive sampling techniques and laboratory investigation and analysis were performed. CG is a pyroclastic material associated with recent volcanic activity and occurs in characteristically straight-sided cone-shaped hills. These hills frequently have large concave depressions on their tops or sides where mixtures of solids and gases are released during the formation of the cone. The compaction of CG is challenging owing to its light weight, rough circular surface, and high porosity.
RCA is generally produced by the two-stage crushing of demolished concrete and screening and removal of contaminants such as reinforcement, mortar, plastics, and gypsum. The aggregates made from recycled aggregates are called recycled concrete aggregates.

### 2.2 Standard procedures adopted during an investigation

The test method adopted to investigate the physical engineering properties of the materials used in this study, such as RCA, CG, and CSA, is listed in Table 1.

**Table 1. Laboratory test type for aggregate test and their reference codes**

| S/N | Test type | Objective of the experiment | Reference codes |
|---|---|---|---|
| 1 | Specific Gravity and Water Absorption of Aggregates | To determine the specific gravity and water absorption of aggregates by a perforated basket. | • AASHTO T 85 /ASTM methods are C 127/ for coarse<br>• AASHTO T 84 /ASTM C 128/ for fine aggregates.<br>• BS EN 1097-6 |

| | | | |
|---|---|---|---|
| 2 | Flakiness Index | To determine the flakiness index of coarse aggregate | • BS812: Part 105:1990 |
| 3 | Elongation Index | To determine the Elongation index of coarse aggregate | • BS812: Part 105:1990 |
| 4 | Aggregate Crushing Value (ACV) | To measure the strength of coarse aggregate | • BS 812: Part 110:1990 |
| 5 | Aggregate Impact value (AIV) | To determine the Aggregate Impact Value (AIV) of a given aggregate sample | • BS 812: Part 112:1990<br>• IS 2386-Part-4 |
| 6 | Los Angeles Abrasion (LAA) | To assess the hardness of coarse aggregates used in pavement construction. | • AASHTO T 96-94<br>• ASTM C 131-89<br>• BS 812: Part 113:1990 |
| 7 | Ten Percent Fines Value Test (TFV) | To determine the TFV by measuring the load required to crush a prepared aggregate sample to give 10% material passing a specified sieve after crushing | • BS 812: Part 111:1990 |
| 8 | California Bearing Ratio (CBR) | To evaluate the bearing capacity of the sub-base | • AASHTO T193<br>• AASHTO T180 |
| 9 | Soundness of Aggregate | To measure the aggregate's ability to withstand weathering | • AASHTO T104 |
| 10 | Particle size distribution | To classify soil or aggregate | • AASHTO T-27-93 |
| 11 | Blending of materials | For effective utilization of available aggregate to be economical during road construction | • ASTM D 3515 |

### 2.3 Research design method adopted

The research followed an experimental design which began with the collection of samples. The stages involved in this study were as follows:

- Literature review.
- Samples of CG and RCA were collected. The RCA was separated from the concrete by hammering. The mortar that adhered to the aggregate was removed to the greatest extent possible.
- Preparation of samples for each laboratory test.
- Laboratory tests to characterize natural untreated CG and RCA samples.
- The process of blending CG with RCA determined the maximum replacement amount that satisfied the requirements of the Ethiopian Road Authority (ERA) pavement design standard specifications.

The physical properties of the mechanically blended samples were investigated in the laboratory. The test types used during the investigation included gradation, aggregate impact value (AIV), compaction/moisture density relationship, California bearing ratio (CBR), compaction test, aggregate crushing value (ACV) and ten percent fines value (TFV), flakiness index (FI), Los Angeles abrasion (LAA), soundness and specific gravity, and water absorption. All the aforementioned tests were conducted on neat samples and CG blended with varying proportions of RCA from 0 to 100 %, with varying percentages of 10 %. The samples were collected according to the AASHTO T-2 methodology for sampling from stockpiles and reducing the samples of aggregates to the testing size according to AASHTO-T248. For each test, sampling techniques such as quartering, riffle splitting, and weighing were employed. For this investigation, eight (8) samples of materials were studied individually, as listed in Table 2.

**Table 2. Blending proportion of representative samples of RCA and CG**

| S/N | Material Descriptions | Detail compositions |
|---|---|---|
| CG | Neat Cinder gravel | 0 %RCA + 100 % Cinder gravel |
| $RCACG_1$ | RCA & Cinder gravel blend | 10 % RCA + 90 % Cinder gravel |
| $RCACG_2$ | RCA & Cinder gravel blend | 20 % RCA + 80 % Cinder gravel |
| $RCACG_3$ | RCA & Cinder gravel blend | 30 % RCA + 70 % Cinder gravel |
| $RCACG_4$ | RCA & Cinder gravel blend | 40 % RCA + 60 % Cinder gravel |
| $RCACG_5$ | RCA & Cinder gravel blend | 50 % RCA + 50 % Cinder gravel |
| $RCACG_6$ | RCA & Cinder gravel blend | 60 % RCA + 40 % Cinder gravel |
| RCA | Neat RCA | 100 % RCA + 0 % Cinder gravel |

Figure 1 shows the samples prepared for various laboratory tests based on the standard test procedures described in Table 1.

**Figure 1. Prepared sample for laboratory tests**

## 3 Results and discussions

### 3.1 Particle size distribution or sieve analysis RCA and CG

A comparison of the particle size distribution results for RCA and CG in Figure 2 reveals that the gradation of the samples does not meet the ERA standard specification for GB2 and GB3, specifically for the 37,5 mm nominal maximum aggregate sizes for base course materials. Both materials were classified as A-1-a type soils according to the AASHTO soil classification system, indicating that less than 15 % of the particles passed through a 0.075 mm sieve opening and had a plasticity index (PI) of zero. Although both CG and RCA are preferred for road construction based on the AASHTO classification, the USCS classifies CG as GP-GM, which is poorly graded gravel with silt owing to its Cu and Cc values, and RCA is similarly classified.

Initially, the detailed engineering properties of the materials used in this investigation were studied separately for RCA and CG. The test results showed that SG, ACV, AIV, LAA, FI, EI, PI, water absorption, soundness, and CBR were 2,54 %, 38,37 %, 20,10 %, 33,17 %, 5,59 %, 12,09 %, non-plastic (NP), 3,52 %,10,60 %, and 38,08 %, respectively, for 100 % CG and 2,70 %, 9,56 %, 5,30 %, 9,20 %, 15,30 %, 15,84 %, NP, 0,23 %,1,49 %, and 105,87 %, respectively, for 100 % RCA.

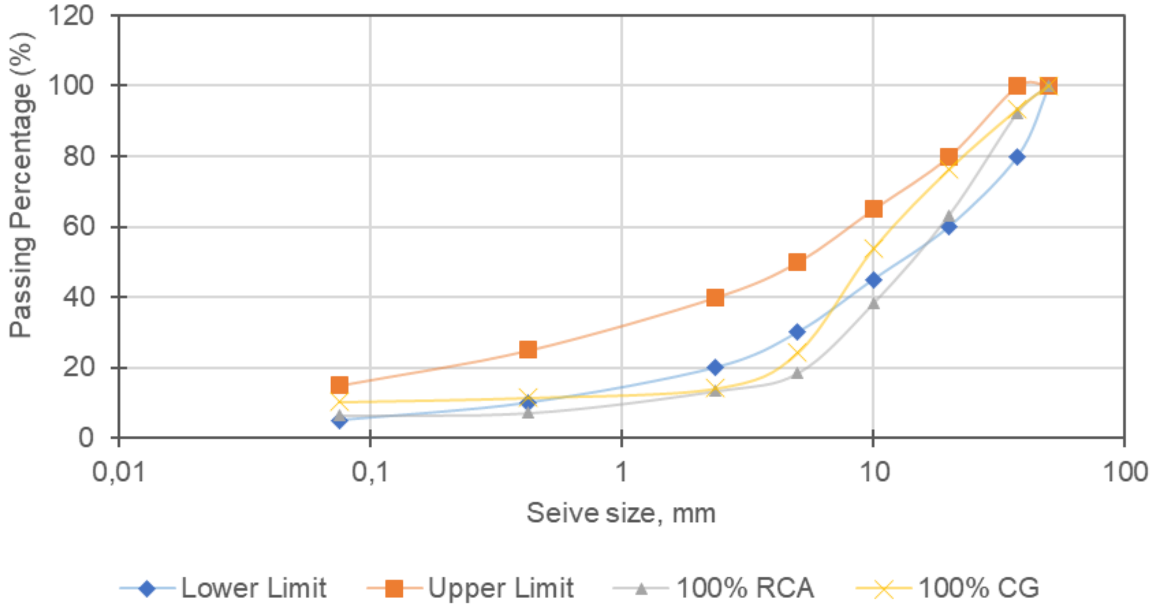


**Figure 2. Gradation curve for comparisons of unblended RCA and CG**

The investigated RCA and CG materials did not fully meet the requirements of the ERA standard specifications for base-course materials, including the specified gradation ranges for GB2 and GB3. The proposed blending proportion, as outlined in Table 2, was used to enhance the engineering properties of the materials for base-course construction through mechanical stabilisation. Specific gravity (SG) and water absorption tests were conducted on coarse aggregates (> 4,75 mm) according to AASHTO T-84/85, with specific gravity values falling within the typical construction range of 2,5 to 3,0, indicating satisfactory material strength. Additionally, water absorption measurements demonstrated a porosity below the 2 % requirement. This value is considered a measure of resistance to frost action and sustained weathering action [11]. Therefore, the test results of SG and water absorption of the neat RCA sample, as shown in Table 3 satisfy the standard specifications for specific gravity and water absorption for base-course construction as per AASHTO T-85.
The test results of the specific gravity of neat CG satisfied the standard specification of specific gravity for base-course construction; however, the water absorption of the raw CG sample did not satisfy the standard specifications. Various studies have highlighted the variability in recycled concrete aggregate (RCA) absorption capacity, ranging from 0,57 to 11,60 %, which is a critical factor in assessing RCA quality. Moreover, as the replacement levels of RCA increase in new concrete mixes, there is a proportional rise in water absorption rates [12].

**Table 3. Result for specific gravity and water absorption of RCA and CG**

| Particle size | Average specific gravity | | | Average absorption (%) | Remark | Standard of SG ranges | Standard specification for water absorption (%) |
|---|---|---|---|---|---|---|---|
| | The bulk (Dry) | The bulk (SSD) | Apparent | | | | |
| RCA | 2,68 | 2,69 | 2,70 | 0,23 | Not satisfied | 2,5 - 3,0 | < 2 |
| CG | 2,33 | 2,42 | 2,54 | 3,52 | Not satisfied | | |

## 3.2 Engineering property determination of blending RCA and CG

### *3.2.1 Particle size distribution of blended RCA and CG*

The gradation and other grading properties of the blended RCA and CG are presented in Figure 3 and Table 4, and are classified using the standard specifications of AASHTO and USCS.
According to AASHTO and USCS, the blended aggregates are classified as A-1-a and GW-GM, respectively, indicating that they can be used for road base construction.

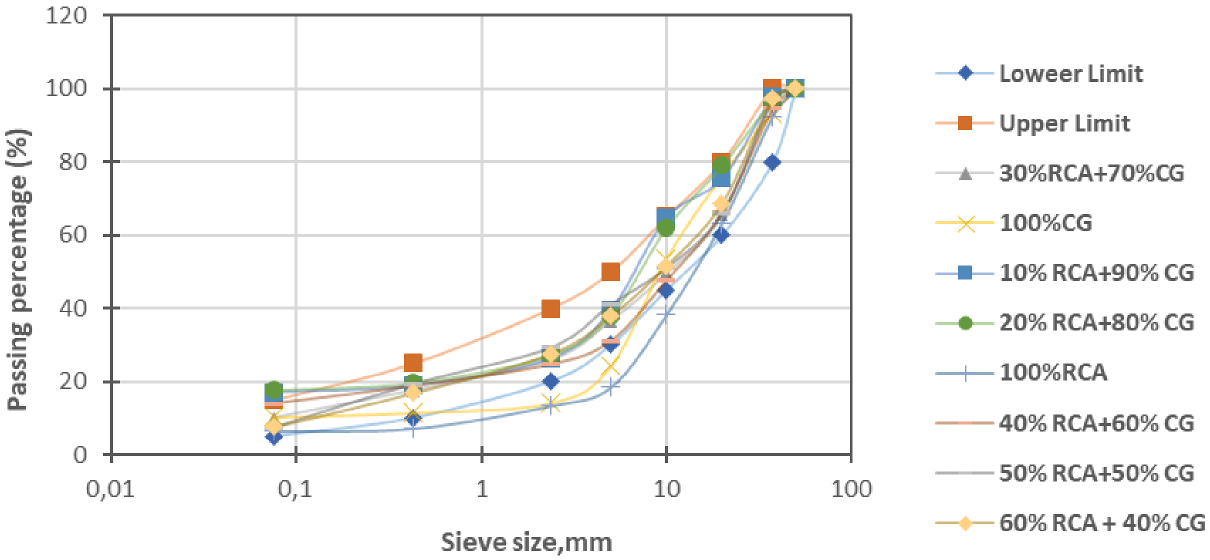


**Figure 3. Particle size distribution of all mixtures used in this study**

According to the ERA standard specification, the minimum grading modulus is 2 for natural materials to be used as base-course materials [13]. Table 5 shows the grading moduli calculated for different proportions of RCA and CG, and the values of the grading modulus in all cases were above the minimum required specification. Therefore, the aggregates satisfied the grading modulus requirements for all mix proportions as the base coarse materials.

**Table 4. Aggregate classification by using AASHTO and USCS for blended RCA and CG**

| Parameters used for classification | Appropriate sample composition selected for the study | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | CG | RCA | 10 %RCA +90 %CG | 20 %RCA +80 %CG | 30 %RCA +70 %CG | 40 %RCA +60 %CG | 50 %RCA +50 %CG | 60 %RCA +40 %CG |
| $D_{10}$ (mm) | 0,13 | 0,70 | 0,30 | 0,20 | 0,10 | 0,10 | 0,10 | 0,18 |
| $D_{30}$ (mm) | 6,00 | 7,00 | 4,90 | 5,00 | 3,00 | 5,80 | 2,90 | 3,00 |
| $D_{60}$ (mm) | 13,00 | 20,00 | 12,00 | 15,00 | 17,00 | 18,00 | 17,00 | 16,90 |
| Coefficient of Uniformity, Cu | 100,00 | 28,57 | 40,00 | 75,00 | 170,00 | 180,00 | 168,31 | 93,88 |
| Coefficient of Curvature, Cc | 21,30 | 3,50 | 6,67 | 8,33 | 5,29 | 18,68 | 4,89 | 2,95 |
| Gravel Content % | 75,82 | 81,60 | 67,41 | 69,06 | 63,42 | 71,70 | 58,98 | 62,10 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sand Content % | 13,93 | 11,98 | 25,17 | 22,11 | 26,59 | 18,12 | 33,67 | 30,33 |
| Fine Content, % | 10,25 | 6,42 | 7,42 | 8,84 | 9,99 | 10,19 | 7,35 | 7,57 |
| AASHTO Classification | A-1-a | A-1-a | A-1-a | A-1-a | A-1-a | A-1-a | A-1-a | A-1-a |
| USCS Classification | GP-GM | GP-GM | GP-GM | GP-GM | GP-GM | GP-GM | GP-GM | GW-GM |

**Table 5. Grading and fineness modulus of neat RCA, CG, and their mixtures**

| Blending ratio | Grading modulus (GM) | Fineness modulus (FM) |
|---|---|---|
| 100 % RCA | 2,73 | 3,67 |
| 100 % CG | 2,64 | 3,27 |
| 10 % RCA + 90 % CG | 2,37 | 2,77 |
| 20 % RCA+ 80 % CG | 2,36 | 2,78 |
| 30 % RCA + 70 % CG | 2,41 | 3,06 |
| 40 % RCA + 60 % CG | 2,42 | 3,16 |
| 50 % RCA + 50 % CG | 2,44 | 2,96 |
| 60 % RCA + 40 % CG | 2,48 | 3,00 |

### *3.2.2 Specific gravity of blended RCA and CG*

The specific gravity and water absorption results for the RCA, CG, and different mix proportions of the aggregate test results are summarised in Table 6. Except for 100 % CG and 10 % RCA + 90 % CG, which showed water absorption values of 3,52 and 2,52 %, respectively, all the other tested aggregates demonstrated values below the specification limit, ranging from a maximum of 1,64 % for 20 % RCA + 80 % CG to a minimum of 0,23 % for 60 % RCA + 40 % CG, as detailed in Table 6. Specific gravity, a measure of density relative to water, indicates that CG has lower strength than RCA due to its lower specific gravity. However, the blended materials met the minimum specific gravity requirement (2,63 for the base-course and sub-base construction, with values ranging between 2,56 for 10 % RCA + 90 % CG and 2,65 for 60 % RCA + 40 % CG, making them suitable for use as base-course materials according to the ERA standard specification.

**Table 6. Result for specific gravity and water absorption of blended RCA and CG**

| Mixture Name | Average Specific Gravity | | | Average Absorptions (%) | Remark |
|---|---|---|---|---|---|
| | The bulk (Dry) | The bulk (SSD) | Apparent | | |
| 100 % CG | 2,33 | 2,42 | 2,54 | 3,52 | Fail |
| 10 % RCA + 90 % CG | 2,40 | 2,46 | 2,56 | 2,52 | Fail |
| 20 % RCA + 80 % CG | 2,47 | 2,51 | 2,58 | 1,64 | Pass |
| 30 % RCA + 70 % CG | 2,49 | 2,53 | 2,59 | 1,52 | Pass |
| 40 % RCA + 60 % CG | 2,56 | 2,57 | 2,60 | 0,65 | Pass |
| 50 % RCA + 50 % CG | 2,61 | 2,61 | 2,62 | 0,29 | Pass |
| 60 % RCA + 40 % CG | 2,63 | 2,64 | 2,65 | 0,26 | Pass |
| 100 % RCA | 2,68 | 2,69 | 2,70 | 0,23 | Pass |

*Note: The range of specific gravity is b/n 2.5 & 3.0, as per AASHTO T-84/85. Water absorption of aggregate does not exceed 2 %.*

### *3.2.3 Aggregate crushing value (ACV) and Ten percent fines value (TFV)*

The ACV serves as a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load. According to the standards, the ACV should not exceed 45 % for concrete aggregates used on non-wearing surfaces and 30 % for those used on wearing surfaces, such as runways and roads for pavements [14]. This test, prescribed by BS 812: Part 110:1990, assesses the resistance of an aggregate to crushing, indicating its ability to withstand compressive loads. However, for softer aggregates, the TFV crushing test is recommended, a method incorporated into both British and South African standards [15]. The test results, detailed in Table 7, reveal that the ACV for RCA was 9,56 %, meeting the ERA standard specifications for the base-course material, whereas CG was out of specification at 38,37 %. This suggests that RCA exhibits greater resistance to static impact loads than CG, prompting an improvement in the CG resistance through blending, as shown in Table 7, during the ACV and TFV tests.

**Table 7. Aggregate crushing value (ACV) for neat RCA & CG**

| Samples | ACV % | ERA, 2013 Standard specification | Remark |
|---|---|---|---|
| RCA | 9,56 | < 25 % | RCA is within the specification limit |
| CG | 38,37 | | CG is out of specification |

The TFV test, an extension of the ACV test, was conducted using the same apparatus and involved crushing samples under various loads to determine the load that will produce ten percent of the material finer than 2,36 mm. This test offers the advantage of applicability to all aggregates regardless of their strength, allowing for direct comparisons between strong and weak materials.
The relationship between the ACV and 10 % FACT, as indicated by the provided equation, is within the strength range of 14-30 ACV and 100-300 kN 10 % FACT. The TFV results for the RCA and CG are presented in Table 8, with the general requirement for most rock types specified as 110 KN according to BS-812-Part-111.

**Table 8. Ten percent fines value result for RCA & CG**

| Samples | Ten percent fines value (TFV) (kN) | ERA 2013, standard specification for a base course (kN) |
|---|---|---|
| CG | 125 | >110 |
| RCA | 280 | >110 |

The laboratory tests, with the results shown in Figure 4, involved trials on specimens prepared by combining RCA with CG in varying proportions (10 % + 90 %, 20 % + 80 %, 30 % + 70 %, 40 % + 60 %, 50 % + 50 %, and 60 % + 40 %) for the base-course material. The TFV test indicated the ERA standard specifications for GB2 and GB3 base-course materials, which require a minimum value of 110 kN TFV, were met even when RCA was replaced with different percentages of CG. However, the ACV for mixing ratios below 60 % RCA + 40 % CG did not meet ERA standards.As clearly observed in Figure 4, as the percentage of RCA increases, the loss due to crushing decreases. The blended materials (RCA + CG), such as 0 % RCA + 100 % CG, 10 % RCA + 90 % CG, 20 % RCA + 80 % CG, 30 % RCA + 70 % CG, 40 % RCA + 60 % CG and 50 % RCA + 50 % CG, were not within the standard specifications for use as a base-course material as per the ERA standard, whereas the remaining were within the standard specifications. This indicates that CG is a low-strength material compared to RCA under gradual crushing force. The samples with higher CG percentages exhibited poorer crushing resistance. Samples containing higher RCA percentages had higher crushing values than samples with lower CG percentages, which implies that the base course in the CG was more sensitive to crushing than that in the RCA.

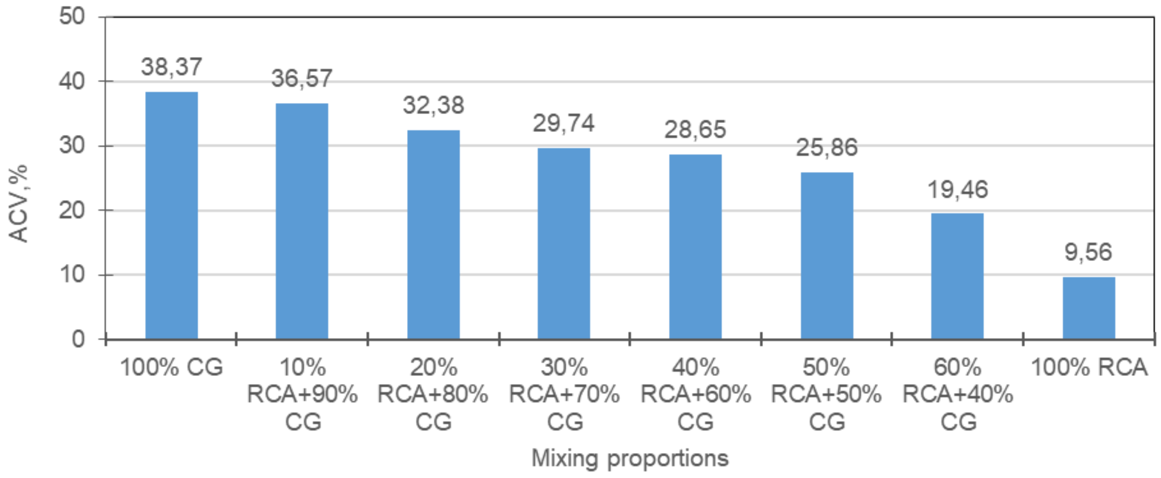


**Figure 4. ACV (%) vs different mix ratio of RCA & CG**

Similarly, as observed in Figure 5, the TFV increased as the percentage of CG decreased. The TFV for the dry condition increases from 125 to 220 kN for 0 % and 60 % RCA replacement with CG, respectively. In this study, the blending of 60 % RCA with 40 % CG and the above material satisfied the principal mechanical properties of base coarse materials, and it was satisfactory for resisting the crushing load under the roller during road construction. The mixes above this percentage were sufficiently strong and within the limit of a standard specification to be used for the base-course layer of the GB2 and GB3 layers, according to the ERA standards.

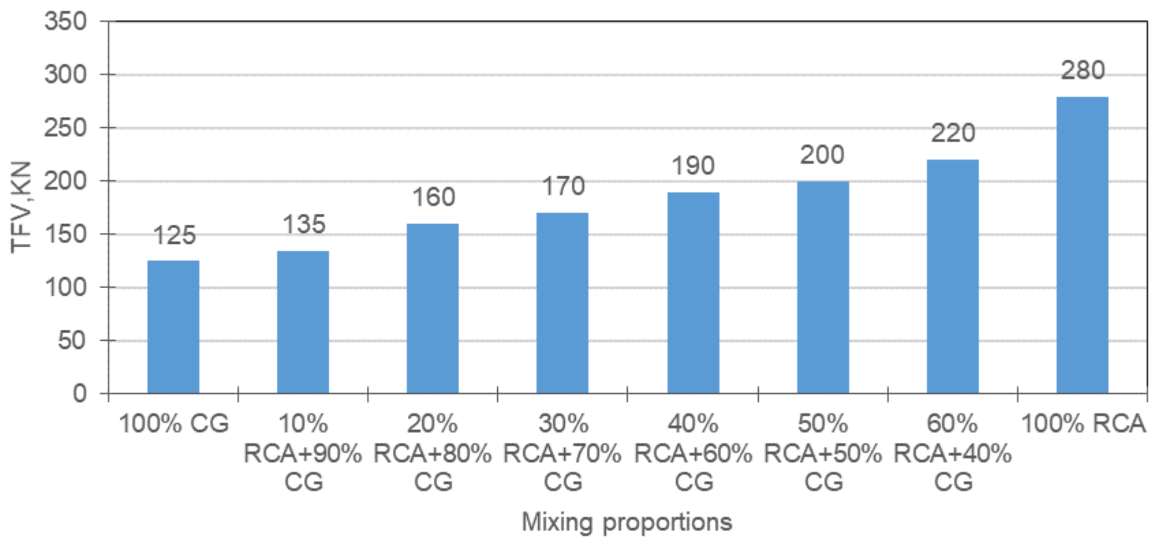


**Figure 5. TFV, kN vs different mix ratio of RCA and CG**

*3.2.4 Aggregate impact value (AIV)*

BS 812: Part 112 outlines the methods for determining the AIV, which is a measure of an aggregate's resistance to a sudden shock or impact. This study focused on the dry condition test for aggregates passing through a 14,0 mm sieve and retained on a 10,0 mm sieve, with sizes larger than 14 mm deemed unsuitable for the AIV test. Table 9 illustrates that the 100 % RCA sample exhibits a significantly higher impact load resistance (5,30 %) than the 100 % CG sample (20,10 %), yet both meet the criteria for base course materials per BS 812 Part 112:1990 standards. A lower aggregate impact value indicates a greater resistance to sudden impact loads, indicating the toughness of the material. If the AIV is greater than 30 %, the results should be treated with caution [16]. With the application of machine learning models, the results obtained from this experiment can be numerically predicted as stated in [17] which was used to predict the compressive strength of high-strength concrete.

**Table 9. Results of AIV test for 100 % RCA and 100 % CG samples**

| Sample name | Average AIV (%) | BS-812 Part 112 (ERA2013 Governing Specification) | Remark |
|---|---|---|---|
| 100 % RCA | 5.30 | AIV < 25 % | Satisfied |
| 100 % CG | 20.10 | | Satisfied |

Figure 6 presents a comprehensive overview of the test results for various weight percentages of CG blended with RCA (0 %, 10 %, 20 %, 30 %, 40 %, 50 %, 60 %, and 100 %). The figure indicates a decrease in the AIV from 20,10 % for neat CG to 10,70 % for 60,00 % RCA replacement, highlighting the trend of decreasing AIV with increasing RCA composition. The study, conducted following the BS 812: Part 112:1990 standards, revealed a significant reduction in the maximum impact value with increasing percentages of RCA. Figure 7 shows the AIV ranges for different compositions (0 % RCA + 100 % CG to 60 % RCA + 40 % CG) with values of 20,10 %, 17,10 %, 16,40 %, 16,10 %, 14,00 %, 12,30 %, 10,70 %, and 5,30 %. Consequently, the data suggest that the resistance against impact, reflected by the minimum AIV values, increases as the percentage of RCA in the mixture increases, ultimately satisfying the BS 812: Part 112:1990 standard specification requirement for base coarse materials with a recommended AIV of less than 25 %. These results can be predicted numerically using a CNN which was used by [18} to determine the compressive strength of geopolymer concrete using fly ash and blast-furnace slag.

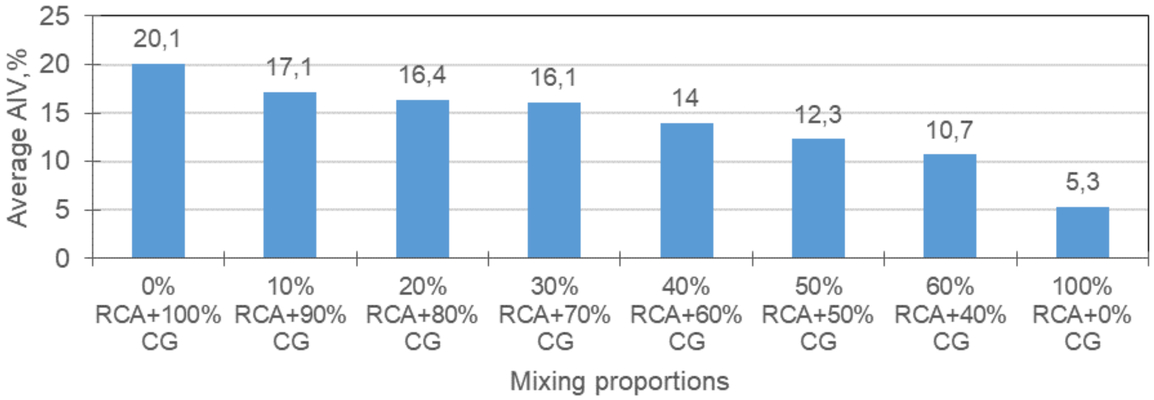


**Figure 6. Average AIV of blended RCA and CG graph**

### *3.2.5 Los Angeles Abrasion (LAA) value*

The LAA test is a common test method used to determine aggregate toughness and abrasion characteristics. As shown in Table 10, the test results indicate that both RCA and CG samples before blending met the ERA standard specifications for base-course materials.

**Table 10. LAA results for neat RCA & CG**

| Sample type | LAA Value | ERA2013, Standard Specification | Remark |
|---|---|---|---|
| 100 % RCA | 9,20 | < 35 % | Fulfill the standard |
| 100 % CG | 33,17 | | Fulfill the standard |

Notably, RCA demonstrated the minimum value of LAA, signifying its superior resistance to wearing loads without crushing. Both RCA and CG met the ERA requirement, which sets the maximum LAA value at 35 % for unbound base-course materials.
According to the ERA specifications, the maximum abrasion value of the base course was limited to 35 %. As shown in Table 11, the LAA values decreased as the percentage of the composition LAA value decreases. The RCA had a lower abrasion value than the CG, which implies that the RCA has a higher resistance to abrasion. Hence, the results of this test indicated that the use of 100 % CG in base-course construction did not cause any abrasion.

**Table 11. LAA test result of blended RCA and CG**

| Sample compositions | LAA value (%) | ERA2013, Standard Specification | Remark |
|---|---|---|---|
| 0 % RCA + 100 % CG | 33,17 | < 35 % | Fulfill the standard |
| 10 % RCA + 90 % CG | 19,89 | | Fulfill the standard |
| 20 % RCA + 80 % CG | 18,59 | | Fulfill the standard |
| 30 % RCA + 70 % CG | 17,66 | | Fulfill the standard |
| 40 % RCA + 60 % CG | 15,51 | | Fulfill the standard |
| 50 % RCA + 50 % CG | 12,08 | | Fulfill the standard |
| 60 % RCA + 40 % CG | 10,88 | | Fulfill the standard |
| 100 % RCA + 0 % CG | 9,20 | | Fulfill the standard |

### *3.2.6 Moisture-density relation of unblended RCA and CG*

The Density-Moisture Content relationship graph in Figure 7 indicates that for RCA, the optimum moisture content (OMC) and maximum dry density (MDD) were 1,58 % and 1,98 g/cm$^3$, while for CG, they were 8,56 % and 1,39 g/cm$^3$. The OMC of the CG sample was notably higher than that of pure RCA, which was attributed to the elevated water absorption of CG resulting from its high porosity. This discrepancy accounts for the observed difference in moisture content between the two materials.

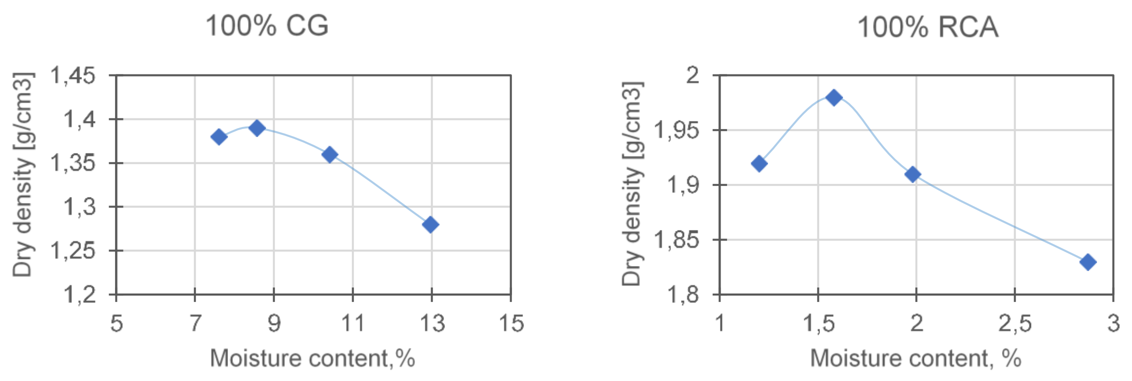


**Figure 7. Graph of moisture-density relation of RCA and CG**

Figure 8 clearly illustrates that, as the percentage of RCA in the mixtures increased, the optimum moisture content decreased. Specifically, the values decreased from 7,67 % for the mix with 10 % RCA and 90 % CG to 1,58 % for the mix with 60 % RCA and 40 % CG, a trend attributed to the porosity of CG. Additionally, the results indicated that the maximum dry density of the mixtures containing RCA was slightly higher than that of the CG alone. Consequently, the maximum dry density increases with the percentage of RCA in the mixture, rising from 1.54 g/cm$^3$ for the mix with 10 % RCA and 90 % CG to 1,83 g/cm$^3$ for the mix with 60 % RCA and 40 % CG.

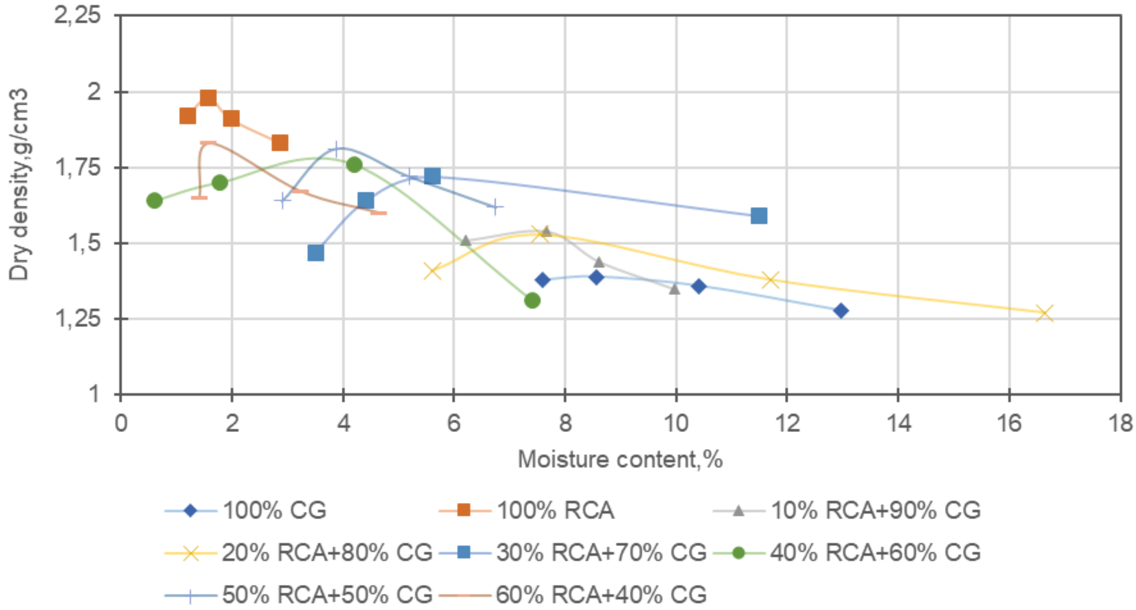


**Figure 8. Moisture-density relation curve of blended RCA and CG**

### *3.2.7 California Bearing Ratio (CBR)*

This test procedure focuses on determining the CBR of materials used in pavement subgrades, subbases, and base courses using laboratory-compacted specimens. According to the 2013 ERA manual, the soaked CBR for base-course materials must exceed 80 % according to the requirements of AASHTO T193.

**Table 12. CBR test results for unblended RCA and CG**

| **Sample Type** | **Blows** | **Penetration** (mm) | **Resistance load** (kN) | **Corrected CBR** (%) | **Max. corrected CBR** (%) | **CBR at 95 %MDD** (%) | **Swell** (%) |
|---|---|---|---|---|---|---|---|
| CG | 10 | 2,54 | 3,15 | 23,86 | 28,1 | 38,08 | 0,02 |
| | | 5,08 | 5,76 | 28,12 | | | |
| | 30 | 2,54 | 4,92 | 37,27 | 46,5 | | 0,00 |
| | | 5,08 | 9,53 | 46,49 | | | |
| | 65 | 2,54 | 6,56 | 49,70 | 65,7 | | 0,07 |
| | | 5,08 | 13,47 | 65,72 | | | |
| RCA | 10 | 2,54 | 8,96 | 67,88 | 67,9 | 105,87 | 0,03 |
| | | 5,08 | 12,99 | 63,04 | | | |
| | 30 | 2,54 | 12,52 | 94,85 | 94,8 | | 0,03 |
| | | 5,08 | 17,78 | 86,31 | | | |
| | 65 | 2,54 | 14,65 | 110,98 | 111,0 | | 0,00 |
| | | 5,08 | 22,67 | 110,05 | | | |

Table 12 shows that the CBR test outcome for 100 % CG at 98 % density was 38,08 %, falling below the ERA standard for mechanically stable natural gravel and weathered rocks in base course material (GB2 and GB3), which mandates a minimum CBR of 80 %. In contrast, the CBR result for the 100 % RCA at 98 % MDD is 105,87 %, surpassing the ERA standard for base-course materials (GB1). These findings suggest that blending CG with RCA at varying percentages ranging from 0 to 100 % has the potential to reinforce the strength of CG as a base-course material.

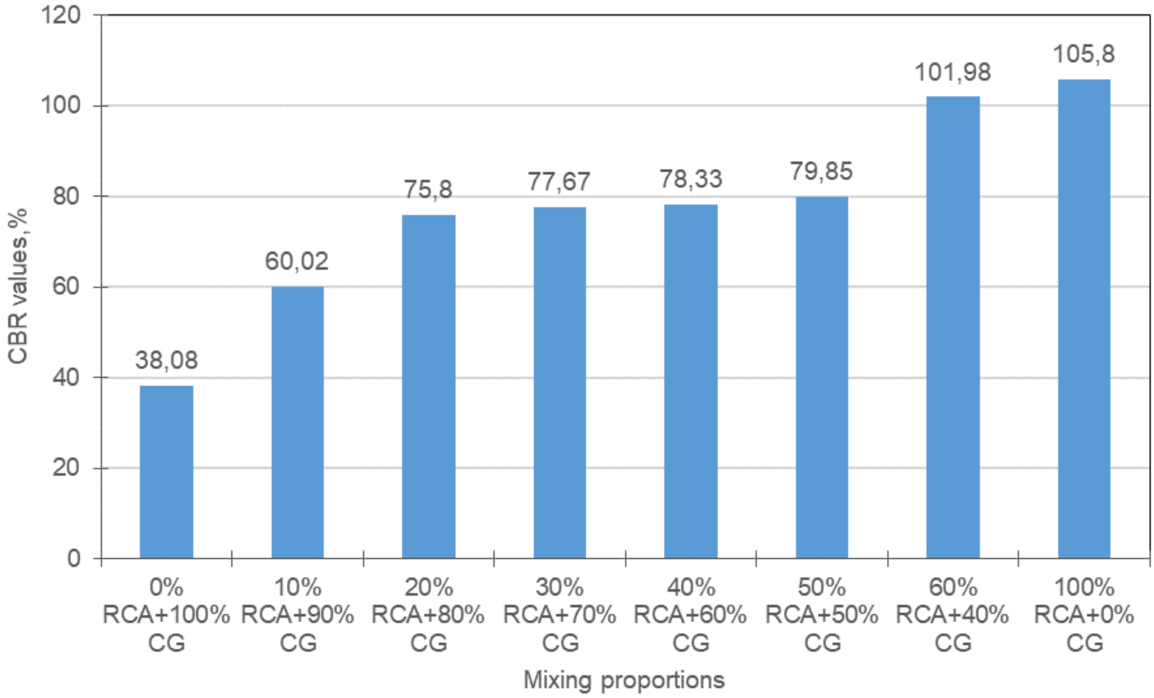


**Figure 9. CBR at 98% of MDD of blended RCA and CG**

Figure 9 shows the results of the CBR test for blended RCA with CG at different proportions to meet the required ERA standard specification for mechanically stable natural gravels and weathered rocks for use as base-course materials (GB2 and GB3). The values for the percentage composition of 60 % RCA + 40 % CG blending (CBR = 101,98) satisfy the ERA standard specification recommended CBR value, which is > 80 % for the base coarse material of (GB2 and GB3). Further, the value of swelling was between 0,00 and 0,02, indicating that soaking of the aggregate material has no significant effect on the values of the swelling property. Therefore, up to 60 % RCA and 40 % CG in percentage composition can be used for unbounded base course (GB2 and GB3) materials as pavement construction material. These results can be numerically validated using a machine-learning approach, as suggested in [19]. The authors used this method to predict the compressive strength of concrete with GGBS and alkali. This result is similar to that for RCA, indicating that using up to 40 % coarse RCA to replace natural aggregates results in pavements that are equivalent in all aspects to pavements made with conventional aggregates [20].

### *3.2.8 Flakiness and elongation index results for unblended RCA and CG*

Shape tests such as FI and elongation index (EI) tests were conducted to evaluate the suitability of materials produced by crushing aggregates for pavement construction. Flaky and elongated materials should be avoided because they reduce resistance to traffic loads during their service life. Flakiness and elongation tests were conducted as per ERA, 2013. As shown in Figure 10, the FI and EI obtained from laboratory tests for RCA were 15,30 % and 15,84 %, respectively. This result indicated that the tested RCA sample was within the ERA standard specification limit, and hence suitable for use as a base coarse material. The ERA and BS standard specifications recommend a maximum FI value of 30 %, and the recommended value for the EI is 10-35 % as per the BS standard. Hence, the RCA satisfied both requirements of the shape test. The FI and EI of CG were 5,59 % and 12,09 %, respectively, which were also within the ERA standard specifications for coarse base materials in road construction.

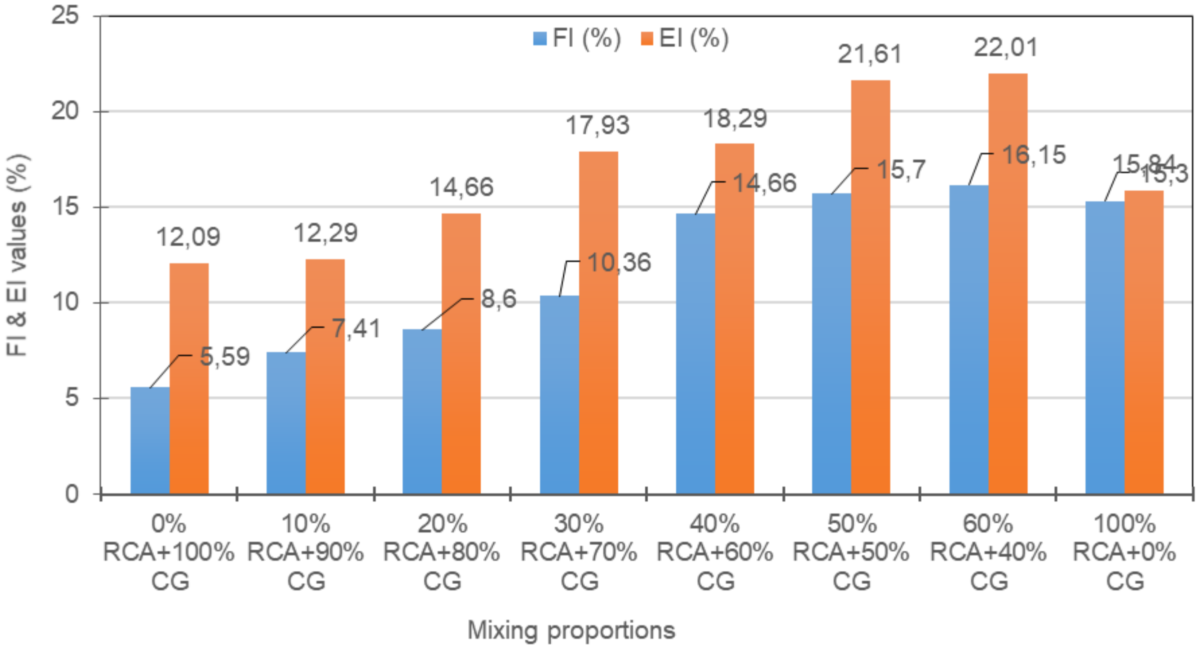


**Figure 10. Graph for flakiness and elongation index of different percentage composition of RCA and CG**

### *3.2.9 Soundness test (sodium or magnesium sulfate test)*

Soundness, measured by the percentage loss of material during a sodium or magnesium sulfate soundness test on an aggregate blend, assesses the resistance of the aggregate to in-service weathering, as outlined in ASTM C88 and AASHTO T104 [21]. Table 13 presents and analyses the results of the soundness (sodium sulfate) tests for various blending proportions of RCA and CG. The findings indicated that as the percentage of RCA increased, the percentage loss decreased. Notably, 100 % CG exhibited a percentage loss of 10,60 %, indicating that it fell outside the standard limit. However, all the other compositions conformed to the ERA standard specifications, which stipulate a maximum soundness loss of <10 %.

**Table 13. Test result of soundness (Na2SO4) test for neat and blended RCA & CG**

| Sample Compositions | Soundness (5 cycle Loss, %) | $Na_2SO_4$ Test ERA Specifications for coarse aggregate |
|---|---|---|
| 0 % RCA + 100 % CG | 10,60 | < 10 % |
| 10 % RCA + 90 % CG | 6,39 | |
| 20 % RCA + 80 % CG | 5,28 | |
| 30 % RCA + 70 % CG | 3,34 | |
| 40 % RCA + 60 % CG | 2,83 | |
| 50 % RCA + 50 % CG | 2,33 | |
| 60 % RCA + 40 % CG | 2,09 | |
| 100 % RCA + 0 % CG | 1,49 | |

## 4 Conclusions

In their natural states, the particle size distributions of both samples deviated from the ERA standard specification because the distribution curve did not align with the specified lower and upper limits for the fine and coarse aggregate materials. Using a trial-and-error blending approach, a mixture comprising 60 % RCA and 40 % CG was successfully adjusted to meet the ERA standard specifications for GB2 and GB3 base-course materials, which are commonly utilised for base-course applications.

The specific gravity test results indicated that CG was lighter than RCA, with CG having a lower specific gravity and significantly higher water absorption owing to its pronounced porosity. Although both specific gravity values complied with the ERA standard, the water absorption of 100 % CG and 10 % RCA + 90 % CG exceeded the specified standards.

The soaked CBR result for the CG samples fell below the ERA standard specifications at 38,08 %, whereas a blend comprising60% RCA and 40% CG passed the standard with a value of 101,98 %.

The results showed that, as the percentage of RCA increased, the values of CBR, MMD, SG, and TPFV also increased. However, as the RCA percentage increased, the ACV, AIV, LAA value, and OMC values decreased.

RCA has higher resistance to ACV, AIV and LAA value, lower water absorption, higher CBR value, and lower moisture content than CG. The ability to resist impact, crushing, abrasion, and compaction loads depends on the mix ratio of RCA and CG. When the RCA ratio increases, the resistance load also increases. This indicates that CG lost its strength compared to RCA.

The results showed that blending 60 % RCA and 40 % CG and a higher RCA percentage is recommended for base-course construction materials.

Based on this investigation, in places where CG is abundantly available or can be easily sourced from nearby areas, using a blend of 60 % RCA + 40 % CG might help meet increasing demands, reduce the extraction of conventional aggregates, and mitigate any damaging effects on the environment.

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