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Original Research Article

Physico-Mechanical Properties of Geopolymer Concrete made from Metakaolin and Recycled Concrete Aggregate

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ABSTRACT

Due to the negative implications of carbon dioxide emissions from cement manufacture and excessive demands on naturally available resources, the construction industry's developmental contributions to both developing and developed countries have been deemed unsustainable. A circular economy approach, which includes material recycling, reuse, reduction, and repair, is becoming more popular. In this study, metakaolin was synthesized using sodium hydroxide and sodium silicate to create metakaolin-based geopolymer (Mk-Gp). Recycled concrete aggregate (RCA) obtained from crushed concrete cubes was used to replace natural coarse aggregate (granite) at 0, 20, 40, 60, and 80% replacement levels to produce Mk-Gp concrete containing recycled concrete aggregate (Mk-GpRCA) and Ordinary Portland Cement (OPC) concrete containing recycled concrete aggregate (OPC-RCA) which serves as the control. Compressive strength test, splitting tensile strength test and water absorption test were carried out. The results for compressive strength at 28 days of curing revealed that 20% Mk-GpRCA had an increase of 11.85% over 20% OPC-RCA, while 20% Mk-GpRCA had an increase of 12.7% over 20% OPC-RCA in splitting tensile strength. Therefore, this study established that RCA can be used to replace granite in Mk-GpRCA up to 40% replacement level for sustainable construction.

1. INTRODUCTION

The artful assembling of unique pieces to create a building is what construction as a process entails. According to Turner *et al.* (1993), it is an action intended to accomplish a short-term goal by gathering a variety of resources.

The continuous increase in construction works around the world and the increase in the demand for cement which contributes to the release of greenhouse gases leading to climate change and global warming can be minimized by using alternative environmentally friendly materials in construction (Abiodun *et al.,* 2020). Construction must be sustainable to allow for a safe, healthy and productive environment without exceeding its bearing capacity (Neuman and Churchill, 2011). Some agricultural wastes such as palm oil fuel ash (Fauzia *et al.,* 2013; Pourakbar *et al.,* 2015; Abiodun *et al.,* 2020), Rice husk ash (Abiodun and Jimoh, 2018; Kumar *et al.,* 2020), Sugarcane bagasse ash (Khalil *et al.,* 2021; Anshul and Anita, 2022), and others like coconut shell ash, cassava peel ash, groundnut husk ash have been utilized to replace cement in building and construction (Priya and Partheeban, 2013).

Inorganic binders such as metakaolin and fly ash are geopolymers made by mixing amorphous aluminosilicates and natural pozzolanic materials like coal ash and metakaolin with alkali activators such as potassium hydroxide (KOH) or sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) (Abiodun and Adeosun, 2023). Furthermore, sustainable development initiatives have been made to lessen the need for principal aggregate and promote the reuse and recycling of concreting debris from the building industry as aggregates for construction projects that are suitable from a technical, financial, or environmental standpoint (Otoko, 2014; Olaoye *et al.,* 2018). Recycled aggregate may replace up to 50% of natural aggregate without significantly compromising the quality of concrete in both the fresh and hardened phases (Bairagi *et al.,* 1993). The outcome of an investigation conducted by Akinkurolere and Franklin (2005), showed that materials should be used and handled carefully because their cost as a percentage of the total project cost may be above 50%. Construction waste management alternatives include replacing natural coarse aggregate with recycled materials like broken aggregates or crumbled concrete (Swapna *et al.,* 2011). Verian *et al.* (2013) observed that when recycled concrete aggregate (RCA) has lower specific gravity and more water absorption and that when used to make concrete with ordinary Portland cement (OPC), a lower degree of compressive and tensile strengths was recorded as a result of the discovery of two different interfacial transition zones (ITZs) in concrete produced with RCA.

Various researchers have produced Geopolymer Concrete (GPC) using different geopolymer binders like fly ash, and metakaolin with natural coarse aggregate but limited research has been carried out on incorporating RCA in producing geopolymer concrete. In the study reported by Adejo *et al.* (2017), the use of geopolymer-based concrete containing recycled concrete aggregate using metakaolin leads to an increase in compressive strength by 22.76% at 28 days when compared to the conventional concrete containing RCA. In this study, the performance of metakaolin-based geopolymer concrete formed using aggregate from recycled concrete was investigated. The research findings put a spotlight on the applicability and authenticity of a metakaolin-based geopolymer binder when used as a replacement for OPC in the production of metakaolin-based geopolymer concrete containing recycled concrete aggregate (Mk-GpRCA). Additionally, it assists in fostering a culture of circular economy, where the 3Rs (reduce, reuse, and recycle) are employed to effectively manage waste in the building and construction industries. Therefore, the goal of this study is to employ ecologically friendly building materials to reduce both construction waste and carbon dioxide emissions.

2. MATERIALS AND METHODS

2.1. Materials

Cement, metakaolin, recycled concrete aggregate (RCA), natural coarse aggregate (NCA; granite), fine aggregate, alkaline solutions (NaOH and Na_2SiO_3), and potable water were the materials employed in this investigation. The binder for the control specimens was Ordinary Portland cement (OPC) and it complies with the BS 12 minimum criteria (BS 12, 1996). Kaolin sourced from Isan Ekiti town in Oye local government of Ekiti State, Nigeria was calcined at 800 ^oC/60 minutes to obtain metakaolin. The granite utilized for the natural coarse aggregate has a size range of 4.75 mm to 20 mm. River sand passing through a 600 μm sieve size was used as the fine aggregate. The aggregates were selected based on the limitation of BS 882-103 (1992). RCA was obtained from breaking concrete cubes that have already undergone crushing test in the laboratory. These concrete cubes are also used for foundation filling in new construction sites. According to BS 933-1 (2012), sieve analysis was performed, and the RCA diameters ranged from 4.75 mm to 20 mm. For the alkaline solution, the combination of NaOH and Na_2SiO_3 was obtained from the supplier and used as the alkaline activators to synthesize metakaolin. NaOH in flake form with 97-98% purity and 10 M concentration was used throughout this study. This indicates that the amount of NaOH solids in grams per litre of water is given by multiplying the molarity by the molecular weight of NaOH (10 x 40 g = 400 g).

2.2. METHODS

2.2.1. Determination of the chemical composition of untreated kaolin and metakaolin

The major and minor oxides present in both the kaolin (before calcination) and metakaolin (after calcination) samples were determined through an X-ray fluorescence spectrometry (XRF) carried out at the Chemistry Laboratory, University of Lagos, Nigeria. Under this technique, the kaolin and metakaolin samples were examined using a plastic sample cup and plastic support sheet. For homogeneity, 15g of each sample was grounded. Each sample was given the proper amount of additives in a platinum crucible before being placed in a thermal processing chamber that could reach temperatures of up to 1250 °C.

2.2.2. Particle size distribution test on aggregates and other physical tests.

Sieve analysis and specific gravity tests were carried out on the river sand (fine aggregate), granite (NCA) and the aggregate from recycled concrete (RCA). Only the coarse aggregates (NCA and RCA) were subjected to the aggregate crushing value (ACV) and aggregate impact value (AIV) tests as stipulated by BS 812-112 (1990) and the water absorption test as stipulated by ASTM C127 (1993).

2.2.3. Mixing of the metakaolin-based geopolymer concrete

The ratio of the alkaline activators; NaOH to Na_2SiO_3 was 1:1 (Anuradha *et al.,* 2012) at 10M NaOH. The alkaline solution produced an exothermic reaction and subsequently was used to create geopolymer concrete after cooling for 24 hours at room temperature.

2.2.4. Mechanical properties of Mk-GpRCA and OPC-RCA

Slump test to determine the workability of fresh concrete was performed according to ASTM C143 (2000). To determine the compressive strength as stipulated by BS EN 12390-3 (2019), ten concrete mixes were considered in this study. The 150 mm cube specimens as seen in Figure 1 were prepared with a mix design for the concrete grade 25 N/mm^2 (mix ratio 1:1:2) and water-to-cement ratio (w/c) of 0.4 to evaluate the compressive strengths.

Figure 1: Mk-GpRCA specimens

In both OPC concrete (control) and Mk-Gp concrete mixes, RCA was used to partially replace NCA at 0, 20, 40, 60 and 80 wt. %. Three replicate samples were cast at each data point throughout the experiment. 90 cubes specimens in total were cast. Tests were conducted in line with BS EN 12390-6 (2019) for the splitting tensile. Cylindrical specimens with dimensions 150 mm × 300 mm were cast. At a rate of 120 kN/min, the specimens were tested on a 600 kN Avery Denison Universal Testing Machine till failure. The load that caused cracks to form along the middle of the specimen was recorded. The parameters stated under the compressive strength test also apply to this situation. A total of 90 cylinder specimens were cast. All Mk-Gp concrete specimens and OPC concrete (control) specimens were cured at 7, 28 and 90 days. However, Mk-Gp concrete specimens were cured at an ambient temperature of 27 ± 3°C to allow for the polymerization process to take place while the OPC concrete (control) specimens were water-cured.

2.2.5. Durability test

Water absorption capacity test was carried out at 90 days of curing for OPC-concrete and Mk-Gp concrete containing 0, 20, 40, 60 and 80 wt. % RCA in agreement with BS 1881-122 (2011). 30 cubes in total were cast.

The samples were dried for 24 hours at 105 ºC in an oven. They were allowed to cool at room temperature after being removed from the oven so that the starting weight could be determined. This weight was recorded as (P_1). After the concrete specimen had been submerged in water for 24 hours, the final weight was calculated. It was taken out and dried with a piece of cloth. It was then weighed again, and its weight was recorded as (P_2). The equation for the computation of water absorption capacity is given in Equation 1 and Table 1 lists the specifics of the total number of specimens per curing day that were cast for this study's various assessments.

$$\text{Water absorption} = \frac{P1-P2}{P2} \times 100 \quad (1)$$

Where: P_1 = Weight of the concrete sample after oven dry and P_2 = Weight of the saturated surface dry concrete sample

Table 1: Details of the number of samples cast in the study

S/N	Tests	Categories of samples for OPC-conc. and Mk-GpRCA	Total number of samples cast
1	Compressive strength test	0%RCA (100%NCA)	90
2	Split tensile test	20% RCA; 40% RCA	90
3	Water absorption	60%RCA; 80%RCA	30

3. RESULTS AND DISCUSSION

3.1. Chemical Composition of Untreated Kaolin and Metakaolin

The chemical composition of untreated kaolin and metakaolin evaluated using the XRF is presented in Table 2. The major chemical compounds present in kaolin and metakaolin as seen in Table 2 were silica, alumina and ferric oxide. The cumulative percentages of these three chemical oxides were 73.93% and 86.39% for kaolin and metakaolin respectively (Abiodun and Adeosun, 2023) and can therefore be designated as pozzolan class N according to the requirements of ASTM C618-12a (2012). Though there was the absence of some trace elements in the study sample, the result obtained was however comparable to what Gambo *et al.* (2020) and Ayeni (2017) stated. It was noted that the maximum value of Loss on Ignition (LOI) at temperature 800ºC/ 60 mins calcination was significantly less than the maximum value (6%) recommended by codes (Shetty, 2009).

Table 2: Chemical composition of raw kaolin and metakaolin

Chemical oxides	Percentage composition (%)	
	Untreated kaolin	Metakaolin
SiO_2	42.54	56.21
Al_2O_3	29.07	28.89
Fe_2O_3	2.32	1.29
CaO	1.09	1.32
MgO	0.54	2.62
Na_2O	-	0.05
K_2O	1.03	0.98
SO_3	-	5.02
LOI	13.46	3.57
Specific gravity	2.54	2.42

3.2. Particle Size Distribution Test on Aggregates and Other Physical Tests

The sieve analysis result of the fine aggregate showed that the percentage of fines that passed through the 600 µm sieve size was 23.5% as observed on the curve of fine aggregate in Figure 2. This result is by the range specified in BS 882 (1992) and therefore can be classified to be in zone 1. For the coarse aggregates, the fineness modulus obtained for NCA and RCA were 7.5 and 7.18 respectively. The average size in both the coarse aggregates is mainly within the 20 mm sieve size and it accounts for 65% of the total coarse aggregate. Figure 2 illustrates the curves showing the distribution of the particle sizes.

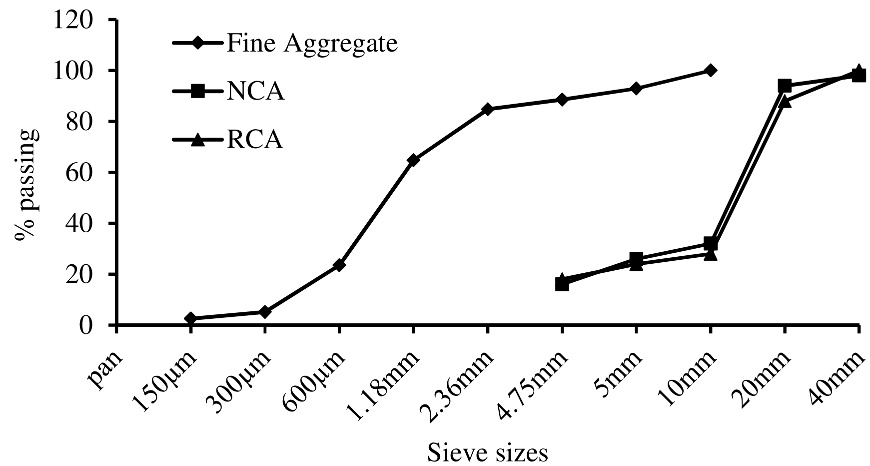

Figure 2: Particle size distribution curves of study aggregates

The fine aggregate's specific gravity was 2.51 while for NCA and RCA, 2.69 and 2.65 were recorded respectively. These values fall within the 2.5–2.8 range that BS 812-12 specifies (1990). The specific gravities of both aggregates are within the specified limit for normal-weight aggregates. The results for NCA and RCA's moisture contents were 0.18% and 1.14%, respectively, indicating that RCA had more moisture than NCA. The absorption capacity of RCA was 3.60% compared to NCA's 1.25%, indicating that RCA had a greater absorption capacity. According to Verian *et al.* (2013), this could be a result of the porous system from existing mortar during its first production which spontaneously bonds to the RCA, therefore, increasing the absorption capacity (Fauzia *et al.,* 2013). NCA and RCA's bulk densities were determined to be 1654 kg/m^3 and 1575 kg/m^3 respectively. This demonstrated that while RCA and NCA both meet the standards of BS 812 (1990), which says that the range for normal weight aggregates is between 1280 and 1920 kg/m^3, RCA is less in weight than NCA. The aggregate crushing values (ACV) for NCA and RCA were determined at 22.43% and 35.62% respectively. This indicated that compared to RCA, NCA showed greater resistance to crushing. The aggregate impact values (AIV) recorded for NCA and RCA were 18.34% and 28.64% respectively. It may be concluded that NCA is impact-resistant relative to RCA. These values are within the scope of what Sani *et al.* reported (Sani *et al.,* 2017).

3.3. Workability of Mk- GpRCA and OPC-RCA.

The outcome of the Mk-GpRCA and OPC-RCA slump test is presented in Figure 3. Workability in the two major concrete types (Mk-GpRCA and OPC-RCA) decreases as the percentage replacement with RCA increases. This result corroborates what Roesler and Hunley (2009) observed that the decline in the workability of the concrete produced with RCA might be attributable to its rough surface texture and increased water absorption capacity. Smith and Tighe (2008) also noted that, at the same water-to-cement ratio (w/c), concrete built with RCA yielded a lower slump value than concrete made with NCA. In this study, OPC-RCA specimens exhibited higher workability when compared with Mk-GpRCA.

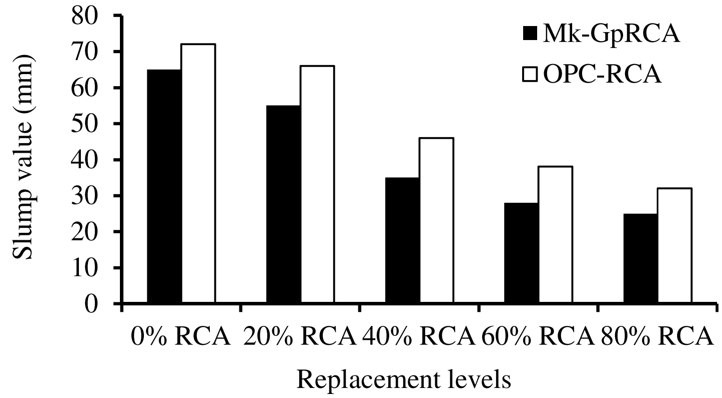

Figure 3: Slump test of concrete specimens

3.4. Mechanical Properties of Mk-GpRCA and OPC-RCA

3.4.1. Compressive strength of Mk-GpRCA and OPC-RCA

Results for the mean compressive strength of Mk-GpRCA and OPC-RCA specimens with 0%, 20%, 40%, 60%, and 80% RCA are shown in Figure 4 for 7, 28, and 90 days of curing, respectively. Overall, it was discovered that as curing age increased, compressive strength increased.

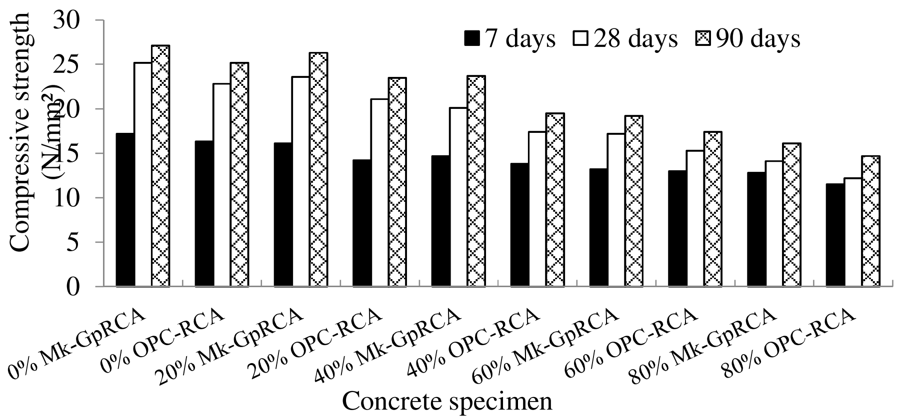

Figure 4: Compressive strength of *Mk-GpRCA and OPC-RCA*

However, when the proportion of RCA in the mix increased, a loss in strength was noticed. Mk-Gp concrete demonstrated a 10.5% improvement in compressive strength when compared to OPC concrete (control) for specimens with 0% RCA at 28 days of curing. Figure 4 shows that for all RCA replacement levels, the compressive strength of Mk-Gp concrete surpassed OPC concrete. The increased strength Mk-Gp concrete could be a result of the alkaline solutions that aid in the geopolymerization process of metakaolin and with an increase in NaOH molarities, the compressive intensity increases (Bachhav *et al.,* 2016). At 40% replacement with RCA and 28 days of curing, Mk-GpRCA gave a compressive strength of 20.1 N/mm² while OPC-RCA gave 17.4 N/mm². These values show that replacement with RCA above 40% should not be encouraged for load-bearing structural elements.

3.4.2. Splitting tensile strengths of Mk-GpRCA and OPC-RCA

The splitting tensile strength results of Mk-GpRCA and OPC-RCA specimens with 0%, 20%, 40%, 60%, and 80% RCA are shown in Figure 5 for 7, 28, and 90 days of curing, respectively. It was found that splitting tensile strengths improved as the curing age increased. Splitting tensile strengths for the metakaolin mixtures generally ranged between 3.2 and 8.6 N/mm^2 while OPC mixtures ranged between 2.8 and 7.9 N/mm^2 across the curing ages. The increase in splitting tensile strength of 0% Mk-GpRCA over 0% OPC-RCA at 28 days of curing was 10.8%. Metakaolin improved concrete performance in this test. Qian and Li (2011) reported an average tensile strength increase over control of 10 wt. % for metakaolin replacement levels of 15 wt. % at 28 days curing. Guneyisi *et al.* (2012) studied the tensile strength of metakaolin and reported that the highest tensile strength value was obtained from concrete made with 15% replacement of metakaolin at a constant w/b ratio. In this study, all specimens failed by splitting along the vertical axis.

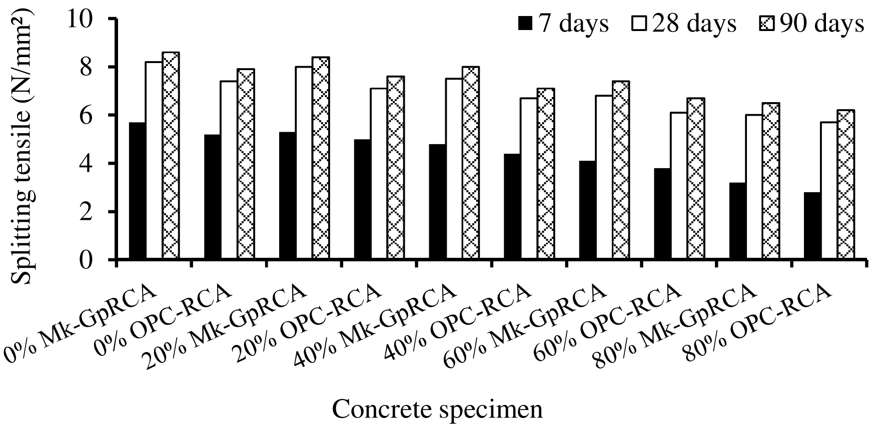

Figure 5: Splitting tensile strength of Mk-GpRCA and OPC-RCA

3.5. Water Absorption Capacities of Mk-GpRCA and OPC-RCA

Figure 6 displays the mean water absorption capacities of the 90-day-cured Mk-GpRCA and OPC-RCA specimens. The Mk-Gp concrete specimens containing 0% RCA had high absorption capacity of 7.7 N/mm² while the OPC concrete specimens (control) had 5.4 N/mm². This showed that Mk-Gp concrete specimens had high water absorption capacity than the OPC concrete specimens. This result consequently supports the assertions of Rangan (2010) that water is lost during the production of geopolymer, leaving behind nano-pores. It follows that Mk-Gp concrete could become vulnerable to attack as a result.

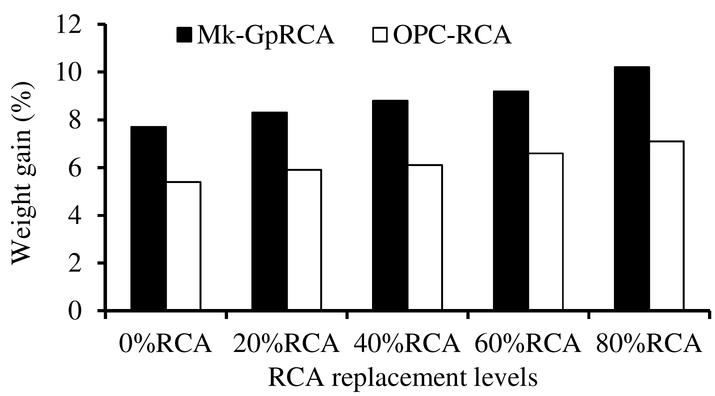

Figure 6: Water absorption capacity of Mk-GpRCA and OPC-RCA

4. CONCLUSION

The absorption capacity of RCA was 3.60% compared to NCA's 1.25%, indicating that RCA had a greater absorption capacity. However, NCA has a high impact-resistant relative to RCA. It was observed that OPC-RCA specimens exhibited higher workability when compared with Mk-GpRCA at the same replacement level. Additionally, because of the rough surface appearance associated with RCA, concrete specimens prepared with it had a lower slump value than those made with NCA at the same water-to-cement ratio. Mechanical characteristics of cured concrete specimens revealed that Mk-GpRCA had greater compressive and splitting tensile strengths than OPC-RCA. The durability study however showed that Mk-GpRCA specimens showed higher water absorption capacity than the OPC-RCA specimens.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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