Performance Assessment of Mechanical and Durability Properties of Cupola Slag Geopolymer Concrete with Fly and Rice Husk Ashes

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ABSTRACT: Research into substituting recycled materials for cement and aggregates can yield beneficial natural resource conservation, waste management, cost savings, and reduced embodied energy in concrete. Hence, this research investigates the potential adoption of coal fly ash (CFA) and rice husk ash (RHA) as geopolymer binders to partially substitute cement in varying proportions up to 25%. However, cupola furnace slag (CFS) was also used as a partial substitute of crushed granite from 0% to 35% in steps of 5% in the production of geopolymer concrete (GPC). The selected geopolymer binders were synthesized using an alkaline solution. Workability, compressive strength, and rapid chloride penetration tests on fresh and hardened normal concrete (NC) as control and GPC containing CFS were evaluated at different water-binder ratios. The findings revealed that integrating 15%CFA, 20%RHA, and 30%CFS with w/b of 0.50 and 0.65 improved the workability by 180% and 105.7%, respectively, but compressive strength is significantly reduced. The findings further showed that combining 75%OPC, 20%CFA, 5%RHA, 100%RS, 20%CFS, and 80%CG results in optimal compressive strength of 19.68 N/mm² and, 21.49 N/mm² at 28 days and 56 days with w/b of 0.50, respectively, as contrasted to the lowest possible strength requirement. The Rapid Migration Test (RMT) was used to determine the chloride ions permeability in various concrete mixes. The results show that GPC produced with the combination of 15%CFA, 20%RHA 65%OPC, 30%CFS, and 70%CG with w/b of 0.65 is more durable and has higher chloride ion penetration resistance than most other mix proportions.

KEYWORDS: Chloride ion; Compressive strength; Cupola furnace slag; Geopolymer concrete; Pozzolans.

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I. INTRODUCTION

Waste recycling and re-use have become necessary due to rising demand, diminishing reserves, and increased pressure on natural deposits to make concrete. The potential utilization of recycled aggregates and pozzolanic cement in place of traditional aggregates and cement can benefit natural resource conservation, waste management, and cost reduction. The utilization of recyclable materials in construction are is becoming more popular as people become more aware of the vast amount of waste generated every day due to modern lifestyles, extensive resource exploitation, and environmental concerns (Lau et al., 2014; Murali et al., 2012).

Furthermore, cement clinker production is energy-intensive and environmentally unfriendly, with large amounts of CO₂ emitted depleting the ozone layer (Thiedeitz et al., 2020). As a result, there is a need for non-traditional cementing materials that are innovative, environmentally friendly, effective, and affordable. Pozzolans are a possible replacement material. Similarly, cupola furnace slag (CFS) is a viable substitute for traditional coarse aggregate and cement. The evolution of concrete production a short time ago has resulted in new sustainable concrete types. Geopolymer concrete (GPC) is one such concrete (Pilehvar et al., 2018; Yazdi et al., 2018). GPC is a type of eco-friendly concrete that eliminates or reduces the utilization of Portland cement in concrete (Abdollahnejad et al., 2019; Shalika and Hemant, 2016; Torres-Carrasco et al., 2015). It is the mixture of alkaline solution and pozzolans such as coal fly ash (CFA) (Bouaissi, et al., 2019; Parveen et al., 2018; Nuaklong et al., 2017) Silica fume (SF) (Mo et al., 2016), rice husk ash (RHA) (Alabi and Mahachi, 2020), Ground Granulated Blast furnace slag (GGBS) Panesar et al., 2017; Islam et al., 2015), and waste glass powder (Demirel et al., 2018; Tho-In et al., 2017) as source materials having almost the same mechanical and physical properties as compared to ordinary Portland cement (OPC) (Lim et al., 2018; Vistin et al., 2017; Un et al., 2015).

Geopolymer has appealing properties that have prompted several researchers to look into this type of concrete (Gholampour et al., 2019; Zabihi et al., 2018; Mohseni, 2018; Nath and Sarker, 2015). Despite this, a small number of researchers have reported that geopolymer concrete has higher compressive strength and chloride-ion resistance (Mesgar et al., 2020; Saloni et al., 2020; Saini and Vattipalli, 2020; Bouaissi, et al., 2019; Noushini and Castel, 2018). These studies, however, have had little or no application in buildings and infrastructures in harsh environments. However, there appears to be no study based on the combination of CFA and RHA as a geopolymer binder in the production of GPC utilizing CFS as a partial replacement of coarse aggregate. The

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innovative utilization of pozzolanic geopolymer cement (PGC) containing CFS will provide less expensive and environmentally friendly concrete.

In practice, due to differences in the quality and grade of the products, other concrete constituents, and the interactivity of the various components, most countries have variations in the production and performance of GPC using these by-products. Currently, there is little GPC activity in the South African construction industry and most developing countries such as Nigeria (Attwell, 2014). Consequently, comprehensive studies on local materials, demands, and capacities are required to understand possibilities. As a result, it is necessary to investigate local materials to optimize concrete mixtures that will significantly impact sustainability. However, this study reported the mechanical and durability of CFS-based GPC containing CFA and RHA as a combined binder. The compressive strength and chloride-ion resistance obtained from different replacements of traditional aggregates (granite) with CFS; and OPC with CFA and RHA were used to assess the best combination of CFS, CFA, and RHA. The GPC-based CFA and RHA’s compressive strength was tested at 7, 28, and 56 days compared to concrete without CFS, CFA, or RHA (control). Oxide composition and microstructure analyses were performed using X-ray Fluorescence (XRF), X-ray Diffraction (XRD), and Scanning Electron Microscope to distinguish the interaction in the material formation and morphological structure of CFA and RHA (SEM).

II. MATERIALS AND METHODS

A. Materials

The materials used in this study include water, ordinary Portland cement (OPC), rice husk ash (RHA), coal fly ash (CFA), river sand (RS), alkaline activator, crushed granite (CG), and cupola furnace slag (CFS). The details of the properties of these materials and how they are obtained are described below:

1) Water

In the production of GPC, water is essential. In other words, water was used to hydrate cement, moisten aggregate, mix the concrete constituents, and cure. The portable water used in this study conformed to the recommendation of ASTM 1602 (2012).

2) Binding materials

OPC is the most common binding material used as an essential concrete ingredient worldwide. The class 42.5 of OPC conforming to BS 12 (1996) was used. The cement class number denotes its lowest possible compressive strength that the cement is presumed to achieve within 28 days. To avoid being affected by atmospheric conditions, adequate care was made to ensure that the procurement was made from a single bunch in an impermeable paper bag. The cement quality in terms of its chemical and physical properties was tested to follow ASTM C127-12 (2012) and ASTM C114-04 (2004) recommendations.

Rice husk (RH) has been certified as one of the potential pozzolanic materials majorly from agricultural waste and is available in a large quantity worldwide each year (Fapohunda et al., 2021; Piyarat et al., 2021; Thiedeitz et al., 2020; Nalobile et al., 2019; Akeke et al., 2016). It is one of the source materials used as a geopolymer binder activated with alkaline liquids in this study. The RH was procured in an Ekiti State paddy field. Then it was incinerated for more than 24 hours in an open space at a relative temperature of about 700 °C. After that, the RH was allowed to burn gradually and was allowed to cool, before collecting the ash for further testing. The ash was grounded for approximately 2 hours in a Los Angeles (LA) mill before being taken through a mesh with a size of 0.074 mm opening.

The CFA used in this study as a source material was procured from a thermal energy plant in Lokoja. CFA is a natural, organometallic outcome of coal from thermal energy plants. It is a cementitious material with no binding properties. When calcium hydroxide is chemically reacted at room temperature in the presence of moisture, a compound with cementitious properties is formed. Calcium silicate hydrates are formed when alumino-silicates in the CFA interact with calcium ions in water.

i) Alkaline activator

An 8M sodium hydroxide (NaOH) and sodium silicate (Na2SiO3) mixture with a mix proportion of 1:2.5 was used as an alkaline solution to synthesize the geopolymer binders. Because of the significant heat emission, the alkaline solutions were mixed a day before making geopolymer concrete.

ii) Aggregates

The river sand (RS) is used as a fine aggregate. However, this is usually blended with other concrete constituents to fill the pores with the concrete matrix. The grading pattern of the RS was carried following the recommendation of BS 812 (1985). Hence, the outcome revealed that the specimen meets the general classification limit recommended by BS 882 (1992). The measured values of some selected physical properties of RS such as bulk density, specific gravity, fineness modulus, moisture content, and absorption rate are 1.82, 2.34, 1390 kg/m³, 7%, and 2.42, respectively.

A smooth-surfaced CG obtained from a quarry site in Akure metropolis was used as coarse aggregate. The aggregate size being used for concrete production varies from 10 mm to 19 mm. The measured values of some selected physical properties of CG, such as specific gravity, fineness modulus, absorption rate, and bulk density, are 2.65, 5.78, 1.86, and 1635 kg/m³, respectively. Figure 1 shows a sieve analysis of crushed granite. It was discovered that the CG used met the ASTM D6913/D6913M-17 requirements (2017), including specifications for both wearing and non-wearing surfaces. The aggregate crushing value (ACV) standard values range between 30 and 45, according to BS 812: Part 104 (1985). The average ACV for CG was determined to be 30.4. Also, the aggregate impact value (AIV) value of the CG was around 23.1.

The CFS was collected in huge quantities from the Foundry Dump Site within Akure Metropolis. The slag was taken to the Laboratory, scrubbed, and separated to remove visible earth contaminants (Alabi and Mahachi, 2020; Afolayan and Alabi, 2013). The material was therefore crushed into fragments varying in size from 10 to 19 mm. CFS was used as a partial substitute for CG in the development of GPC. Figure 1 presents the particle distribution of CFS. The
measured values of some selected physical properties of CFS, such as specific gravity, absorption rate, and bulk density, are 2.57, 1.81, and 1810 kg/m³.

![Graph showing grain size distribution of crushed granite (CG) and cupola furnace slag (CFS).]

Figure 1: The grain size distribution of crushed granite (CG) and cupola furnace slag (CFS).

B. Making of GPC Specimens

1) GPC mix design

There is presently no unified guideline capable of producing GPC (Li et al., 2019). Hence, this implies that the design of the GPC mix is based mainly on experimentation. As a result, in designing concrete grade C15/20, a mix ratio of 1:2:4 by weight of binder, fine and coarse aggregates were used.

2) Experimental setup for the production of GPC

In this study the potential adoption of coal fly ash (CFA) and rice husk ash (RHA) as geopolymer binders to partially substitute cement (0%, 5%, 5%, 10%, 20%, 15%, 10%, and 20% for CFA; and %, 5%, 10%, 15%, 10%, 5%, 20%, 25%, and 20% for RHA, by weight of cement) was studied. However, cupola furnace slag (CFS) was also used as a partial substitute of crushed granite from 0% to 35%, in steps of 5% in the production of geopolymer concrete (GPC). The strategy for mixing GPC samples is comparable to those used to make Portland cement concrete (PCC). All aggregates used in the production of concrete were maintained at saturated surface dry conditions (SSD). First, all the aggregates, together with CFS, were blended for approximately 5 minutes.

The CFA and RHA were therefore introduced and rigorously dry blended for about 3 to 6 minutes. The alkaline compound was introduced slowly and blended for 3 to 6 minutes. The alkaline composition results and physical properties of OPC, RHA, and CFA using XRF. The most usual identified elements present in CFA, RHA, and OPC are Ca, Fe, Mg, Na, and K. The variation may be due to harvest year, geographic factors, and paddy fields. However, the levels of the identified elements were different across the pozzolans samples analyzed. The sum of silicon dioxide (SiO₂), aluminum oxide (Al₂O₃), and ferric oxide (Fe₂O₃) of CFA is 92.38%, which is accompanied by a low calcium oxide (CaO) content of 1.72%. Furthermore, CFA is more
pozzolanic because the sum of those oxides in pozzolan should be at least 70%. RHA has a SiO$_2$ content of 87.83%, which is significantly higher than that of CFA. According to Table 2, the specific gravities of RHA are slightly higher than that of CFA.

The XRD patterns of CFA and RHA are shown in Figures 2 and 3. CFA mainly was in the crystalline form of SiO$_2$ with a single grain size orientation, as shown in Figure 2(a). The degree of structural order, on the other hand, is very high (i.e., 84.62 percent). Because of the broad peak at a 2θ angle of about 22°, the RHA is mostly amorphous, as shown in Figure 2(b).

The silicate crystallization at a 2θ angle of about 27° indicates that the RHA was burned at temperatures higher than 700°C. The RHA was discovered to be grey. The ignition loss, on the other hand, was significantly higher. This may be attributable to the ash's high concentration of unburned carbon content.

Back Scattered Detector (BSD) images of coal fly ash (CFA) and rice husk ash (RHA) can be seen in Figure 3. The lumps of about 100 µm can be seen from the figure, which may have been formed due to particle agglomeration. The pozzolans (CFA and RHA) had distinct morphological characteristics. The CFA and RHA particles studied were irregularly shaped and ridged. In other words, CFA and RHA particles have spherical and angular shapes, respectively. The observed shape of RHA particles is an essential characteristic in the concrete application as a binder. Energy Dispersive X-ray (EDX) area analysis on different spots, that is, on the light and dark regions, was used to identify the phases present in the RHA and CFA. Figures 4 and 5 show the average composition of the phases obtained from EDX for RHA and CFA, along with representative EDX spectra.

### Table 1: Experimental concrete mix design.

<table>
<thead>
<tr>
<th>Concrete mix</th>
<th>Binding Materials</th>
<th>Fine Aggregate</th>
<th>Coarse Aggregates</th>
<th>Water Content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OPC (kg/m$^3$)</td>
<td>CFA (kg/m$^3$)</td>
<td>RHA (kg/m$^3$)</td>
<td>W/B ($W/B_{kg}$)</td>
</tr>
<tr>
<td>Control</td>
<td>174.91</td>
<td>0</td>
<td>0</td>
<td>349.81</td>
</tr>
<tr>
<td>GPC1</td>
<td>157.42</td>
<td>8.75</td>
<td>0</td>
<td>349.81</td>
</tr>
<tr>
<td>GPC2</td>
<td>148.67</td>
<td>8.75</td>
<td>17.49</td>
<td>349.81</td>
</tr>
<tr>
<td>GPC3</td>
<td>139.93</td>
<td>17.49</td>
<td>17.49</td>
<td>349.81</td>
</tr>
<tr>
<td>GPC4</td>
<td>131.18</td>
<td>34.98</td>
<td>0</td>
<td>349.81</td>
</tr>
<tr>
<td>GPC5</td>
<td>113.69</td>
<td>26.24</td>
<td>34.98</td>
<td>349.81</td>
</tr>
<tr>
<td>GPC6</td>
<td>113.69</td>
<td>17.49</td>
<td>43.73</td>
<td>349.81</td>
</tr>
<tr>
<td>GPC7</td>
<td>104.95</td>
<td>34.98</td>
<td>34.98</td>
<td>349.81</td>
</tr>
</tbody>
</table>

### Table 2: Chemical and physical properties of OPC, RHA, and CFA.

<table>
<thead>
<tr>
<th>Oxide composition</th>
<th>CFA</th>
<th>RHA</th>
<th>OPC</th>
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<tbody>
<tr>
<td>CaO</td>
<td>1.72</td>
<td>0.68</td>
<td>61.52</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>57.2</td>
<td>87.83</td>
<td>21.02</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>28.6</td>
<td>0.46</td>
<td>5.78</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>6.58</td>
<td>0.67</td>
<td>3.28</td>
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<tr>
<td>MgO</td>
<td>1.78</td>
<td>0.44</td>
<td>2.08</td>
</tr>
<tr>
<td>Na$_2$O/K$_2$O</td>
<td>2.81</td>
<td>3.03</td>
<td>0.78</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>0.02</td>
<td></td>
<td>2.04</td>
</tr>
<tr>
<td>LOI</td>
<td>1.18</td>
<td>5.81</td>
<td>8.34</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.21</td>
<td>2.34</td>
<td>2.95</td>
</tr>
</tbody>
</table>
Figure 3: Back Scattered Detector (BSD) images of (a) coal fly ash, (CFA) and (b) rice husk ash, (RHA).

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight (%)</th>
<th>Atomic (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O K</td>
<td>57.27</td>
<td>70.76</td>
</tr>
<tr>
<td>Al K</td>
<td>2.33</td>
<td>1.70</td>
</tr>
<tr>
<td>Si K</td>
<td>37.51</td>
<td>26.40</td>
</tr>
<tr>
<td>K K</td>
<td>0.54</td>
<td>0.27</td>
</tr>
<tr>
<td>Ti K</td>
<td>0.57</td>
<td>0.24</td>
</tr>
<tr>
<td>Fe K</td>
<td>1.79</td>
<td>0.63</td>
</tr>
<tr>
<td>Totals</td>
<td>100.00</td>
<td></td>
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Figure 4: Energy Dispersive X-Ray (EDX) area analysis showing (a) the composition and (b) spectra of the CFA.
Figure 6: Slump test results of the fresh concrete mixes. The slump values were found to be higher in all GPC mixes containing CFS with a w/b ratio of 0.50 than in the control sample. On the other hand, slump values range between 24 mm (GPC1) and 55 mm (GPC7), while the control has 20 mm. Except for GPC7, which had medium workability. The slumps of all mixes averaged 37.7 mm, indicating low workability. As a result, such concrete may be suitable for foundations and light reinforcement rather than standard reinforced concrete work.

Using a w/b ratio of 0.65, the slump increased slightly in all mixes. The slump varied between 38 mm (GPC1) and 72 mm (GPC7), with a mean of 54 mm. This indicates that the concrete has medium workability because it falls within the

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight (%)</th>
<th>Atomic (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O K</td>
<td>52.58</td>
<td>66.22</td>
</tr>
<tr>
<td>Si K</td>
<td>45.88</td>
<td>32.92</td>
</tr>
<tr>
<td>P K</td>
<td>0.51</td>
<td>0.33</td>
</tr>
<tr>
<td>K K</td>
<td>0.73</td>
<td>0.38</td>
</tr>
<tr>
<td>Ca K</td>
<td>0.30</td>
<td>0.15</td>
</tr>
<tr>
<td>Totals</td>
<td>100.00</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5: Energy Dispersive X-Ray (EDX) area analysis showing the composition and spectra of the RHA.

A. Slump Test

Figure 6 depicts the slump test results of the fresh concrete mixes. The slump values were found to be higher in all GPC mixes containing CFS with a w/b ratio of 0.50 than in the control sample. On the other hand, slump values range between 24 mm (GPC1) and 55 mm (GPC7), while the control has 20 mm. Except for GPC7, which had medium workability. The slumps of all mixes averaged 37.7 mm, indicating low workability. As a result, such concrete may be suitable for foundations and light reinforcement rather than standard reinforced concrete work.

Using a w/b ratio of 0.65, the slump increased slightly in all mixes. The slump varied between 38 mm (GPC1) and 72 mm (GPC7), with a mean of 54 mm. This indicates that the concrete has medium workability because it falls within the

Figure 6: Slump value of different fresh concrete mixes.
standard range of 50 – 90 mm. This concrete is appropriate for simple strip footings and cast-in-place hard-standing slabs. On the other hand, the low workability observed could be attributed to the lower CFA and RHA contents, which may not fill the pores of the mixes and bind well with other constituents. However, because of their ability to absorb free water, concrete mixtures with higher levels of hybrid alkali-activated binders had higher slump values.

Many factors, in general, can be said to have contributed to the low workability of the GPC. The samples were mixed in the laboratory while dry, implying less water was available, as the aggregates require some water to wet their surfaces. As a result, the water content was not adjusted to account for dry aggregates. The physical properties of the aggregates, such as fineness modulus and shapes, were also discovered to influence workability. The water absorption of the fine aggregate used in this study exceeds the ASTM C127-15 maximum limit of 2.3% (2015). The greater the water absorption, the more water is required to produce workable concrete. According to Rangan (2010), the molar concentration of sodium hydroxide has a significant effect on the workability of GPCs. As a result, all slump values were within the ACI 211.1 (1991) range for various constructions.

B. Compressive Strength

Figure 7 depicts the effect of different percentage replacements of recycled aggregate (CFS) and hybrid alkali-activated binder (OPC/CFA/RHA) contents on the compressive strength of GPC with various water-binder ratios. Compressive strength generally increases with curing age. The compressive strength was found to decrease as the CFS and binders' content varied. It was also discovered that water-binder ratios have only a minor impact on strength development. In other words, GPC samples with a lower water-binder ratio (w/b = 0.50) have greater compressive strength than samples with a higher water-binder ratio (w/b = 0.65).

Moreover, since RHA and CFA contain a high Si content, the decrease in strength may be due to change in the Si/Al ratio. However, according to De Silva et al., (2007) and Tho-In et al., (2017), this may significantly alter the properties of GPC while causing relatively minor changes in Si and Al contents during aluminosilicate geopolymerization. Furthermore, the development of low-crosslinked aluminosilicate materials resulting from a high Si/Al ratio may be responsible for decreased compressive strength (Rattanasak et al., 2010; Tho-In et al., 2017).

For w/b = 0.50, the compressive strength of normal concrete (control) increased by 69.37%, 72.89%, and 2.08% from 7 days to 28 days, 7 days to 56 days, and 28 days to 56 days, respectively. As a result, the strength development from 28 days to 56 days was relatively slow compared to other days. Hence, this could be due to insufficient binder hydration at the interfacial zone (ITZ). However, the control sample's strength increased by 73.18%, 77.21%, and 2.32% from 7 days to 28 days, 7 days to 56 days, and 28 days to 56 days, respectively, at w/b = 0.65. The control samples with a w/b of 0.65 developed greater strength than the control
samples with a w/b of 0.50. It was also discovered that as the CFS and binder contents increased, the compressive strengths at all ages gradually decreased with w/b.

Furthermore, the maximum increase in compressive strength of GPCs with w/b of 0.65 was approximately 68.14%, 66.67% percent, 59.34%, 53.52%, 68.55%, 54.45%, and 63.10% from 7 days to 28 days. In w/b of 0.50 from 7 days to 28 days, the maximum compressive strength increase observed for GPCs was approximately 84.67%, 81.73%, 71.48%, 70.25%, 76.13%, 90.02%, and 71.43%. The observed maximum increase in compressive strength for concrete mixes in w/b of 0.50 at 7 days to 56 days was approximately 83.72%, 75.09%, 66.87%, 74.03%, 80%, 87.72%, and 68.67%.

However, for both w/b considered, a relatively slow increase in the concrete mixes' compressive strength from 28 days to 56 days was also observed. Hence, this could be because most geopolymerization reactions occur during the early stages of concrete curing. Control concrete developed early strength faster than other GPC, as shown in Figure 9. The amount of CFA and hybrid binders in GPC decreases its strength. This could be attributed to the high water absorption capacity of the binders or the pozzolanic activity of the microparticles of the binders when combined with cement compounds. Finally, compressive strengths of 19.68 N/mm² and 21.49 N/mm² are obtained at 28 days and 56 days from specimens containing 20% CFS, 70% OPC, 5% RHA, and 20% CFA, with compressive strengths of 19.68 N/mm² and 21.49 N/mm², respectively. In contrast to the designed strength of 20 N/mm², the compressive strength of normal concrete (control) is 25.39 N/mm² at 28 days and 25.92 N/mm² at 56 days, with a w/b of 0.50.

The compressive strength of concrete produced with w/b ratios of 0.50 and 0.65 did not differ significantly, as shown in Figure 8. The ratio of control sample compressive strength to GPC compressive strength for both w/b ratios was also discovered to be heavily influenced by GPC compressive strength, as the ratio decreased with increasing GPC compressive strength and varies between 1.09 and 2.54 at compressive strength up to 23.2 N/mm².

C. Chloride ion Penetration Performance of GPC

Figures 9 and 10 show the relative effect of the charge passed on the GPC at 7 and 56 days with varying w/b ratios. However, some GPC had lower charges passed than the control concrete, especially concrete blends with a w/b of 0.50. Charge reductions ranged from 500 mA to 1500 mA at 7 days with a w/b of 0.50; 900 mA to 1700 mA at 56 days with a w/b of 0.50; 320 mA to 600 mA at 7 days with a w/b
of 0.65; and 480 mA to 1200 mA at 56 days with a w/b of 0.65. This may be mainly attributable to the micro-filler effect of the RHA and CFA, which also caused matrix densification.

On the other hand, the difference in current variability before and after chloride-ion passes through the specimen shows that the effects of other ions in the pore solution on the current are negligible. This means that chloride ion ratio to other ions in the pore solution is assumed to be constant after the chloride-ion passage. It is also evident in Figs. 9 and 10 that current variations in control samples decrease reasonably fast at 7 and 56 days compared to samples made with different binders.

Figure 11 depicts chloride ion penetration depth after 7 and 56 days of curing for control concrete samples and GPCs with a w/b ratio of 0.65. GPC5 has a final depth of 8 mm, GPC6 has a final depth of 15 mm, and GPC3 has a final depth of 19 mm. GPC7, GPC2, GPC1, and GPC4 have final depths of 20 mm, 25 mm, 30 mm, and 30 mm, respectively. With a final depth of 10 mm, it is evident that the control sample is resistant to chloride. As a result, only GPC2 outperformed the control sample after 7 days with a w/b ratio of 0.65. The addition of hybrid binders and recycled coarse aggregate improved the permeability resistance of concrete. GPC5 is far more durable after 56 days of curing, with a final depth of penetration of 7 mm, followed by GPC6 with a final depth of penetration of 11 mm, and then GPC1 and GPC7 with final penetration depths of 14 mm, GPC2, GPC3, and GPC4 have final depths of 16 mm, 16 mm, and 22 mm, respectively, while the control sample has a final depth of 8 mm. In this particular instance, GPC5 outperformed the control sample and thus lasted longer. In general, adding hybrid binders to GPCs improved their durability. Mixes with a w/b ratio of 0.50 had the same tread as mixes with a w/b ratio of 0.65, as shown in Figure 12. At 7 days, only GPC3 performed exactly like the control sample. All 56 days mixes performed poorly with a w/b ratio of 0.50. It can be concluded that the w/b ratio has a significant influence on the chloride ion penetration performance of concrete.

It was observed for all samples in general, that the resistance to chloride-ion penetration increased with the number of curing days. The implication is that as curing days increase, so will the durability of the concrete. Previous studies on chloride ion penetration produced comparable results for various GPC (Ikumapayi et al., 2019). The improved interfacial zone and the reduced average pore size of the concrete contributed to the increased chloride penetration resistance. The GPC has a relatively high resistance to chloride penetration, because of its lower median pore diameter and porosity values.

Furthermore, the hydrated structures of control samples contain more Ca(OH)₂. The reaction of the binders with the obtainable Ca(OH)₂ from OPC allows for complete binder hydration, resulting in higher quality concrete structure with the least potential porosity. These findings and those of many other researchers highlight the benefits of incorporating pozzolans into concrete exposed to aggressive conditions to reduce chloride ion penetration (Ikumapayi et al., 2019). It is worth noting that, regardless of w/b, chloride ion penetration depth increased as the binders and CFS contents increased in most mixes.

Chloride penetration depth was found to reduce with increase in the concrete age (see Figures 11 and 12) which implies that the age of the concrete can improve its resistance to chloride migration. It was also discovered that concrete with a w/b ratio of 0.50 has significantly better chloride

\[ \text{ complimentary text } \]
penetration resistance regardless of age than mixes with a w/b ratio of 0.65. The high alumina (Al₂O₃) content of CFA can cause a pozzolanic reaction with cement to produce tricalcium aluminate (3CaO·Al₂O₃ or Ca₆A), which may be responsible for the chemical binding of chloride ion in GPCs to form Friedel’s salt (Ca₆Al₂O₆·CaCl₂·10H₂O).

IV. CONCLUSION

The mechanical and durability performance of cupola furnace slag geopolymer concrete-based CFA and RHA is reported in this paper. A comprehensive set of laboratory experiments was conducted to estimate the workability, compressive strength, and rapid chloride penetration of fresh and hardened concrete at water-binder ratios of 0.50 and 0.65. The concrete mix with the lowest compressive strength has the highest slump value, according to the GPC experiment results. It has been observed that the compressive strength of concrete decreases as CFA and binder content increases. As the curing ages increased, so did the control and GPC. It has been observed that the w/b ratio has a direct relationship with compressive strength.

Based on the chloride ion penetration test results for GPCs performed using RMT, it is possible to conclude that the GPC has higher chloride ion penetration resistance than the samples made from different mixes. As a result, GPC has become more durable, particularly in harsh or coastal environments. The partial replacement of OPC and CG in concrete production, particularly with 15%CFA, 20%RHA, 65%OPC, 30%CFS, and 70%CG, improves its durability. In general, resistance to chloride-ion penetration increased with the number of curing days and as a result, the concrete durability may change with age. Eventually, the geopolymers used have a natural, environmentally friendly sustainability. It can contribute positively to the significant decrease of global greenhouse gases and the overall sustainability of building materials.

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