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**STRUCTURAL PROPERTIES OF METAKAOLIN – BASED GEOPOLYMER
CONCRETE CURED IN AMBIENT CONDITION**

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ABSTRACT

Geopolymer concretes are becoming popular as viable alternative to conventional concrete regarding green concrete. The initial experiences from small scale tests in the use of geopolymer concrete confirmed its viability as structural materials. However, the absence of standard mix design for geopolymer concrete owing to various effect of its constituent materials, couple with the use of different prime material render the structural reliability of this unconventional concrete questionable. This paper focuses on the structural behaviour of metakaolin – based geopolymer concrete in ambient curing condition. The objective of this paper is to establish the mechanical properties of MGC and to determine the relationship between its strength property. Such mechanical strength tests as compressive strength, flexural strength, split tensile strength are conducted on ambient cured MGC and the results compared with Portland cement concrete (PCC) of equivalent mix proportioning. The results obtained indicates that the mechanical strength properties of MGC is significantly higher than that of PCC at early stage, but at later age, the difference becomes marginal. Also, the correlation of the flexural strength and split tensile strength pattern of MGC is relatively lower than that of PCC albeit marginally. The prediction of the flexural and split tensile strength from the compressive strength of MGC requires slight modification of the existing equations for PCC. It was concluded from this study that the ambient cured MGC is relatively advantageous over PCC for fast construction with no extra cost on special curing.

Keyword: Metakaolin – based geopolymer concrete, Portland cement concrete, structural behaviour, mechanical strength,

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1. Introduction

Achieving sustainable development in most developing societies with serious infrastructural deficit like Nigeria involves exploring alternative options to conventional Portland cement technology to achieve a more efficient and eco-friendly structural product. The entrenched production technology and processing of Portland cement has been identified as a major contribution to the greenhouse effect. Portland cement industry contributes approximately 5% - 7% of global CO₂ emissions (Kumar *et al*, 2018). The ever increasing demand for Portland cement/concrete to tackle the infrastructure deficit in Nigeria emphasises the need for alternative material to Portland cement/concrete. The aggregate/cement consumption in Nigeria expanded by 2.1% to about 20.7mta in 2018. (Anifowoshe and Akinremi, 2019).

About 50% reduction of CO₂ emission is associated with the replacement of Portland cement with supplementary cementitious materials such as silica fume, fly ash and blast furnace slag in the range of 20% - 50% (van Deventer, *et al*, 2012). However, a more efficient approach to reducing the negative impact of Portland cement/concrete in sustainable infrastructural drive is the 100% substitution of Portland cement with an alkali – activated aluminosilicate rich material known as Geopolymer binder (Duxson, *et al*, 2007; Shi, *et al*, 2011). There is energy reduction of about 55% in the production of Geopolymer concrete in comparison with conventional Portland cement concrete (Thamilselvi *et al*, 2017). It was also reported that Geopolymer concrete exhibit excellent mechanical properties and resistance to fire and acid attack (Neupane, *et al*, 2018).

Geopolymer binder can be obtained from the alkali activation of any material rich in alumina and silica oxides. Such materials can be naturally sourced like metakaolin or as industrial by – product like fly ash, Blast furnace slag, silica fume etc. Metakaolin is produced from natural clays (Kaolin) by calcination at a moderate temperature (600 – 800⁰C). In addition to aluminosilicate material, there is need for alkali activators to initiate geopolymerization reaction of prime material in order to achieve Geopolymer binder. Most popular alkali activators in Geopolymer mixtures are a combination of either sodium hydroxide (NaOH) and sodium silicate or potassium hydroxide (KOH) and potassium silicate (Albidah, *et al*, 2021).

Several authors have reported different works on the geopolymers as construction material, however, most of these works explore fly ash – based geopolymer (Hardjito and Rangan, 2005; Ariozi *et al*, 2012; Chuah, *et al*, 2016; Lahoti *et al*, 2018), slag – based geopolymer (Atis, *et al*, 2009; Allahverdi *et al*, 2010; Kathirvel and Kaliyaperumal, 2016), rice husk ash – based geopolymer (He, *et al*, 2013; Zabihi, *et al*, 2018), kaolin (Heah, *et al*, 2011; Okoye *et al*, 2015). Most popular research works on metakaolin – based geopolymer are limited to mortar and paste (Weng and Sagoe – Crentsil, 2007; Yao *et al*, 2009; Kamaloo *et al*, 2010; Medri, *et al*, 2010; Zhang, *et al*, 2016). Other works on geopolymer material include methods of curing (Rovnanik, 2010; Muniz – Villarreal, *et al*, 2011).

Research works on metakaolin – based geopolymer material may be limited, but their relevance to the present study cannot be overemphasized. Pouhet, (2015) reported the use of flash – calcined metakaolin and sodium silicate to serve as geopolymer binder and study the workability and compressive strength. Rapid reaction of the alkalis was observed in the geopolymer paste and the addition of sodium hydroxide in the mix led to greater dispersions of the strength values. Nur *et al*, (2017) investigated the performance of metakaolin geopolymers exposed to seawater and found that metakaolin geopolymers did not substantially change in dimension and remain structurally intact. Pouhet and Cyr, (2016) studied the effect of H₂O/Na₂O molar ratio and aggregate content on the workability, porosity, and compressive strength of metakaolin – based

geopolymer material. Zhang, *et al*, (2020) investigated the spalling behaviour of metakaolin – fly ash based geopolymer concrete under the influence of elevated temperature. Albidah *et al* (2021) studied the characteristics of metakaolin – based Geopolymer concrete for different mix design parameters. Different properties like workability, density, compressive strength, water absorption, split tensile strength, ultrasonic pulse velocity were determined and some useful models were proposed for predicting these properties.

From the foregoing, it is clear that existing studies on metakaolin – based geopolymer concrete are limited to parametric studies and the effect of various mix parameters on the mechanical properties of geopolymer material. It is clear that the structural behaviour of metakaolin – based geopolymer concrete within the full range of compressive strength, flexural strength, split tensile strength and the level of correlation they shared are still shrouded in uncertain conclusions, therefore, inhibiting accurate prediction of such mechanical properties as flexural and split tensile strength from the compressive strength property. The objective of this study therefore is to determine the structural properties of metakaolin – based geopolymer concrete in view of its mechanical properties.

2.0 Materials and Methods

2.1 Geopolymer Binder

Geopolymer binder was obtained as the combination of prime material and the alkali activator. In this study, metakaolin was used as the aluminosilicate prime material. The metakaolin was obtained from the calcination of locally sourced kaolin at 750⁰C for 3 hours. The physical and chemical characteristics of the metakaolin is as presented in table 1 and 2 respectively. The metakaolin was classified as low – calcium precursor based on the ASTM C618 criteria i.e. $SiO_2+Al_2O_3+Fe_2O_3= 87.4 \geq 70$.

Table 1: Physical characteristics of Portland cement and metakaolin

Parameter	Portland Cement	Metakaolin
Percentage retain on 75micron sieve (%)	<15%	<15%
Normal consistency (%)	29	40 – 45
Initial setting time (min)	115	60 – 90
Final setting time (min)	309	110 – 150
pH	11.5	11.7
Specific gravity	2.98	2.26

Table 2: Chemical composition in percent of Portland cement and metakaolin

Compound	Formula	Portland Cement	Metakaolin
Silica	SiO ₂	21.0	49.10
Alumina	Al ₂ O ₃	4.20	37.93
Ferric oxide	Fe ₂ O ₃	3.30	0.38
Calcium oxide	CaO	62.5	0.34
Magnesium oxide	MgO	1.86	0.11
Sodium oxide	Na ₂ O	0.37	0.28
Potassium oxide	K ₂ O	0.37	1.32
Loss on ignition	LOI	1.52	1.03

Alkali activators used for the synthesis of the geopolymer concrete was a mixture of sodium hydroxide and sodium silicate solutions. The sodium hydroxide flake was mixed with distilled water to achieve a solution of certain molar concentration. The sodium silicate solution with chemical characteristics as shown in table 3 was obtained from local supplier.

Table 3: Chemical characteristics of sodium silicate solution

Characteristics	Value
SiO ₂ (%)	29.4
Na ₂ O (%)	14.7
Ratio (SiO ₂ /Na ₂ O)	2.0
H ₂ O (%)	55.9
Solids (%)	44.1
pH	12.4
Density (kg/m ³)	1530
Viscosity (centipoises)	380
Appearance	Opalescent liquid

2.2 Aggregates

The fine and coarse aggregates used in this study include natural sand and crushed granite respectively, and they are obtained from local aggregate market. No special treatment was carried out on the aggregate except sieving with appropriate set of sieves to achieve a controlled particle gradation. The aggregates were used in saturated surface dry condition. Table 4 shows the physical properties of aggregates used in this study

Table 4: Physical properties of aggregates

Property	Coarse Agg.	Fine Agg.
Particle density (kg/m ³)	2650	1950
Bulk Specific gravity	2.64	2.60
Water absorption (%)	0.62	0.85
Aggregate impact value (%)	21.5	-
Aggregate crushing value (%)	23.3	-
Fineness Modulus	2.67	3.17

2.3 Concrete Mixing and Curing Process

Table 5 presents the mixture proportion for PCC and MGC. The MGC mix proportion was obtained from optimized mix design by Taguchi method for the entire research project work. Table 6 shows the test properties that were determined and the relevant standard guides that were followed.

Table 5: Mix proportion for PCC and MGC (kg/m³)

Concrete	Cement	MK	F.A	C.A	SS	SH	H ₂ O
PCC	715	-	715	715	-	-	255
MGC	-	558	725	725	235	157	-

Table 6: Test properties and relevant standard

Type of Test	Reference Standard	Age of test (day)
Compressive strength	BS EN 12390 – 3 (2002)	3, 7, 14, 28, 56, 90
Flexural strength	BS EN 12390 – 5 (2000)	3, 7, 14, 28, 56, 90
Split tensile strength	BS EN 12390 – 6 (2000)	3, 7, 14, 28, 56, 90

The MGC specimens were prepared by first mixing all the dry components including fine aggregate, metakaolin powder and coarse aggregate in that order in an electric mixer for about 3mins. Then the combined alkali solutions were added albeit gradually while the mixing continue until homogeneous mix was achieved. The concrete mixture was placed in slump cone for slump test after which it was remixed and placed in standard cube steel moulds of 100mmx100mmx100mm and vibrated on a vibrating table. The cast concretes were covered with polythene sheet for the next 24hrs, after which they were demoulded and kept in bags placed in an open air within the laboratory for ambient curing at temperature range of 24^oC – 28^oC and relative humidity range of 50 – 75%.

The PCC control specimens were prepared following the same procedure except for the replacement of metakaolin powder and alkali activator with Portland cement and water. The control specimens were demoulded after 24 hours and cured in water bath until testing days.

3.0 Results and Discussions

The compressive strength of PCC and MGC is presented in figure 1, while the flexural and split tensile strengths are presented in figure 2.

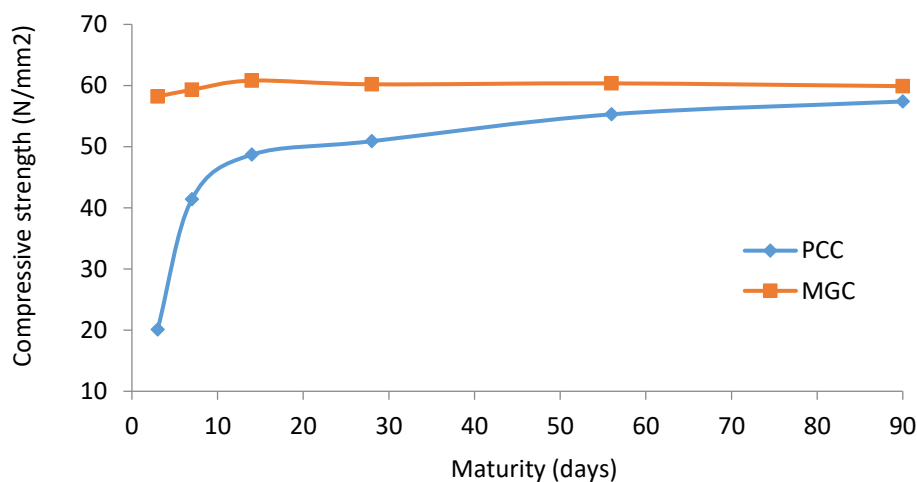


Figure-1 Compressive strengths of Portland cement and metakaolin geopolymer concrete

Figure 1 shows that ambient cured MGC specimens achieved 90% - 95% of its ultimate compressive strength at 3 days. This observation gives credence to the rapid hardening property of MGC and it is in agreement with the idea that geopolymer concrete exhibit very rapid strength development. Similar finding was reported by Albidah, *et al*, (2021) in which MK – based GPC specimens achieved 90% – 95% of the 28 – day compressive strength at 7 days of ambient curing.

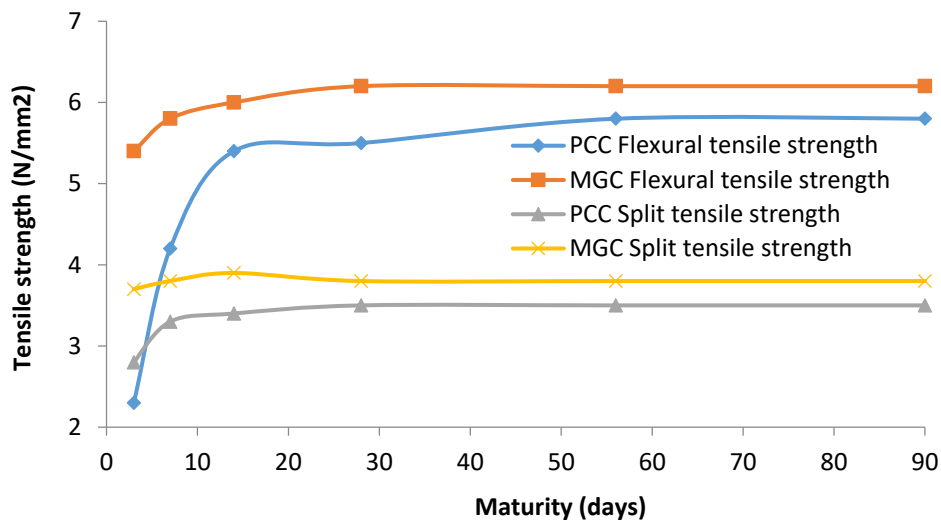


Figure 2: Flexural and split tensile strength development of Portland cement concrete and metakaoline geopolymers concrete at different ages of maturity

Figure 2 indicates that at early age, the flexural strength of MGC is clearly higher than that of PCC but at later age, the difference becomes marginal. This observation may be due to high early compressive strength of MGC. The flexural strength of PCC increases from a low value at early age and nearly meet up with that of MGC around 90 days, as a result of constant rise in compressive strength of PCC over curing period. This observation was in agreement with the findings of Gautam, *et al*, (2015) where it was reported that the average flexural strength developed by geopolymers concrete at 7 days is about 74% of the 28days strength whereas, the flexural strength developed by conventional concrete of grade M50 was about 39% of the 28days strength.

Also the split tensile strength of MGC remains almost the same over a 90day period and it is clearly higher than that of PCC from early age up to the 90day period of testing. Unlike the ambient curing condition which contributes no significant increase to tensile strength of MGC over the 90day period, it can be observed that the water curing condition of PCC contributed to its increasing tensile strength over the 90day period. This observation was in agreement with the compressive strength pattern of MGC and PCC and it clarifies the rapid geopolymersization process for MGC before 3days of ambient curing, as well as the active hydration process for PCC during an extended of water curing.

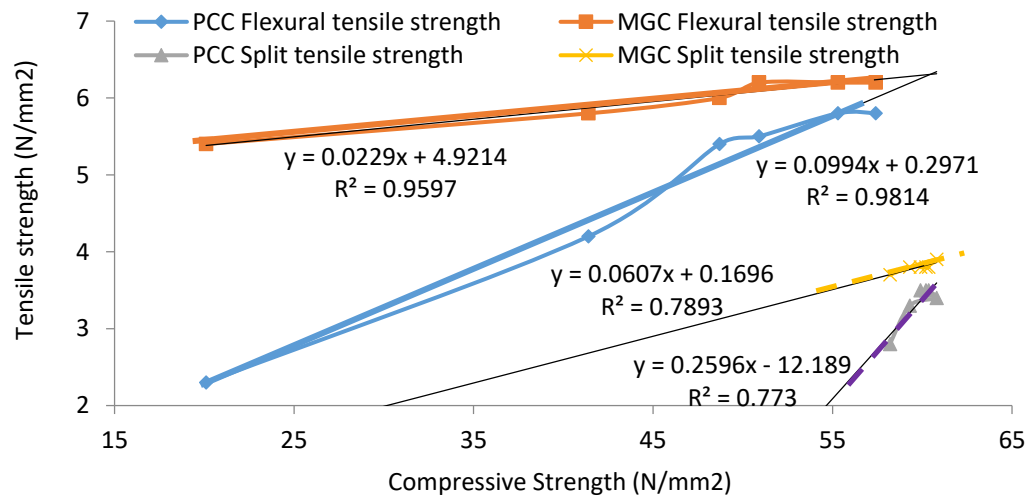


Figure 3: Variation of the flexural and split tensile strength of Portland cement and metakaolin geopolymer with respect to their compressive strengths

Figure 3 shows that the flexural strength pattern correlates more with the compressive strength for PCC than MGC, owing primarily to difference in curing condition for the PCC and MGC. In PCC, the strength increases over time in moist condition, whereas in MGC, the ambient curing does not lead to continuous increase in strength over time.

Also, the correlation of split tensile strength and compressive strength for both PCC and MGC is linearly strong, however the correlation is relatively stronger for PCC than MGC albeit marginally. It therefore indicates that the prediction of split tensile strength of MGC can be achieved by slight modification of the existing equation for PCC prediction. For example, prediction model equation for split tensile strength of PCC according to AS 3600 (2009), and ACI 318 (2014) are presented in equation 1 and 2; while equation 3 is the prediction model for MK – based geopolymer concrete (Albidah, *et al*, 2021).

$$\text{AS 3600 (2009)} \quad f_{ct} = 0.4\sqrt{f'_c} \text{ (MPa)} \quad (1)$$

$$\text{ACI 318 (2014)} \quad f_{ct} = 0.56\sqrt{f'_c} \text{ (MPa)} \quad (2)$$

$$\text{Albidah et al (2021)} \quad f_{ct} = 0.35f'_c{}^{0.68} \text{ (MPa)} \quad (3)$$

Where f'_c is the average compressive strength of concrete after 28 days

From the above equations, the experimental and estimated results of split tensile strength of PCC and MGC was obtained and presented in table 7

Table 7: Split tensile strengths at 28 days in MPa from prediction equations

Models/Age	Concrete	
	PCC	MGC
This Study	3.5	3.8
AS 3600 (2009)	2.9	3.1
ACI 318 (2014)	4.0	4.3
Albidah <i>et al</i> (2021)	5.1	5.7

It can be seen from table 7 that the split tensile strength of ambient cured MGC obtained from this study is relatively higher than the estimated value using equation 1 by about 23%, while it is lower

than the estimated value obtained from equation 2 by about 13% and from equation 3 by 50%. Based on the tensile strength property of ambient cured MGC, the tensile strength of MGC can be predicted from its compressive strength value using the modified relation in equation 4

$$f_{ct} = 0.49\sqrt{f'_c} \quad (4)$$

4.0 Conclusions

The results on the investigations conducted on the structural properties of ambient cured metakaolin – based geopolymer concrete indicate that the unconventional concrete exhibit higher early strength properties than the conventional concrete. It can be concluded that the stress bearing capacity of MGC is comparatively higher than that of PCC at early age, but at a later age, the difference seems marginal. Early strength development is prominent in MGC and this behaviour imposes special advantage on MGC over PCC, most especially where fast construction is essential or cost savings against prolong construction process is important. The mechanical properties of MGC under ambient curing condition encourage its use as in – situ construction material and this imposes clear advantage on MGC over other type of geopolymer concrete which often requires elevated temperature curing condition at least for the first 24hours of casting. Also it was established that the flexural and split tensile strength of ambient cured MGC generally correlated consistently with the compressive strength and they can be predicted by slightly modification of existing standard/model equations for PCC.

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