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EXPERIMENTAL INVESTIGATION OF THE STRENGTH PROPERTIES OF CONCRETE PRODUCED WITH VOLCANIC ASH AND METAKAOLIN AS PARTIAL REPLACEMENT OF CEMENT

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ABSTRACT

Cement being the binder in concrete production, is an extensive industrial commodity, the production of which leads to the emission of a vast amount of carbon dioxide which causes greenhouse gas emission and global warming. There is need for alternative materials that are environmentally friendly, economical and accessible. The research investigates the strength properties of concrete produced with volcanic ash and metakaolin as a partial cement replacement. Cement was partially replaced at 5%, 10%, 15%, 20%, 25% and 30%. Volcanic-metakaolin Fresh and hardened strength tests on mortar and concrete were carried out by adding 0–30% pozzolana, in which the water-to-binder ratio was 0.5 kept the same for all replacement levels. Density, compressive strength, flexural strength, and water absorption tests were carried out. Incorporation of volcanic ash and metakaolin reduces total voids in concretes. The result showed that VA-MTK has a pozzolanic effect on concrete properties by considering the strength activity index, higher compressive strength, higher flexural and splitting strength comparable to the control concrete 10% pozzolanic content. The maximum compressive strength at 28 days was the 10% VA/MTK as partial cement replacement, which achieved 28.5N/mm^2 compared to the control, which achieved 28.2N/mm^2. The flexural strengths at 10% achieved 5.22N/mm^2, while the control concrete achieved 5.11 N/mm^2. Considering the environmental and strength performance, a 15% cement replacement with metakaolin was convincing. Thus, the research shows that the use of VA/MTK as a partial replacement for cement in concrete, at a lower volume of replacement, will enhance the reduction of cement usage in concretes, thereby reducing the production cost and the environmental pollution from the exploration of cement material and the production of cement.

Keywords: Compressive Strength, Density, Flexural Strength, Metakaolin, Volcanic Ash

INTRODUCTION

Concrete is the most widely used construction material required to exhibit the necessary capacity to serve its intended purpose, dependent upon specific properties. Properties such as strength and durability depend on adequate curing at an early age and hardened state (Nodehi et al., 2022). Concrete is a composite material composed of coarse and fine aggregates bonded with cement paste that hardens over time. The cement and water together form a paste that binds the aggregates to a permanent stone-like material upon hardening. Cement, the binder in concrete production, is an extensive industrial commodity that produces a vast amount of carbon dioxide, which causes greenhouse gas emissions and global warming. Cement production releases significant carbon dioxide (CO_2) to the atmosphere. For each tonne of cement produced, it is estimated that one tonne of CO_2 is released into the environment (He et al., 2019). The amount of CO_2 that results from the modern practices averages about 0.30kg per kg of cement produced, while the number of overall gases produced by the kiln would average as high as twice the amount of cement produced (Petroche & Ramirez, 2022). Cement is one of the essential ingredients of concrete that both contributes to the construction industry and environmental problems (Agboola et al., 2022; Naik, 2020; Mohammad, 2010). As cement manufacturing is responsible for 5% of global greenhouse gas emissions (GHG) (Crawford, 2022; Mikulčić et al., 2016; Kajaste & Hurme, 2016), this process has become a worrying issue due to its negative environmental impact. The effect of increasing carbon emissions on environmental protection has led to worldwide interest in investigating replacements for cement as a construction material.

While Nigeria is committed to actively reducing greenhouse emissions (CO_2 emissions), the trending global issue, the construction industry has also been searching for ways to reduce its production. This leads to research in order to develop alternative materials that could be used as partial replacement, such as rice husk ash, fly-ash, saw dust ash, metakaolin, volcanic ash, waste glass powder (Chowdhury et al., 2015; Rahmat et al., 2024; Ndahi et al., 2024; Agboola et al., 2020). The problems of pollution and other concrete properties have led to research on cement alternatives or substitutes that will fully or partially replace cement in the construction industry (Ogunbode & Hassan, 2011). Dadu (2011) reported that the global move is to reduce the amount of Portland cement content used in the concrete mixtures with cheaper Supplementary Cementitious Material (SCM)/pozzolans to improve specific properties of concrete. The American Society for Testing and Material (ASTM C125-06) defined pozzolan as a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but which will, in finely divided form and the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

These materials are used to create blended cements, improving concrete durability, early and long-term strength, workability and economy (Agboola, et al., 2021; Bjegovic, et al., 2012). Volcanic ash, one of the classifications of Natural pozzolans and an area of study for this research, is environmentally friendly, economical and accessible

(Agboola, et al., 2020). Among the pozzolanic materials used in concrete applications, volcanic ash has been identified as having potential for use in the construction industry. Research indicated that volcanic ash has a chemical composition and phase comparable to traditional SCMS (Dadu, 2011; Agboola et al., 2020). Studies also focused on using volcanic ash as a partial replacement of cement in concrete production (Agboola et al., 2020; Agboola et al., 2021; Dadu, 2011; Olawuyi et al., 2012). Volcanic ash, referred to as "original pozzolan", is a finely fragmented magma or pulverised volcanic rock, measuring less than 2mm in diameter, which is emptied from the vent of a volcano in either a molten or solid state (Olawuyi et al., 2012). Olawuyi et al. (2012) further stated that it has been known for millennia that the mixture of volcanic ash or pulverised tuff (siliceous), with lime, produces hydraulic cement. An examination of ancient Greek and Roman structures provides sample evidence of this cement's effectiveness and durability (Olawuyi et al., 2012).

According to Joergensen (2014), using pozzolan to replace OPC in concrete lowers heat development during hardening and improves the properties of the final concrete structures. Also, the deficiency of volcanic ash (VA) in the optional requirements for a pozzolan allows it to be further researched with the aim of boosting its pozzolanic activity. To assess the practicability of boosting pozzolanic activity of volcanic ash (VA), Metakaolin (MTK) was introduced in the concrete mix. Apart from possessing a high silica content (above the 25% required for a pozzolan), metakaolin (MTK) has potential for excellent binding properties in concrete. Metakaolin is obtained by heat-treating kaolin, a naturally occurring, finely divided, alumina siliceous mineral abundant in Nigeria (Agboola et al., 2024). According to Getso (2014), Kaolin can be obtained in abundance from the following states in Nigeria: Kastina, Plateau, Ogun, Imo, Rivers, Bauchi, Anambra, Kebbi, Ekiti, Kogi, and Akwa Ibom. Matakaolin is produced under controlled temperature to refine its colour and remove inert impurities so that a much higher degree of purity and pozzolanic reactivity can be obtained (Sanjay *et al*., 2013). Therefore, the research aims to assess the strength properties of concrete produced with volcanic ash and metakaolin as partial replacement of cement in concrete to create options for sustainability and availability of alternative cost-effective materials needed to produce concrete.

MATERIALS AND METHODS

Materials

The materials for the laboratory experiment included coarse aggregate, fine aggregate, Cement, volcanic ash, metakaolin and water. Coarse aggregate was obtained from a quarry site within Bauchi metropolis. The fine aggregate was obtained from the Yelwa River flow in Bauchi state. The ordinary Portland cement is the Dangote of Grade 42.5 brand, which was procured from vendors within Bauchi metropolis and conforms to BS EN 196-1 (2016). The particle sizes of fine aggregate were those passing through a sieve with an aperture size of 2.36 mm but retained on sieves of 150µm. It was confirmed to be free from dust and free from deleterious substances and conform to BS 882 (1992). The coarse aggregates used in this study were granite and clean, with a particle size range between 5 mm and 20 mm, which conforms to 882 (1992). Volcanic ash used for this research was obtained from volcanic rock from Kerang in the Mangu local government area of the Plateau state. The volcanic rock is ground through a stone crusher machine, and the mortar and pestle were used to grind it into fine powder. Metakaolin used for this research was obtained from Kaolin in sufficient quantity from the Alkaleri local government area of Bauchi state. The kaolin was grounded using a stone crusher and mortar and pestle was used to grind into fine powder, it was then fired (calcined) in the laboratory at a controlled temperature of 700^{O}C in a kiln furnace, the resulted metakaolin was allowed to cool at room temperature, after cooling the metakaolin was sieved through a 15 µm sieve.

These experiments used portable water that was clean, colourless, odourless, and free of organic matter. For the purpose of this investigation, a mix ratio of 1:2:4 by weight of cement, sand and gravel, and a water-cement ratio of 0.50 was used. The cement in the mix was partially replaced with volcanic ash and metakaolin at intervals of 5% to 30%. The samples with 0% pozzolana served as the control.

Laboratory Tests

Specific Gravity

In determining the specific gravity, a pycnometer (a vessel of 1 liter capacity with a metal conical screw top and a 5mm diameter hole at its apex, giving a water tight connection), tray, scoop, drying cloth and weighing balance were used. The test procedure was carried out per BS 812-2 (1970). The specific gravity was calculated using equation 1.

$$\mathrm{Gs} = \frac{(\mathrm{C}-\mathrm{A})}{(\mathrm{B}-\mathrm{A})(D-A)} \quad (1)$$

Where: A is the weight of the empty density bottle, and it is the stopper, which was clean and dried

B is the weight of the empty density bottle plus water

C is the weight of the empty density bottle plus the sample

D is the weight of the empty density bottle plus water and the sample

Density Test

This was carried out prior to the crushing of the concrete specimen. At the end of each curing period, the concrete specimens were weighed using an electric weighing machine. Density is calculated as the mass of the concrete specimen in kg divided by the volume of the concrete cube (m^3) and expressed in kg/m^3. Density tests were conducted on 100 x 100 x 100mm cube specimens by BS EN 12390-6 (2000).

Compressive Strength Test of Concrete

The compressive strength tests were conducted by BS EN 12390-7 (2009). Cube specimens of 100 x 100 x 100mm were prepared. All the cube specimens were removed from the moulds after 24 hours of casting and cured by total immersion in water until the testing age. Cubes were removed from the curing medium and allowed to drip off and be at saturated surface dry condition before being tested for strength. Compressive strength test was carried out on the cube specimens at ages 7, 14, 28, and 56 days. The cement was replaced with pozzolana at 5% to 30%.

Modulus of Rupture

The modulus of rupture was determined by conducting a simple unreinforced beam test subjected to a point loading. The beam specimens were produced, prepared, and tested following BS EN 12390-5 (2009) guidelines, and the concrete was tested at 7, 14, 28, and 56 days. The test specimens were 100 x 100 x 500 mm beams and were tested under a single-point loading test. The modulus of rupture (Mr) was calculated using Equation 2, which involved measuring the width and depth of the specimen, as well as the length of the span on which the specimen was supported, and the maximum load applied to the specimen. Modulus of rupture (Mr) in N/mm^2 was computed using the equation below.

$$\mathrm{Mr} = \frac{\mathrm{PL}}{bd^2} \quad (2)$$

Water Absorption Capacity Test

This test was conducted at 28 and 56 days curing per BS 1881-122:(1983). Specimens were tested for absorption capacity, and on each day of testing, three cubes each were placed in the electric oven to dry the specimens at 105^0 °c for 72 hours. The specimens were removed from the oven and allowed to cool at room temperature before determining the initial weight, which was recorded as (W_1). The final weight was determined after the concrete specimen had been immersed in water for 30 minutes. It was removed and dried with a cloth; re-weighed and recorded as (W_2). The equation below was used to compute the absorption capacity for the specimens:

Water Absorption Capacity

$$= WA = \frac{W2-W1}{W1} x\, 100 \quad (3)$$

Where: W_1 = Weight of the concrete sample after oven drying

W_2 = Weight of the saturated surface dry concrete sample.

RESULTS AND DISCUSSION

Physical Properties of Materials

Table 1 presents the result on specific gravity of coarse aggregate (gravel), which was determined to be 2.73. The result falls within the specified range of specific gravities for coarse aggregates, as Shetty (2005) stated that the average specific gravity of coarse aggregate varies between 2.6 and 2.8. The Specific gravity of Fine aggregate (Sand) was determined to be 2.59. This falls within the specified range specified by BS 882 of specific gravities of Fine aggregate, as 2.4 to 2.9. The specific gravity of volcanic ash was determined to be 3.21; This value is close to values determined in the research done by Agboola et al. (2020), who stated the specific gravity of coconut shell ash as 3.28. The specific gravity of metakaolin is 2.39. Siddique and Siddique (2008) report a value of 2.50.

Table 1: Specific Gravity of Materials

Materials	Specific Gravity (g)
Fine Aggregate	2.59
Coarse Aggregate	2.73
Volcanic Ash	3.21
Metakaolin	2.39

Strength activity index

The result for the strength activity index of cement mortar is presented in Table 2. The result shows an increasing strength trend at 7 days and 28 days, respectively, for both control mortar and mortar produced with metakaolin and volcanic ash as partial cement replacement. The result also shows that, at both 7- and 28-day curing ages, the strength activity index of 20% VA-MTK/cement mortar meets the minimum requirement specified by ASTM C311, and that the strength activity index of pozzolana must meet 75% of the control strength at 7 and 28 days. This indicates that volcanic ash and Metakaolin are good pozzolanic materials and can replace cement in concrete production.

Table 2: Strength Activity of Cement

% CSA	Compressive Strength (N/mm^2)		Strength Activity Index	
	7 days	28 days	7 days	28 days
0% Control	22.6	31.5	100	100
20%	17.1	26.1	75.7	82.9

Setting Time and Consistency Test of Materials

Figure 1 shows the setting time of Portland cement and composite volcanic ash—metakaolin paste. The setting test corresponds with BS EN 196-3 (1995). Volcanic ash and Metakaolin slightly reduce the cement paste's initial and final setting times. The result shows that the higher the addition of pozzolanic materials, the longer the time it takes for the mortar to set. The lowest setting time was achieved at 0% pozzolana, while the highest setting time was attained at 30% VA-MTK as partial cement replacement.

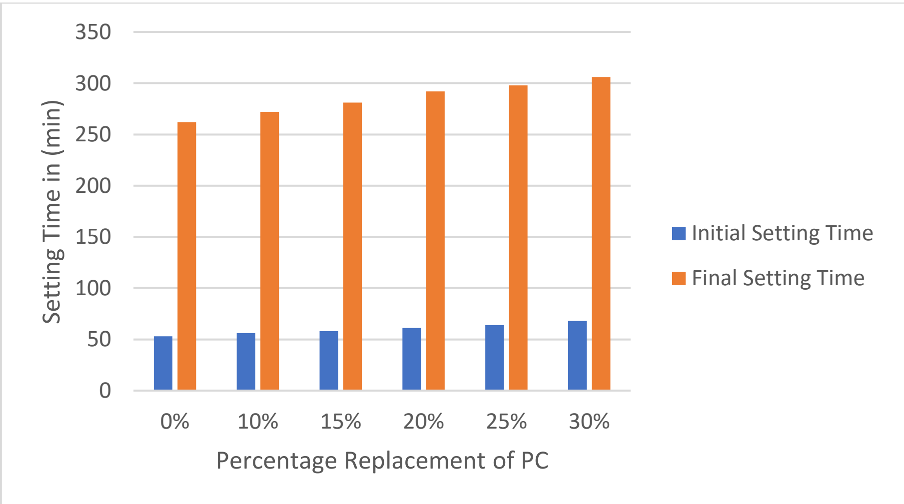

Figure 1: Setting Time Test of Composite VA-MTK as percentage replacement of PC

Workability test

Figures 2 and 3 present the results for the slump and compacting factor tests of concrete made with volcanic ash-metakaolin as partial PC replacement. According to Neville and Brooks (2010) and as specified by BS EN 12350-2 (2000), the degree of workability for the slump test is medium to low from the values of the six different mixes. The slump test value for the Percentage replacement of cement decreases with the increase of pozzolana. For compacting factor test value, the degree of workability ranges from low to medium, which falls within the range specified by BS EN 12350-2 (2000) and Neville and Brooks (2010). Mixes with 0%-15 % show higher workability, while 20%-30 % show lower workability.

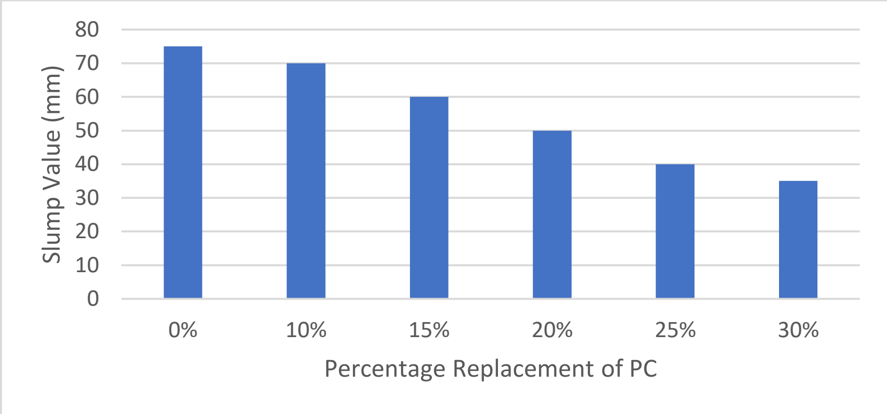

Figure 2: Slump heights Composite VA-MTK in (mm) versus percentage replacement of PC

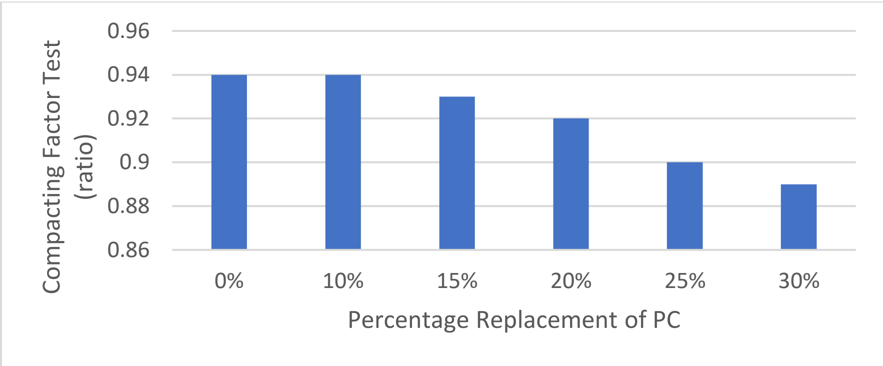

Figure 3: Compacting Factor of Composite VA-MTK versus percentage replacement of PC

Density of Cubes

Figure 4 present the average density of concrete samples produced with ordinary Portland cement and volcanic ash-metakaolin as partial replacement of cement, cured in normal water (H_2O) and weighed at 7, 14, 28, and 56 curing days respectively, and produced at 10%, 15%, 20%, 25% and 30% of volcanic ash and metakaolin as partial replacement of cement respectively. The density of concrete cube samples varies from 2392 kg/m^3 to 2537 kg/m^3, and it increases with increasing curing periods. The result is close to that of Agboola et al. (2020), who report that the density of concrete cubes increases with increasing curing periods. Concrete samples with a density higher than 2600kg/m^3 are called higher density concrete samples (Kazjonovs *et al.,* 2010). Values obtained at 28 days exceeded the 2400 kg/m^3 expected for a normal-weight concrete. Therefore, concrete produced with volcanic ash and metakaolin as partial replacement of cement in concrete is a concrete with ordinary density, though samples with pozzolanic material replacements were denser than the control samples.

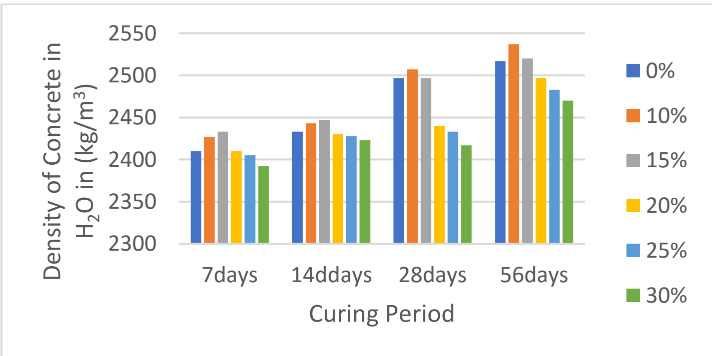

Figure 4: Density of concrete specimen cured in H_2O

Beam Density

From Figure 5 analysis can be drawn that the concrete beams produced with volcanic ash and metakaolin achieved a density of 2467 kg/m^3 to 2537 kg/m^3 at 28 days, and achieved a density of 2490 kg/m^3 to 2562 kg/m^3 at 56days, the result is close to that of Agboola et al., (2020) who report that the density of beam increase with increase curing periods, the result from this study conform to the density of normal-weight concrete, which favor higher durability due to the higher values than 2400 kg/m^3 value recorded for beam sample which is in line with the work carried out by (Kazjonovs *et al.,* 2010).

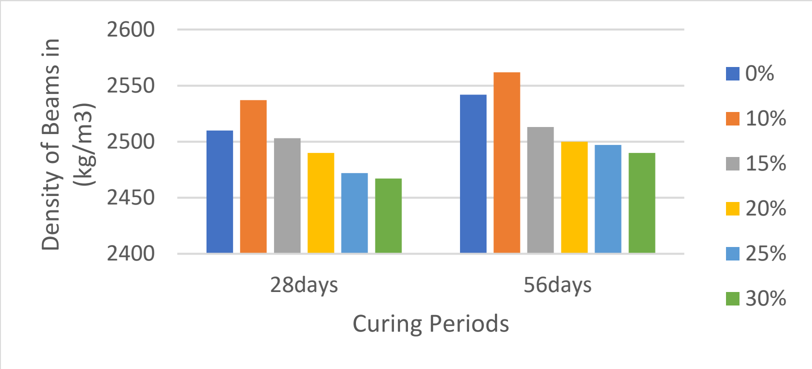

Figure 5: Density of concrete Beams

Compressive strength of concrete specimens

Figure 6 shows the compressive strengths of Portland cement/volcanic ash-metakaolin concrete specimens crushed at 7-, 14-, 28-, and 56-day hydration periods. Concrete samples with 10%, 15%, 20%, 25% and 30% replacements of Portland cement with volcanic ash and metakaolin achieved 28.5 N/mm^2, 27.6 N/mm^2, 25.6 N/mm^2, 24.5 N/mm^2 and 23.9 N/mm^2, respectively, while 0% replacement achieved 28.2 N/mm^2 at 28 days. The result shows that the 10% cement replacement shows a high strength ratio beyond control concrete, with 10% replacement showing a strength increase of 1.05% above control concrete. At 56 days, concrete produced with 10%, 15%, 20%, 25% and 30% replacements of Portland cement with volcanic ash and metakaolin achieved 29.3 N/mm^2, 28.2 N/mm^2, 26.3 N/mm^2, 25.1 N/mm^2 and 23.9 N/mm^2, respectively, while 0% replacement achieved 28.6 N/mm^2. This represents a 2.36% increase for 10% replacement of cement in concrete with volcanic ash and metakaolin over the control concrete in compressive strength. The result is in range with the work carried out by (Agboola, et al., 2020; Jehad & Kemal, 2014). The compressive strength achieved for control and percentage replacement was below the BS EN 197-01 (2000) requirement, which states that the concrete sample should achieve 32.5 N/mm^2 at 28 days. This could be due to the method of compaction applied (manual compaction) during the concrete production. The standard requires the use of mechanical compaction to achieve this result.

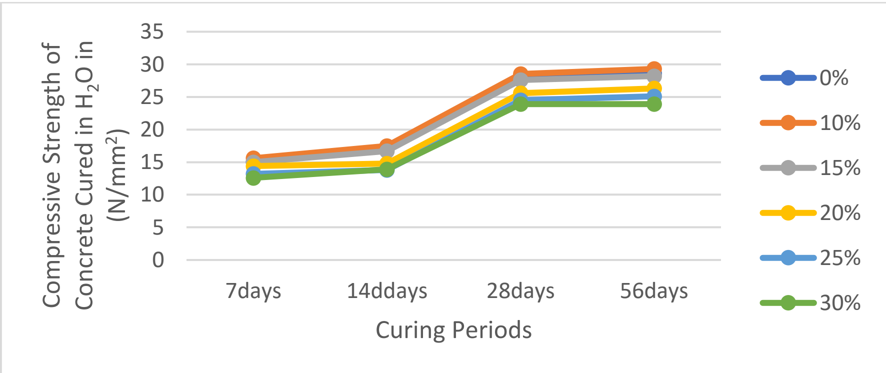

Figure 6: Average compressive strength of hardened concrete specimen cured in H_2O

Flexural Strength

Figure 7 presents the flexural strengths of Portland cement and volcanic ash-metakaolin concrete specimens tested at 28- and 56-day hydration periods. Concrete specimens with 0% replacement achieved 5.11 N/mm^2, while 10%, 15%, 20%, 25% and 30% replacement of Portland cement with volcanic ash and metakaolin achieved 5.22 N/mm^2, 4.86 N/mm^2, 4.61 N/mm^2, 4.33 N/mm^2 and 4.20 N/mm^2 at 28 days. This represents a 2.11% strength decrease of 0% concrete from 10% concrete produced with volcanic ash and metakaolin as cement replacements in strength.

Concrete specimens with 0% replacement achieved 5.28 N/mm^2, while 10%, 15%, 20%, 25% and 30% replacement of Portland cement with volcanic ash and metakaolin achieved 5.31 N/mm^2, 4.88 N/mm^2, 4.63 N/mm^2, 4.43 N/mm^2 and 4.24 N/mm^2 at 56 days. This represents a 0.56% decrease in compressive strength of 0% concrete from 10% concrete produced with volcanic ash and metakaolin as cement replacements. The strength increase in concrete could be perhaps as a result of the type of pozzolana used in concrete production as posited by Vijayakumar *et al.* (2013); Agboola et al. (2020) and Agboola et al. (2024b;2024c) who posited that the flexural strength of concrete increases with increasing curing days for both regular concrete and concrete produced with pozzolana. The percentage replacement of volcanic ash-metakaolin up to 15% gives higher flexural strength because it makes good bonding and is an excellent filler between the aggregates and the paste of the concrete.

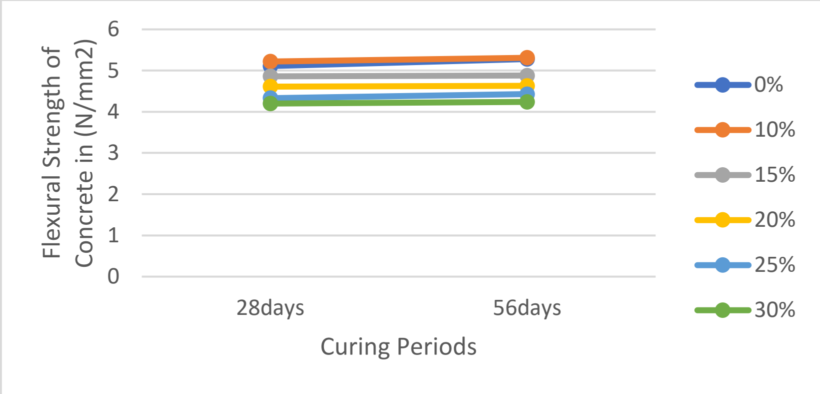

Figure 7: Average Flexural Strength of Concrete Beams

Water absorption tests of concrete

Figure 8 presents the water absorption test result of Portland cement/metakaolin-volcanic ash concrete specimens cured in water (H_2O) and tested at 28- and 56-day hydration periods. The degree of sorption of the concrete specimen tallies with the work conducted by Pitroda and Shah (2014), which stated that the average absorption of the concrete test specimens shall not be greater than 5%—the level of sorptivity of concrete samples reduced with increase in curing days. Concrete samples with 0% replacement absorbed 1.76%, while 10%, 15%, 20%, 25% and 30% replacement absorbed 1.79%, 1.88%, 1.98%, 2.14% and 2.33% respectively. Also, at 56 days, concrete samples with 0% replacement absorbed 1.66%, while 10%, 15%, 20%, 25% and 30% replacement absorbed 1.73%, 1.86%, 1.94%, 2.10% and 2.15% respectively. At 28 days, 0% replacement absorbed less curing agent than 10%, 15%, 20%, 25% and 30% replacement. The result of this research is in line with the work of Agboola et al. (2020), who stated that volcanic ash has a glassy structure and is impermeable to water and chloride ions. Falade et al. (2024) also assert that metakaolin aids in the reduction of concrete permeation.

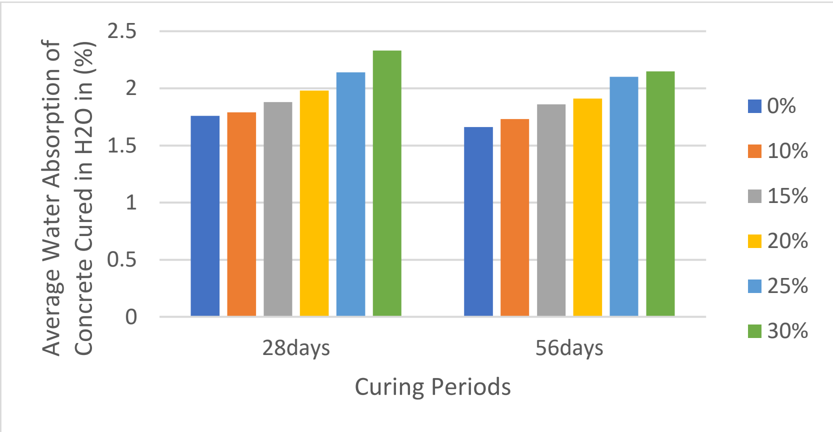

Figure 8: Average Water Absorption of Hardened Concrete Specimen

CONCLUSION

The density of concrete increases with the curing period. There was more density loss in control concrete samples than in 5% and 10% volcanic ash-metakaolin concrete samples. The workability of concrete at all replacement levels was lower than that of ordinary Portland cement concrete (control) specimen for slump, while concrete with 10% cement replacements had workability compared to that of control concrete samples for the compacting factor. The control concrete had the maximum compressive strength at 7 days and 28 days. It was observed that up to 10% replacement of cement with volcanic ash and metakaolin resulted in an increase in the strength of concrete at later stages of 56 and 90 days. Compressive strength of concrete increases at higher curing ages and with volcanic ash and metakaolin as cement replacement up to 10%. The flexural strength results revealed that the concrete with a 10% replacement level at the ages of 28 and 56 days was comparable to that of control concrete and met the expected 4.0N/mm^2 flexural strength of concrete at 28 days. Adding volcanic ash and metakaolin in concrete significantly reduces water absorption by blocking capillary voids and making a denser concrete microstructure, mainly through the pozzolanic materials and cement's pozzolanic reaction. Replacement of cement up to 20% by metakaolin has reduced compressive strength range only marginally, and therefore it still has potential for applications in flexible and rigid pavements and mass concrete. The results indicate a potential use of volcanic ash and metakaolin in concrete production for structural and non-structural building materials—the addition of 30% VA-MTK yields acceptable strength of concrete for non-structural purposes. Strength properties of hardened concrete specimens showed that concrete with 10% replacement of cement with metakaolin and volcanic ash has optimal compressive and flexural strengths for pozzolanic concrete. Generally, metakaolin as cement replacement up to 20% improves the mechanical properties of concrete, in addition to protecting the environment from pollution compared to conventional concrete. Durability properties, such as exposure to other aggressive environments and elevated temperature, should be carried out on a composite of metakaolin and volcanic ash concrete as cement replacement. Research should be carried out on the effects of admixtures on the properties of composite metakaolin–volcanic ash concrete, especially admixtures that may improve the curing of pozzolans in general. Research should be carried out on the effects of a different water-cement ratio on the porosity of metakaolin–volcanic ash concrete.

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