Strength Performance of Concrete Produced with Volcanic Ash as Partial Replacement of Cement

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Abstract: There is global need for the preservation of natural resources, reduction of carbon dioxide emission and sustainability of concrete structures; this and other problems associated with material production have fueled the search for alternative cementing material to produce environment-friendly construction materials. The mining of cement raw materials leads to depletion of natural resources and degradation of environment. Cement production also pollutes the environment due to the emission of CO₂. Volcanic ash is suitable material for replacement of cement in concrete production. Chemical composition of volcanic ash as well as the specific gravity, bulk density, workability, compressive strength, split tensile strength and flexural strength properties of varying percentage of volcanic ash blended cement concrete and 100% cement concrete of mix ratio 1:2:4 and water-cement ratio of 0.5 were examined and compared. Slump test and compacted factor test was carried out to check the effect of volcanic ash on the workability of fresh concrete. Volcanic ash partially replace cement in the order of 0%, 5%, 7.5%, 10%, 12.5%, 15% and 20% were cast. The concrete were tested at the ages of 7, 14, 21 and 28 days. The results showed that volcanic ash is a good pozzolan with combined SiO₂, Al₂O₃ and Fe₂O₃ of 74.8%. The highest compressive strength at 28 days was 29.2N/mm²; in addition 5% replacements of cement with volcanic ash present same value with the control concrete. The highest split tensile strength at 28 days was 3.42N/mm²; in addition 5% replacements of cement with volcanic ash present same value with the control concrete. The highest flexural strength at 28 days was 4.75N/mm²; in addition 5% replacements of cement with volcanic ash present higher value of 4.91N/mm²; which is higher than the control concrete. The strength test results indicated that volcanic ash concrete gave better strength compared to control samples. A 10% replacement of cement with volcanic ash was found convincing and indicate the optimum replacement level of cement. However can be used up-to 15% replacement level due to its promising result. The research recommends use of volcanic ash as partial replacement of cement in aggressive environment, increased water cement ratio.

Keywords - Chemical Properties, Specific Gravity, Bulk Density, Workability, Compressive Strength, Split Tensile Strength, Flexural Strength, Volcanic Ash.

I. INTRODUCTION

Cement as a material is used as a major constituent in the production of concrete. Cement as an important constituent of concrete which is gradually becoming expensive compared to other ingredients of concrete and its exploitation is posing threat to the environment. The mining of its raw materials leads to depletion of natural resources and degradation of environment. Its production pollutes the environment due to CO₂ emission. The emission of CO₂ is such that for every ton of cement produced almost a ton of CO₂ is emitted [1 and 2]. In view of this and other problems associated with production and use of cement, a lot of research efforts were made to find an alternative material that will partially or fully replace cement in concrete production.

A way out is replacing a proportion of cement with cheap and available pozzolanic materials. [3] defined pozzolana as “siliceous or siliceous and aluminous material which in themselves have little or no cementitious properties but in finely divided form and in the presence of moisture they can react with calcium hydroxide which is liberated during the hydration of portland cement at ordinary temperatures to form compounds possessing cementitious properties”. [4] classify pozzolans as either natural or artificial pozzolan. Natural pozzolans include; clay and shales, opaline cherts, diatomaceous earth, volcanic ash, volcanic tuffs and pumicities, while Artificial pozzolans include; fly ash, blast furnace slag, silica fume, rice husk ash, metakaoline and surkhi. In view of this, the concept of using volcanic rock in the production of replacement for cement which require little energy in its processing and is environmentally friendly was developed to be used as an alternative to cement in concrete production. Volcanic ash, being one of the classifications of natural pozzolans, is environmentally friendly, economical and accessible. Volcanic ash, referred to as “original pozzolan” or “natural pozzolan”; is a finely fragmented magma or pulverized volcanic rock, measuring less than 2mm in diameter, which is emptied from the vent of a volcano in either a molten or solid state [5]. [5] Further state that it has been known for millennia that the mixture of volcanic ash or pulverized tuff (siliceous), with lime produces reduced the permeability of concrete and improves its

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resistance to chemical attack [6]. According to [7] the use of pozzolan to replace OPC in concrete lower heat development during hardening and improve durability of the final concrete structures. Other researches carried out include using By-products mineral admixtures such as fly ash, rice husk ash and ground granulated blast furnace slag contribute to improvement of concrete performance (for example, high strength, high durability and reduction of heat of hydration) as well as reduction of energy and carbon dioxide generated in the production of cement. [8] uses fly-ash to replace ordinary Portland cement with fly ash at 20%, 30%, 40%, 50%, 60% and 70% replacements of cement. The results showed that the compressive strength decreases at 3, 7 and 28 days as the replacement of fly ash approach 30% replacement. Groundnut shell ash was used by Mahmoud et al., (2012) at 10%, 20%, 30%, 40% and 50% as a partial replacements of cement in sandcrete blocks production. The optimum replacement achieved at 20% with a corresponding strength of 3.58 N/mm². However various researchers carried out research on volcanic rock thus [10] is one out of many researchers that carried out a research on Jos Plateau volcanic ash to replaced OPC with 5%, 10%, 15%, 20%, 30% and 40% the results showed that 5% and 10% were the best replacement by achieving highest compressive strength. [5] Used volcanic ash from Kerang of Mangu Local Government Area of Plateau State to replaced OPC with 10%, 20% and 30% the results showed that 20% was the optimum replacement level with greatest compressive strength. Extensive study is needed to find the optimum percentage replacement of volcanic ash which can be used without any effect on the properties of the produced concrete. Also, there is a need to study the possibility of using the volcanic ash as a raw material in the production of cement. Currently world production rate of cement increasing and is expected to grow significantly in the nearest future. This increasing demand for cement is expected to be met by partial cement replacement. This research examined the strength performance of concrete produced with volcanic ash as partial replacement of cement to determine the potential of volcanic ash in produce sustainable concrete.

II. MATERIALS AND METHODS
All the materials used for laboratory experiment were procured from the immediate environment. The relevant standards were used in the process of conducting the experiments.

Materials: The materials for this study included, coarse aggregate fine aggregate, Cement, volcanic ash and water. Volcanic ash was sourced from Kerang Mangu local government of Plateau State, Nigeria. It is a rock material which is predominant in the locality. The rock form and its particulate are as a result of volcanic eruption which has been there for decades. The coarse aggregate was obtained from a quarry site within Bauchi metropolis. The fine aggregate was obtained from Bayara River-flow in Bauchi state. The ordinary Portland cement is the brand of Dangote of Grade 42.5 which was procured from vendors within Bauchi metropolis. Samples of bottle fragments collected were washed and dried then crushed. To pulverize the volcanic stone into powder, a locally fabricated mill was used. The ash was sieved through a 75μm sieve. 

Chemical Analysis of VA: The volcanic ash was analyzed to determine its suitability as a pozzolana. The chemical analysis was conducted at Sodexmines Nigeria limited Plateau State, Nigeria, using EDXRF method. The machine used to carry out this test was Minipal 4 Energy Dispersive X-Ray Fluorescence. The major oxides, minor oxides and Lost on Ignition (LoI) were measured and recorded. 

Workability Tests of the wet VA-Cement Concrete: The Compacting factor test was conducted in accordance with [11]. Slump test was also conducted using the relevant cone for measurements. The tests were conducted in accordance with [11].  

Density Test: This was carried out prior to crushing of the concrete specimen. At the end of each curing period, the concrete specimens were weighed using an electric weighing machine balance. Density is calculated as mass of concrete specimen in (kg) divided by volume of concrete cube (m³) and expressed in kg/m³.

Compressive Strength Test for volcanic ash blended cement concrete: The compressive strength test was conducted in accordance with [12]. The 1: 2: 4 mix ratios were adopted using a water cement ratio of 0.5. The ratio was that of OPC (with replacement levels of VA), fine aggregate and coarse aggregate respectively. The cubes were cast for cement replacement levels at 0%, 5%, 7.5%, 10%, 12.5%, 15% and 20%, and cured for 7 days, 14 days, 21 days and 28 days respectively. For each mix, 3 cubes were crushed to obtain the average strength of the concrete samples. The compressive strength is the ratio of the weight of cube and the cross sectional area.

Split Tensile Strength Test for volcanic ash blended cement concrete: In the determination of split tensile strength of cylindrical concrete specimen, the procedure was in accordance with [13]. The cylinder were cast for cement replacement levels at 0%, 5%, 7.5%, 10%, 12.5%, 15% and 20%, and cured for 7 days, 14 days, 21 days and 28 days respectively. For each mix, 3 cylindrical specimens were crushed to obtain the average strength of the concrete samples. Jig with packing strips and loading pieces were carefully positioned along the top and bottom of the plane of loading if the specimen. The jig was then place on the machine so that the specimen is placed centrally. The upper platen was parallel to the lower platen. The load was applied steadily and without shock such that the stress in increased at a rate within the range of 0.04 MPa/s to 0.06 MPa/s, the rate was maintained at ± 10% until failure. The split tensile strength Fct in N/mm² was computed using equation 1.

\[
Fct = \frac{2F}{\pi x L x d}
\]

where: 
F is the maximum load in (KN) 
L is the average measured length in (mm) 
d is the average measured diameter in (mm) 

The split tensile strength is measured is expressed to the nearest 0.05 MPa.

Flexural Strength Test for volcanic ash blended cement concrete: In the determination of flexural strength of concrete beams, the procedures as in accordance with [12] were followed. The beams were cast for cement replacement levels at 0%, 5%, 7.5%, 10%, 12.5%, 15% and 20%, of volcanic ash and cured for 7 days and 28 days respectively.
For each mix, 3 beams were crushed to obtain the average strength of the concrete samples. The compressive strength is the ratio of the weight of cube and the cross sectional area.

**Specific Gravity:** In determining the specific gravity of aggregate a pycnometer (a vessel of 1 litre 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 in accordance to [15]. The apparatus used during the test include density bottle and stopper, funnel, spatula and weighing balance.

The specific gravity of aggregates was calculated using equation 2.

\[ G_s = \frac{C - A}{B - A} \]

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

B is the weight of empty density bottle plus water

C is the weight of empty density bottle plus aggregate sample

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

**Bulk Density and Voids:** In determining the bulk density and void for volcanic ash a weighing balance, metal cylinder of 7dm³ capacity, scoop, straight edge, tamping rod of 16mm diameter and a drying duster (towel) were used. The test was carried out according to [15]. The bulk density of aggregates was calculated using equation 3.

\[ D = \frac{M}{V} \]

Where D is the density of the aggregate specimen in kg/m³

M is the mass of the aggregate specimen in kg

V is the volume of the aggregate specimen in m³

Also mass of the aggregates sample was determined by subtracting the weight of empty container from the weight of container plus aggregate sample using equation 4.

\[ m = B - A \]

Where m is the mass of the aggregate specimen in kg

A is the weight of the empty container in kg

B is the weight of container plus aggregate sample in kg

III. RESULTS AND DISCUSSION

**Chemical Analysis:** The result of the chemical analysis showing the oxide composition of VA is presented in Table 1. The total combined content of silica, alumina and ferric oxides was 74.8%. ASTM C618 (1981) specifies that for a pozzolana to be used as a cement blend in concrete it requires a minimum 70% amount combined of silica, alumina and ferric oxides. Hence VA from Kernag Mangu of Plateau State shows that VA as possessing pozzolanic characteristics. The proportion of VA content and with highest value at 20% replacement level produces the optimum strength. However addition at 14 days and 21 days curing ages the strength reduction in strength as compared to 0% plain concrete. In 28 days curing the result shows increased compressive strength with from 5% to 10% replacement of cement with volcanic ash as compared to 0% control concrete. Which shows increase in strength of 0.56% at 5% cement replacement, 1.65% strength increase at 7.5% and 3.76 increase in strength at 10% as compared to 0% replacement, while cement replacement above 10% shows reduction in strength as compared to 0% plain concrete. In 28 days curing the result of the experimental study shows that 7.5% and 10% replacement of cement with volcanic ash indicate higher strength than all other replacement and the control concrete specimen, while 5% replacement of cement with volcanic ash has same value with the control concrete. The 5%, 7.5% and 10% level replacement shows high strength over the control specimen and other replacement levels, however higher replacement levels beyond 10% shows decrease in strength index. It is indubitable that 10% replacement level produces the optimum strength. However the trend of the compressive strength shows that replacing cement with 10% shows it is the ideal replacement level but up-to 15% shows improved and promising strength.
Split tensile strength of the volcanic ash blended cement Concrete: The results of the tensile strength test are shown in Figure 7. The tensile strength at 7 days shows increased strength index at 5% - 15% beyond the control concrete, while above 15% the strength decreases. At 14 days replacement level at 5%, 7.5% and 10% shows better strength than 0% but above 10% replacement ratios shows reduction in strength as compared to the control specimen. At 21 days the strength of concrete at the strength index shows same properties at 5%, 7.5% and 10% indicated better strength than 0% cement replacement, while at 28 days curing ages 7.5% and 10% cement replacement levels shows increased strength above plain concrete. While 15% replacement level shows same strength index with 0% replacement but better than 5%, 12.5% and 20% replacement levels. However 7.5% and 10% shows better strength than 0% and it was obvious that 10% present optimum cement replacement.

Flexural strength volcanic ash blended cement Concrete: The results of the flexural strength test are shown in Figure 8. The flexural strength was tested at 7 and 28 days only. At 7 days the strength of the beams at 5% 7.5%, 10% and 12.5% increased beyond the control, while 15% has same value with the control specimen. Furthermore at 28 days 5%, 7.5%, 10% and 15% increased beyond the control at 0%, while 12.5% maintain same strength index with 0% replacement ratio. 20% cement replacement shows decreased in strength as compared to the control sample. It is apparent that 10% replacement level produces the optimum strength. However the optimum volcanic ash replacement ratio of cement is 10%.

Table 1: Energy Dispersive X-Ray Fluorescence (EDXRF) Method of kerang Mangu Volcanic Ash

| Elements                      | % Composition |
|-------------------------------|---------------|
| Aluminum Oxide (Al₂O₃)        | 18.60         |
| Silicon Oxide (SiO₂)          | 32.10         |
| Iron Oxide (Fe₂O₃)            | 24.10         |
| Potassium Oxide (K₂O)         | 0.70          |
| Calcium Oxide (CaO)           | 2.30          |
| Titanium Oxide(TiO₂)          | 3.50          |
| Vanadium Oxide (V₂O₃)         | N.D           |
| Chromium Oxide (Cr₂O₃)        | 0.03          |
| Manganese Oxide (MnO)         | 0.10          |
| Magnesium Oxide (MgO)         | 2.10          |
| Nickel Oxide (NiO)            | 0.30          |
| Sodium Oxide (Na₂O)           | 0.10          |
| Sulphur trioxide (SO₃)        | N.D           |
| Loss on Ignition (LOI)        | 14.20         |

Table 2: Specific Gravity Test on Coarse Aggregate

| Trial                          | Trial 1 | Trial 2 | Trial 3 |
|-------------------------------|---------|---------|---------|
| Weight of empty cylinder (M₁) g | 117.4   | 117.6   | 117.6   |
| Weight of cylinder + sample (M₂) g | 224.7   | 257.8   | 255.1   |
| Weight of cylinder + water + sample (M₃) g | 504.6   | 524.6   | 525.2   |
| Weight of cylinder + water (M₄) g | 496.2   | 436.8   | 435.3   |
| Specific Gravity = | (M₂−M₁)/(M₄−M₁)−(M₃−M₂) | 2.75    | 2.68    | 2.89    |
| Average Specific Gravity | 2.77    |         |         |

Table 3: Specific Gravity Test on Fine Aggregate

| Trial                          | Trial 1 | Trial 2 | Trial 3 |
|-------------------------------|---------|---------|---------|
| Weight of empty cylinder (M₁) g | 13.7    | 12.4    | 13.6    |
| Weight of cylinder + sample (M₂) g | 646.3   | 308.2   | 628.2   |
| Weight of cylinder + water + sample (M₃) g | 646.3   | 308.2   | 628.2   |
| Weight of cylinder + water (M₄) g | 596.0   | 247.2   | 594.5   |
| Specific Gravity = | (M₂−M₁)/(M₄−M₁)−(M₃−M₂) | 2.49    | 2.92    | 2.52    |
| Average Specific Gravity | 2.64    |         |         |

Table 4: Specific gravity test on Volcanic Ash

| Trial                          | Trial 1 | Trial 2 | Trial 3 |
|-------------------------------|---------|---------|---------|
| Weight of empty cylinder (M₁) g | 13.4    | 13.6    | 13.7    |
| Weight of cylinder + sample (M₂) g | 64.5    | 65.2    | 65.2    |
| Weight of cylinder + water + sample (M₃) g | 119.6   | 119.3   | 119.6   |
| Weight of cylinder + water (M₄) g | 84.1    | 83.8    | 83.4    |
Specific Gravity: \[ \text{Specific Gravity} = \frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_2)} \]

Average Specific Gravity: 3.28

Table 5: Bulk Density for Coarse Aggregate

| Trials | COMPACTED | UNCOMPACTED |
|--------|-----------|-------------|
|        | C1        | C2          | C3          | C1        | C2          | C3          |
| Weight of empty cylinder \((M_1)\) kg | 8.10      | 8.10       | 8.10       | 8.10      | 8.10       | 8.10       |
| Volume of cylinder \((10^{-3})\) m\(^3\) | 1.55      | 1.55       | 1.55       | 1.55      | 1.55       | 1.55       |
| Weight of cylinder + sample \((M_2)\) | 11.01     | 10.68      | 10.64      | 10.25     | 10.29      | 10.26      |
| Weight of sample \((M_2 - M_1)\) kg | 2.91      | 2.58       | 2.54       | 2.15      | 2.19       | 2.16       |
| Bulk density \(\rho\) \(=\frac{M_1 - M_2}{\text{volume}}\) | 1877     | 1665     | 1639     | 1387     | 1413     | 1394     |
| Average = \(\frac{C_1 + C_2 + C_3}{3}\) | 1727      |            |            | 1398      |           |            |
| Percentage void \(\rho\) \(=\frac{\text{weight of compacted CA} - \text{weight of uncompacted CA}}{\text{weight of uncompacted of CA}}\) | 23.53 | | |

Table 6: Bulk Density for Fine Aggregate

| Trials | COMPACTED | UNCOMPACTED |
|--------|-----------|-------------|
|        | C1        | C2          | C3          | C1        | C2          | C3          |
| Weight of empty cylinder \((M_1)\) kg | 8.10      | 8.10       | 8.10       | 8.10      | 8.10       | 8.10       |
| Volume of cylinder \((10^{-3})\) m\(^3\) | 1.55      | 1.55       | 1.55       | 1.55      | 1.55       | 1.55       |
| Weight of cylinder + sample \((M_2)\) | 10.46     | 10.45      | 10.48      | 10.14     | 10.20      | 10.19      |
| Weight of sample \((M_2 - M_1)\) kg | 2.36      | 2.35       | 2.38       | 2.04      | 2.10       | 2.09       |
| Bulk density \(\rho\) \(=\frac{M_1 - M_2}{\text{volume}}\) | 1523     | 1516     | 1535     | 1316     | 1355     | 1348     |
| Average = \(\frac{C_1 + C_2 + C_3}{3}\) | 1525      |            | 1340      |           |            |            |
| Percentage void \(\rho\) \(=\frac{\text{weight of compacted FA} - \text{weight of uncompacted FA}}{\text{weight of uncompacted of FA}}\) | 13.81 | | |

Table 7: Bulk Density for Volcanic Ash

| Trials | COMPACTED | UNCOMPACTED |
|--------|-----------|-------------|
|        | C1        | C2          | C3          | C1        | C2          | C3          |
| Weight of empty cylinder \((M_1)\) kg | 8.10      | 8.10       | 8.10       | 8.10      | 8.10       | 8.10       |
| Volume of cylinder \((10^{-3})\) m\(^3\) | 1.55      | 1.55       | 1.55       | 1.55      | 1.55       | 1.55       |
| Weight of cylinder + sample \((M_2)\) | 10.72     | 10.75      | 10.75      | 10.41     | 10.43      | 10.43      |
| Weight of sample \((M_2 - M_1)\) kg | 2.62      | 2.65       | 2.65       | 2.31      | 2.33       | 2.33       |
| Bulk density \(\rho\) \(=\frac{M_1 - M_2}{\text{volume}}\) | 1690     | 1710     | 1710     | 1490     | 1503     | 1503     |
| Average = \(\frac{C_1 + C_2 + C_3}{3}\) | 1703      |            | 1499      |           |            |            |
| Percentage void \(\rho\) \(=\frac{\text{weight of compacted VA} - \text{weight of uncompacted VA}}{\text{weight of uncompacted of VA}}\) | 13.61 | | | | | |

Figure 1: Slump Test

Figure 2: Compacting Factor Test

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Volcanic ash was cleaned, dried, then grinded and sieved. The oxide composition of the ash showed that it possess and can be used as a pozzolanic material with essential constituent of a pozzolana which include 32.1% SiO$_2$, 18.6% Al$_2$O$_3$ and 24.1% Fe$_2$O$_3$ content summing up-to to 74.8% as

IV. CONCLUSION

Volcanic ash was cleaned, dried, then grinded and sieved. The oxide composition of the ash showed that it possess and can be used as a pozzolanic material with essential constituent of a pozzolana which include 32.1% SiO$_2$, 18.6% Al$_2$O$_3$ and 24.1% Fe$_2$O$_3$ content summing up-to to 74.8% as
The VA was used to replace cement at 5% - 20% in ratios. The workability of the fresh mixes fell within the low and medium classifications. The Compressive strengths declined at above 10% replacement level of cement at 28 days curing, the result also which indicates up-to 15% replacement levels meet the requirement of BS EN 206-1:2000 for class C25/30 and C20/25 respectively for heavy weight concreting and LC25/28 and LC20/22 respectively for light weight concreting. In addition at 28 days the tensile strength decreased above 15% while the flexural strength also decreases at above 15% replacement levels; however 10% replacement level presents the highest strength index. The study suggests that volcanic ash could be replaced up-to 15% with 10% replacement level having the best mix using W/C ratio of 0.5. The density related values shows similar result with reduced density above 15% cement replacement with volcanic ash at 28 days. The research concluded that volcanic ash is a good pozzolanic material for concrete and at 10% optimum replacement levels can produce very strong concrete but can be used up-to 15%. Further study are recommended on other properties such as setting times, water absorption capacity, permeability, shrinkage resistance, fire resistance, durability on concrete and mortars made with volcanic ash cement replacements. Admixtures may be added to improve performance, also using a different mix and altering water cement ratio is also recommended.

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