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Influence of Dicalcium Silicate and Tricalcium Aluminate Compounds in Different Local Cement Brands on the Compressive Strength of Normal Concrete

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Abstract. The mould-ability of concrete into intricate forms and the versatility of its constituent materials has made concrete to be the most preferred construction material. However, in developing nations such as Nigeria, poor quality of concrete is listed among the common causes of building collapse. Thus, this study investigated the effects of chemical compounds of four commonly used local ordinary Portland cement brands on the compressive strength of normal concrete. The cement was labelled brands A, B, C, and D, respectively, while all the other constituent materials remained constant in this study. The HACH DR 200 direct reading spectrophotometer method was used to analyze the composition of the oxide in each of the cement samples, while the Bogue composition formula was used to estimate the compound compositions of the cement samples. A designed mix proportion of 1:2:4 (cement: sand: granite) at water-cement ratio (w/c) of 0.6 was used to produce the concrete with an expected target strength of 25 N/mm^2. Also, the initial and final setting time of the cement samples and the workability of the concrete mixes were determined. Forty-Eight (48) numbers cube samples were cast and tested for compressive strength at 3, 7, 14, and 28 curing days, respectively, using a 150 mm concrete cubes. The result shows the setting time of the cement samples to be within an acceptable period. Also, results indicated that the cement brands have a significant percentage of Tricalcium Silicate (C_3S) content and low percentage Dicalcium Silicate (C_2S) content responsible for faster hydration rate and higher early strength gain of the concrete. However, it was observed that a higher percentage of Tricalcium aluminate (C_3A) leads to higher strength gain from 7 to 28 days of curing age.

Introduction

All over the world, many types of materials are used for infrastructure construction; however, concrete remains the most universally preferred materials for structural buildings than any other materials[1]. The excellent property of concrete in compressive strength, ability to be adapted to virtually any form, and excellent fire resistance coupled with the availability of constituent materials have all contributed to making it to be adopted massively worldwide [1 – 3]. In a study by Penttala [2], it was stated that concrete is one of the most malleable and continuously evolving building materials around the world. Studies within the last few years have shown that concrete can be transformed into a custom-made material consisting of several new constituents to meet the particular requirements of the construction industry [3 – 7]. The desire to meet the needs of the ever-increasing population of the world has led to an overstretching demand for essential infrastructural development and therefore, higher demands for concrete materials. Concrete is mostly useful in compressive, but weak in tension, for which it is regularly reinforced with tensile such as steel. Steel is manufactured under controlled environment and the properties easily certified, making it easier for adoption for safe construction [8]. Conversely, concrete properties vary considerably because of the influence of many internal and external factors involved in the production. According to the study of Ede et al. [9] that concrete quality is hard to guaranteed due to factors such as quality of cement, types of aggregates, the procedure of mixing, placement, compaction and operators' skill.

Furthermore, concrete elasticity is somewhat constant under low stress but decreases excessively at higher stress as cracking of matrix begins. Other known characteristics of concrete is a low coefficient of thermal expansion and shrinkage as it matures. Concrete is a composite material that is highly influenced by the water-to-cement ratio adopted, aggregates or cement types used, or by production methods. Enough water is needed for good mixing and for the concrete to be liquid enough for effective pouring and spreading. The amount of cement must be proportionate to the aggregate for enhanced durability. Fine aggregate sizes fluctuate between 0.025 and 4.75 mm while coarse aggregates go from 4.75 to 38 mm [3]. Aggregates must be free of silt or any harmful materials to reduce the risk of undesirable chemical reactions of organic soil compounds. Environmental factors such as temperature and moisture have a great influence on concrete strength.

In Nigeria, most of the engineering and building structures are made of concrete material [5], [9]. Meanwhile, in recent years, Nigeria is becoming known for the incidence of frequent collapses of building structures, and weak quality concrete has been variously identified as being responsible for the collapsed [9 - 11]. Based on these facts, this research is influence to examine the performance of the commonly used Portland cement in the strength development of concrete used for construction. This will help to further enrich the understanding of professionals and policymakers and guide towards improving the quality of structural concrete production in Nigeria. Consequently, this study examines how the chemical composition of four commonly available Portland cements brands available in the Nigerian market affect compression of normal strength concrete. The influence of chemical oxides of the different cement brands on the compressive strength was analyzed. Some fundamental aspects of normal concrete constituent materials such as cement, aggregates and water, and aspects of concrete technology relevant to this research are presented.

Review of Basic Aspects of Concrete Technology

Concrete is of two principal types; the lightweight and dense-weight concrete. According to International Energy Atomic Agency (IAEA), dense concrete is the most commonly used for civil engineering works [12]. Concrete is a composite material produced with coarse and fine aggregate particles embedded in a cement matrix which fills the space in between and bind them together. Water plays a very significant role in concrete production for the commencement of the hydration process [8].

Portland Cement

According to Neville [13], the two common class of cement are non-hydraulic and hydraulic cement. Cement is a crystalline compound of calcium silicates and compounds with hydraulic properties. That is, it has a good resistance in water which has helped the extensive use of concrete as a construction material [14]. Portland cement, developed in the early nineteen century, derived its name from the natural stone from the Isle of Portland. Portland cement is obtained by mixing calcareous and argillaceous materials and burning them at elevated temperature of 1450 ^oC in a rotary kiln. The resulting clinker is ground with gypsum, water and grinding aids. The critical steps of cement production include quarrying, crushing, blending and fine grinding, packaging and shipping [15]. The raw material constitutes of the mixture of about 80% limestone, rich in $CaCO_3$ with about 20% clay, rich in silica (SiO_2), alumina (Al_2O_3) and iron (Fe_2O_3). Explosives are used to blast the rocks from the ground. Lime and silica provide the strength, while iron provides the typical grey colour reduces the temperature of the reaction. The materials are transported to the plant, crushed, analyzed, mixed through a dry process or the wet processes before the burning process, which is fundamental in the production of clinker, the base for making cement. After cooling, the clinker is finely ground together with a small amount of gypsum, which regulates the setting time of cement. The ready cement product is packaged and then conveyed to users.

Chemical Composition of Portland Cement

Cement as a binding material is known to be derive from various chemical reactions. Lime was obtained by calcining limestone as:

$$CaCO_3 \rightarrow CaO + CO_2 \quad (1)$$

while CaO mixed with water gives:

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (2)$$

Which when reacted with CO2 gives rise again to limestone:

$$Ca(OH)_2 + CO_2 + H_2O \rightarrow CaCO_3 + 2H_2O \quad (3)$$

The hydraulic types of cement are produced from lime, silica and alumina with small proportions of iron oxide, magnesia, sulphur trioxide and alkalis. In recent years, the trend is for an increase in lime content with a minor reduction in silica content. An excess content of lime makes the combination with other compounds difficult, while excess content of silica without increasing ferric and alumina oxide is detrimental to the formation of clinker. The acceptable limits for chemical composition are shown in Table 1.

Composition of cement clinker

The compounds obtained from the burning process, known as Bogue compounds are expressed by Bogue formulas as:

$$C_3S = 4.07C - 7.60S - 6.72A - 1.43F - 2.85\hat{S} \quad (4)$$

$$C_2S = 2.87S - 0.75C_3S \quad (5)$$

$$C_3A = 2.65A - 1.69F \quad (6)$$

$$C4AF = 3.04F \quad (7)$$

where,
C = Percentage of Calcium oxide (CaO),
S = Percentage of Silicon dioxide (SiO_2)
A = Percentage of Aluminium oxide (Al_2O_3),
F = Percentage of Ferric oxide (Fe_2O)
These compounds can be classified as Alite, Belite, Celite, and Felite (see Table 1)

Table 1. Principal compounds in Portland cement

Principal mineral compounds	Formula	Name	Symbol	Weight (%)
Tricalcium silicate	$3CaO.SiO_2$	Alite	C_3S	55-65
Dicalcium silicate	$2CaO.SiO_2$	Belite	C_2S	15-25
Tricalcium aluminate	$3CaO.Al_2O_3$	Aluminate	C_3A	8-14
Tetracalcium aluminoferrite	$4CaO.Al_2O_3.Fe_2O_3$	Brownmillente	C_4AF	8-12

(Source: Bensted and Barnes [16])

The cement of unique characteristics can be manufactured by adding new additives and raw materials to the chemical composition of ordinary Portland cement (OPC) [17]. Typical examples are for rapid hardening, sulphate resistant, waterproofing, air entrainment and quick setting.

Aggregate

Aggregates occupy 70-80 per cent of the volume of concrete, serve as filler material in the making of mortar and concrete [8]. They are of natural sources such as sedimentary, igneous and metamorphic rocks or industry by-products sources such as furnace slag. Aggregates significantly influence concrete properties, reducing shrinkage and impacting greatly on the economy [18]. Aggregates are mainly classified according to sizes; fine, less than 4.75 mm and coarse aggregates, greater than 4.75 mm, with a maximum of 20 mm sizes for normal concrete. The shape and texture influence greatly the fresh and hardened properties of concrete. According to Neville [13], the most important shape classifications are rounded and angular shapes. Example of rounded is the river or seashore gravel, while that of angular shape is crushed rocks (granite). The particle sizes of aggregates are determined through the sieve analysis, which consists of separating, by means of series of sieve sizes a material into several particle size classification of decreasing mesh sizes. In addition, the characteristics of aggregate affect the workability, placing and compaction.

Water

Water is essential for concrete production as it is necessarily needed for hydration and achieiving a workable mix. It is also needed for adequate strength development for hardened concrete and durability [13]. Water content is one of the significant factors influencing the workability of concrete and is usually expressed as water-to-cement (w/c) ratio, which is measured by cement content. Excessive water content weakens concrete, while insufficient water affects the workability negatively [19]. The quality of water adopted for concrete mixing must be devoid of impurities, as excess impurities affect setting time, concrete strength, corrosion of reinforcement, volume instability and durability. Cement paste content serves as coating, filling, and lubrication for aggregate particles and influences the consistency of concrete.

Fresh Properties of Concrete

Fresh concrete is a state in which its strength has not yet developed, and it greatly affects the choice of handling, consolidation, construction speed and construction sequence. It greatly affects the hardened state properties [9] and can be expressed in terms of workability. The property of fresh concrete, such as workability is usually short-term in nature [20]. This affects principally the fresh concrete operations such as placing, compacting, and finishing. Mindess et al. [21] defined workability of concrete as the mechanical work needed to produce full compaction of concrete without separation or segregation. The fresh concrete properties affect decision making, construction speed, and choice of handling, consolidation, and construction sequence. This also affects the hardened concrete properties [9]. High temperature reduces the workability because of a higher rate of hydration and faster loss of water. Standard test methods for fresh normal concrete include; Slump test, Vebe test and Ball-Penetration test [22]. Evaporation of the mixing water, due to exposure to sun or wind, absorption of water by the aggregate, and water consumption in the formation of hydration products all contribute to stiffening freshly mixed concrete. The stiffening process will depend on the constituent materials and environmental conditions. Having introduced the basic materials and concrete technologies that will shape this research, it will be apt to proceed with the fact-finding part of the study. This study is focused on investigating how the chemical composition of four commonly used ordinary Portland cements brands available in the local Nigerian market affect the characteristic compressive strength of normal concrete. These cement brands are widely used for most general purpose local construction.

Materials and Method

The selection of materials, preparation of specimen and testing procedures on concrete materials used for this research are presented here. Summary of the processes to achieve the aim of this research are presented in Fig. 1.

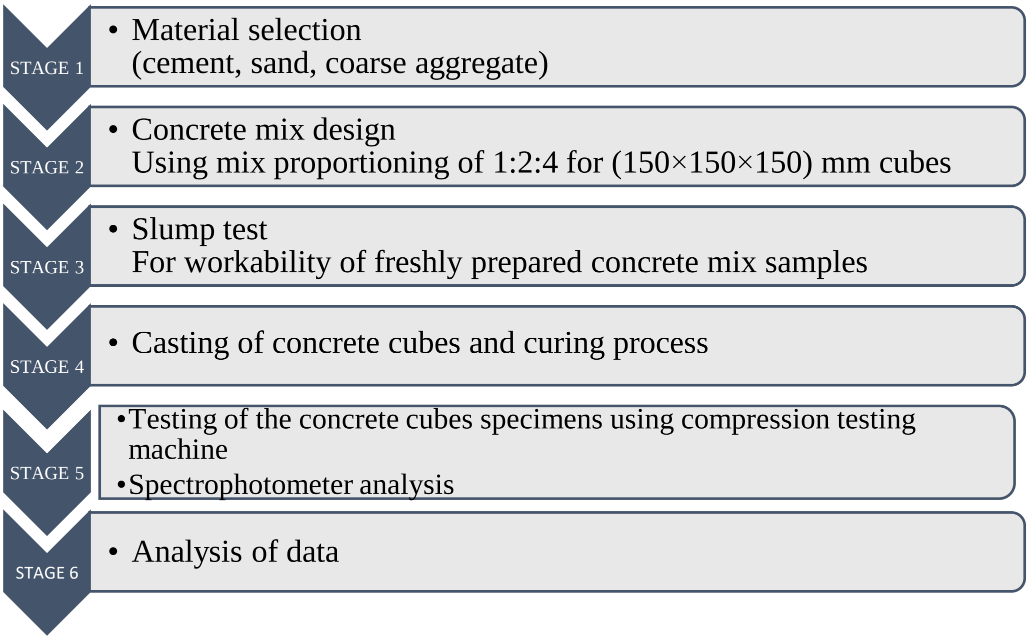

Fig. 1. Schematic diagram showing the sequence used in facilitating this study

Material Selection

Four brands of ordinary Portland cement categorized as A, B, C and D were adopted for this research. Concrete samples from these cement brands were labelled NC1, NC2, NC3 and NC4. Natural river sand without deleterious materials was adopted as fine aggregate, while crushed angular granite of 20 mm maximum size and not containing adverse filths was adopted as coarse aggregate. Fig. 2 depict the aggregates adopted for this research. The elements of the various cement brands were determined using HACH DR 200 direct reading spectrophotometer method. 25 ml of reagent was used for the cement sample with deionized water and the wavelength of the particular elements measured in mm.

Fig. 2. Fine and coarse aggregates

Concrete Mix Design

The constituent materials and the proportion procedure for the production of the concrete samples required to reach the desired workability and strength are presented. Table 2 shows the various ratios of concrete mixes used for each cement brand. A standard cube size specimen of 150 mm and a mix ratio of 1:2:4 was used while adopting a water-cement (w/c) ratio of 0.6. All constituent materials were thoroughly mixed together correctly to ensure a homogenous concrete mix, coating all aggregates particles surface with the cement paste. The coarse aggregates were put in first followed by the sand and cement. The materials were thoroughly mixed to form an even mixture; then a specified amount of water was carefully added into the concrete mix. It was then mixed until all aggregates were coated and bonded together. After the right consistency was achieved for the mix, the fresh concrete mix was checked for workability.

Table 2. Normal concrete samples

Materials	NC1	NC2	NC3	NC4
OPC (kg)	15	15	15	15
Fine (kg)	30	30	30	30
Coarse (kg)	60	60	60	60
w/c ratio (%)	0.6	0.6	0.6	0.6

Fresh Property Test: Slump Test and Setting Time

Normal consistency of initial and final setting times of cement is determined by Vicat apparatus. Then follows by slump test to check the consistency of the freshly made concrete. For the slump test, the cone was cleaned and oiled and filled one-third at a time. Each layer was compacted 25 times with a tamping rod. The cone mould was lifted vertically, and the slump was measured to the nearest mm and recorded [23].

Compressive Strength Test

The mounds are cleaned, oiled and filled with concrete in three layers of about 50 mm thick with each layer compacted 35 times via a tamping rod and the top surface smoothened with a trowel. The test specimens were adequately marked for identification and stored in a moist air environment for 24 hours. The cube samples were removed from the moulds and then submerged in clean, freshwater until a few hours prior to compression test according to BS EN 12390 [24]. Forty-eight (48) number cubes were made with different types of cement and shown in Fig. 3. The most valued property of concrete is the compressive strength, which is needed for concrete design and determined by a standard uniaxial compressive strength test. The cube crushing machine used as shown in Fig. 3 is the 2000 kN loading capacity Eccles compressive testing machine at a loading rate of 0.5 N/mm^2.

Fig. 3. (a) Cube samples; (b) Compression crushing machine

Results and Discussion

The data acquired from the tests carried out according to the implemented methodology of this research is hereby presented. The influence of the chemical compositions of the different cement brands was examined using the compressive strength of the different cube samples.

Chemical Compositions of Cements

Chemical compositions are analyzed using a direct reading spectrophotometer. Percentages of SiO_2, Al_2O_3, Fe_2O, CaO, MgO, SO_3, Na_2O_3, and K_2O were measured individually. The results were used to estimate the chemical compound compositions in the brands of cement through the Bogue composition formulas, which is valid only when the ratio of aluminium to iron content (A/F) is less than 0.64. The results obtained are presented in Tables 3 and 4 showing the percentage oxides composition presence in each of the cement samples.

Table 3. Chemical properties of brands of cement

Oxide compositions	Brand A Value (%)	Brand B Value (%)	Brand C Value (%)	Brand D Value (%)
K_2O	0.34	0.35	0.37	0.32
SiO_2	19.07	20.28	20.05	21.30
NaO_2	0.42	0.58	0.60	0.54
CaO	64.22	63.79	63.84	64.52
Fe_2O_3	0.72	0.94	0.63	0.85
MgO	2.20	2.02	1.98	2.10
MnO	0.08	0.05	0.02	0.07
Al_2O3	4.96	4.51	4.97	4.60
SO_3	2.33	2.21	2.03	2.59

Table 4. Values of compounds for different cement brands

Compounds	Percentage (Standard)	Brand A Value (%)	Brand B Value (%)	Brand C Value (%)	Brand D Value (%)
C_3S	55-65%	75.45	67.54	67.36	61.21
C_2S	15-25%	1.86	7.65	6.62	15.22
C_3A	8-14%	11.93	10.36	12.10	10.75
C_4AF	8-12%	2.18	2.85	1.92	2.58

Brand A cement has very high C_3S content (75.45%) and very C_2S content (1.86%) not up to the standard which brought about faster hydration and contributed to more significant early strength gain. Thus, higher C_3S leads to higher early strength and will facilitate early formwork removal or post-tensioning. Conversely, cement with higher C_3S will lead to the heat of hydration, especially in mass pouring. Also, all the brands have C_3S content slightly higher than the maximum standard content of 65% except for Brand D cement with a C_3S content of 61.21%, but within the limit specified. Low C_2S was also verified for each of the other brands. Tricalcium Aluminate (C_3A) is within the standard range for all the four cement brands considered. C_3A content facilitates the liberation of a large amount of heat in the early days of hardening and, together with C_3S and C_2S somewhat increased the early strength of hardening cement. A low percentage of C_3A cement is more resistant to sulphates. Tetracalcium Aluminoferrite (C_4AF) did not fall within the standard range of 8 – 12% for all the cement brands. The Tetracalcium Aluminoferrite (C_4AF) compound contributes very little to cement setting and strength gain, but more to the colour effects that make cement grey.

Setting Time of Cement Paste and Workability

The setting time of the cement pastes for the four (4) brands of ordinary Portland cement used in this study is presented in Fig. 4. The results clearly show that the OPC has their initial setting time to be about 30 mins except for NC3 (Brand C) having the initial setting time to be 45 mins, indicating a little change in the initial setting time of the commonly used Nigerian brands of cement. Furthermore, most Portland cement types have their final setting time at most 10 hours (600 mins) for the complete hardening of the cement paste to have to occur. For this study, the recorded final setting time for the pastes are also presented in Fig. 4. The plot shows the final setting time varying between 540 mins to 600 mins. The various setting time has a substantial influence on the final 28 days development of strength of the hardened concrete.

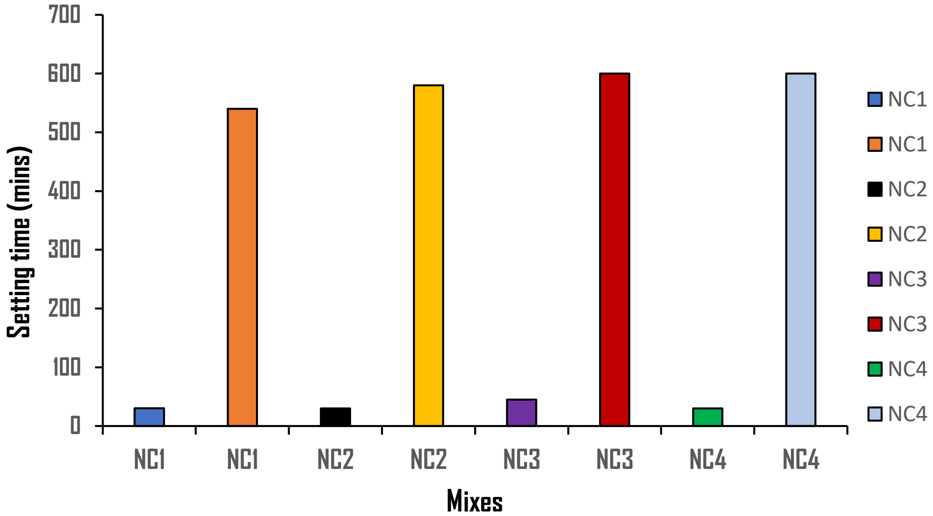

Fig. 4. Initial and final setting times

Results on the slump tests recorded for the freshly prepared concrete mixes are shown in Fig. 5. The Fig. shows no significant difference in the workability and consistency of the concrete mixes produced using the four (4) brands of Portland cement at a constant water-cement ratio. However, even though the differences are not significant, slump values recorded ranges from 29 – 31 mm. During the process of mixing and casting of the cube samples, no forms of segregation were noticed for the concrete mixes.

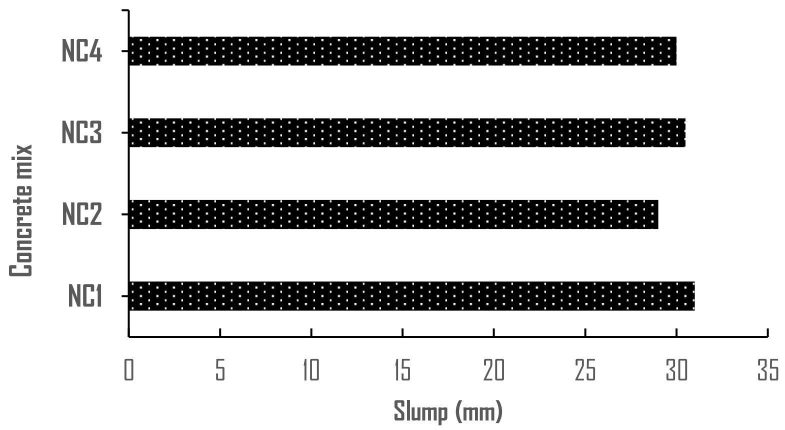

Fig. 5. Slump of the freshly concrete mixes.

Hardened Property – Compressive Strength

The samples for the various types of cement were tested on the 3, 7, 14, 28 days for compressive strength, using a 200 kN compression testing machine. The test results on the cube compressive strengths of the normal concrete are shown in Fig. 6. From the results obtained, it can be observed that there is a progressive increase in the compressive strength of the concrete samples as the curing day's increases; however, optimum strength is reached after 28 days. The maximum compressive strength at 28 days of curing for the concrete samples produced from different cement brands varied from 17.78 N/mm² to 25.48 N/mm². All the concrete cube samples tested except NC4, met the minimum requirements of the characteristic strength of concrete cubes in 3 days and 7 days which should not be less than 8 N/mm^2 and 14 N/mm^2, respectively. The high values of compressive strength recorded for both NC1 and NC3 samples can be attributed to the higher percentage of C_3S and C_3A content in the cement brand A and brand C. The presence of these two compounds in ordinary Portland cement ensure the required hardening and quality strength development of the concrete especially at optimum age of 28 days. Also, both cement brands were observed to contain a low percentage content of C_2S compound compare to the high percentage content in NC4 (brand D) cement.

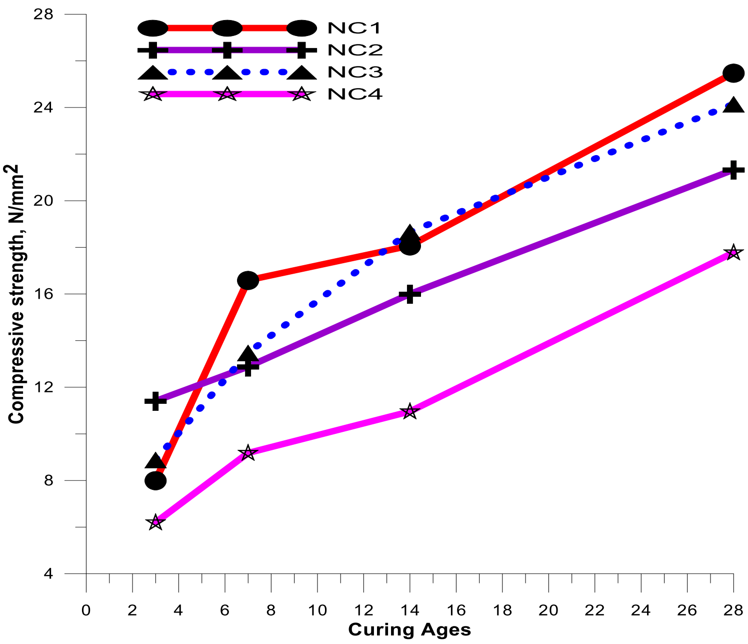

Fig. 6. Compressive strength development for the concrete mixes

Conclusion

The chemical properties and the compressive behaviour of concrete made with different OPC brands available in Nigeria have been established by laboratory tests. Based on the results obtained, of this research work, we conclude that:

i. The maximum compressive strength for concrete made from the various cement brands ranged from 17 N/mm^2 to 25.48 N/mm^2.

ii. Cement brands A, B and C considered in this research had a greater than desirable content of C_3S, while brand D was with the limit. This was reflected in the strength gain for the three samples from 3 days to 28 days of curing. This shows that the faster hydration rate of C_3S leads to greater early strength gain.

iii. Brand A with an exceedingly high content of C_3S maintained the highest strength gain from 7 to 28 days of curing.

iv. For brands B and C having almost the same value of C_3S, Brand C with 12.10% of C_3A, regained strength better than brand B with 10.36% of C_3A. That shows that the combination of C_3S and C_3A aids strength gain in concrete.

These results will aid the professionals in obtaining good concrete that will respond to their respective needs. It is, however, recommended that the curing period be extended, so as to establish the durability of the concrete made from each different brands of Portland cement.

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