International Journal of Civil Engineering and Technology (IJCIET)
Volume 8, Issue 10, October 2017, pp. 288–301, Article ID: IJCIET_08_10_030
Available online at http://http://www.iaeme.com/ijciet/issues.asp?JType=IJCIET&VType=8&IType=10
ISSN Print: 0976-6308 and ISSN Online: 0976-6316

PREDICTION OF FRESH AND HARDENED PROPERTIES OF NORMAL CONCRETE VIA CHOICE OF AGGREGATE SIZES, CONCRETE MIX-RATIOS AND CEMENT

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ABSTRACT

Concrete is the most commonly used building material for building most of the world's buildings and infrastructure. After centuries of usage, it still remains the most widely adopted construction material worldwide. But in many developing nations, the frequent occurrence of building collapse has been mostly ascribed to poor quality concrete. As Nigeria is noted for frequent building collapse, this research reproduces standard concrete practices commonly adopted in Nigerian construction industry with the intent to predict design strength via choice of coarse aggregate sizes (12.5 mm, 19 mm, 30 mm and mixed), concrete mix-ratios (1:2:4, 1:3:6, 1:2:3) and ordinary Portland cement types (42.5R and 32.5N). Cement compound's composition tests, fresh property tests and hardened property tests were conducted on samples. Test results from building cites of different Local Government Areas of Lagos State, Nigeria obtained in 2010 are compared with the compressive test results of this research via statistical tools. Results indicate that the fresh properties and hardened properties are influenced in a proportional manner by the sizes of aggregates and that the choices of aggregate sizes, concrete mix-ratios and cement types can be used to predict the fresh and hardened properties of normal concrete. This study also show that poor concrete production is one of the principal cause of frequent building collapse in Nigeria.

Key words: Building Collapse, Coarse Aggregates Sizes, Concrete Mix-Ratios, Cement, Compression Test.

Cite this Article: A. N. Ede, O. M. Olofinnade, G. O. Bamigboye, K. K. Shittu and E. I. Ugwu, Prediction of Fresh and Hardened Properties of Normal Concrete Via Choice of Aggregate Sizes, Concrete Mix-Ratios and Cement, International Journal of Civil Engineering and Technology, 8(10), 2017, pp. 288–301.
http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=8&IType=10

1. INTRODUCTION

Building and construction activities are as old as the human existence as man has always required shelter as residence and for activities as to guarantee survival, safety, comfort and endurance [1]. The human habitations through the phases of transition from the primitive age to the current information/knowledge-worker age have changed and evolved from caves to huts and normal houses to skyscrapers and most recently to buildings that respond to environmental stimuli. These structures corresponded to the applications of discoveries to the dominant construction materials ranging from earth to wood, to stone to concrete, to steel to composites materials [2].

A high percentage of structures in developed and developing nations are made of reinforced Portland cement concrete. The major reason concrete is commonly used worldwide is because of the availability of its constituent materials. It is universally adopted in multi-purpose constructions because of its strength, economy related to availability and sustainability of its constituent materials [3-7]. Concrete has very good compressive strength but poor tensile strength [8-9]. As there has not been a better alternative over the years, modern structures in developed and developing nations are mostly built in concrete. It is a composite material of aggregates (fine and coarse) embedded in a Portland cement matrix [10].

The potential for in-situ production of concrete has greatly enhanced its versatility in construction worldwide [8]. Concrete is a mixture of fine and coarse aggregates (sand and granite or gravel) and a controlled amount of entrained air, held together by a binding material such as Portland cement. Furthermore, how a concrete structure performs throughout its projected service life of about 100 years is largely dependent on the method of production. Concrete mix should be well designed and proportioned, appropriately batched, accurately mixed, handled, placed, compacted and properly cured as all these activities affect the strength development of hardened concrete. In the design stage of a structure, a particular strength is assumed for the concrete which is used for the design and analysis. It is important that this assumed strength is achieved on the field when the project is being executed and this is dependent on a lot of factors and technologies. From here, it can be seen that concrete production comes in innumerable ways and its quality can be greatly influenced by the constituent materials and production technologies such that the compressive strength is very easily compromised [11-12]. Moreover, lower compressive strength of concrete below design limit states leads to excessive cracks, deflections and eventually failure or total collapse. The cost of building collapse, repairs or recovery of damaged structures have grave implications for the society and the environment [13]. In developing nations where building collapse is common, reinforced concrete structures are the most collapsed buildings and researchers [14-16] have identified substandard materials (especially poor quality concrete) as the leading cause of building collapse in these developing nations.

Poor quality of reinforced concrete structures are linked to the poor quality of the concrete constituents and substandard batching practices. Inconsistent development of concrete technology is greatly affecting the quality of structures that will serve the present and future generations in developing nations. For instance, in Nigeria, the use of concrete dominates other conventional building materials such as steel, timber, glass, and composites. According to Mbamali and Okotie [17], a look at the growth of construction development in Nigeria helps to comprehend better the actual state of its construction industry. Organized building practices began in Nigeria in the 1930s and intensified in the 1940s up to 1960's when the British colonialist were in charge. The construction works handled by the Public Works Department (PWD) and the Royal Army Engineers were executed to international standards. In the successive years of massive constructions, the construction projects became open to a lot of unqualified individuals who lacked the technical knowledge and experiences required for good construction practices. This led to the decline of quality in successive construction projects [17]. Ever since then, poor quality structures have become common and has been responsible for the frequent building collapse that is damaging the image of Nigerian construction industry. For instance, in most construction sites in Nigeria, on-site concrete works are habitually batched by volume. This according to Neville and Brooks [18] is an unacceptable practice for producing normal concrete of good quality especially for structural application or high strength concrete. However, this method of concrete batching is conventionally practice on construction sites in most parts of Nigeria for both structural and non-structural works.

According to [19] nominal concrete mix for normal concrete is conventionally batched in ratios depending on the targeted design strength. In Nigeria, on-site concrete mix ratio are batched by volume using wheelbarrow or head pan gauges [20]. However, volume batching is prone to possible sources of inaccuracy in the quantity of aggregate in a prescribed volume and often times these inaccuracy affects the fresh and hardened properties of normal concrete batched on sites resulting in their deviations as against the prescribed characteristics properties [19]. Furthermore, the prescribed design strength can be achieved on site if the concrete mix ratio is batched by weight using measured equipment that is well calibrated; hence resulting in good proportioning of concrete constituent materials. This practices will enables the achieving of the prescribed fresh and hardened properties of concrete [20]. As also affirmed by Goldbeck and Gray [21] that there is a need to institute a proper mix proportion of materials for on-site concrete production which will allow suitable mix proportion for a specified strength characteristic to be achieved instead of the usual procedures of using unapproved mix ratio for a targeted design strength.

A study by Woode et al. [22] stated that among the various factors that influence the specified characteristic strength of concrete is the size of coarse aggregates. The function of coarse aggregate in concrete is vital to the overall strength of the concrete. Aggregate sizes have been reported to have significant effects on both the fresh and hardened properties of concrete [20, 22-26]. Thus implying that poor judgement in the selection of maximum coarse aggregate sizes could have an adverse effect on the quality of concrete, hence the construction of poor quality structures. That is the concrete may not be able to achieve the desire specified characteristic strength. Studies by Olanitori [27] and Olagunju et al. [28] asserted that the root causes of building failures and collapsed in most parts of Nigeria can be attributed to low quality building materials and construction in terms of concrete production and placement. In addition, Adewole et al. [29] stated that poor knowledge of the different Portland cement grades in the Nigerian market by many craftsmen and practitioners in the construction industry could also contribute to the construction of poor quality of structures which often times leads to incessant building failures. Consequently, this paper intend to investigate the fresh and hardened properties of concrete produced in the laboratory using the commonly adopted concrete mix ratios and coarse aggregate sizes combined with the different cement grades available in the Nigerian market.

This paper focuses on normal concrete which is the most commonly adopted construction material in developing countries. In Nigeria, the production of normal concrete is very attainable as there are cement producing industries such as Dangote Cement, Elephant Cement among others, making access to Portland cement very stress-free. Also, the abundance of aggregates, both fine and coarse all contribute to make concrete production cheap in most developing countries. This research reproduces standard concrete practices commonly adopted in Nigerian construction industry with the intent to predict design strength via choice of aggregate sizes, concrete mix-ratios and cement types. Results from this research will be compared with test results of samples from many construction sites in Lagos, Nigeria.

2. METHODOLOGY

The approach of this study was to investigate the fresh properties and compressive strength of normal concrete that is produced adopting common concrete practices used in Nigeria. Different concrete cubes were made by varying different factors which commonly influence the compressive strength of concrete used in Nigeria, such as the aggregate sizes, concrete mix-ratios and cement types. All concrete mixes were batched by weight and not by volume. Fresh concrete tests were carried out and compressive strength tests were performed on the hardened concrete cubes at different curing days. No admixtures were used in the production of all the concrete cubes as the use of admixtures is not common in most developing countries like Nigeria. Statistical tools were used to analyze the results obtained in this research.

2.1. Materials and Design mix

The materials used in this research were Portland cement, fine aggregate (river sand) and coarse aggregate (12.5 mm, 19 mm and 30 mm) and portable water for mixing. Two types of Ordinary Portland Cement (OPC) obtained locally were used in the preparation of all the concrete mixes. They are of grade 42.5 R cement and of grade 32.5 N cement and conform to the specifications of [30]. The properties of Portland cement varies markedly with the proportions of the four principal compounds that are formed in the burning process that leads to the formation of cement clinker (known as Bogue compounds). These compounds are known as Alite (C_3S), Belite (C_2S), Celite (C_3A) and Felite (C_4AF) and were determined for the two cement brands adopted for this research as to thoroughly monitor how the cement brands influence the strength concrete. The values obtained are compared to ones obtained by [31]. The oxide compositions were determined using HACH DR 200 Direct Reading Spectrophotometer instrument while the compound compositions are calculated using the Bogue composition formulas. River sand passing sieve opening of 6.3 mm to 0.075 mm according to [32] was used in the production of all the concrete cubes. Crushed granite which was obtained locally was used in the production of all concrete cubes. Coarse aggregate grading was done according to [33]. Three different angular shaped aggregates sizes of 12.5 mm, 19 mm and 30 mm were used in the production of the concrete mixes. Particle size distribution tests were carried out via sieve analysis on the three granite sizes based on [32]. A weight of 700.5 g for 12.5 mm aggregate, of 1500 g for 19 mm aggregate and of 1517.6 g for 30 mm aggregate were used to carry out the sieve analysis. Potable water was used in the production of all the concrete mixes and as such did not jeopardize the properties of the concrete based on some of the criteria listed in [34].

2.2. Preparation of samples

Concrete cube samples of 150 mm dimensions were used for this research. Three factors were varied in the preparation of the concrete cubes: the mix ratios, the aggregate size and the cement brand. The concrete constituents were batched by weight according to the ACI Standard [35] to obtain the appropriate proportions of concrete ingredients. Three mix ratios (cement: fine aggregate: coarse aggregate) adopted for the research are in the range of 1:2:3, 1:2:4 and 1:3:6 with corresponding water-cement ratios of 0.57, 0.6 and 0.68 respectively. Aggregates used in this research are of four categories: 12.5 mm, 19 mm and 30 mm aggregates and a mixture of the three aggregate sizes. A flow chart showing the preparation of the samples is provided in

Fig.1. A total of sixteen groups of mix samples were produced for this research. The cubes were cured by complete immersion in water bath for 7, 14, 21 and 28 days. All the sample preparations are followed the work of [36].

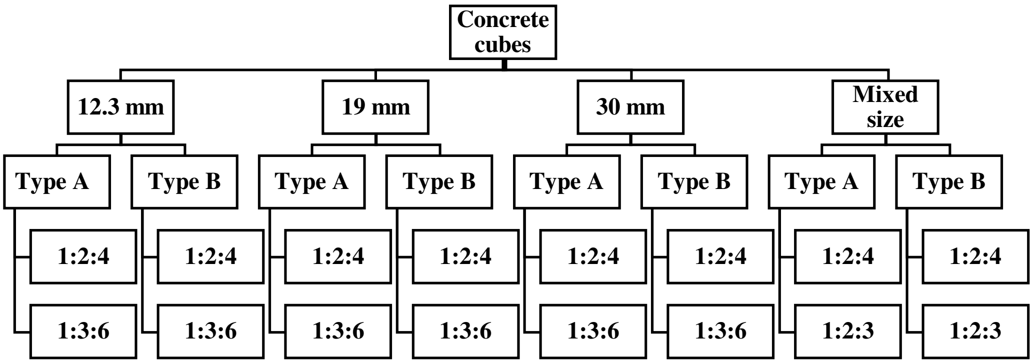

Figure 1 Framework for the Preparation of Concrete Cubes

2.3. Experimental investigations

2.3.1. Test on Fresh Concrete (Slump Test)

Slump tests were carried out on all fresh concrete prepared according to [37]. Adopting slump cone and tampering rods, the slump test was used to assess the workability of the concrete. For an acceptable workability of normal concrete, the slump must be between 25 mm and 75 mm. After mixing the concrete, the slump cone was cleaned, oiled and its larger base placed on a rigid, flat surface. Then the slump cone was filled with the freshly mixed concrete in three layers with each layer approximately one-third of the volume of the slump cone, tamping each layer 25 times with a tamping rod before filling in the next. After the topmost layer have been tamped, excess concrete is removed and the top of the slump cone smoothen. The slump cone is immediately removed by raising it up very carefully without disturbing the sample. Finally, the slump is measured by taking the difference between the height of the slump cone and the height of the slumped concrete sample.

2.3.2. Test on Hardened Concrete (Compressive Strength Test)

The compressive strength test on hardened concrete cubes were carried out according to [38]. The concrete cube specimen were removed from water after the specified curing days and left to dry. The surface of the testing machine is then cleaned. The concrete sample is placed on the testing machine in such a way that the load is applied on both sides, ensuring that it is well aligned. The door to the testing machine is then shut and the switch turned on. At the end of the process, the load is recorded. This load is then divided by the area of the concrete sample and recorded as the compressive strength. Three concrete cubes were tested for each of the four curing age of 7, 14, 21, and 28 days for the sixteen mix samples emanating from 2 different brands of Portland cement and four aggregate types. A collection of compressive strength test results carried out between January and September 2010 on samples from building cites of different Local Government Areas of Lagos State, Nigeria were compared with the test results of this research.

3. RESULTS AND DISCUSSION

This research work is aimed at studying the fresh and hardened properties of concrete made in Nigeria. 192 concrete cubes were made from sixteen groups of mix samples produced using site practices common to Nigeria. Here, the results of the particle size distribution tests for fine and coarse aggregates, chemical composition tests on the two cement types, workability test (slump test) performed on different fresh concrete mixes and the compressive strength obtained from the hardened concrete cubes of the concrete produced at different curing days (7, 14, 21 and 28 days) are presented. Finally, concrete test results from building cites of different Local Government Areas of Lagos State, Nigeria obtained in 2010 are compared with the compressive test results of this research.

3.1. Aggregate test results

The particle size distribution curves of the fine aggregate, 12.5 mm, 19 mm and 30 mm coarse aggregates are presented in Figure 2. It can be observed that the sharp sand is gap graded. The results show that the granites were well graded.

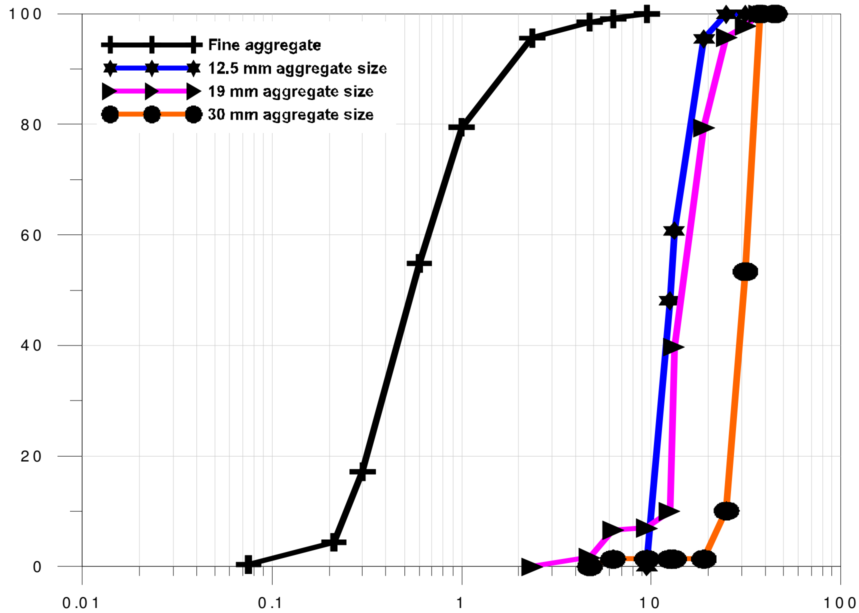

Figure 2 Particle size distribution curve for fine aggregate, 12.5, 19, and 30 mm coarse aggregate.

3.2. Compound compositions of cement test results

Results of compound compositions tests for grade 42.5 R cement and grade 32.5 N cement are shown in Table 1. The results were compare with the standard values indicated in [19].

Table 1 Compound compositions of Portland cement

Principal Compounds		Standard	Grade 42.5R cement (%)	Grade 32.5N cement (%)
$3CaO.SiO_2$	(C_3S)	55-65	75.45	67.54
$2CaO.SiO_2$	(C_2S)	15-25	12.48	7.65
$3CaO.Al_2O_3$	(C_3A)	8-14	11.93	10.36
$4CaO.Al_2O_3.Fe_2O_3$	(C_4AF)	8-12	2.18	2.85

The two cement types have high tri-calcium silicate (C_3S) content, though with a near standard value for grade 32.5N cement. All the cement grades have low di-calcium silicate (C_2S) content, which lead to much faster hydration rate and contributes to higher early strength gain. Thus, these cement types with a higher proportion of C_3S, will tend to have higher early strength and allow for early form removal or post tensioning while it pose problems of heat of hydration specially in mass pouring. These cements show desirable C_3A contents.

3.3. Workability test (slump test) results

The results of the slump test carried out on all the different concrete mixes are presented in Figure 3. The results clearly show that concrete mixes produced with the large aggregate sizes exhibit higher slump values than the concrete mixes produced with the smaller aggregate sizes. Moreover, the concrete produced with mix ratio1:3:6 was observed to exhibit lower slump values compare to other mix ratios of 1:2:4 and 1:2:3. The results clearly demonstrate the influence of aggregate sizes and mix ratios on the workability of concrete mixes. The concrete mixes produce with the 12 mm and 19 mm aggregate sizes was observed to also exhibit good workability for the two types of cement used, while the 30 mm aggregates shows very high slump values indicating poor workability. However, the concrete mixes produce with the mixed aggregates shows intermediate values.

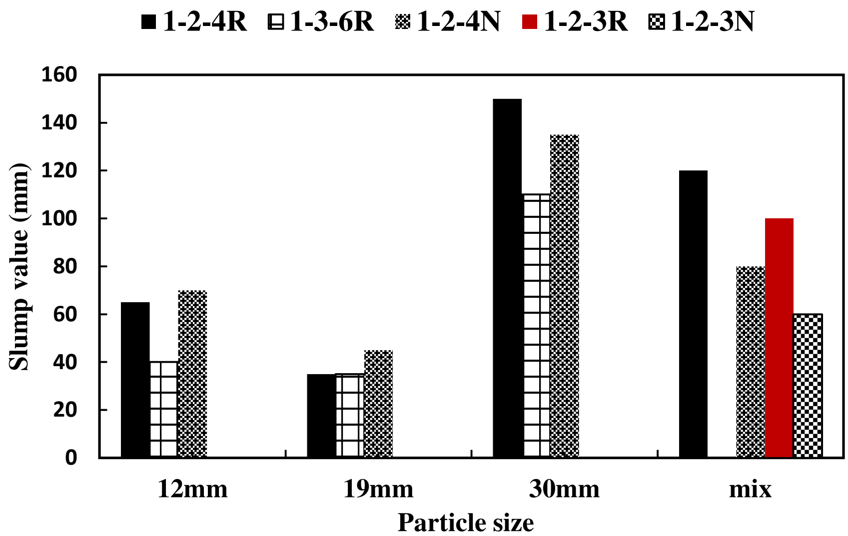

Figure 3 Slump test results for the various samples.

3.4. Compressive strength test results

The compressive strength is the hardened property considered in this research. Average results of all the concrete cubes cured at 7, 14, 21 and 28 days are analyzed in this section. The strengths were obtained by applying the BS 8110 [39] expression for characteristic strength (f_{cu}) based on the mean strength (f_m):

$$f_{cu} = f_m - 1.64\ \text{s.d.} \qquad 1$$

where s.d. is the standard deviation.

Figures 4 – 9 show the various behaviour of the harden concrete verified in this research. Figure 4 and Figure 5 show the compressive strength gain of the 1:2:4 mix design for grade 42.5R cement and of grade 32.5 N cement respectively. For the grade 42.5R cement of Figure 4, the 30mm aggregate sample had a very high early strength above 25 N/mm^2 at 7 days and maintained high values up to near 35 N/mm^2 at 28 days. This confirms that high tri-calcium silicate (C_3S) content leads to high early strength. The mixed aggregate sample had a moderate initial strength of less than 15 N/mm^2 at 7 days, which gradually rose in the successive curing days up to 37.32 N/mm^2 at 28 days. The 12 mm aggregate sample had an average initial strength of 17.90 N/mm^2 at 7 days accompanied by a gradual rise up to 25.48 N/mm^2 at 28 days, while the 19 mm aggregate sample had a low initial strength of less than 13.36 N/mm^2 at 7 days and sluggishly attained the value of 23.53 N/mm^2 at 28 days, which is below the desired strength of

25 N/mm^2. These results point to the fact that the choice of aggregate can reduce the early high strength essentially linked to high tri-calcium silicate (C_3S) content of grade 42.5 R cement. Depending on the design strength desired for normal concrete, these curves can be a guide on the choice of aggregates to adopt so as to achieve desired strength with grade 42.5 R cement.

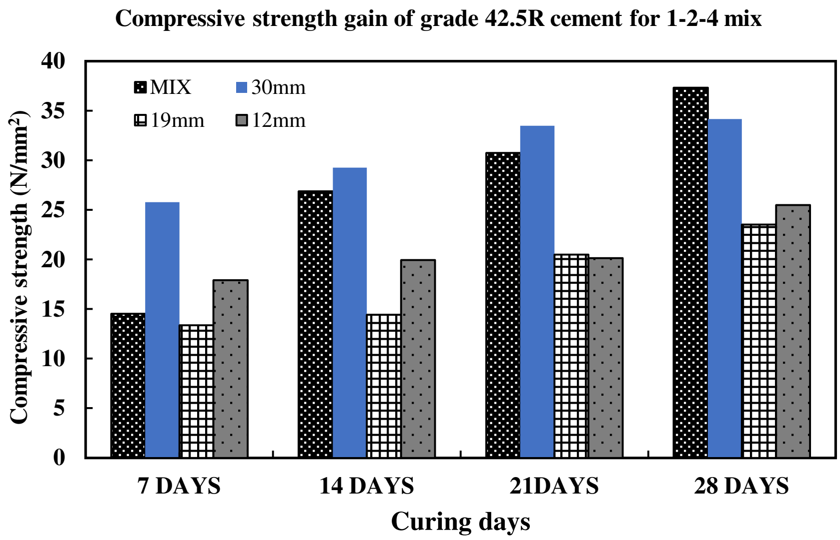

Figure 4 Compressive strength gain of Type R cement for 1-2-4 mix

In Figure 5, the mixed aggregate and the 30 mm aggregates exhibit consistent gradual strength growth from fairly above 15 N/mm^2 at 7 days to the values of 30.31 N/mm^2 and 26.21 N/mm^2 respectively at 28 days of age. The 12 mm and 19 mm aggregates attained maximum strength of 24.59 N/mm^2 and 22.57 N/mm^2 respectively at 28 days of age. These results confirm that moderate tri-calcium silicate (C_3S) content leads to moderate early strength of concrete. These curves can also be used as a guide on the choice of aggregates to adopt as to achieve desired strength with grade 32.5 N cement.

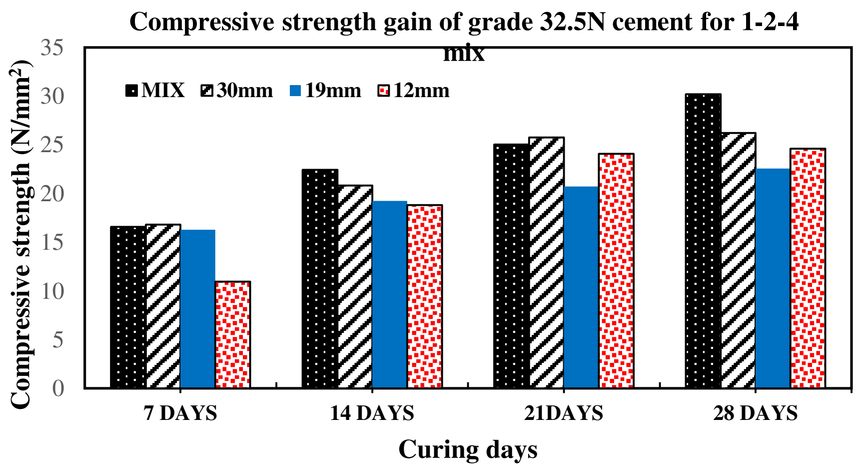

Figure 5 Compressive strength gain of grade 32.5N cement for 1-2-4 mix

Figures 6 – 9 consider the results for each of the four types of aggregate (12 mm, 19 mm, 30 mm and mixed aggregate) concrete with emphasis placed on the achieved strength at 28 days curing age. Considering the 12 mm aggregates in Figure 6, the 1:2:4 mixes met the desired strength of 25 N/mm^2 while, the 1:3:6 fall short of more 30% of the desired strength. For the 19 mm aggregates as shown in Figure 7, none of the concrete cube samples tested achieved the desired 25 N/mm^2 with the 1:3:6 N (N for grade 32.5 N cement) mix falling short of more than 45% of the desired strength. In Figure 8, the 30 mm aggregates had the 1:2:4 mixes met the desired strength of 25 N/mm^2 with the 1:2:4R (R for grade 42.5R cement) cube sample getting as high as 34.15 N/mm^2 with an abnormal early strength of 25.78 N/mm^2. But the concrete cube samples produce from the 1:3:6 mix ratio failed to achieve the desired strength. However, Figure 9 depict the results for hardened concrete produce with the mixed aggregates (i.e. combination of the 12.5, 19 and 30 mm as coarse aggregate). The results clearly show that all the concrete produce with the various mix ratios considered were able to achieve and exceed the target strength of 25 N/mm^2 compare to the single aggregate sizes concrete. The results clearly show that the compressive strengths exceeding 30 N/mm^2 which reinforces the need to adopt mixed aggregates in our quest to attain the target design strengths of concrete. A comparison of the slump test results and the hardened property results shows that the 19 mm aggregates with the minimal slump for all mix sample produced the lowest strengths, 12 mm aggregates with intermediate slumps had average strengths while the 30 mm aggregates with the highest slump values provided the highest strengths of the samples. The mixed aggregate did not follow the trend.

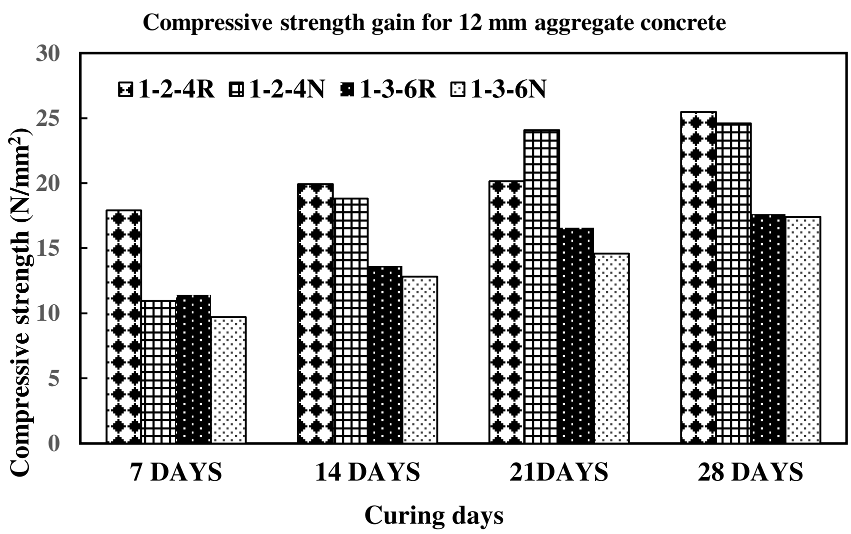

Figure 6 Compressive strength gain for 12 mm aggregate concrete

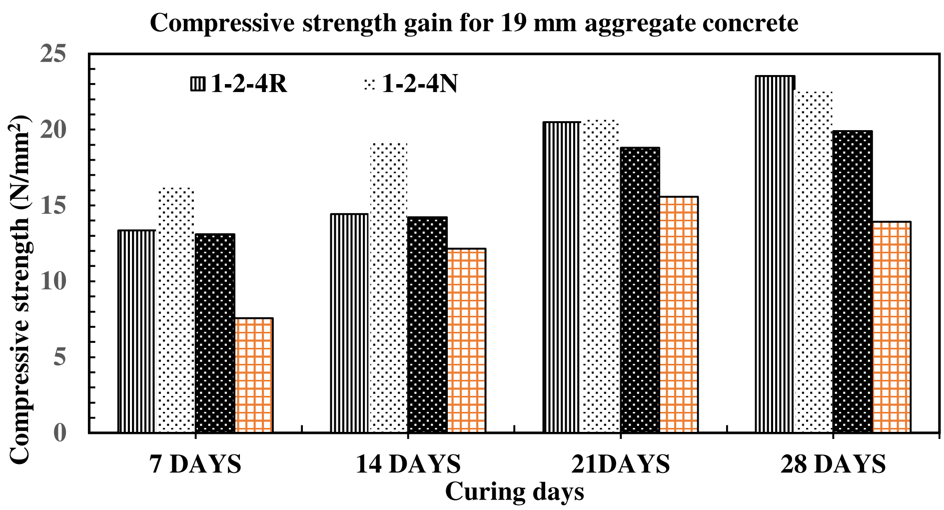

Figure 7 Compressive strength gain for 19mm aggregate concrete

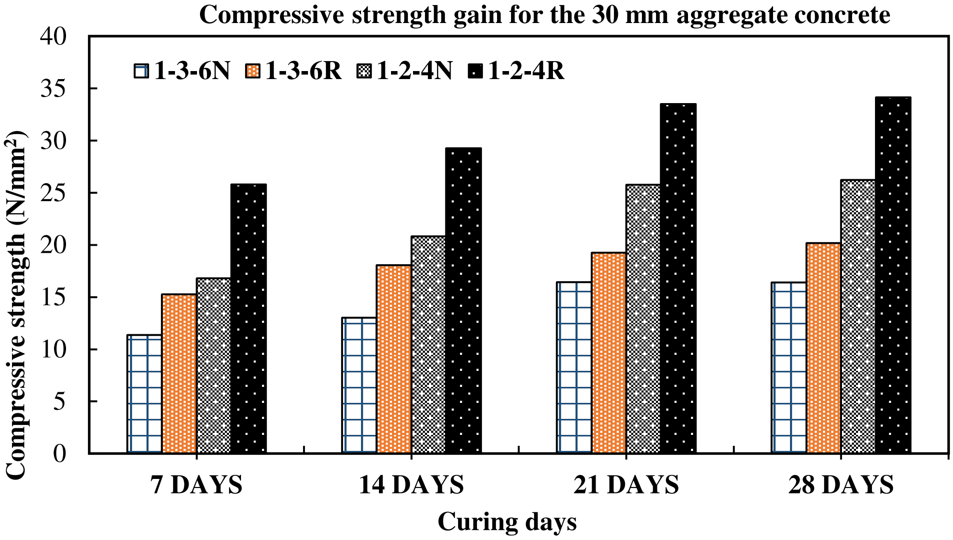

Figure 8 Compressive strength gain for the 30mm aggregate concrete

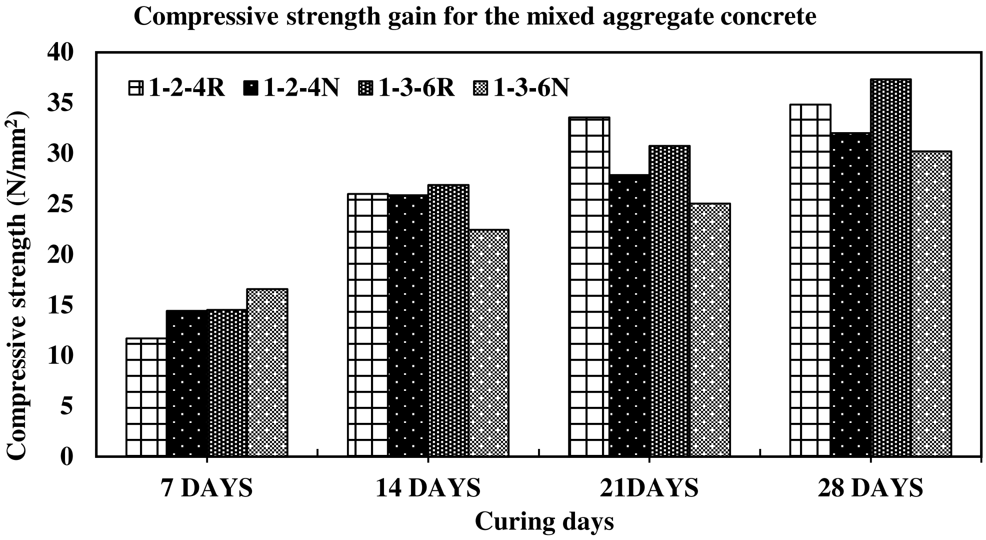

Figure 9 Compressive strength gain for the mixed aggregate concrete

3.5. Comparison of test results with data from building sites in Lagos, Nigeria

Figure 10 shows a comparison of the compressive strengths results of this research with test results of concrete strengths used for construction of some structural members in Lagos – Nigeria in 2010. Of the 94 samples obtained from a pool of 946 concrete cube specimen, only 46 exceeded the minimum design characteristic strength of 25 N/mm^2 prescribed by BS codes [39] and reported in [40] for structural applications. The 48 failed samples did not qualify to be used at all. From the Lagos State data, more than 20% of the samples considered fell below 18 N/mm^2. These results confirms that most concrete adopted for the construction of buildings within the state fell below the usual targeted design strength of 25 N/mm^2 for normal weight concrete. The Pearson product moment correlation coefficient R^2 of 0.0406 exposes the high scatter of the data considered. This heighten the risk that poor production of quality concrete is one of the causes of the frequent building collapse that occurs in within the state. Comparison of the laboratory and the field results on cube compressive strengths clearly indicate that production of on-site concrete of minimum 25 MPa characteristic strength can be produced using a mix ratio of 1:2:4 with uniformly mixed coarse aggregate sizes combined with Portland cement grade 42.5. This combination can be used for general concrete production for building's load carrying members. The results of the 1:3:6 mix samples fell within the same region of the failed Lagos sample results. This indicates that this mix should not be adopted for important structural elements on the basis of BS8110 [39]. Moreover, as pointed out by [13], the low strength of concrete below the specified design limit states which might be as a result of substandard materials, poor batching and construction procedures could leads to excessive cracks, deflections and eventually failure or total collapse.

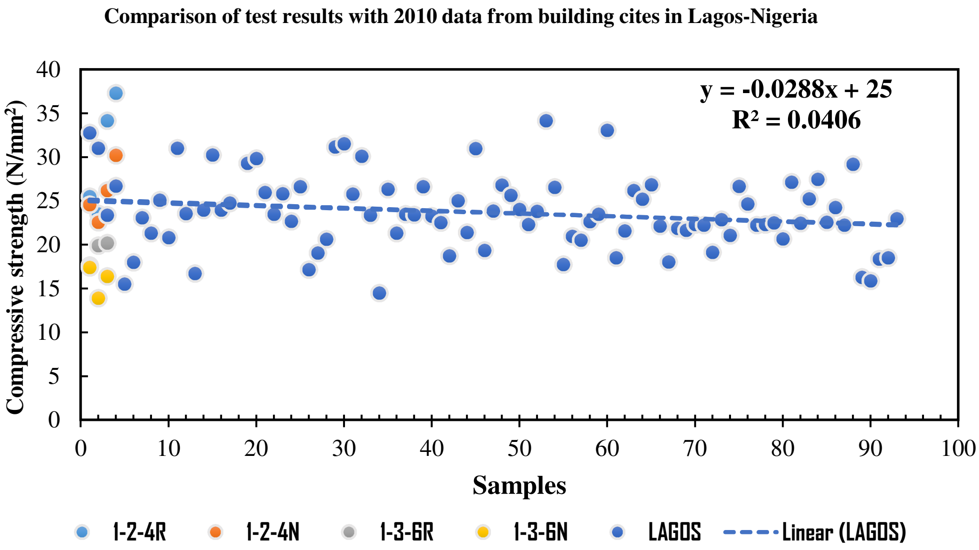

Figure 10 Comparison test results with 2010 data from building sites in Lagos-Nigeria

4. CONCLUSION

From the results obtained from this experimental research, the following conclusions can be drawn.

- From the mix ratio variation, it can be concluded that the different mix ratios (1:2:4, 1:2:3 and 1:3:6) should be adopted for different purposes. The 1:2:4 mix ratio is a very suitable mix ratio for normal concrete while the 1:2:3 mix ratio (very high in cement content and therefore more expensive) should be used for constructions where extra compressive strength may be required as it has a higher strength than the 1:2:4 mix ratio. The 1:3:6 mix ratio has the lowest compressive strength of the three and is not suitable for the casting of major structural elements such as beams and columns. It could be used for blinding purposes and for structural elements of less importance.

- From the variation of the Portland cement used i.e. grade 42.5 R and grade 32.5N cement, it was discovered that grade 42.5 R cement generally produced higher compressive strength than and grade 32.5 N cement and this could be attributed to the fact that grade 42.5 R cement had higher tri-calcium silicate and di-calcium silicate contents than the grade 32.5 N cement. This shows clearly how the chemical composition of cements can affect the compressive strength of normal concrete.

- Based on the aggregate size used, it was also discovered that the aggregate sizes did affect the compressive strength. Particularly, it was observed that the concrete produced with the mixed-size aggregate had the highest compressive strength of the four. This may be due to the fact that all pore spaces between the aggregates were completely filled with the smaller aggregates and cement. This confirms the preference of mixed aggregate sizes to single aggregates in practice.

- This research has established that design strength of normal concrete can be replicated with a good concrete practice, contrary to what is obtainable in most building sites in Nigeria. This is proven on the collection of compressive strength test data of between January and September 2010 from different Local Government Areas within Lagos State, Nigeria. The poor quality of this data from building sites in Lagos when compare to the result of this research indicates that concrete production in construction sites is not adequately prepared and remains one of the principal causes of frequent building failures in Nigeria.
- Finally, Based on the BS8110 [39] threshold of 25 N/mm^2 for normal reinforced concrete, it can be concluded that to achieve an acceptable structural element, grade 42.5 R cement can be used in 1:2:4 mix with all the single aggregate types or the mix aggregate while grade 32.5 N cement can only be used in the 1:2:4 mix with the 30 mm aggregate types or the mix aggregate. The 1:2:3 mix ratio with very high compressive strengths for both cement types, though more expensive for the high cement content, can be recommend for important works that require high strength.

The result of this research will be a vital guide for whosoever desires to achieve a designed concrete compactible with structural design value based on cement type, concrete mix ratios and aggregate sizes. It can also serve as reference point for forensic investigations of the frequent building collapses that occur in Nigeria as the strength of samples from any site can be obtained via numerous non-destructive tests and then confronted with the results of this research to stabilize which factors among cement type, concrete mix ratios and aggregate sizes gave rise to the non-destructive result obtained.

5. ACKNOWLEDGEMENTS

The authors acknowledged the management of Covenant University, Ota, Nigeria for the funding supports and for providing the enabling environment for this research. The reviewers are also well acknowledged for their contributions.

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