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RESEARCH ARTICLE

Influence of Aggregate Size and Shape on the Compressive Strength of Concrete

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ABSTRACT - This paper investigates the effect of the size and shape of coarse aggregates on the compressive strength of concrete. Concrete strength is affected by the surface texture, grading and maximum aggregate size. Six different sizes of coarse aggregate have been selected for both angular and rounded coarse aggregate. The coarse aggregates were used in the production of concrete and tested for workability, density and compressive strength. The specimen was cured for 3, 7, 14, 21 and 28 days by full water immersion. The results indicated that under the same curing conditions and water-cement ratio, the compressive strength of concrete produced with both angular and rounded aggregates increased with increasing aggregate size, up to an aggregate size of 14 mm. The optimum compressive strength of 27.58 N/mm^2 and 25.88 N/mm^2 were achieved at 28 days curing and 14 mm aggregate size for concrete with angular and rounded aggregates respectively. Coarse aggregates with angular shape result in concretes with better compressive strength than coarse aggregates with a rounded shape. The model equation developed to predict the compressive strength of rounded aggregate has R^2 value of 95.66%, and the higher the value of R^2, the better the model fits the data.

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1.0 INTRODUCTION

Strength properties of concrete depend on many parameters such as cement content, water-cement ratio, type and quality of aggregates used, curing period, setting times and other admixtures and/or additives. Since compressive strength is the governing strength condition giving an indication of the concrete mix's ability to withstand axial compressive forces, other miscellaneous mechanical properties could be predicted as functions of concrete compressive strength. Traditionally, cement content, water-to-cement ratio, aggregates and curing periods have been thought to be solely responsible for compressive strength development, but studies have shown that aggregate size and shape, along with many other factors determine compressive strength development of concrete [1].

Concrete strength is affected by surface texture, grading, and maximum aggregate size. Cube specimens generally give more strength than cylinder specimens. In addition, increasing the specimen size decreases the compressive strength [1]. The sizes of the aggregates are determined using the sieve analysis test, this test helps determine the particle size distribution of the aggregates. Aggregates that pass through the no. 4 sieve are characterized as fine aggregates while those retained on sieve no. 4 are referred to as coarse aggregates. Aggregates are very important in concretes as they form structural framework of the concrete [2], therefore this study investigated how the size and shape of the aggregate affects the concrete properties.

Depending on the situation, coarse aggregates make up around 50-70% of the entire concrete. Since the mixing ratio plays a very significant role in concrete production, the aggregates are bonded to the concrete mass by the cement paste that hardens over time [3,4]. In order to achieve the desired compressive strength, attention must therefore be paid to the dimensioning of the aggregate in order to produce a high-quality concrete mix and to prevent segregation in the concrete matrix [5]. If segregation occurs, admixtures and/or increased cement content must be used to restore workability and this could be very expensive.

2.0 RELATED WORK

Zhou et.al. [6] conducted an investigation by preparing concrete mixes with different coarse aggregate sizes. The research shows that as the size of the coarse aggregate increases, so does the compressive strength of the concrete. Likewise, Ekwulo and Eme [5] conducted a study to determine how aggregate size and grading affect the compressive strength development of normal weight concrete for rigid pavement. The results show that the compressive strength of concrete produced from uniform size aggregates increases with increase in the sizes of the aggregates.

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However, studies by Walker and Bloem [7] & Bloem and Gaynor [8] established that compressive strength development of concrete decreases with increasing coarse aggregate size. Similarly, Woode et.al. [9] investigated the influence of maximum coarse aggregate size on the compressive strength development of concrete, they concluded that compressive strength values of concrete made with 10 mm maximum coarse aggregate size are higher than the values for concrete made with 14 and 20 mm maximum coarse aggregate size produced with the same water-cement ratio. The results were attributed to the fact that the larger the coarse aggregate size, the smaller the wetted surface area per unit mass at constant water-cement ratio, which in turn increases the workability for concrete with larger coarse aggregate size. Albarawy et.al. [4] investigated the influence of maximum coarse aggregate size on the compressive strength of concrete. The size of coarse aggregates has been found to affect the compressive strength of concrete, as smaller coarse aggregates provide more surface area for bonding with cement paste, resulting in higher compressive strength values. Test results show that the compressive strength value increases with decreasing coarse aggregate size, while optimum compressive strength was recorded using coarse aggregate size of 9.5 mm.

Furthermore, Ogundipe et.al. [10] experimented with two different concrete mixes to determine how coarseness of the aggregate affects the compressive strength development of concrete. Two different nominal blend, 1:2:4 and 1:3:6, were used for the experiment. Each batch of concrete was produced for both mixes with different nominal coarse aggregate sizes of 6, 10, 12.5, 20 and 25 mm. The results show that the values for both mixes follow a similar trend, with compressive strength values increasing with aggregate size from 6 to 12.5 mm, while concrete made with 20 mm coarse aggregate has higher compressive strengths values than concrete made with 25 mm coarse aggregate. This shows that the influence of coarse aggregate on the compressive strength of concrete does not follow a linear relationship for all aggregates.

The size, shape and texture of aggregates affect the strength properties of concrete differently depending on the type of concrete considered. Coarse aggregate size and shape can affect the bond strength of cement-aggregate, where large coarse aggregate creates high stress concentration in cement paste, leading to increased cracking, especially in high strength concrete [1].

Depletion and increased demand for natural resources necessitated the introduction of natural aggregates in the construction industry. Some of these aggregates occur naturally in various sizes and shapes, while in most cases they are mined from quarries. In this context, the authors investigated how coarse aggregates sizes and shapes influence the compressive strength of concrete. Since literature have established non-linearity in the relationship between coarse aggregate size and compressive strength, this study considered the following aggregate sizes, 5.0, 6.3, 10, 14, 20 and 25 mm, while angular and rounded coarse aggregates for the different sizes were used.

3.0 EXPERIMENTAL PROGRAM

The aim of the experimental program is to study the effect of coarse aggregates on the compressive strength of concrete. The correlation between compressive strength and the size and shape of coarse aggregates was also studied. The evaluation of the prepared samples utilizing six different sized angular and rounded coarse aggregates each was carried out at the Structural Engineering Laboratory of the Department of Civil Engineering of Abubakar Tafawa Balewa University, Bauchi. Judging criteria include compressive strengths and densities of standard 100 x 100 x 100 mm cube shapes. The tests were carried out in accordance with BS EN standard [11].

4.0 MATERIALS

4.1 Cement

Dangote brand of Ordinary Portland Cement (OPC) was used for the experiment. The cement has a specific gravity of 3.15 and was kept away from moisture in the laboratory to avoid lumps formation during the tests. The properties of the cement correspond to BS EN [12].

4.2 Fine Aggregates

The fine aggregates used was river sand obtained from local suppliers in the metropolitan area of Bauchi. The fine aggregate has a fineness modulus of 2.7, a specific gravity of 2.57, and a bulk density of 1611 kg /m^3 and water absorption of 1.18%. The fine aggregate passed through sieve no. 4 (4.75 mm) and retained on sieve no. 100 (150 µm), is free of silt, clay and other harmful materials. All tests are conducted in accordance with BS standard [13].

4.3 Coarse Aggregate

Coarse aggregates of six different nominal sizes (5.0, 6.3, 10, 14, 20 and 25 mm) were used for the experiment for both angular and rounded coarse shapes. The angular coarse aggregates were sourced from local suppliers in in the metropolitan area of Bauchi, while the rounded aggregates were sourced from a stream around Sabon-Kaura, a municipality bordering Abubakar Tafawa Balewa University, Bauchi. All tests were performed according to BS standard [13]. The properties of the coarse aggregates are listed in Table 1.

Table 1. Properties of coarse aggregates

Properties	Angular	Rounded
Specific Gravity	2.74	2.68
Bulk Density (kg/m^3)	1592	1568
Water Absorption (%)	0.15	0.11
Aggregate Crushing Value (%)	12.17	10.22

4.4 Water

Water suitable for drinking was used for the concrete production.

5.0 PROPORTION OF MIXTURES

All mixtures were proportioned using the absolute volume method according to ACI standard [14]. The concrete was designed with a target strength of 20 N/mm^2. Volume fractions and water-to-cement ratio are the same for all mixes. However, weights of coarse aggregates have been modified to account for differences in specific gravities. The mix proportions are shown in Table 2.

Table 2. Mix proportions for concrete production

Material	Absolute Volume
Cement	0.161
Fine Aggregate	0.313
Coarse Aggregate	0.450
Water	0.076
Total	1.000

6.0 TESTING PROGRAM

Concrete specimens were prepared from each mix proportion and tested for compressive strength development, also the densities were evaluated for all mixes at 3, 7, 14, 21 and 28 days. All samples were cured using immersion method. Three specimens were produced for each case and average of the results were recorded for all tests.

7.0 RESULTS AND DISCUSSION

7.1 Slump

The slump values increase as the coarse aggregate size increases for both angular and rounded aggregate at constant water-cement ratio as shown in Table 3. This proportional relationship is consistent with the results of other investigators [9]. Larger aggregates have less surface area to be wetted per unit mass and when the water-cement ratio is kept constant, more water will be available in the mix to increase workability and thereby increasing the slump values of the concrete mix. Consequently, larger aggregates will require less water to achieve high strength [15]. Therefore, it can be stated that slump values are indicators of compressive strengths of hardened concrete. Concretes made with smaller coarse aggregates tends to have higher compressive strength than concretes produced with larger sized coarse aggregates, which is attributed to weak bonds in concretes with larger aggregates as a result of heterogeneity, internal bleeding and micro cracks development [16]. Figure 1 shows the relationship between slump values of concrete mix made with angular shaped coarse aggregates with those of concretes mix made with rounded coarse aggregates. Although slump values increase with increasing size of coarse aggregate for both angular rounded shaped aggregates, it has been observed that concrete mix produced with rounded coarse aggregate have higher slump values than concrete mix produced with angular coarse aggregate. This is due to the smooth surface texture of rounded aggregates that is responsible for improving workability.

Table 3. Slump test results

Aggregate Size (mm)	Slump (mm)	
	Angular	Rounded
5.0	25	26
6.3	27	30
10.0	32	36
14.0	37	43
20.0	42	47
25.0	49	57

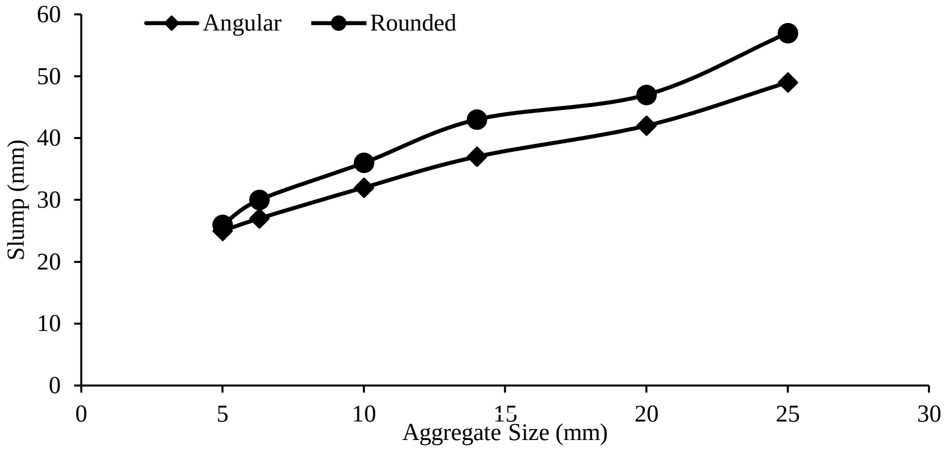

Figure 1. Graph of slump of concrete for angular and rounded aggregates

7.2 Density

The results of densities of concrete produced using both angular and rounded coarse aggregates fall within the range of normal weight concrete as shown in Table 5. Concretes with densities ranging from 2200 to 2600kg/m^3 are classified as normal weight concrete and are suitable for the production of reinforced concrete member [15]. Quality concretes are produced to satisfy compressive strength and durability criteria. Denser concretes offer higher strength due to the presence of fewer voids and porosity [17]. Dense concretes are less permeable, resulting in lower water absorption with better durability.

7.3 Compressive Strength

The average compressive strengths result for different concrete mixes with different aggregate sizes and shapes are also presented in Table 4. Figures 2 and 3 show the average compressive strengths for angular and rounded coarse aggregates in both cases with 5.0, 6.3, 10, 20 and 25 mm coarse aggregates sizes. In general, the results show that compressive strengths of all concrete mixes increased with age, as expected. The results obtained clearly indicate how coarse aggregate size and shape influence the compressive strength of concrete. Strength development was observed for both aggregate shapes with increasing size of the coarse aggregate. The compressive strength values increased with increasing coarse aggregate size from 5.0 mm to 14 mm. The optimum value of compressive strength has been recorded at 14 mm for most of the concrete mixes. A slight decrease in the compressive strength values was observed for most of the mixes when a coarse aggregate size of 20 mm was used. Likewise, concretes produced with 25 mm coarse aggregate generally have lower compressive strength values than those made with 20 mm coarse aggregate. This trend of strength development collaborates findings of other researchers [10].

Findings from the results indicate that using larger aggregates not exceeding 20 mm produce concrete with better compressive strengths, which is attributed to the difficulty in compacting the concrete, resulting in more voids in the concrete mass when using smaller size aggregates.

Table 4. Density and compressive strength test results

Days	Aggregate Size (mm)	Density (kg/m^3)		Compressive Strength (N/mm^2)	
		Angular	Rounded	Angular	Rounded
3	5.0	2590	2640	14.40	14.23
	6.3	2580	2290	14.72	14.21
	10.0	2510	2360	14.87	14.44
	14.0	2580	2390	15.28	14.56
	20.0	2510	2330	14.91	15.82
	25.0	2550	2420	14.03	15.07
7	5.0	2572	2360	18.28	16.98
	6.3	2261	2350	18.36	17.25
	10.0	2492	2330	18.37	17.19
	14.0	2500	2420	19.01	18.39
	20.0	2580	2450	18.37	18.12
	25.0	2530	2440	18.00	18.01

Table 4. (cont.)

Days	Aggregate Size (mm)	Density (kg/m^3)		Compressive Strength (N/mm^2)	
		Angular	Rounded	Angular	Rounded
14	5.0	2470	2390	19.37	17.16
	6.3	2490	2330	19.51	17.82
	10.0	2460	2400	20.14	19.31
	14.0	2390	2460	20.72	19.52
	20.0	2510	2420	19.92	18.33
	25.0	2500	2420	18.75	17.21
21	5.0	2480	2380	21.25	19.58
	6.3	2470	2350	21.28	20.25
	10.0	2320	2390	23.58	21.33
	14.0	2470	2370	24.05	21.97
	20.0	2500	2450	24.10	20.52
	25.0	2560	2450	23.76	20.50
28	5.0	2480	2330	25.91	23.29
	6.3	2450	2300	26.37	24.16
	10.0	2420	2360	26.91	25.28
	14.0	2560	2320	27.58	25.88
	20.0	2550	2360	26.86	25.22
	25.0	2560	2350	26.25	25.20

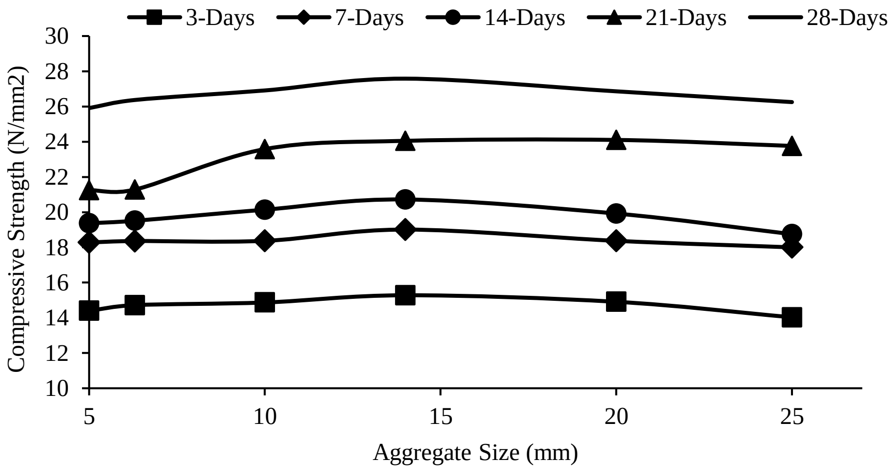

Figure 2. Graph of compressive strength of concrete produced using angular coarse aggregates

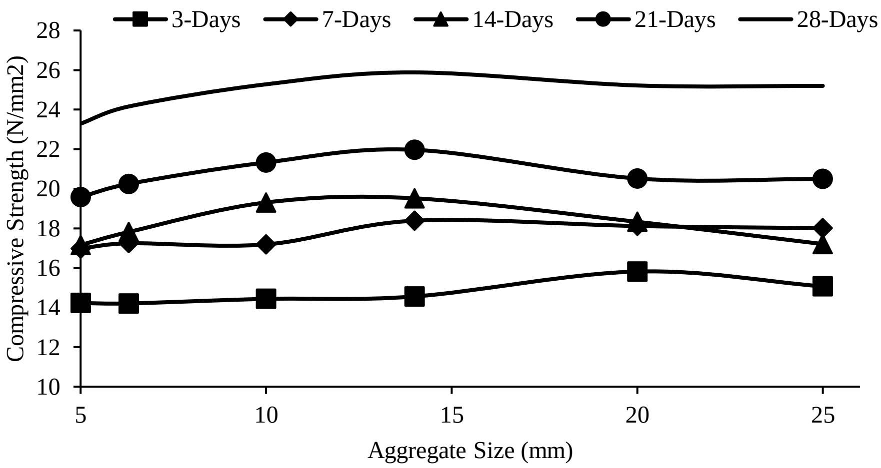

Figure 3. Graph of compressive strength of concrete produced using rounded coarse aggregates

Figure 4 shows the 28-days compressive strength of angular and rounded coarse aggregates. The results show that concrete produced with angular coarse aggregates have higher compressive strength values than those produced with rounded coarse aggregates. Angular aggregates are generally rough in texture, while rounded aggregates are smooth in texture. Rough surfaces are believed to bond better to cement paste than smooth surfaces, although at microscopic level rounded aggregates have surfaces rough enough to form an adequate bond with cement paste since cement paste has particles sizes in the smaller range [18]. The specific surface area of angular aggregates is higher than that of rounded aggregate, higher specific surface areas result in better surface adhesion and coupled with better interlocking effects, the angular aggregates result in concrete with better compressive strength than rounded aggregates [19].

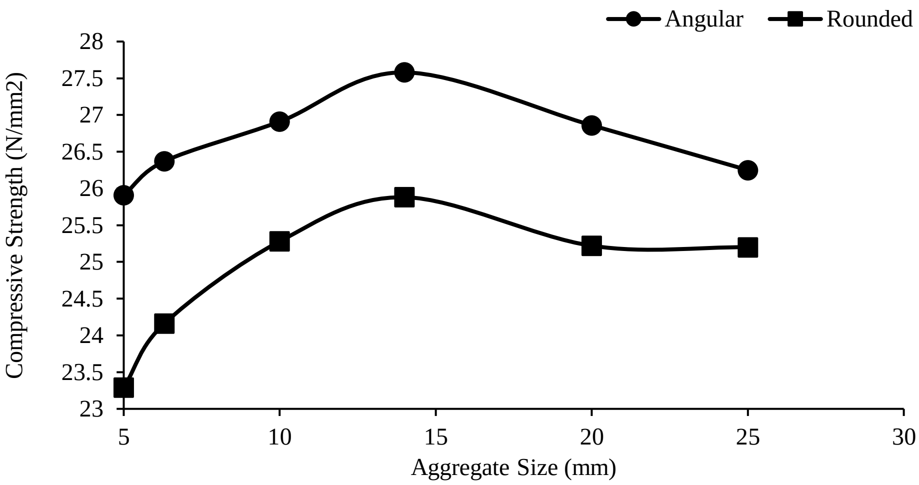

Figure 4. Graph of 28-days compressive strength of concrete for angular and rounded coarse aggregates

Figure 5 shows the relationship between compressive strengths of angular and rounded aggregates. The model equation for predicting the compressive strengths of rounded coarse aggregate concrete (CS_r) from angular coarse aggregate concrete (CS_a) is presented in equation (1). The Model has coefficient of determination (R^2) of 0.9566 (95.66%), indicating that the model fits the data (the higher the value of R^2, the better the model fits the data).

$$CS_r = 0.8224CS_a + 2.3697 \quad (1)$$

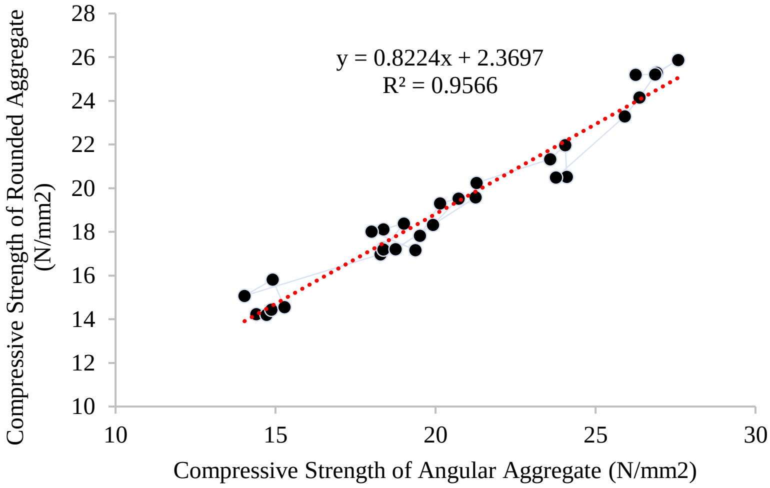

Figure 5. Relationship between the compressive strengths of rounded and angular coarse aggregates

8.0 CONCLUSION

This research presented results of effect of the size and shape of coarse aggregate on the compressive strength of concrete. Six aggregate sizes were selected for both angular and rounded coarse aggregates. Concrete specimens were produced and tested for workability, density and compressive strength. The following conclusions were drawn from the results:

1) Under the same curing conditions and the same water-cement ratio, the compressive strength of concrete produced with both angular and rounded aggregates increased with increasing aggregate size up to aggregate size of 14 mm.

The optimum compressive strengths of 27.58 N/mm^2 and 25.88 N/mm^2 were achieved at 28 days curing and 14 mm aggregate size for concrete with angular and rounded aggregates respectively.

2) Coarse aggregates with angular shapes produced concretes with better compressive strength than coarse aggregates with rounded shape.

3) The model equation developed to predict the compressive strength of rounded aggregate has R^2 value of 95.66%, and the higher the value of R^2, the better the model fits the data.

Based on the results of this research, it is recommended when producing concrete for load-bearing components, careful attention must be paid to the size and shape of the aggregate.

9.0 AUTHOR CONTRIBUTIONS

Claudius Konitufe.: Conceptualization, Methodology, Investigation.

Aliyu Abubakar.: Data Analysis, Writing- Reviewing and Editing.

Abubakar Sabo Baba.: Writing- Original draft preparation.

All authors have read and agreed to the published version of the manuscript.

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Not applicable.

11.0 DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

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13.0 CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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