

STRENGTH CHARACTERISTICS OF CONCRETE MADE WITH CRUSHED GRANITE OF VARYING PARTICLE SIZES FOR STRUCTURAL APPLICATIONS

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ABSTRACT

The selection of appropriate coarse aggregate characteristics is essential for producing concrete with adequate strength for structural applications. This study investigated the strength characteristics of concrete produced with crushed granite of varying particle sizes. Five aggregate treatments comprising 12, 14, 16 and 20 mm granite fractions and an equal-proportion combined aggregate were evaluated using a 1:2:4 mix proportion and a water–cement ratio of 0.50. Portland limestone cement, River Benue sand and crushed granite were used for concrete production. Aggregate properties, workability, density, compressive strength and splitting tensile strength were determined using standard laboratory procedures. Concrete specimens were cured for 7, 14 and 28 days. The results showed that the 20 mm aggregate produced the highest 28-day compressive strength (29.40 N/mm²) and splitting tensile strength (2.33 N/mm²), while the 12 mm aggregate recorded the lowest values of 25.33 and 2.06 N/mm², respectively. Both compressive and splitting tensile strengths generally increased with curing age. Two-way analysis of variance (ANOVA) showed that aggregate treatment, curing age and their interaction significantly affected compressive strength ($p < .001$), with the model explaining 99.3% of the observed variation ($R^2 = .993$). For splitting tensile strength, aggregate treatment and curing age had significant effects ($p < .001$), whereas their interaction was not significant ($p = .135$). The study concludes that coarse aggregate particle size significantly influences concrete strength, with 20 mm producing the highest strength under the conditions investigated. The use of 20 mm coarse aggregate is recommended where higher strength is required and member dimensions permit its use.

Keywords: Coarse aggregate; Crushed granite; Particle size; Concrete strength; Compressive strength; Splitting tensile strength; Curing age; Structural concrete

1.0 INTRODUCTION

Concrete is one of the most widely used construction materials because of its high compressive strength, durability, versatility, and availability of constituent materials (Surahyo, 2019). It is extensively used in foundations, columns, beams, slabs, bridges, pavements, retaining structures, and other load-bearing elements (Afsoosbiria & Machowska, 2025; Salgado, 2022). Concrete is generally produced by combining cement, fine aggregate, coarse aggregate, and water, and its performance depends considerably on the properties and proportions of these constituents. Among these constituents, coarse aggregate occupies a substantial volume of concrete (Dehghan *et al.*, 2021) and therefore plays an important role in determining its fresh and hardened properties. Crushed granite is one of the major coarse aggregates used in concrete production in Nigeria (Ogunbayo & Aigbavboa, 2019). It is obtained by mechanically crushing granite rock into particles of different sizes (Akinpelu *et al.*, 2021). Its physical characteristics, including particle size, grading, shape, surface

texture, specific gravity, and cleanliness, influence aggregate packing, cement-paste demand, workability, the interfacial transition zone, and ultimately the strength of concrete (Rao & Kanth, 2025). Neville and Brooks (2010) noted that aggregate characteristics have considerable influence on concrete performance because aggregates constitute the major solid component of the concrete matrix. Similarly, Mehta and Monteiro (2014) reported that aggregate properties influence concrete through their effects on particle packing, paste requirements, and the aggregate–paste interface.

Particle size and grading are particularly important because aggregate particles form the skeletal framework of concrete. The distribution of particle sizes determines the efficiency with which particles pack together. Well-graded aggregates can reduce voids and the quantity of cement paste required to fill the spaces between particles, whereas poorly graded or excessively coarse aggregates may increase voids and affect concrete homogeneity. Conversely, an excessive proportion of fine aggregate particles can increase specific surface area and paste demand. These conditions can influence workability, compaction, and strength development. Concrete strength is commonly evaluated through compressive, splitting tensile, and flexural strength (Suda & Paul, 2022). Compressive strength is particularly important for structural concrete, while tensile and flexural strengths provide additional information about resistance to cracking and bending. These properties are affected by the water–cement ratio, cement content, curing conditions, aggregate properties, compaction, and concrete age (Beushausen & Dittmer, 2015). Among these factors, aggregate size and grading can influence strength by affecting particle packing, internal voids, and the interaction between aggregate and cement paste. In Nigeria, crushed granite is commonly available in nominal sizes such as 10, 14, 20, and 25 mm (Omopariola & Jimoh, 2018). Although 20 mm aggregate is frequently used for structural concrete, the use of different particle sizes or combinations may produce differences in strength because of variations in packing density, surface area, void content, and aggregate–paste interaction. Selection of aggregate size based mainly on conventional practice or availability, without adequate consideration of its influence on concrete performance, may result in variations in concrete quality (Alexander *et al.*, 2025). Inappropriate particle-size distribution may increase voids, cement-paste requirements, and difficulties in achieving adequate compaction, potentially reducing concrete strength. Conversely, suitable particle sizes and grading may improve packing density, reduce voids, enhance aggregate–paste interaction, and contribute to improved mechanical performance. Therefore, experimental investigation is necessary to establish how varying crushed-granite particle sizes affect the strength characteristics of concrete under controlled mix, curing, and testing conditions. The problem addressed by this study is the limited experimental understanding of the relationship between crushed-granite particle size and the strength characteristics of concrete intended for structural applications. Establishing this relationship is important for informed aggregate selection and concrete mix proportioning. This study therefore investigates the strength characteristics of concrete made with crushed granite of varying particle sizes for structural applications.

2.0 MATERIALS AND METHODS

2.1 Materials

The materials used for the production and testing of concrete specimens comprised Portland limestone cement, fine aggregate, coarse aggregate and water. Dangote 3X Portland limestone cement of strength class 42.5N, obtained from a Dangote Cement depot in Makurdi, Benue State, Nigeria, was used as the cementitious material. River sand obtained from River Benue was used as the fine aggregate. The coarse aggregate was crushed granite obtained from a construction site in Benue State. Four nominal coarse aggregate sizes, namely 12, 14, 16 and 20 mm, were investigated separately. A combined aggregate consisting of equal proportions of

the four aggregate sizes was also used for comparison. Clean tap water obtained from the Civil Engineering Laboratory of Joseph Sarwuan Tarka University, Makurdi, Benue State, Nigeria, was used for mixing, curing and other experimental procedures.

2.2 Concrete Batching and Production

The concrete was produced using a nominal mix proportion of 1:2:4, representing cement, fine aggregate and coarse aggregate, respectively. A water–cement ratio of 0.50 was adopted. The materials were batched by weight to improve consistency and accuracy of the mixtures. Separate concrete mixes were prepared using 12, 14, 16 and 20 mm coarse aggregates. A fifth mix containing equal proportions of the four coarse aggregate sizes was also prepared to represent the combined aggregate. The aggregates were measured according to the required mix proportions and thoroughly mixed with cement and water until a uniform concrete mixture was obtained. The concrete was cast into standard 150 mm × 150 mm × 150 mm cube moulds and standard cylindrical mould of 150mm x 300mm for splitting tensile strength testing. A total of 45 cubes and 45 cylinders were produced. The specimens were demoulded after 24 hours and cured for 7, 14 and 28 days in accordance with BS EN 12390-2:(2019).

2.3 Experimental Methods

Laboratory tests were conducted to characterize the aggregates and evaluate the fresh and hardened properties of the concrete. The tests included particle-size distribution (sieve analysis), aggregate crushing value, aggregate impact value, slump, density, compressive strength and splitting tensile strength. The procedures were carried out in accordance with the relevant British Standards.

(a) Sieve Analysis

Sieve analysis was conducted on the fine and coarse aggregates to determine their particle-size distribution and grading characteristics. A series of standard sieves was used to separate the aggregate particles according to size. The procedure was conducted in accordance with BS 812-103 (1990).

(b) Aggregate Crushing Value Test

The Aggregate Crushing Value (ACV) test was conducted to determine the resistance of the coarse aggregate to crushing under a gradually applied compressive load. The test was performed on each coarse aggregate size and the combined aggregate in accordance with BS 812-110:1990. The ACV was calculated using equation 1.

$$\text{Aggregate Crushing Value} = \frac{M_2}{M_1} \times 100 \quad (1)$$

where,

M_2 = Weight of sample passing through sieve size 2.36mm after crushing

M_1 = Weight of dry sample

(c) Aggregate Impact Value Test

The Aggregate Impact Value (AIV) test was conducted to assess the resistance of the coarse aggregate to sudden impact or shock. The test was carried out for the 12, 14, 16 and 20 mm aggregate sizes and the combined aggregate in accordance with BS 812-112:1990. The AIV was calculated using equation (2).

$$AIV = \left(\frac{B}{A}\right) \times 100 \quad (2)$$

where:

A = mass of the oven-dried aggregate sample before impact (g)

B = mass of material passing through the 2.36 mm sieve after impact (g).

(d) Specific Gravity Test

The specific gravity of the aggregates was determined to establish the ratio of the density of the aggregate particles to the density of an equivalent volume of water. The specific gravity test was carried out in accordance with the method described in BS EN 1097-6:(2022). The specific gravity was calculated using equation (3).

$$Gs = \frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_2)} \quad (3)$$

Where, Gs = specific gravity, M₁ = weight of empty flask, (g), M₂ = weight of empty flask + weight of the sample, (g), M₃ = weight of empty flask + weight of the sample + water, (g), M₄ = weight of empty flask + water, (g)

(e) Slump Test

The slump test was conducted to determine the consistency and workability of the fresh concrete. The test was carried out immediately after mixing, before significant loss of moisture or commencement of setting. The procedure was conducted in accordance with BS EN 12350-2:(2019).

(f) Water Absorption Test

The water absorption test was conducted to determine the amount of water absorbed by the hardened concrete cube specimens. The test was carried out in accordance with BS EN 1097-6:(2022). Water absorption was calculated using equation (4):

$$W_a = \frac{W_2 - W_1}{W_1} \times 100 \quad (4)$$

W_a = Water absorption (%), W₁ = weight of oven dried cube (kg), W₂ = weight of wet cube (kg)

(g) Density of Concrete Test

The concrete density was determined by dividing the mass of each cube by its volume as specified by BS EN 12350-6:(2019). The volume of each specimen was calculated using equation (5).

$$\text{Density } (\rho \text{ in kg/m}^3) = \frac{\text{mass of cube (kg)}}{\text{volume of cube (m}^3\text{)}} \quad (5)$$

(h) Compressive Strength Test

The compressive strength test was conducted to determine the load-bearing capacity of the hardened concrete. The cured 150 × 150 × 150 mm cube specimens were tested using a compression testing machine at the

specified curing ages. The test was conducted in accordance with BS EN 12390-3:(2019). The compressive strength was calculated using equation (6).

$$\text{Compressive Strength } (\sigma \text{ in N/mm}^2) = \frac{\text{crushing load of cube (N)}}{\text{Area of cubes (mm}^2\text{)}} \quad (6)$$

(i) Splitting tensile strength

The splitting tensile strength test was conducted in accordance with the provision of BS EN 12390-6:(2023) using universal testing machine with accuracy of $\pm 1\%$ of test force. In order to obtain the splitting tensile strength (T_s), the expression in equation (7) was used.

$$T_s = \frac{2P}{\pi ld} \quad (7)$$

where: T_s is the splitting tensile strength (N/mm^2), P is the maximum applied load (in Newtons) by the testing machine, l is the length of the specimen (mm), and d is the diameter of the specimen (mm).

2.4 Experimental Design and Statistical Analysis

The experiment consisted of five coarse aggregate treatments: 12, 14, 16 and 20 mm aggregate sizes and the combined aggregate. Each treatment was evaluated at three curing ages (7, 14 and 28 days), with three replicate specimens per treatment-age combination. The data obtained from the concrete tests were summarized using means and standard deviations. A two-way analysis of variance (ANOVA) was used to determine the effects of coarse aggregate size, curing age and their interaction on compressive strength and split tensile strength. Statistical significance was evaluated at the 5% probability level. Where significant differences were detected, appropriate post-hoc or simple-effects comparisons were considered to identify the specific treatment means responsible for the differences. The statistical analysis was performed using Statistical Package for the Social Sciences (SPSS).

3.0 RESULTS AND DISCUSSION

3.1 Grading Characteristics of the Aggregates

Figures 1 and 2 shows the grading curve for river sand and coarse aggregates. The river sand recorded a coefficient of uniformity (C_u) of 3.01, coefficient of curvature (C_c) of 1.04, and fineness modulus (FM) of 2.97. The C_u value is below the conventional value of 6 for well-graded sand, indicating a poorly graded or relatively uniform sand, while the C_c value falls within the acceptable range of 1–3. The FM of 2.97 indicates a relatively coarse sand suitable for concrete production. This agrees with Omoregie and Alutu (2006), who reported that variations in fine-aggregate grading influence particle packing and concrete-related properties. The individual granite fractions recorded C_u values of 1.41–1.93 and C_c values of 1.00–1.10, reflecting their narrow particle-size ranges. The combined aggregate had higher C_u (2.35) and C_c (1.13), indicating a broader particle-size distribution due to blending. Ogundipe *et al.* (2018) similarly demonstrated that coarse aggregate size significantly affects concrete performance, confirming the importance of aggregate grading and particle size in concrete production. ASTM C33/C33M also emphasizes appropriate aggregate grading and permits blending of aggregate sizes where necessary.

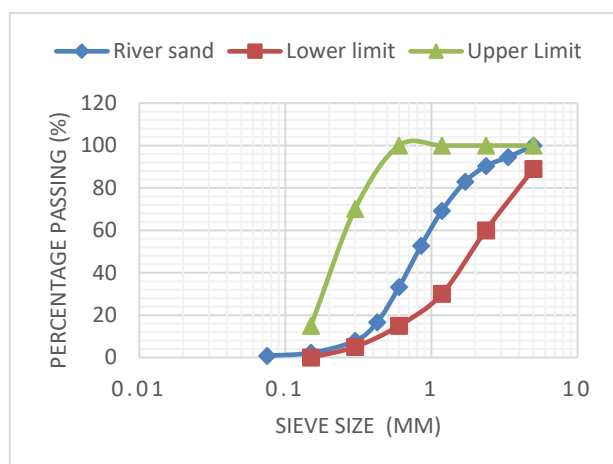


Figure 1: Grading Curve for River Sand

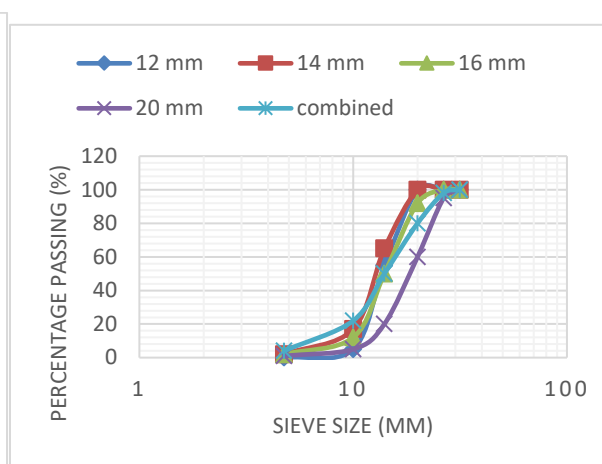


Figure 2: Grading Curve for Coarse Aggregates

3.2 Water Absorption of Coarse Aggregates

Figure 3 shows water absorption of coarse aggregates. The result revealed that water absorption decreased with increasing aggregate size, from 2.10% for 12 mm to 1.20% for 20 mm, while the combined aggregate recorded the lowest value (1.18%).

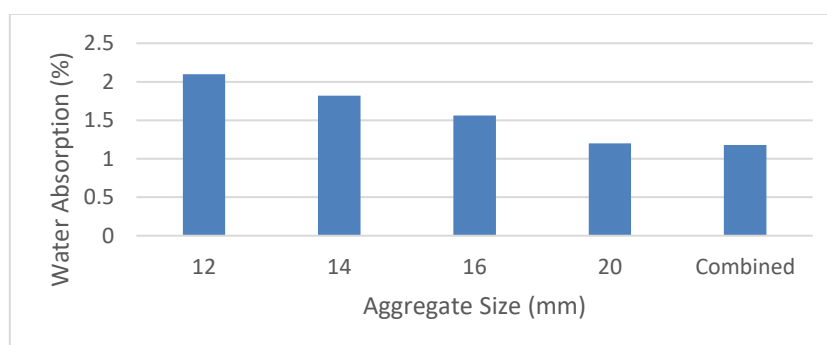


Figure 3: Water Absorption of Coarse Aggregates

The higher absorption recorded for the smaller aggregate fractions may be associated with differences in pore structure and the amount of water-accessible surface associated with the crushed particles. Aggregate absorption is an important physical property because it reflects the amount of water that can enter the pores of aggregate particles and is used in concrete mix-water adjustment (ASTM International, 2024). The relatively low absorption values obtained indicate that the granite aggregates were generally dense and had limited water-accessible porosity. This is consistent with Xu *et al.* (2026), who found that aggregates with higher water absorption were associated with greater interfacial transition-zone porosity and reduced concrete durability and mechanical performance. However, the observed decrease in absorption with particle size should be interpreted cautiously because aggregate absorption is influenced not only by particle size but also by the pore structure, mineralogy and surface characteristics of the parent rock. Yang *et al.* (2021) specifically reported that coarse-aggregate particle size did not necessarily affect the water absorption of unsaturated concrete, demonstrating that particle size alone does not determine water absorption behaviour.

3.3 Specific Gravity of Aggregates

Figure 4 shows specific gravity of aggregates. The results indicated that the specific gravity of the river sand was 2.51, while that of the coarse aggregate increased from 2.54 for 12 mm to 2.65 for 20 mm, with the combined aggregate recording 2.63. The values indicate that the aggregates are relatively dense and suitable for normal-weight concrete. Similar trend was observed by Sidi *et al.* (2021) that specific gravity values of 2.63–2.71 for granite and granite-gneiss aggregates and classified them as suitable normal-weight construction materials. Similarly, Omopariola & Jimoh (2018) reported specific gravity values of 2.63–2.71 for granite. Specific gravity is primarily influenced by the mineralogical composition and density of the parent rock. The results are consistent with Joshua *et al.* (2021) reported specific gravity range of 2.60–2.70 for granite aggregates in Nigerian construction materials studies.

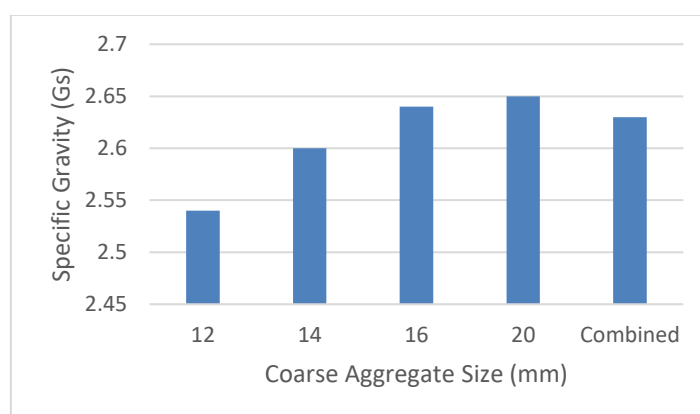


Figure 4: Specific Gravity of Aggregates

3.4 Aggregate Crushing Value

Figure 5 shows the result of aggregate crushing value. The ACV ranged from 15.60% to 29.53%. The 12 mm aggregate recorded the highest ACV (29.53%), whereas the 16 mm aggregate had the lowest value (15.60%), indicating greater resistance to crushing. The combined aggregate also exhibited good crushing resistance with an ACV of 17.21%. Similar observations have been reported by Sidi *et al.* (2021) where granite aggregates generally demonstrated satisfactory resistance to crushing and were considered suitable for construction applications. The variation among the aggregate sizes suggests that crushing resistance was influenced not only by particle size but also by particle shape, internal defects and the mineralogical characteristics of the parent rock. The results are comparable with those reported by Uche and Muhammad (2011), who obtained an ACV of 25.04% for crushed granite from Nigeria. Their results demonstrate that Nigerian crushed granite can possess relatively good resistance to crushing and can be suitable for construction applications. Similarly, Raheem *et al.* (2021) reported ACV values of 15.67–16.98% for granite obtained from four locations in Ogbomoso, Nigeria. These values are very close to the lower ACV values obtained in the present study, particularly the 15.60% recorded for the 16 mm aggregate. Further support was provided by Omopariola and Jimoh (2018), who reported ACV values ranging from 6.21% to 9.45% for granitic aggregates from Ogun State, although their values were lower than those obtained in the present study. Adigun *et al.* (2019) reported porphyritic granite, granite gneiss and charnockite recorded ACV values between 26.2% and 27.8%, which fall within the range obtained in the present study.

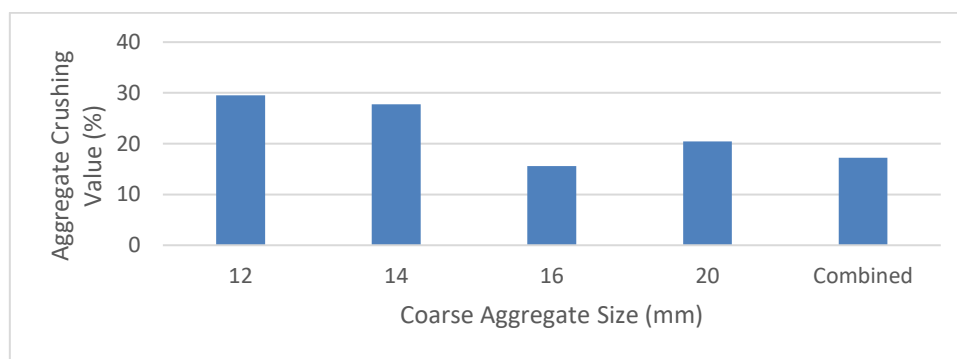


Figure 5: Aggregate Crushing Value

3.5 Aggregate Impact Value

Figure 6 shows the aggregate impact value for the granite. The result revealed that the AIV decreased from 33.61% for the 12 mm aggregate to 20.97% for the 20 mm aggregate, while the combined aggregate recorded 24.59%. The decreasing values indicate increasing resistance to sudden impact or shock loading with increasing aggregate size. The 12 mm fraction therefore exhibited the lowest impact resistance, whereas the 20 mm fraction showed the highest resistance among the individual aggregate sizes. The present results are comparable with the findings of Omopariola and Jimoh (2018), who reported AIV values of 18.30–28.12% for granitic aggregates from Ogun State. Their results also demonstrated that AIV varied with aggregate size and quarry location. Similarly, Raheem *et al.* (2021) obtained AIV values of 10.00–12.50% for granite from four locations in Ogbomoso, indicating considerably higher impact resistance than the aggregates investigated in the present study. The difference may be attributed to differences in rock source, mineralogical composition, particle shape and aggregate production processes. Uche and Muhammad (2011) also demonstrated the importance of aggregate source in mechanical performance by testing crushed granite, river gravel, slag and all-in aggregate from Nigeria. Their crushed granite recorded an ACV of 25.04%, illustrating the variability that can occur among Nigerian aggregate materials. Furthermore, Ademila (2019) evaluated granite, granite-gneiss, quartzite, migmatite gneiss and charnockite from Akure and emphasized that aggregate impact and crushing resistance vary according to rock type and geological characteristics. The 20 mm aggregate (20.97%) and combined aggregate (24.59%) therefore demonstrated relatively good resistance to impact, while the 12 mm aggregate (33.61%) showed comparatively lower resistance. These results confirm that the mechanical quality of coarse aggregate is influenced by both particle size and the intrinsic characteristics of the aggregate source.

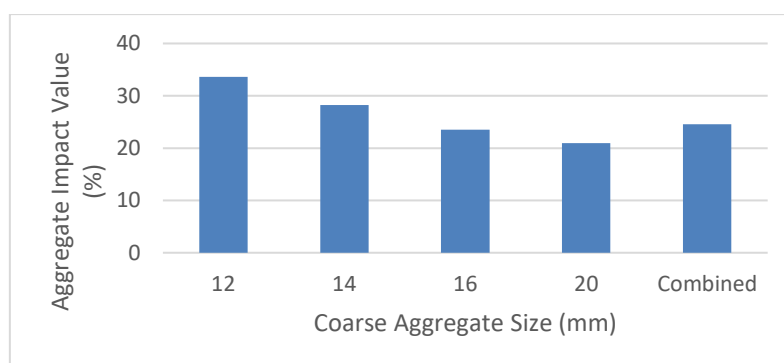


Figure 6: Aggregate Impact Value

3.6 Workability

Figure 7 presented slump test result. The slump values ranged from 23 to 34 mm. The 20 mm aggregate produced the highest slump (34 mm), while the combined aggregate recorded the lowest (23 mm). The results indicate generally low workability across the mixtures. The absence of a consistent increase or decrease in slump with aggregate size suggests that workability was influenced by several factors, including aggregate grading, particle shape, surface texture and water absorption, rather than particle size alone. This agrees with Mkpaidem *et al.* (2022), who reported variations in concrete workability with different coarse-aggregate sizes and noted the influence of aggregate characteristics on fresh concrete behaviour. Similar observations have been reported by Neville and Brooks (2010), who explained that aggregate size, shape, texture and grading can substantially affect concrete workability.

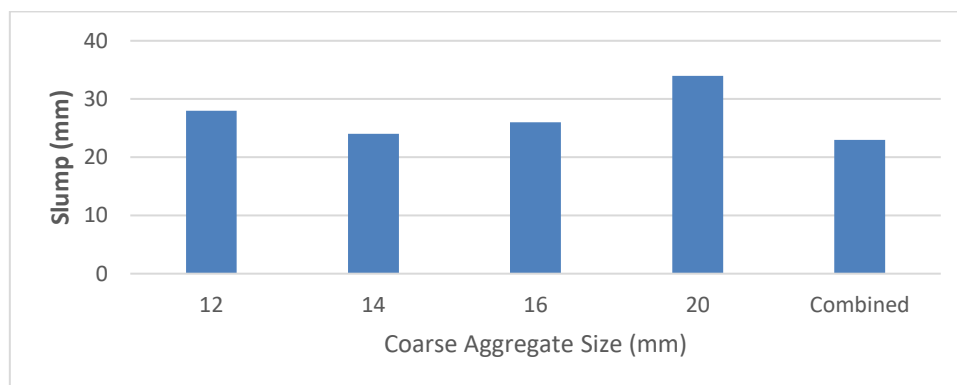


Figure 7: Slump Result

3.7 Density of Concrete

Figure 8 shows the density of concrete produced with different aggregate sizes at 7, 14 and 28 days of curing. The results indicate that concrete density generally increased with curing age, while higher density values were observed with the larger aggregate sizes. For the 12 mm aggregate, density increased from 2343 kg/m³ at 7 days to 2352 kg/m³ at 14 days and 2371 kg/m³ at 28 days. Similarly, the 14 mm aggregate recorded 2380, 2392 and 2410 kg/m³, while the 16 mm aggregate increased from 2399 to 2404 and 2427 kg/m³ at 7, 14 and 28 days, respectively. The 20 mm aggregate recorded the highest density values, increasing from 2407 kg/m³ at 7 days to 2418 kg/m³ at 14 days and 2433 kg/m³ at 28 days. The combined aggregate also showed an increase from 2388 kg/m³ at 7 days to 2390 kg/m³ at 14 days and 2415 kg/m³ at 28 days.

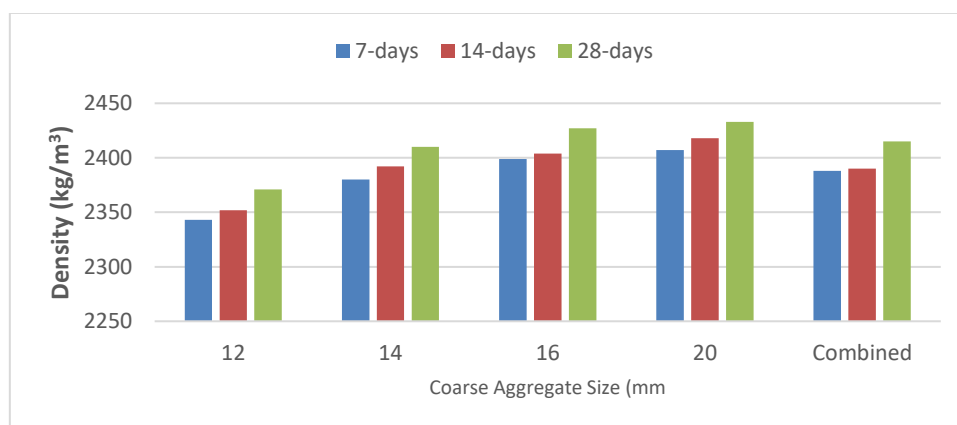


Figure 8: Density of Concrete

The increase in density with curing age can primarily be attributed to continued cement hydration and progressive densification of the cement paste–aggregate matrix. As curing progresses, hydration products develop within the cement paste and progressively refine the internal pore structure, resulting in a more compact concrete matrix. Li *et al.* (2016) reported that changes in micropore structure during later curing ages are associated with continued hydration and the development of concrete properties. Similarly, Ode and Eluozo (2017) observed that curing age influences concrete density, with density development associated with continued hydration and changes within the concrete matrix. In the present study, the mean density increased from 2383.4 kg/m³ at 7 days to 2391.2 kg/m³ at 14 days and 2411.2 kg/m³ at 28 days. At 28 days, density increased from 2371 kg/m³ for the 12 mm aggregate to 2433 kg/m³ for the 20 mm aggregate. These values are comparable with those reported by Jagba *et al.* (2026) and Sulymon *et al.* (2017), who obtained concrete densities within the normal-weight concrete range. The density values obtained in the present study are within the typical range reported for normal-weight concrete. Neville and Brooks (2010) reported that normal-weight concrete generally has a density of approximately 2200–2600 kg/m³, with about 2400 kg/m³ being typical. Differences in aggregate size were also associated with differences in concrete density. The increase in density from the 12 mm to the 20 mm aggregate may be related to differences in particle packing, aggregate arrangement, void content, specific gravity and compaction. Behera *et al.* (2022) demonstrated that aggregate size distribution and particle characteristics influence packing density. Similarly, Kwan *et al.* (2014) showed that particle-size distribution affects packing density by influencing interparticle voids. Farahani *et al.* (2025) further demonstrated that aggregate size can affect concrete behaviour through changes in particle arrangement and the aggregate skeleton. Therefore, the higher density obtained with the 20 mm aggregate shows favourable particle arrangement under the mix proportions and compaction conditions adopted in this study. The combined aggregate recorded densities of 2388, 2390 and 2415 kg/m³ at 7, 14 and 28 days, respectively. These values were generally intermediate between those obtained for the individual aggregate sizes. This may be attributed to the broader particle-size distribution of the combined aggregate, which could improve particle packing and reduce interparticle voids. Behera *et al.* (2022) and Kwan *et al.* (2014) similarly identified particle packing and particle-size distribution as important factors affecting aggregate packing and concrete compactness.

3.8 Compressive Strength of Concrete

Figure 9 shows the compressive strength of concrete. The compressive strength generally increased with curing age from 7 to 28 days for all aggregate sizes. At 7 days, strength ranged from 17.02 N/mm² (12 mm) to 21.05 N/mm² (20 mm). At 14 days, values ranged from 22.09 N/mm² (16 mm) to 23.58 N/mm² (20 mm), while at 28 days, strength increased further to 25.33, 26.73, 27.69 and 29.40 N/mm² for 12, 14, 16 and 20 mm aggregates, respectively. The combined aggregate recorded 27.82 N/mm² at 28 days. The increase with curing age is attributed to continued cement hydration and progressive densification of the cement matrix (Neville & Brooks, 2010). The 20 mm aggregate produced the highest strength at all curing ages, with a 16.1% higher 28-day strength than the 12 mm aggregate. This agrees with Ogundipe *et al.* (2018), who reported that coarse aggregate size significantly influenced concrete compressive strength and found comparatively high strength with 20 mm aggregate. Muoneke (2021) similarly reported increasing compressive strength from 12 to 20 mm aggregate at 7, 14 and 28 days. The result is also consistent with Mkpaidem *et al.* (2022), who reported increasing compressive strength with increasing coarse-aggregate size in concrete produced.

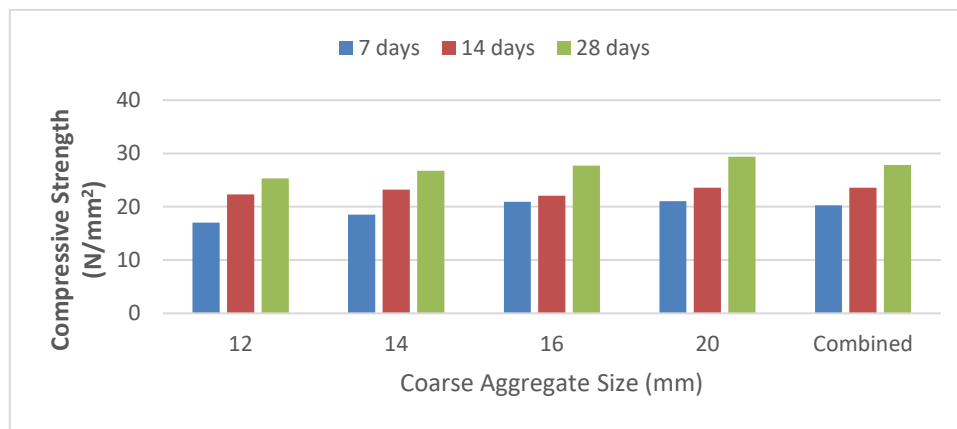


Figure 9: Compressive Strength of Concrete

3.9 Splitting Tensile Strength of Concrete

Figure 10 presents the splitting tensile strength of concrete produced with different coarse aggregate sizes at 7, 14 and 28 days. The result shows a progressive increase in splitting tensile strength with curing age for all aggregate sizes. At 7 days, the values ranged from 1.71 N/mm² for the 12 mm aggregate to 1.83 N/mm² for the 20 mm aggregate. At 14 days, the values increased to between 1.90 and 2.19 N/mm², while the 28-day values ranged from 2.06 to 2.33 N/mm². This progressive increase indicates the continued development of cement hydration and improvement of the paste–aggregate bond with curing age. At 28 days, the 20 mm aggregate produced the highest splitting tensile strength of 2.33 N/mm², followed by the combined aggregate (2.30 N/mm²), 16 mm aggregate (2.30 N/mm²), 14 mm aggregate (2.19 N/mm²), and 12 mm aggregate (2.06 N/mm²). Thus, the 20 mm aggregate produced 13.1% higher splitting tensile strength than the 12 mm aggregate. The results suggest that aggregate size influenced the tensile resistance of the concrete, although the differences between the 16, 20 mm and combined aggregates were relatively small. The observed increase in splitting tensile strength with aggregate size is consistent with the findings of Mmekaka *et al.* (2020), who reported that splitting tensile strength increased with curing age and generally increased with coarse aggregate size. Their study attributed the improvement partly to the interaction between aggregate particles and the cement paste, which influences crack initiation and propagation under tensile loading. Similarly, the present result agrees with the general observation that the aggregate–paste interfacial transition zone plays an important role in the tensile behaviour of concrete (Mehta & Monteiro, 2014). However, aggregate size should not be considered independently of aggregate grading, shape, surface texture, paste content and compaction, since these factors can modify the bond and crack development characteristics of concrete. The relationship between splitting tensile and compressive strength also provides an indication of the consistency of the results. At 28 days, the splitting tensile strength represented approximately 7.9–8.1% of the corresponding compressive strength across the five aggregate conditions. The relatively narrow range indicates that the tensile behaviour was broadly consistent with the compressive-strength development of the concrete.

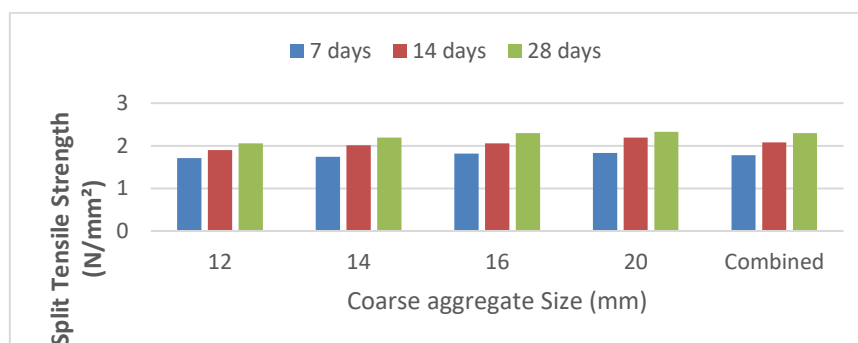


Figure 10: Splitting Tensile Strength of Concrete

3.10 Two-Way ANOVA of Compressive Strength of Concrete

Tables 1 and 2 show two-way analysis of variance. A two-way analysis of variance (ANOVA) was conducted to determine the effects of coarse aggregate size and curing age on the compressive strength of concrete. The descriptive statistics showed that the overall mean compressive strength increased from 19.53 N/mm² at 7 days to 22.87 N/mm² at 14 days and 27.47 N/mm² at 28 days. Across aggregate sizes, the overall mean strengths were 21.56, 22.82, 23.58, and 24.68 N/mm² for the 12, 14, 16, and 20 mm aggregates, respectively, while the combined group had an overall mean of 23.88 N/mm². These descriptive results indicate that curing age and aggregate size were associated with changes in compressive strength. The two-way ANOVA confirmed that aggregate size had a statistically significant effect on compressive strength, ($F(4,30)=102.333$, $p<0.001$). This indicates that the differences in compressive strength among the five aggregate-size treatments were unlikely to be due to random experimental variation alone. Curing age also had a highly significant effect on compressive strength, ($F(2,30)=1785.167$, $p<0.001$), confirming that the strength development from 7 to 28 days was statistically significant. Importantly, the interaction between aggregate size and curing age was also significant, ($F(8,30)=15.583$, $p<0.001$). This indicates that the effect of aggregate size on compressive strength was not exactly the same at all curing ages. Therefore, the influence of aggregate size should be interpreted together with curing age rather than considering either factor independently. The overall model was statistically significant, ($F(14,30)=293.167$, $p<0.001$), with ($R^2=0.993$) and an adjusted ($R^2=0.989$). Thus, approximately 99.3% of the observed variation in compressive strength was explained by aggregate size, curing age and their interaction, while approximately 0.7% remained unexplained by the model. The very small error mean square (0.133) relative to the treatment effects also indicates relatively low unexplained experimental variation.

Table 1: Descriptive Statistics of Compressive Strength

Aggregate Size (mm)	Curing Age (Days)	Mean (N/mm ²)	Std. Deviation	N
12	7	17.02	0.000	3
	14	22.33	0.000	3
	28	25.33	0.577	3
	Total	21.56	3.786	9
14	7	18.51	0.577	3
	14	23.22	0.000	3
	28	26.73	0.577	3
	Total	22.82	3.689	9
16	7	20.96	0.000	3
	14	22.09	0.000	3
	28	27.69	0.000	3
	Total	23.58	3.053	9

20	7	21.05	0.000	3
	14	23.58	0.577	3
	28	29.40	0.577	3
	Total	24.68	3.887	9
Combined	7	20.25	0.000	3
	14	23.56	0.577	3
	28	27.82	0.000	3
	Total	23.88	3.407	9
Total	7	19.53	1.598	15
	14	22.87	0.834	15
	28	27.47	1.457	15
	Total	23.29	3.590	45

N = number of specimens

Table 2: Two-Way ANOVA of the Effects of Aggregate Size and Curing Age on Compressive Strength of Concrete

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	547.244 ^a	14	39.089	293.167	.001
Intercept	24406.756	1	24406.756	183050.667	.001
Aggregate Size (mm)	54.578	4	13.644	102.333	.001
Curing Age (Days)	476.044	2	238.022	1785.167	.001
Aggregate Size * Curing Age	16.622	8	2.078	15.583	.001
Error	4.000	30	.133		
Total	24958.000	45			
Corrected Total	551.244	44			

a. R Squared = .993 (Adjusted R Squared = .989)

3.11 Two-Way ANOVA of Split Tensile Strength of Concrete

Table 3 presents the descriptive statistics for the split tensile strength of concrete produced with 12, 14, 16, and 20 mm coarse aggregates and cured for 7, 14, and 28 days. The results show a consistent increase in split tensile strength with curing age across all aggregate sizes. For 12 mm aggregate, the mean strength increased from 1.71 N/mm² at 7 days to 1.90 N/mm² at 14 days and 2.06 N/mm² at 28 days. Similarly, the 14 mm aggregate recorded 1.74, 2.01, and 2.19 N/mm², while the 16 mm aggregate produced 1.82, 2.06, and 2.30 N/mm² at the corresponding ages. The 20 mm aggregate recorded the highest values of 1.83, 2.19, and 2.33 N/mm², respectively. Overall, the mean split tensile strength increased from 1.776 N/mm² at 7 days to 2.048 N/mm² at 14 days and 2.236 N/mm² at 28 days. This increase is attributable to continued cement hydration and progressive development of the concrete matrix with curing. The results also indicate that split tensile strength generally increased with aggregate size. At 28 days, strength increased from 2.06 N/mm² for 12 mm aggregate to 2.33 N/mm² for 20 mm aggregate.

Table 3: Descriptive Statistics of Split Tensile Strength

Aggregate Size (mm)	Curing Age (Days)	Mean (N/mm ²)	Std. Deviation	N
12	7	1.71	0.01	3
	14	1.90	0.02	3
	28	2.06	0.02	3
	Total	1.89	0.15248	9
14	7	1.74	0.01	3
	14	2.01	0.01732	3
	28	2.19	0.02	3
	Total	1.98	0.19666	9
16	7	1.82	0.01	3
	14	2.06	0.02	3
	28	2.30	0.20	3
	Total	2.06	0.23092	9
20	7	1.83	0.01732	3
	14	2.19	0.01	3
	28	2.33	0.03	3
	Total	2.12	0.22411	9
Combined	7	1.78	0.02	3
	14	2.08	0.02	3
	28	2.30	0.02	3
	Total	2.05	0.22672	9
Overall Total	7	1.776	0.04896	15
	14	2.048	0.09901	15
	28	2.236	0.12944	15
	Total	2.020	0.21373	45

N = number of specimens.

Table 4 shows that aggregate size had a significant effect on split tensile strength, $F(4,30) = 23.070$, $p < .001$, with a partial eta squared of 0.755. Curing age also had a significant effect, $F(2,30) = 269.235$, $p < .001$, with a partial eta squared of 0.947, indicating a strong influence of curing age. However, the aggregate size $\times$ curing age interaction was not significant, $F(8,30) = 1.718$, $p = .135$, suggesting that the effect of aggregate size did not vary significantly across curing ages. The overall model was significant, $F(14,30) = 46.035$, $p < .001$, with $R^2 = .956$, indicating that 95.6% of the variation in split tensile strength was explained by the model.

Table 4: Two-Way ANOVA of the Effects of Aggregate Size and Curing Age on Split Tensile Strength

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	1.921 ^a	14	14.137	46.035	.001	.956
Intercept	183.618	1	183.618	61616.779	.001	1.000
Aggregate Size (mm)	.275	4	.069	23.070	.001	.755
Curing Age (Days)	1.605	2	.802	269.235	.001	.947
Aggregate Size (mm) * Curing Age (Days)	.041	8	.005	1.718	.135	.314
Error	.089	30	.003			

Total	185.628	45
Corrected Total	2.010	44
a. R Squared = .956 (Adjusted R Squared = .935)		

4.0 CONCLUSION

This study demonstrated that the particle size of crushed granite and curing age are important factors influencing the strength characteristics of concrete. The results showed a progressive increase in compressive and splitting tensile strengths with curing age for all aggregate treatments. Among the aggregate sizes investigated, the 20 mm crushed granite consistently produced the highest strength, attaining a 28-day compressive strength of 29.40 N/mm² and splitting tensile strength of 2.33 N/mm². In contrast, the 12 mm aggregate recorded the lowest 28-day values of 25.33 N/mm² and 2.06 N/mm², respectively. The higher strength obtained with the 20 mm aggregate indicates that aggregate particle size can influence the packing characteristics, paste requirement and internal structure of concrete. The two-way ANOVA confirmed that aggregate treatment, curing age and their interaction significantly affected compressive strength ($p < .001$), with the model accounting for 99.3% of the observed variation. For splitting tensile strength, aggregate treatment and curing age had significant effects ($p < .001$), whereas their interaction was not statistically significant ($p = .135$). These results confirm that the influence of aggregate particle size on concrete strength depends partly on the type of strength property being considered and its interaction with curing age. The combined aggregate produced intermediate strength values and exhibited a more continuous particle-size distribution than the individual aggregate fractions. The study indicates that the selection of coarse aggregate particle size should be considered alongside curing age, aggregate grading, workability, and other mix parameters in the production of concrete for structural applications. Under the mix conditions investigated, 20 mm crushed granite produced the highest measured compressive and splitting tensile strengths and may therefore be considered where higher strength is required, provided that its use is compatible with the dimensions and design requirements of the structural member.

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