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Size Effect of Coarse Aggregate Within Concrete Matrix on the Mechanical Properties of Concrete

John Ayibatunimibofa TrustGod
Niger Delta University, Wilberforce Island Bayelsa State, Nigeria

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Abstract

This investigation focuses on how aggregate size affect the performance of plain concrete. Three concrete grades (M10, M15, and M20) with varying water-cement ratios (0.3, 0.35, 0.4, 0.5, 0.55, and 0.6) and coarse aggregate sizes (7 mm, 18 mm, and 22 mm) were examined. Slump tests evaluated workability, while compressive strength tests assessed mechanical properties. The results consistently indicates that larger aggregate sizes tend to reduce the compressive strength (f_c) of concrete mixes. This trend was observed across M10, M15, and M20 concrete mixes. As aggregate size increases, the f_c generally decreases. This was due to the reduced interlocking and load transfer efficiency within the concrete matrix, as larger aggregates have fewer contact points with the cement paste, leading to weaker bonds and lower overall strength. Larger aggregate sizes greater 7 mm but less than 24 mm enhance the workability of concrete, as specified by higher slump values. However, this increased workability does not necessarily translate into higher compressive strength. The ease of mixing and placing concrete with larger aggregates must be balanced against the potential reduction in strength. Smaller aggregate sizes, such as 7 mm, tend to provide better compressive strength due to improved interlocking and load transfer mechanisms. Concrete mixes with smaller aggregates showed higher compressive strength values compared to those with larger aggregates. For instance, a concrete mix with a water-cement ratio of 0.55- and 7 mm aggregate achieved a compressive strength of approximately 34.22 Mpa at 28 days, which decreased as the aggregate size increased to 18 mm and 22 mm.

1.0. Introduction

Concrete is a commonly used building material well-known for its versatility, strength, and durability. Its performance is meaningfully affected by the properties of its constituents, particularly the size and characteristics of the coarse aggregate (CA) [1, 2]. The coarse aggregate, which typically comprises gravel or crushed stone, plays a vital role in evaluating the performance of concrete. This introduction delves into the impact of CA size on concrete strength, drawing insights from various studies and highlighting the potential implications for the construction industry.

The size distribution of CA has been extensively studied due to its effect on the compressive strength (f_c), flexural strength, and overall outcome of concrete [3, 4]. Larger CA sizes can contribute to increased concrete strength, as they provide better interlocking and load transfer within the matrix [5, 6]. However, excessive CA content can also lead to reduced workability, increased porosity, and potential segregation, adversely affecting the concrete's strength and durability [7].

The influence of CA size extends beyond static loading conditions. Recent research has focused on the dynamic behaviour of plane concrete, which is essential for applications involving blast resistance, seismic events, and other extreme loading scenarios [8, 9]. The size and distribution of

CAs can significantly impact the energy dissipation mechanisms, crack propagation, and overall dynamic response of concrete [10, 11]. Understanding these effects is crucial for designing structures that can withstand extreme loading conditions.

In addition to size, the shape, texture, and angularity of CAs play a vital role in determining the concrete's mechanical properties [5, 12]. Irregular and angular aggregates can enhance the bond strength with the cement paste, potentially improving the concrete's overall strength [13, 14]. However, excessive angularity or roughness can negatively impact workability and lead to potential segregation issues [15, 16].

The incorporation of coarse aggregates into ultra-high-performance concrete (UHPC) has garnered significant consideration lately [17, 18]. UHPC is a specialized type of concrete characterized by excellent durability and strength, making it suitable for applications requiring superior performance. The presence of CAs can potentially increase the fracture properties and influence resistance of UHPC, while also reducing material costs [19, 20].

Also, the use of alternative coarse aggregates, such as lightweight aggregates or recycled materials, has been explored to address sustainability concerns and cut down the environmental influence of concrete production [21, 22]. These alternative aggregates may exhibit different properties and behaviours compared to conventional aggregates, necessitating a thorough understanding of their influence on concrete strength and performance.

To accurately predict and optimize the performance of concrete, various theoretical equations and analytical systems have been developed to capture the complex interactions between coarse aggregates and the cement matrix [23, 24]. These models incorporate factors such as aggregate size, shape, and distribution, enabling more accurate simulations and design optimization.

The size of coarse aggregates significantly affects the mechanical properties of concrete, including modulus of elasticity, tensile strength, compressive strength, and durability. A good number of investigate has been directed toward understanding the intricate relationships between CA parameters and strength, durability, and impact resistance. According to Ekwulo & Eme [25] and Woode et al. [26] f_c decreases as CA size increases. Ogundipe et al. [27], Kabir et al. [28] and Wang et al. [29] reported a different trend of correlation between strength and aggregate size. The authors reported that concrete strength increases as the CA size increases. Based on the reports available on this subject, there is no common agreement on the performance of CA size.

Overall, there is a clear gap in developing a consistent and universally accepted relationship between CA size and the mechanical properties' performance of concrete. Further experimental investigation is required to reconcile the conflicting findings and provide more clear guidelines for designing concrete mixes optimized for static performance.

Given these considerations, this research seeks to investigate the effect of coarse aggregate size on the mechanical properties of concrete. Studying the size effect of coarse aggregate is relevant due to its direct impact on various mechanical properties. Understanding how aggregate size influences the concrete matrix is crucial for optimizing concrete performance, especially in the design of high-performance structures used in modern construction.

2. Materials and Methods

2.1. Materials

The materials considered for the experimental research include crushed aggregate, sand, water, cement and crushed chippings. The binder which had a class strength of 32.5R adopted was Portland limestone cement and was compliant with BS EN 197-1 [30]. Drinkable water sourced from the Civil Engineering laboratory, Niger Delta University campus, Wilberforce Island was used. Fine aggregate used was river sand and was acquired at dredging site in Amassoma, Southern Ijaw, Bayelsa. Crushed chippings were used and coarse aggregate. The materials were sourced from a vendor in Amassoma from the nearby quarry. The CAs were sieved to three separate but consistent sizes: 6.8, 17.5, and 22. A uniform proportion of fine aggregate comprising all the sizes. The physical properties of the aggregate considered in this study were examined in accordance with ASTM C128 [31], BS EN 933-1 [32] and BS 812-2 [33].

2.2. Test Sample Preparation

A concrete mix ratio of 1:3:6, 1:2:4, and1:1.5:3 with a target f_c of 10, 15, 20 MPa, respectively, was considered to produce all concrete samples. Varying water-cement (W-C) ratios of 0.3, 0.35, 0.4, 0.5, 0.55, and 0.6, and was adopted. The decision to consider varying water-cement (W/C) ratios of 0.3, 0.35, 0.4, 0.5, 0.55, and 0.6 is based on the need to investigate a broad spectrum of concrete properties, as the W/C ratio has a significant influence on key characteristics such as strength, workability, and durability. Twenty-four (24) different mixes were adopted to produced two hundred and eighty-eight of 150x150x150 mm concrete cubes. For each aggregate size (6.8, 17.5, 22 and uniform amount of the chippings containing all the three sizes), a varying W-C ratios of 0.3, 0.35, 0.4, 0.5, 0.55, and 0.6 was adopted for the production of the concrete cubes. The entire batching and curing process of cubes were done in line with BS EN 12390-2 [24] in the Niger Delta University.

2.3 Determination of Workability

A slump test was performed on each of the fresh concrete (FC) mixes to study their workability. A 30 cm-high FC frustum of a cone was produced in accordance with BS EN 12350-2 [34] and allowed to settle on its own weight. Slump, or the drop in height of the FC was determined to study the workability of the concrete.

2.4 Determination of Compressive Strength

The f_c test was done on the cube samples as seen in Figure 1. The cube samples were loaded to failure according to the methods outlined in BS EN 12390-3[24]. The load at which the concrete cube failed was measured, and the f_c was calculated using Eq. 1. In this equation, N is the failure load (N), A is the cross-sectional area of the cube (mm^2).

$$f_c = \frac{N}{A} \tag{1}$$

Figure 1: Compressive test

3.0 Results and Discussion

3.1 Compressive strength results

The results as displayed in Tables 1, 2, and 3 and Figures 2–4 provide an understanding of the correlation between the f_c, workability and CA size of M10, M15, and M20 concrete mixes. These results are in line with other research on how CA size affects concrete performance.

Rui et al. [1] and Li et al. [3] conducted a study on the effect of aggregate size on concrete strength and found that larger aggregate sizes can contribute to increased f_c. This was due to the bigger grains in the concrete matrix, which promote higher load transfer and interlocking. Woode et al. [26] reported that f_c increases as the CA size increases. The results of M20 presented in Table 1 and Figures 2-4 aligned with the findings of Woode *et* al. [26], where increasing aggregate size generally leads to lower compressive strength values. Larger aggregates tend to induce micro-cracks within the concrete matrix, which may reduce the material's toughness, while smaller aggregates may improve fracture resistance.

The results presented in Table 2 and Figures 4-6 is for M15. It is clear that as the aggregate size increases from 7mm to 22mm, there is an equivalent decrease in the f_c values. This is in agreement with Ekwulo & Eme [25] and Woode *et al. [26]* reports, which suggest that smaller aggregate sizes have a positive effect on strength performance. Furthermore, the shape, texture, and angularity of the aggregates can also influence concrete properties, as highlighted by Zhang *et al.* [5] and Güçlüer [12]. Therefore, a comprehensive understanding of all these factors is vital for enhancing concrete mix designs and achieving the anticipated performance.

Table 3 and Figure 4 illustrate the variation in strength due to different aggregate sizes for M10 concrete mixes. It is noticeable that as the aggregate size increases, it f_c generally decreases. This finding aligns with the work of Li et al. [3], who report a similar trend in their study. The decrease in strength with increasing aggregate size can be attributed to the reduced interlocking and load transfer efficiency within the concrete matrix. Larger aggregates have fewer contact points with the cement paste, leading to reduced bond strength and lower overall f_c. From the results, it can be observed that the concrete mix with a W-C ratio of 0.3 and a 7-mm aggregate size achieved a f_c of approximately 12.66 MPa. As the aggregate size increased to 18mm and 22mm, the compressive strength slightly decreased. This trend indicates that smaller aggregate sizes tend to result in slightly higher f_c.

Furthermore, the concrete mix with a W-C ratio of 0.35, the f_c increases for the 7-mm aggregate size. However, both the 18mm and 22mm aggregate sizes exhibited lower compressive strengths. The variation in compressive strength can be credited to the interlocking and load transfer mechanisms within the concrete matrix. Smaller aggregate sizes provide better interlocking, resulting in increased strength. On the other hand, larger aggregate sizes may lead to reduced interlocking and increased porosity, resulting in a slightly lower f_c. The analysis of Tables 1, 2, and 3 and Figures 2-4 demonstrates that aggregate size significantly influences the compressive strength of concrete mixes. Smaller aggregate sizes generally enhance compressive strength due to better interlocking and load transfer, while larger aggregates tend to reduce strength due to fewer contact points and increased porosity. Understanding these relationships is critical for optimizing concrete mix designs to achieve desired performance characteristics.

Table 1: Slump and strength M20 (1:1.5:3)

w/c ratio	gradation		7mm Agg.		18mm aggr		22mm aggr	
	Slump (mm)	f_c MPa	Slump (mm)	f_c (MPa)	Slump (mm)	f_c (MPa)	Slump (mm)	f_c (MPa)
0.3	0	12.66	124	13.62	114	12.88	14	12.44
0.35	3	14.21	182	15.47	175	13.7	164	13.18
0.4	60	16.21	200	16.96	214	15.92	183	16.29
0.5	160	29.48	230	30.07	220	26.96	190	27.87
0.55	178	27.7	255	34.22	225	32.58	230	31.25
0.6	190	24.66	272	28.44	232	27.92	252	27.4

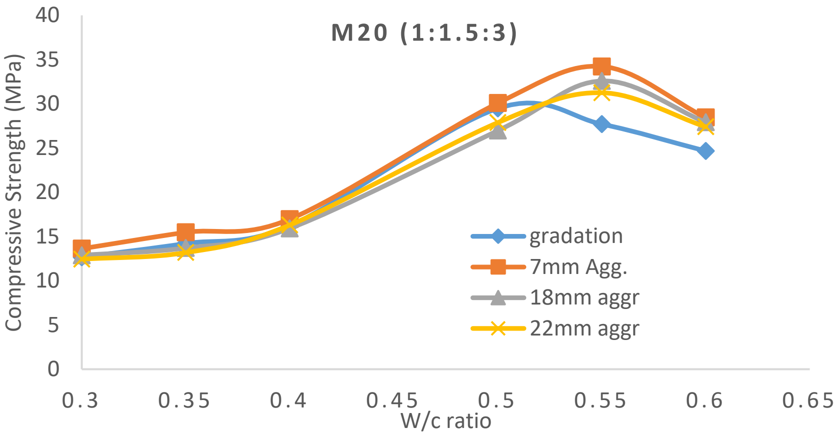

Figure 2: Strength variation due to aggregate sizes (M20)

Table 2: Slump and strength M15 (1:2:4)

w/c ratio	gradation		7mm Agg.		18mm aggr		22mm aggr	
	Slump (mm)	f_c MPa	Slump (mm)	f_c (MPa)	Slump (mm)	f_c (MPa)	Slump (mm)	f_c (MPa)
0.3	0	9.92	0	16.73	0	16.81	0	15.55
0.35	3	11.99	4	22.07	149	18.44	0	18.66
0.4	5	20.21	15	22.51	170	20.14	0	19.47
0.5	14	29.1	185	23.7	205	22.07	173	20.73
0.55	40	25.84	190	25.7	209	24.58	185	22.81
0.6	165	24	202	23.45	213	22.37	195	20.36

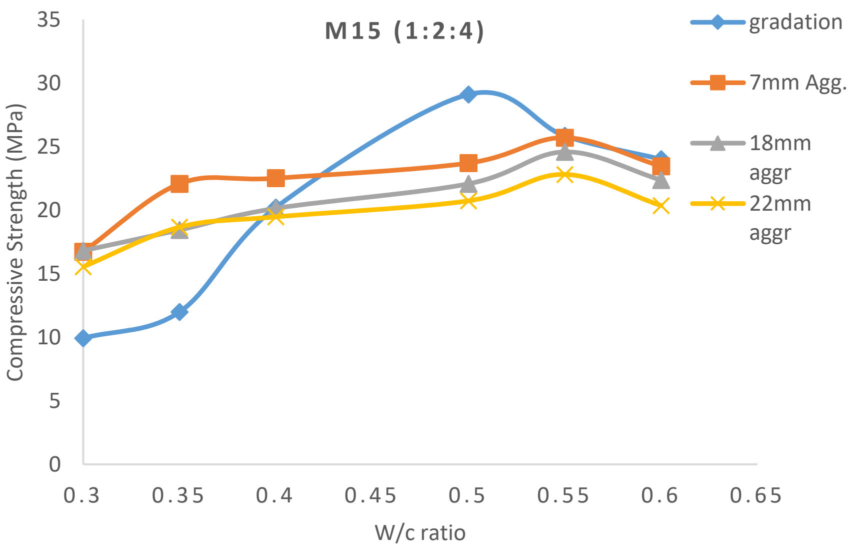

Figure 3: Strength variation due to aggregate sizes (M15)

Table 3: slump and strength M10 (1:3:6)

w/c ratio	gradation		7mm Agg		18mm aggr		22mm aggr	
	Slump (mm)	f_c MPa	Slump (mm)	f_c (MPa)	Slump (mm)	f_c (MPa)	Slump (mm)	f_c (MPa)
0.3	0	1.18	0	5.03	0	4.14	0	3.55
0.35	0	3.33	6	6.14	10	4.21	0	4.66
0.4	0	4.58	10	8.36	14	6.29	0	5.99
0.5	10	10.59	40	9.33	132	10.29	149	7.84
0.55	12	11.55	165	11.84	135	11.84	175	11.4
0.6	87	8.96	180	8.58	155	5.62	0	3.55

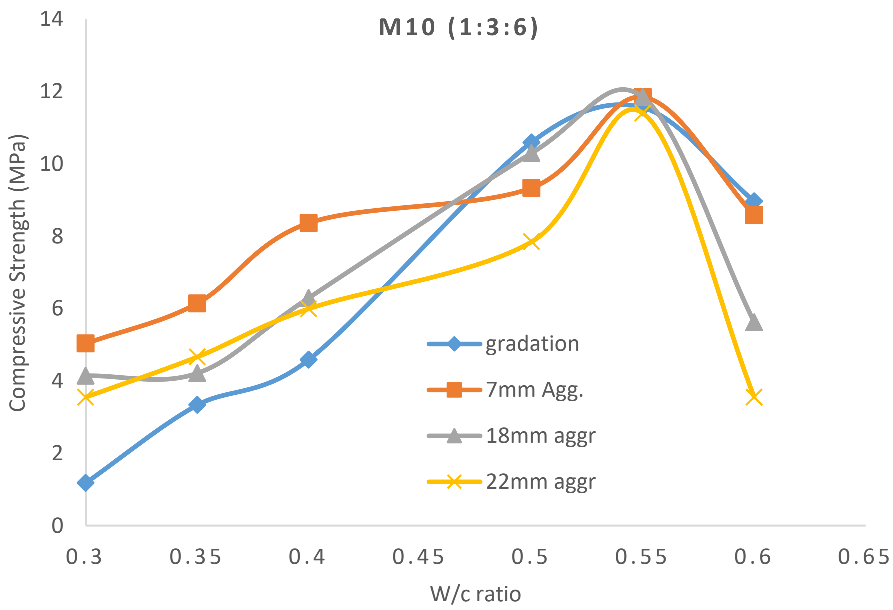

Figure 4: Strength variation due to aggregate sizes (M10)

3.1 Workability Results

In addition to strength, workability is a critical factor to consider when designing concrete mixes. Workability refers to the ease with which concrete can be mixed, transported, and placed, and it significantly impacts the overall quality and performance of the concrete. One of the most common methods for assessing workability is the slump test, which measures the uniformity and flowability of fresh concrete.

Figures 5, 6, and 7 present the variations in workability due to different aggregate sizes in M20, M15, and M10 concrete mixes, respectively. These figures demonstrate a clear relationship between aggregate size and slump value, with larger aggregate sizes generally resulting in higher slump values. This indicates that as the aggregate size increases, the concrete becomes more workable. The findings align with the observations made by Ndon & Ikpe [35], who noted that larger aggregate sizes enhance the ease of mixing, transporting, and placing concrete.

The water-cement ratio, along with the shape and size of aggregates, significantly influences the workability of concrete. Larger aggregates create less surface area for the cement paste to cover, reducing friction and allowing the mix to flow more easily. This is reflected in the slump values shown in Figures 5, 6, and 7. For instance, in Figure 7, which depicts the workability of M10 concrete mixes, the slump values increase with the size of the aggregates. Specifically, the 22 mm aggregate size exhibits the highest slump value, followed by the 18 mm size, and the smallest 7 mm size shows the lowest slump value. Larger coarse aggregates tend to improve workability because they reduce the overall surface area that needs to be coated by the cement paste, allowing for easier movement and placement of the concrete. This reduced surface area requires less water and cement paste to cover, making the concrete mix more fluid and workable. In practical terms, this makes concrete easier to handle, especially during casting and compaction, which can be advantageous in situations requiring large-volume pours or intricate formwork designs.

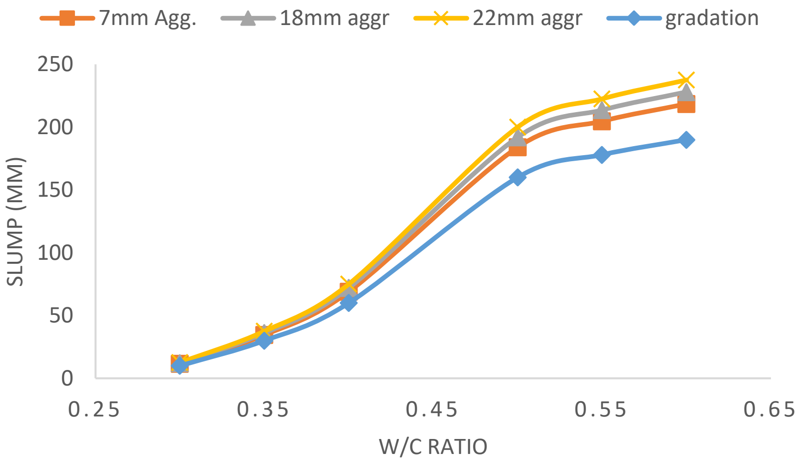

Figure 5: Workability variation due to aggregate sizes (M20)

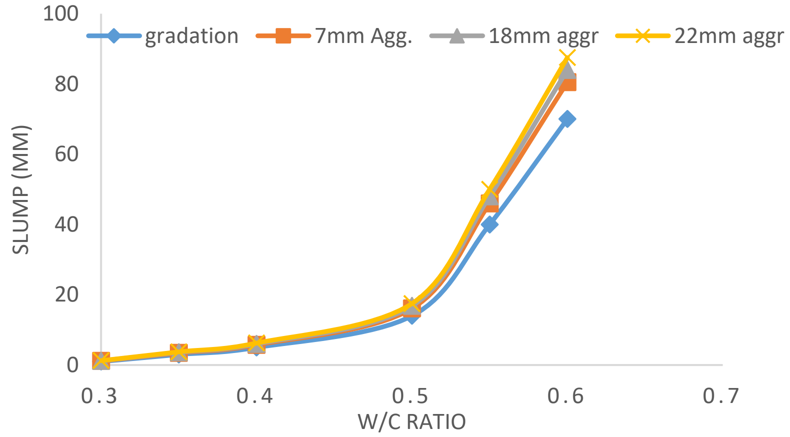

Figure 6: Workability variation due to aggregate sizes (M15)

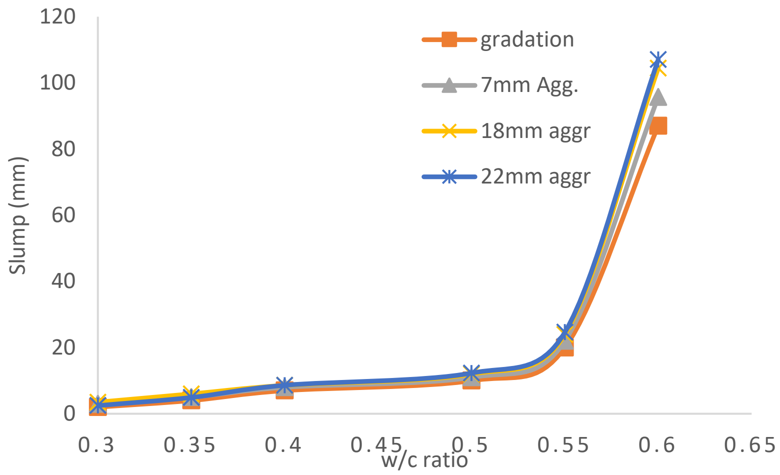

Figure 7: Workability variation due to aggregate sizes (M10)

4. Conclusion

The investigation into the impact of CA size on concrete strength has yielded significant understandings into how aggregate sizes influence the performance of concrete. The following deductions were from the findings:

i. The research consistently indicates that larger aggregate sizes tend to reduce the fc of concrete mixes. This trend is observed across M10, M15, and M20 concrete mixes. As aggregate size increases, the compressive strength generally decreases.

ii. Larger aggregate sizes but not more than 24 mm enhance the workability of concrete, as specified by higher slump values. However, this increased workability does not necessarily translate into higher compressive strength. The ease of mixing and placing concrete with larger aggregates must be balanced against the potential reduction in strength.

iii. Smaller aggregate sizes, such as 7mm, tend to provide better compressive strength due to improved interlocking and load transfer mechanisms. Concrete mixes with smaller aggregates showed higher fc values compared to those with larger aggregates. For instance, a concrete mix with a water-cement (W-C) ratio of 0.3 and 7mm aggregate achieved a compressive strength of approximately 12.66 MPa, which decreased as the aggregate size increased to 18mm and 22mm.

iv. The fc is also affected by the W-C ratio. For a W-C ratio of 0.35, the mix with 7mm aggregates showed higher fc compared to mixes with larger aggregates. This indicates that optimizing both the W-C ratio and aggregate size is crucial for achieving desired concrete strength.

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