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Research Article

Development of Aggregate – Cement Design Curves for the Production of Concrete Mixes for Different Grades of Concrete

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Keywords

Aggregate,
Cement,
Design curve,
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Abstract

Developing aggregate-cement design curves tailored to different concrete grades using locally sourced materials is critical for the growth of Nigeria's construction industry. Such curves provide a systematic approach for optimizing project-specific concrete mixes, enhancing cost-effectiveness, and ensuring structural reliability. This study focuses on creating these design curves by examining the engineering properties and characteristics of raw materials commonly available in Nigeria. Trial mixes were conducted with varying aggregate-cement ratios, and compressive strength tests were performed to identify the most suitable combinations. Using river sand, single-sized aggregates (10–20 mm), and limestone Portland cement, aggregate-cement curves were developed for concrete grades ranging from 20 MPa to 35 MPa. The COREN/2017/016/RC concrete mix design method was adopted to guide the research process. The study found that a mix of 35% fine aggregate, 65% coarse aggregate, and a water-cement ratio of 0.5 achieved optimal results, providing desired compressive strengths and slump values between 40 mm and 50 mm. These findings establish a framework for producing durable and efficient concrete mixes using locally available materials. This approach supports the need for sustainable construction practices in Nigeria, offering practical solutions for meeting diverse construction demands while ensuring material availability and affordability.

1. Introduction

Concrete stands as the foremost construction material globally, finding application across various construction sectors. It can be conveniently delivered to the construction site in pre-cast or in-situ forms, rendering it the preferred choice in the construction industry. The widespread adoption of concrete is attributed to its adaptable properties, making it indispensable in construction projects. It is universally adopted in multi-purpose constructions because of its constituent materials' strength, economy, availability, and sustainability [1-4]. The fundamental components of concrete remain consistent, but it is their relative ratios that distinguish one mix from another. These proportions are carefully calculated to attain the desired strength and workability in the most cost-effective manner. Various concrete design methods dictate this proportioning process. Even with high-quality materials, thorough mixing, precise transportation and placement, and thorough compaction, the concrete quality may still be compromised if the material proportions are not accurately determined.

The Council for the Regulation of Engineering in Nigeria (COREN) is the statutory body responsible for regulating and controlling the practice of engineering in Nigeria. Established by Decree No. 55 of 1970, now known as the COREN Act, it ensures that engineering practices in the country adhere to professional and ethical standards. COREN registers and licenses qualified engineers, technologists, technicians, and craftsmen, as well as accredits engineering programs in higher institutions. The council also monitors and evaluates engineering projects to ensure compliance with established standards, promotes continuous professional development, and addresses malpractice within the profession. By fostering excellence in engineering, COREN plays a vital role in Nigeria's infrastructural and economic development [4].

The mix design process can be summarized as obtaining both the water-cement ratio and aggregate–cement ratio to obtain a grade of concrete with a type or set of available materials; of which water – cement ratio had been addressed by the COREN mix design approach in the COREN manual, all in a bid to domesticate concrete mix design processes. However, the aggregate-cement ratio appears not to be included in the COREN Manual, and the section on aggregate content appears to concentrate on blending both fine and coarse aggregates to achieve a desirable grading curve for the combined aggregates; curves for aggregate–cement ratio has not been included. Also, Gambhir and Aker reported that aggregates constitute about 75% to 85% of the concrete matrix; hence, the significance and relevance of aggregate in concrete production cannot be ignored [5-6]. Therefore, this study aims to develop aggregate–cement ratio design curves for the production of concrete in Nigeria.

2. Materials and Method

2.1. Materials

Tests were conducted on the constituent materials of the concrete to assess their physical properties and evaluate their suitability for concrete production. These included: Specific gravity (using a pycnometer), Fineness modulus (measured with standard sieve analysis equipment), Moisture content (using oven drying method), Bulk density (using a compaction cylinder), Water absorption capacity (using a soak and weigh method), Aggregate impact value (measured with impact testing machine), Aggregate crushing value (using compression testing machine), Los Angeles abrasion value (conducted with a Los Angeles abrasion testing machine), and Flakiness index (using a thickness gauge). These tests provided a comprehensive understanding of the physical and mechanical

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characteristics of the materials, ensuring their reliability and performance in concrete production.

2.2. Fine Aggregate

River sand from River Kaduna was sourced at the 700 MW Zungeru Hydroelectric Power Plant location. It was sieved through a sieve aperture size of 4.75 mm to remove pebbles, vegetable matter and other unwanted objects. Table 1 shows the physical properties of the river sand.

Table 1. Properties of fine aggregate (river sand)

Physical Properties	Values
Fineness Modulus	2.92
Coefficient of Uniformity	1.0 – 5.0
Specific Gravity	2.74
Moisture Content	6.64
Bulk Density (Compacted)	390.22 kg/m3
Bulk Density (Uncompacted)	314.21 kg/m3

2.3. Coarse aggregate

Based on the classification by Duggal, Anosike and Ezeokonkwo [7-9], artificial aggregate (granite chippings) of various sizes (20 mm max, 15 mm max and 10 mm max) were gotten from the Zungeru Power batching plant section of the company, washed and dried to saturated surface condition before usage. The choice of various sizes of coarse aggregate is necessary because it influences the compressive strength of concrete [10]. Table 2 shows the physical properties of granite chippings of various sizes used.

Table 2. Properties of Coarse Aggregate

Physical Properties	Values		
	10 mm Granite	15mm Granite	20 mm Granite
Fineness Modulus	2.94	1.60	1.94
Specific Gravity	2.49	2.63	2.67
Moisture Content	4.91	6.29	3.54
Bulk Density (Compacted)	394.37 kg/m3	398.05 kg/m3	399.27 kg/m3
Bulk Density (Uncompacted)	355.14 kg/m3	357.40 kg/m3	358.72 kg/m3
Water Absorption Capacity	0.60%	0.70%	0.50%
Aggregate Impact Value	19.79%	20.50%	19.90%
Aggregate Crushing Value	20.79%	21.75%	20.60%
Loss Angeles Abrasion Test	20.85%	21.73%	22.70%
Flakiness Index	20.79%	21.93%	22.90%

2.4. Cement

Grade 42.5R limestone Portland cement of specific gravity 3.13 and conforming to relevant Standards and specifications was purchased from the local market and used [11-13].

2.5. Water

Potable water from Zungeru Public Water Supply was used. Using potable water for concrete mixing is essential to ensure the production of high-quality concrete with consistent properties. It helps maintain the chemical and physical balance of the concrete mixture, which is critical for achieving the desired strength, durability, and appearance of the concrete. The mix design method was adopted for this project work [13]. The aim is to build upon the existing data, methods, and approach. It involves conducting different mixes with different water-cement ratios (0.40, 0.45, 0.50 and 0.55) to achieve suitable, safe, and economically viable mixes for general use. A water–cement ratio of 0.50 was adopted for the mix design for this research because of its workability, consistency and possibility of higher strength. Target mean strength was based on the principle stated in the manual for the case of no data [13]. Concrete grades targeted were 20, 25, 30 and 35 N/mm² with the corresponding target mean strengths of 26.56, 31.56, 36.56 and 41.56 N/mm² at a standard deviation of 4 for the economy as against the Standard deviation of 6 recommended in the COREN design manual. Table 3 shows the concrete mix design, stating all the basic parameters for mix design procedures for concrete grade 35 with 20 mm single aggregates.

2.6. Batching and Mixing

Batching by weight was adopted and mixing was done by a mechanical mixing plant since the volume of the concrete to be cast is in large volume. The quantity of sand was measured first using a weighing balance and poured into the mixing plant. Then, the measured quantity of cement was allowed to mix thoroughly with sand, after which the required quantity of coarse aggregate was added to the mixed component. Finally, the required quantity of water was added and thoroughly mixed for about 5 minutes to produce a workable concrete mix.

Table 3. Mix Design for Concrete Grade 35 N/mm² with Aggregate Size 20 mm

S/No	Item	Values
1	Stage 1	
1.1	Characteristic Strength	35 MPa
1.2	Standard Deviation	4 MPa
1.3	Margin	6.56 MPa
1.4	Target Mean Strength	41.56 MPa
1.5	Cement Grade	42.5 MPa
1.6	Aggregate Type: Coarse	Crushed
1.7	Aggregate Type: Fine	Uncrushed
1.8	Free Water/ Cement Ratio	0.50
1.9	Maximum Free Water/ Cement ratio	None
2	Stage 2	
2.1	Slump	40 – 50 mm
2.2	Maximum Aggregate Size	20 mm
2.3	Free-water Content	185 kg/m3
3	Stage 3	
3.1	Cement content	370 kg/m3
3.2	Maximum cement content [specified]	Specified
3.3	Minimum cement content [specified]	Specified
3.4	Modified free - water/ cement ratio	None
4	Stage 4	
4.1	Concrete density	2400 kg/m3
4.2	Total aggregate content	1845 kg/m3
5	Stage 5	
5.1	Grading of fine aggregate	Zone 2
5.2	Proportion of fine aggregate [%]	35 %
5.3	Fine aggregate content	646 kg/m3
5.4	Coarse aggregate content	1199 kg/m3
6	Stage 6 - Trial Mix Quantities	150 mm cube
6.1	Water [kg]	2.78
6.2	Cement [kg]	5.55
6.3	Fine aggregate [kg]	9.69
6.4	Coarse aggregate [kg]	17.99

2.7. Concrete Workability

Concrete workability is a physical property of fresh concrete which affects the strength, porosity, permeability and finished appearance of hardened concrete. The determination of concrete workability was carried out by determining the slump values of freshly prepared concrete for mix categories following [14] (See Plate 1). The slump value was determined by measuring the difference between the height of the metal slump cone and the concrete cone.

Plate 1. Determination of Concrete Slump

2.8. Casting of Specimens

The casting of concrete cube samples for compression strength tests was carried out immediately after the determination of fresh properties was completed. 150mm x 150mm x 150mm moulds were used and six (6) cube samples each were cast for each of the mix categories. Fresh concrete was poured into the moulds and compacted in accordance with [15]. Pictures of the compacted fresh concrete in the moulds are shown in Plate 2.

Plate 2. Concrete cube samples in moulds

2.9. Compressive Strength Tests

150 mm concrete cube samples were used to test for the compressive strength of concrete. All cubes were tested in saturated condition after drying the surface moisture. The Compressive Strength tests were conducted in the Laboratory of Zungeru Dam Project in accordance with [15, 16]. The specimens were weighed before crushing in an automated compression machine, as shown in Plate 3.

Plate 3. Compressive Strength Test of Concrete Cubes

3. Results and Discussion

3.1. Physical Properties Test Results

The results of the physical properties needed for the determination of concrete mix ratio, such as particle size distribution analysis, specific gravity, moisture content, bulk density, and water absorption capacity, for all concrete constituent materials are presented below. Comparing results from various physical property tests with standards showed the suitability of the various concrete constituent materials, as presented in Table 4. Figures 1 to 4 show the particle distribution curves for all categories of aggregates used.

Table 4. Results of Material Properties Testing of Aggregates

FINE AGGREGATE5			
TEST	RESULTS	LIMITS	REMARKS
a. specific gravity	2.74	≤ 3.5	OK
b. water absorption		≤ 1%	OK
c. clay and silt contents		≤ 10%	OK
d. sieve analysis	ZONE 2	ZONE 2	OK
e. organic impurities		≤ 10%	OK
COARSE AGGREGATE			
TEST	RESULTS	LIMITS	REMARKS
a. Ten(10) % Fines	2.94 (Max.)	≤ 10%	OK
b. specific gravity	2.67 (Max.)	≤ 3.5	OK
c. water absorption	0.70% (Max.)	≤ 1%	OK
d. clay and silt contents		≤ 10%	OK
f. organic impurities		≤ 10%	OK
g. Aggregate Impact Value(AIV)	20.50% (Max.)	≤ 30%	OK
h. Aggregate Crushing Value(ACV)	21.75% (Max.)	≤ 30%	OK
I. Flakiness index	22.90% (Max.)	≤ 30%	OK
J. Elongation Test		≤ 30%	OK
k. Los Angeles Abrasion Test	22.70% (Max.)	≤ 30%	OK

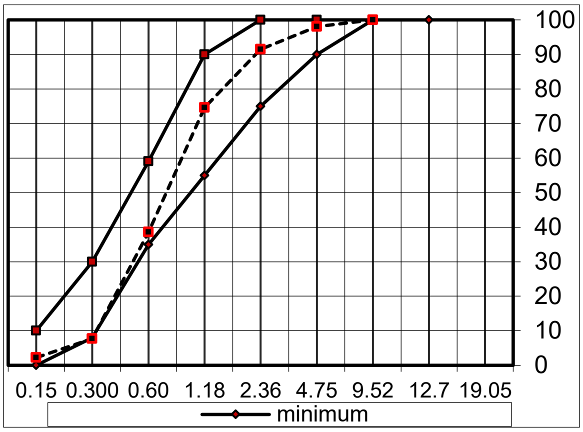

Figure 1. Result of Particle Size Distribution of River Sand (Zone 2)

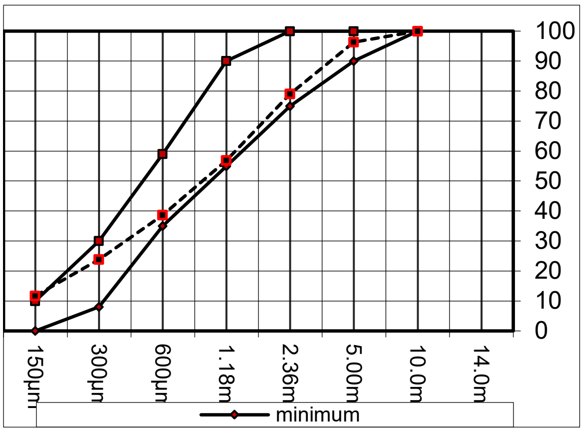

Figure 2. Result of Particle Size Distribution of Coarse Aggregate (10mm Granite)

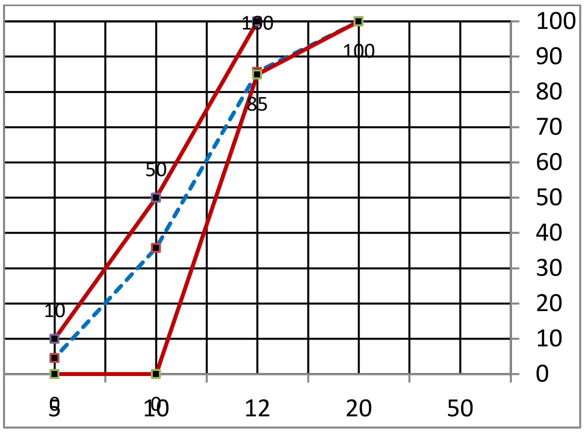

Figure 3. Result of Particle Size Distribution of Coarse Aggregate (15mm Granite)

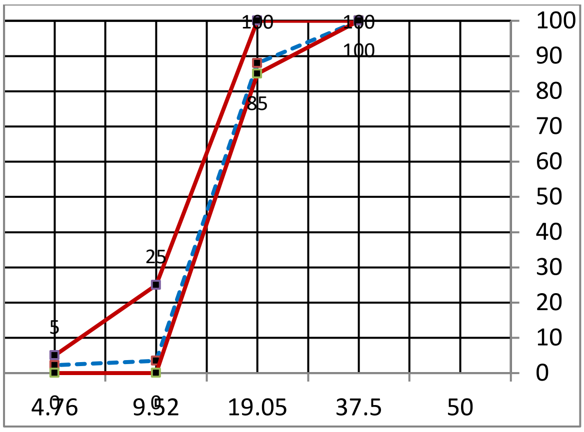

Figure 4. Result of Particle Size Distribution of Coarse Aggregate (20 mm Granite)

3.2. Workability

The results of the concrete slump, as presented in Figure 5, show a considerably progressive increase in workability as the concrete binder increases. The increase in slump value may be a result of the increase in the extra mortar or paste needed to ease the flow of concrete [17].

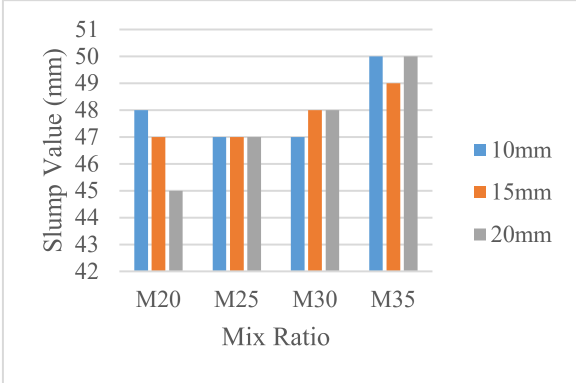

Figure 5. Result of Concrete Slump

3.3. Concrete compressive strength

The results of the mean compressive strength of concrete are shown in Figure 6. An increase in cement content from M20 to M35 shows a corresponding increase in the compressive strength or grade of concrete. This shows that concrete binder (cement) is an important constituent material needed for better performance of concrete [18].

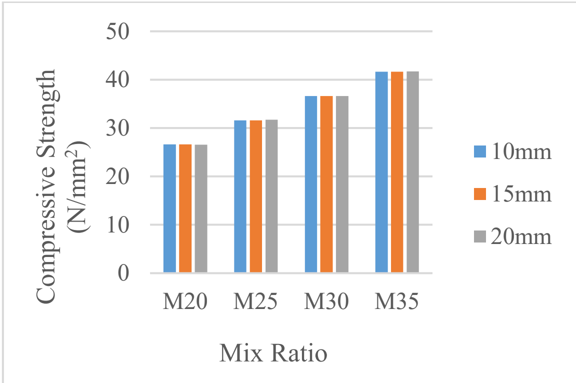

Figure 6. Result of Compressive Strength of Concrete

The increment seen in the quantity of cement is said to be responsible for the reduction noticed in the aggregate – cement ratio as shown in Figure 7.

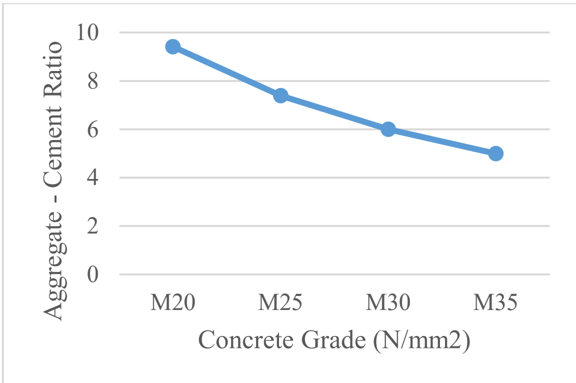

Figure 7. Aggregate – Cement Ratio Curve

4. Conclusion

Having carried out tests on fine and coarse aggregates on concrete production with different mix designs, it can be concluded that concrete with 35% of fine aggregate and 65% of coarse aggregate gave acceptable aggregate mix proportioning for producing mix design for concrete which meets compressive strength and acceptable workability. Also, the curve developed can be used to produce concrete of grades 20 N/mm2, 25 N/mm2, 30 N/mm2 and

35 N/mm2 with a water-cement ratio of 0.5 and workability in the range of 40 mm and 50 mm. This curve is recommended for use by everyone (COREN, the government, engineers and even laymen) in the construction industry [13].

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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