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Optimization of All-In Aggregate Gradation Combination to Improve Concrete Sustainability

Akobo, I.Z.S [#1], Ode, T [#2], Gokana, J. P. B [#3]
Rivers State University, Port Harcourt, Nigeria

Abstract
This study aims to investigate minimum cement content required with an appropriate water to-cement ratio (w/c) to meet given workability and strength requirements in concrete; and reduce carbon dioxide emissions, energy consumption, and costs. Thus to minimize concrete cost and improve its quality, it is necessary to achieve optimum aggregate gradation. Particle size distribution and Coarseness Factor chart, which is one of the recent popular methods for achieving an optimum aggregate gradation, which represents the relationship between Coarseness Factor and Workability Factor of a mix. Thus, the properties of concrete were studied for stage 1 and 2 with a cement content of 350 kg/m^3 and 300 kg/m^{3,} respectively, when the proportions of 12.7mm and 9.52 mm stone in the coarse aggregate were varied when a water/cement ratio (w/c) of 0.45 was held constant. The maximum compressive strength at 28 days was 45.04MPa (MIX-A11) for stage 1 and 44.15MPa (MIX-B7) for stage 2 with the same coarseness factor of 66.22 and different workability factor of 33.75 and 31.51, respectively. For both 350 kg/m^3 and 300 kg/m^3 cement contents, workability decrease slightly as the proportion of the coarse aggregate is increased. The corresponding slumps for MIX-A11and MIX-B7 were the same, that is, 30mm.

Keywords:
Aggregate, optimization, Gradation, Concrete, Coarseness Factor, Workability Factor, and Compressive strength.

I. INTRODUCTION

Cement, the principle segment of concrete, is one of the most significant materials for all kinds of constructions. Cement content is perceived to control concrete strength. Base on this observation, a minimum cement content is often specified that may exceed the amount needed to achieve the desire strength and durability. This excessive amount should be minimized to prevent its negative impact on costs and the environment because:

- Cement is the most costly part of concrete
- Cement contributes about 90% of the CO_2 burden of a concrete mixture
- Cement production emits roughly 5% of global carbon dioxide (CO_2) and 5% of global energy consumption

Previous studies (Wasserman et al. 2009; Popovics 1990) suggest that a high cement content in a mixture does not contribute to greater strength than the required design strength. In addition, the high cement content will cause the concrete to become sticky as well as have shrinkage and cracking problems. Therefore, cement content should be balanced to achieve performance while minimizing the risk of these problems. Despite the published studies and documentation, there continues to be a misconception that more cement in a mix design means a better performing mix.

The Shilstone technique pictures the gradation of the blended coarse and fine aggregates utilizing coarseness factor charts. The chart plots the workability factor against the coarseness factor. The workability factor is simply the weigh percent passing the no. 8 sieve, but with a correction for the cement content; the coarseness factor is the ratio between the cumulative weight percent retained on the 3/8" sieve and the cumulative weight percent retained on the no. 8 sieve. The coarseness and workability factors are related through the use of a chart that is separated into five zones. Zone I represents difficult to work gap-graded mixtures susceptible to segregation. Zone II represents ideal conditions for most concrete paving mixtures. Zone III represents ideal conditions for concrete mixtures with a lower top size coarse aggregate. Zone IV represents over-sanded mixtures, and Zone V represents rocky mixtures. The region above Zone V is a transitional zone exhibiting generally good conditions for concrete mixtures.

II. LITERATURE REVIEW

Optimized aggregate gradations have frequently been specified and endorsed. In contrast, very few practical and comprehensive methods to perform the optimization are available to concrete practitioners (LINDQUIST ET AL., 2015).

The combination of coarse and fine aggregates is typically not well-graded due to the absence of intermediate-sized particles

The workability of a mixture can be drastically changed due to aggregate proportioning and the physical characteristics of aggregate. A dependable method to understand and predict the workability of concrete due to aggregates has not been developed.

The physical characteristics of aggregates cannot be controlled, but the actual gradation of the aggregates can be much more easily controlled. Using available regional aggregates with volume proportions of roughly 60% coarse aggregate and 40% fine aggregate regardless of gradation have been used as the standard for a concrete pavement mixture. Efforts to reduce the cost and improve the sustainability of concrete mixtures have pushed owners to pay closer attention to all aspects of their concrete mixtures. To maintain certain workability for a slip formed pavement application but still reduce the amount of paste has been an important topic for many years. The general philosophies affecting workability have been thought to be the surface angularity of aggregates, the nominal maximum size of coarse aggregates, and proportioning of aggregates by gradation.

The literature review presents a review of three major areas:

- workability
- strength
- sustainability

The literature is discussed how each concrete property is affected by mixture composition. The three mixture characteristics covered include:

- cement content
- water-to-cement ratio (w/c)
- aggregates

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III. MATERIALS AND METHODS

***A**: Portland Limestone Cement (PLC, Grade 42.5R)*

Portland limestone cement by Dangote is in compliance with the requirements of BS12;1996 was adopted in this study based on its track record and satisfactory results in concrete works. The material also complies with toNIS 444, EN. Of cement)

***B**: Water*

Clean tap water sourced for this study was from the structural laboratory of the Rivers State University. The water is potable and suitable for drinking. It meets the requirement of BS EN 1008:2002 for mixing and curing of concrete specimens.

***C**: Coarse Aggregate*

The coarse aggregates used for the concrete were 9.52 and 12.7mm maximum sizes commercially crushed stones obtained from Akamkpa quarry rock deposit in Cross River State. The Akamkpa quarry rock has average consolidated bulk and relative densities of 1650kg/m3 and 2.97, respectively.

Table 1: Properties of Coarse Aggregate Used For Study

	Coarse Aggregates Stockpile
Sieve Size [mm]	% Passing
12.70	100
9.52	64.0
6.35	6.9
4.75	0.7
2.36	0.0
Pan	0.0
Absorption	1.53
Relative Density (SSD)	2.66
Rodded Bulk Density (SSD) [kg/m3]	1563
Loose Bulk Density (SSD) [kg/m3]	N/A

***D**: Fine Aggregate*

Naturally occurring fine aggregates (river sand) of the maximum *size* of 2mm obtained from mile 3 market in the Port Harcourt region confirming to BS 813 part 103:1995 were used for the concrete.

Table 2: Properties of Fine Aggregate Used For Study

	Fine Aggregates Stockpile
Sieve Size [mm]	% Passing
9.5	100.0
6.7	96.9
4.75	92.2
2.36	73.5
1.18	53.9
0.6	40.3
0.3	28.1
0.15	27.6
0.075	7.1
Pan	6.0
Fineness Modulus	2.93
Absorption	1.10
Relative Density (SSD)	2.81
Rodded Bulk Density (SSD) [kg/m3]	1973
Loose Bulk Density (SSD) [kg/m3]	N/A

***E**: Intermediate Aggregate*

The intermediate aggregate used for this study was 9.52mm commercially crushed stones obtained from Akamkpa quarry rock deposits found within in the Cross-River State area. The Akamkpa quarry rock.

Table 3. Properties of Intermediate Aggregate Used For Study

	Aggregates Stockpile
Sieve Size [mm]	% Passing
12.70	100.0
9.52	45.5
6.35	3.3
4.75	1.1
2.36	0.0
Pan	0
Fineness Modulus	1.67
Absorption	2.69
Relative Density (SSD)	
Rodded Bulk Density (SSD) [kg/m3]	1683
Loose Bulk Density (SSD) [kg/m3]	N/A

F*: *Experimental Plan

The following experiments performed in this dissertation according to standards and procedures are:

- Sieve Analysis
- Shilstone Coarseness Factor
- Slump Test
- Compressive Strength Test

G*: *Mix Designs

As previously stated, the experimental program for the current study was divided into two stages, with one stage using the one typical mixture proportions (for 35 MPa compressive strengths), and one stage using variations of the control mixture proportions with reduced cement content and increased total aggregate content.

Shilstone's Coarseness Factor Chart was used to evaluate the combined gradations produced from the optimization technique.

Stage 1 – 35 MPa, 350 kg/m^3 cement content (typical), w/c = 0.45

Stage 1 mixes were the first set of mixes to be tested. All mix designs using the optimization technique, a total of 11 mixes as described in Table 3.8, were cast for measuring fresh property. If the mix design displayed satisfactory workability characteristics, then the mix was made for casting cubes to evaluate hardened concrete properties. The cement, water, and total aggregate were consistent throughout.

Stage 2: 35 MPa, 300 kg/m^3 cement content (reduced), w/c =0.45

Stage 2 mixes batched for workability testing and then made for casting cubes. The mix design list for Stage 2 was governed by the success of Stage 1 workability results. A total of 11 mixes as were cast for fresh and hardened properties testing. The mixture proportions were altered to reduce the cementitious material content while maintaining the same w/c ratio. Therefore, the total aggregate absolute volume was increased.

If the mix design displayed satisfactory workability characteristics, then batched, the mix was made for casting cubes to evaluate hardened concrete properties.

The cementitious, water, and total aggregate absolute volume were consistent throughout.

IV. RESULTS AND DISCUSSION

Shilstone's Coarseness Factor Chart

For Shilstone's Coarseness Factor Chart, detailed particle size distributions are not required for the individual aggregates since the only values needed to calculate the coarseness and workability factors are the % passing the 9.5 mm and 2.36 mm sieves. It was found from the study that the maximum coarseness factor possible (coarse aggregate mass proportion is 1.0) is completely influenced by the choice of coarse aggregate and can control or safeguard against mixtures falling in the gap-graded zone, Zone 1.

4.1.1 Positions in Coarseness Factor Chart For Stage 1:

Figure 1 shows the positions of the mixes in the Coarseness Factor chart. As it was mentioned earlier, the cement content of these mixes was 350 kg/m^3 (590lb/yd^3), which was greater than 6.0 sacks of cement (564lb/yd^3). Therefore the Workability Factor was adjusted for this increased cement content as following

$$WF = W + \frac{2.5(674-564)}{94}(\text{Imperial Unit})$$

The zone of Stage 1's 35 MPa control mixture on the Coarseness Factor Chart varied depending on the coarse aggregate blend used. For stage 1, it was located in Zone 2 (Optimal) except mix 9, which is not within the optimal, and for mix 5, which is in Zone 3.

For Stage 1, it was found that the ternary aggregate blended mix designs points on the Coarseness Factor Chart, as denoted by circles in Figure1, clustered in the workability box of Zone 2 and Zone 3 (spreading from the box to right of the chart).

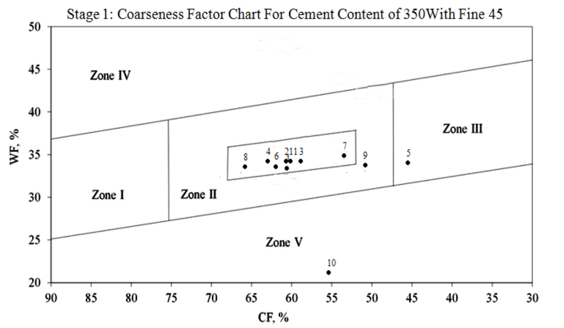

Figure 1. Mix positions on Coarseness Factor Chart

Figure 1 stage1: shows the positions of the mixes in the Coarseness Factor chart.

The lowest and highest coarseness factors are 44.75 and 66.6, respectively, and the lowest and highest workability factors are 33.75 and 35.33

Positions in Coarseness Factor Chart For Stage 2: Figure 2 shows the positions of the mixes in the Coarseness Factor chart. As it was mentioned earlier, the cement content of these mixes was 300 kg/m^3 (506lb/yd^3), which was less than 6.0 bags of cement (564lb/yd^3). Therefore the Workability Factor was adjusted for this decreased cement content as following

$$WF = W + \frac{2.5(674-564)}{94}\ (\text{Imperial Unit})$$

Zone 5 off the chart). The lowest and highest coarseness factors were 44.75 and 66.6, respectively, and the lowest and highest workability factors were 31.51 and 33.1.

Figure 2 shows the positions of the mixes in the Coarseness Factor chart. As it was mentioned earlier, the cement content of these mixes was 350 kg/m^3 (590lb/yd^3), which was greater than 6.0 bags of cement (564lb/yd^3). Therefore the Workability Factor was adjusted for this decreased cement content as following

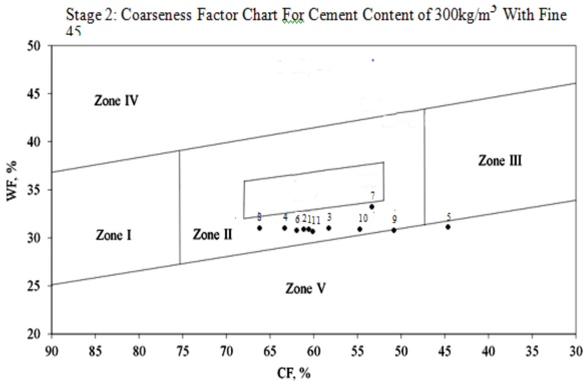

Figure 2: Stage 2 Mix Plan Plotted on Coarseness Factor Chart

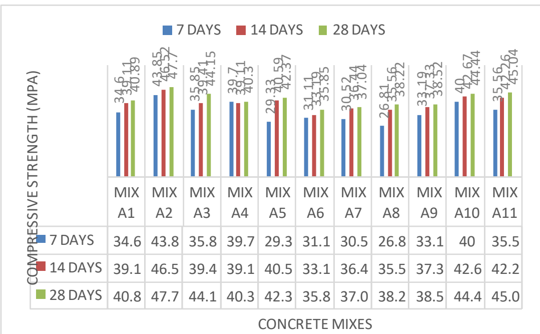

Figure 3: Compressive Strength gain plots for Stage 2

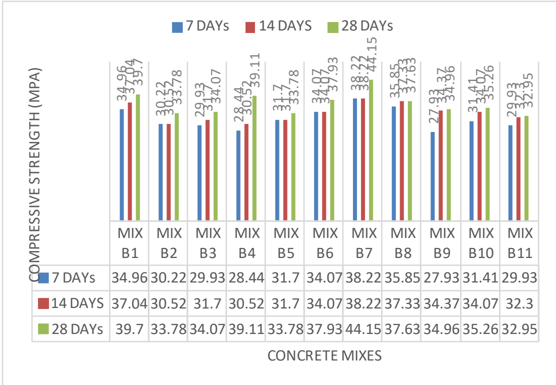

Figure 4: Compressive Strength do not gain plots for Stage 2

V. CONCLUSION

The effects of aggregate characteristics on concrete properties, such as workability and strength, were investigated using mixtures in which the paste content and the water/cement ratio were held constant. The results showed the maximum nominal aggregate sizes, the different aggregate proportions, the combinations of different aggregates, and different aggregate gradations all shown to impacted performance in the strength and slump test. Based on the data collected, the following have been found:

- Using the 350kg/m^3 CMC batches as a reference point, the 300kg/m^3 CMC batches tended to show slight decreases in compressive strength on the order of 2-30% except for Mix-B7, which have a compressive strength of 44.15MPa. This is because the workability factor and coarseness factor plots did not plot in the optimum zone as in the case stage 1. Therefore, stage 1 was the optimum.
- Results indicate an increase in limestone mining for concrete production alone, mostly targeting Akamkpa sources.
- Typical cement costs in concrete can be reduced by 2,520.28 nairas per m^3 of concrete, which is approximately 11% minimum.
- A reduction in CO_2 emissions and cement budget, which has a significant impact on the current and future sustainability of cement production and concrete employed in business-as-usual construction such as pavements and seaports

Increasing cement content does not improve the strength after the required content is reached; it may decrease durability as high cement content both increases air permeability and chloride penetration

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