PRINT ISSN 1119-8362
Electronic ISSN 1119-8362

Full-text Available Online at
https://www.ajol.info/index.php/jasem
http://ww.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 23 (5) 851-856 May 2019

Effects of Combined Aggregate Gradation on the Compression Strength and Workability of Concrete using Fineness Modulus

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ABSTRACT: Aggregate gradation (particle size distribution) is a very important part of concrete production hence the need to combine coarse aggregate with fine aggregate in its simplest form. An improperly graded aggregate structure can have undesirable effects on the properties of concrete as it can produce weak, stiff or porous concretes. In this research, the properties of concrete in terms of strength, slump and density were studied by varying aggregate grades. Proportions of 12.7mm, 25.4mm, and 38.1mm and 50.8mm sizes of granite as coarse aggregates were varied in order to create diverse coarse aggregate grading and then combined with a constant fine aggregate gradation and a fixed water/cement (w/c) ratio of 0.7. The results showed that as the coarse aggregate was spread evenly across all four aggregate sizes the strength was maximum as compared to when the aggregates were concentrated towards the 50.8mm size. The workability was seen to be stiffer as more coarse aggregate sizes were introduced into the mix. When the 50.8mm granite size represented the total coarse aggregate content (60%) of the concrete mix, the mix recorded a slump of 40mm. The workability declined slightly to slumps of 30mm, 20mm and 10mm when the coarse aggregate content was produced by combining granite sizes of 50.8mm and 38.1mm; 50.8mm, 38.1mm and 25.4mm and finally 50.8mm, 38.1mm, 25.4mm and 12.7mm respectively. This indicated that the more coarse aggregate content in the mix the less workable the concrete. Finally the concrete density remained almost constant irrespective of the aggregate grading.

DOI: https://dx.doi.org/10.4314/jasem.v23i5.13

Dates: Received: 19 October 2018; Revised: 22 March 2019; Accepted 13 April 2019

Keywords: Aggregate, combined aggregate gradation, Fineness Modulus

Aggregates are basic constituents of concrete usually constituting about 75 percent of the volume. The high volume of aggregates in concrete underscores its importance. The grading of fine aggregates (size less than 4.7mm) and coarse aggregates (size greater than 4.7mm) are generally required in concrete production. An aggregate combination made up of more coarse aggregates than fines can lead to the production of porous concrete which in most cases is responsible for damage of properties in buildings through leakages of water and moisture in reinforced concrete members. As a result of this, the approach of aggregate particle size distribution or aggregate gradation (adopted in this work) has become one of the most important characteristics regarding the utilization of aggregates in concrete (Dellarard & Belloe, 1999). Not only does it influence the material's mechanical properties such as strength and slump, it also affects its durability. At a time it was believed that aggregate gradation had no influence on the strength of concrete and that only the maximum size of the aggregates was of importance. This led research to focus on the effect of the aggregate size on the compressive strength of concrete (Walker & Bloem, 1960; Bloem & Gaynor, 1963; Cook, 1989; Zhou, Barr, & Lydon, 1995;) with results presented as though only one aggregate size was used for the experiment while disregarding the effect of the finer aggregates used in the mix. It was not until Bloem & Walker (1963) showed that smaller sized graded aggregate with a constant slump and cement content had more strength than larger size graded aggregate, that awareness was directed to the possibility that aggregate gradation was just as important as maximum aggregate size. Most of the earlier works that focused on the effect of aggregate size on the compressive strength of concrete flawed in their methodology as they relied solely on the maximum size of aggregate to draw their conclusions disregarding the fine aggregate content which in itself modified the aggregate gradation of the concrete, a property that could have been responsible for the diverse conclusions reached. Aggregate gradation highly influence the mechanical and durability properties of concrete (Ronnen & Hashem, 2002; Abdel-Jawad & Abdullah, 2002; Ergul, Yasin, & Alaettin, 2004; Sari & Pasamehmetoglu, 2005; Mucteba, Kemalettin, & Metin, 2010; Ashraf & Noor, 2011; Rafat, Paratibha, & Yogesh, 2012; Zalal, 2012; Ioannis & Konstantinos, 2013). The most well-known methods of aggregate gradation include using two different segments of

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aggregates (i.e., fine aggregates and coarse aggregates) or using combined aggregate gradation which is coarse aggregate grading combined with fine aggregate gradation (Chenchen *et al*., 2014). Some studies have shown that the density and strength of concrete can be increased by proper aggregate grading (Chenchen *et al*, 2014) while others have reported that concrete made from graded aggregates are weaker and less workable than its single sized aggregate concrete counterpart (Ekwulo, 2017) due to a high packing density of the aggregates. The aggregates will then require high cement paste content so as to go in between aggregate interfaces for the concrete to be workable and reach high strengths.

Most mix design methods require the maximum size of aggregates to proportion mix ratios. Only a few methods such as the 0.45 power curve and the coarseness factor chart represents aggregate gradations in concrete design by identifying maximum density gradations with the assumption that a densely graded aggregate concrete will produce a better performing concrete than a less dense graded aggregate concrete. Though it is believed that the denser the concrete the stronger it is, there is no empirical evidence to support that and this is shown typically in the 0.45 power curve where aggregate grades lying directly on the 0.45 most dense line are unworkable and harsh (Talbot and Richart 1923; Walsh, 1933; Besson 1935) and may require a lot of water in the mix. To improve on this and limit the demand of water for the concrete mix, the fineness modulus was propounded as a method of representing the aggregate gradation with the mean size of all the aggregates in the mix (Abrams, 1918; Richardson 2005). This method has been generally accepted as a better approach in representing graded aggregates sizes in concrete production and it's believed that not only does the concrete strength increase with an increase in fineness modulus (Zalal, 2012) but any two or more gradation curve of aggregate that has the same fineness modulus will require the same quantity of water to produce the mix of same plasticity and strength (Zhou, et al., 1995).

This work provides an insight into the use of fineness modulus in understanding and generally predicting the effects of aggregate gradation in concrete as it relates to strength, workability and density. It also shows the distinction between the use of aggregate maximum size and fineness modulus in representing concrete having more than one aggregate size in it.

MATERIALS AND METHODS

Material preparations and batching: Portland limestone cement grade 42.5 was purchased from a local store and used in this research. The fine aggregate (sand) was gotten from a local river in Oleh, Isoko South Local Government Area, Delta State, Nigeria. The sand had all its sizes pass through the 4.75mm sieve and was graded. The outcome of the grading is presented in Table 2. Four sizes of granites were used in varying proportions. These were the 12.7mm (1/2 inch) size, the 25.4mm (1 inch) size, the 38.1mm (1.5 inch) and finally the 50.8mm (2 inch) aggregate sizes.

A Universal Testing Machine with a maximum crushing capacity of 15kN which was available in the Structural Laboratory of the Department of Civil Engineering, Delta State University, Oleh Campus was used for this work. For a lack of a higher capacity machine, a weak mix ratio of 1:3:6 and a high water/cement ratio of 0.7 was chosen for the concrete in order to ensure the concrete strength fell below 15kN.

The batching was done with respect to the number of cubes that were to be used in the experiment. The tests made up of 4 groups. Each of those groups were tested on 7, 14 and 28 days. 100mm by 100mm by 100mm cubes were used and three cubes each were tested on each test day of 7, 14 and 28 days making 9 cubes per group. The batches were calculated in the following manner (Sekar, 2015).

Table 1: Calculations showing batching of the aggregates used for the all groups

Description	AD	V	NC	WC	Wt.C	TRS	WCe	WS	WG	WW
Equations	a = 2400	b = 0.1^3	c = 9	D = (a*b)*c	e = d+(0.1*d)	f= 1+3+6+0.7	g = (1/f)*e	h = (3/f)*e	I= (6/f)*e	j = (0.7/f)*e
Results	2400	0.001	9	21.6	23.76	10.7	2.22	6.66	13.32	1.55

AD = Assumed Density of concrete (kg/m3); V = Volume of one 100mm cube. (m3); NC = Number of cubes for testing; WC = Weight of 9 cubes (kg); Wt.C = Wt. of 9 cubes plus 10% waste (kg); TRS = Total ratio sum; WCe = Weight of cement (kg); WS = Weight of sand (kg); WG=Weight of granite (kg); WW= Weight of water (kg)

From the calculations in table 1 it can be seen that the total weight by volume of three cube samples for the three test days each was 21.6kg (21600g). The total volume for the coarse aggregates alone was 13.32kg while that of the fine aggregate was 6.66kg making a total aggregate volume of 19.98kg (19980g).

Aggregate grading methods (groupings): The 6.66kg of sand was graded with the use of a mechanical sieve machine and in accordance with the British Standard (BS 3797:1990) from the available sand acquired. The outcome of the fine aggregate grading is shown in table 2. This sand sample was used in group one as the fine aggregate content of the mix. The sand grade was to be kept constant through subsequent groups to maintain the same grade pattern hence minimise or eliminate the effects of a change in sand gradation on subsequent groups. This was done by separating sand retained on each sieve size in different bags. For example to get the size retained on the 2.8mm sieve, the 4.75mm (which is the size just above the 2.8mm sieve) and the 2.8mm sieves alone were required. The sand is poured through the 4.75mm sieve and whatever passes through the 4.75mm sieve but retained on the 2.8mm sieve is put in a bag tagged 2.8mm. This process was carried out for the 2.8, 2, 1.7, 1.18, 0.85, 0.6, 0.0425 and 0.0212mm sieves. Having one size grades of fine aggregates bagged per size in this manner made it easy in duplicating the fine aggregate grades in table 2 (group 1) for all other groups. The fine aggregate grade duplication was done by taking the weight required from the sand bag of each size that equals the graded weight of group one and mixing them together. Sieve analysis were also conducted to ensure that the sand grades of other groups tallied with the group one grade.

Table 2: Particle size distribution of the sand specimen

size (mm)	weight of sieve (g)	Weight of sieve + Combined Fine AGG.	Weight of sand retained (g)	Percent retained by weight (%)	Percent accum. By weight (%)	Percentage passing by weight (%)
4.75	300	300.00	0.00	0.00	0.00	100.00
2.8	260	497.46	237.46	3.57	3.57	96.43
2	250	478.35	228.35	3.43	6.99	93.01
1.7	210	447.46	237.46	3.57	10.56	89.44
1.18	200	470.36	270.36	4.06	14.62	85.38
0.85	200	634.76	434.76	6.53	21.15	78.85
0.6	200	634.76	434.76	6.53	27.68	72.32
0.0425	200	1950.56	1750.56	26.28	53.96	46.04
0.0212	200	3266.26	3066.26	46.04	100.00	0.00
Base	110	300.00	0.00	0.00	100.00	0.00
TOTAL			**6660**	**100**		

The coarse aggregates were separated into sizes of 50.8mm, 38.1mm, 25.4mm and 12.7mm by applying the methods described above and bagged accordingly. Here though, unlike the sand, the coarse aggregates were varied in other to allow for a change in aggregate gradation. Whenever a change in aggregate weight for any sieve size is required, the granite weight required is taken from the bag of that size of granite. For group 1, granite of 50.8mm size weighing 13.32 kg was combined with the sand content already prepared (Table 2). In this group 100 percent of the granite (coarse aggregate) were of the size 50.8 (ie retained at 50.8mm sieve but passing through the 63mm sieve). In group 2, granite sizes of 50.8mm and 38.1mm are combined 50% each (6.66kg each) to make up the 13.32kg coarse aggregate content of the mix. Here, granite weighing 6.66kg is taken from the bag of 50.8mm which is then mixed with 6.66kg of granite from the 38.1mm bag. These sizes are added to the already prepared sand content (table 2) to get the desired combined aggregate gradation. In group 3, the 13.32kg coarse aggregate content is split into three across 50.8mm, 38.1 mm and 25.4mm sieve sizes with granite weights of 4.44kg each. Again this was added to the sand volume already prepared (table 2). Finally, in group 4 the coarse aggregates are split into four across the 50.8mm, 38.1mm, 25.4mm and 12.7mm sieve sizes weighing 3.33kg each. This coarse aggregate gradation is combined with the already graded sand (Table 2) as the other groups. The combined gradation of these groups can be seen in figure 1.

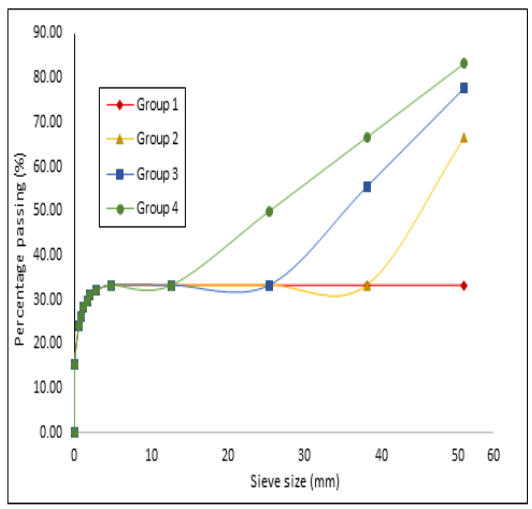

Fig 1: Combined aggregate gradation curves of all groups

The changes in the coarse aggregate proportions was solely responsible for the change in overall aggregate grade. The cement accounted for 10% of the entire mix. The fine aggregate (sand) accounted for 30% of the mix and 33.33% of the total aggregate volume while the coarse aggregate (granite) accounted for 60% of the entire mix and 66.67% of the total aggregate volume. This distribution of 1:3:6 ratio was maintained for all the groups used in this work through the methods described so far.

Finally after combining the fine and coarse aggregates as discussed, the aggregate is then mixed with cement and water of the batched weight (Table 1). Concrete cubes of 100x100x100mm were produced using the moulds and allowed to harden for 24 hours in the moulds. The cubes were then removed from their moulds and transferred to the curing tanks where they were properly tagged and cured. The cubes were totally submerged in water to assist trigger the hydration process and gain sufficient strength. This was where the concrete cubes remained until they were needed for testing at 7, 14 and 28 days.

Test carried out and analysis of results: Slump test for the fresh concrete and compressive strength test for the hardened concrete were carried out. The density of the concrete cubes was also determined. The slump test was carried out in accordance with BS EN 12350-2:2009 while the compressive strength test was carried out in accordance with BS EN 12390-3:2009. All the groups had the same aggregate maximum size of 50.8mm but all had different aggregate gradation curves hence the fineness modulus which is the mean size of all the aggregates was used in analysing the results. The fineness modulus was gotten by dividing the sum of all percentage cumulated sizes of the aggregates in a sieve analysis test by 100 (Abrams, 1918; Richardson 2005).

RESULTS AND DISCUSSIONS

Compressive strength gain, slump and density: Compressive strength increased as the days of curing increased. This was a common factor in all the concrete groups. Groups one (1) and four (4) recorded a slow increase of strength in the concrete from seven to fourteen days then a high increase from fourteen to twenty-eight days. Groups two (2) and three (3) on the other hand had a high increase of strength in the concrete from seven to fourteen days then a low increase rate from fourteen to twenty-eight days, This is shown in the Figure 2.

There was no clear relationship between the aggregate combined gradation of all the groups and the strength of concrete at 7, 14 and 28 days as each group behaved differently. From figure 2, the mix of group 4 (where all aggregate sizes were represented and even), showed a high strength gain at day 7 before the rate of strength gain reduced at the 14th day and finally surpassed all other groups in strength at the 28th day. The reason of the reduction in the rate of strength gain could be as a result of difficulty of free water reaching all the un-hydrated cement due to the compact nature of the aggregate structure. But with further curing up to 28 days, all cement was hydrated leading to a stronger mix. Group 2 and 3 showed a significant strength gain at day 14 and then dropped in the rate of strength gain as the curing approached the 28th day. Here it can be assumed that most of the cement paste had already started the process of hydration at day 14 and had less strength to unlock as the curing reached the 28th day. The gap graded group 1 showed a steady and almost constant rate of strength gain. It however accounted for the lowest strength at the 28th day.

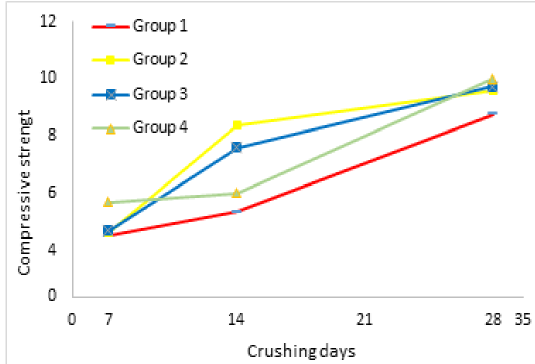

Fig 2: Compressive strength comparison between all concrete mix groups

For the slump test, group 1 mix produced a slump of 40mm, group 2 had a 30mm slump, group 3 was 20mm and group 4 slumped by 10mm. The results are shown in Table 4. The results show that there was a reduction in slump as the coarse aggregate in the concrete became less gap graded and more compact. The more the concrete mix became evenly graded, the less workable the concrete. As the concrete became more compact, the aggregates created a resistance against the flow of other aggregates around them.

The densities of the concrete mixes were taken before and after 28 day curing (just before crushing). The cubes by then had gained additional strengths. The essence of testing for the densities was to observe if the increase in strength led to a change in the density of the concrete. The results of this procedure is presented in Table 3. The results show that there was no significant change in the density of the cubes. This signifies that a gain in strength does not necessarily impact on the density of the cubes.

Table 3: Average densities of concrete cubes before curing commenced at day zero and just before crushing at the 28th day

Group 1		Group 2		Group 3		Group 4	
Average Density kN/m^3		Average Density kN/m^3		Average Density kN/m^3		Average Density kN/m^3	
Before curing	Before crushing	Before curing	Before crushing	Before curing	Before crushing	Before curing	Before crushing
24	24	23.8	24	24	24	23.5	23.7

Table 4: Fineness Modulus and maximum aggregate sizes of each group

Group number	Fineness modulus	Aggregate mean size range (mm)	Maximum aggregate size	Concrete strength	Density (kN/m^3)	Slump (mm)
Group 1	9.46	4.75 - 12.7	50.8 mm	8.77MPa	24	40
Group 2	9.13	4.75 - 12.7	50.8 mm	9.6 MPa	24	30
Group 3	8.80	2.8 - 4.75	50.8 mm	9.73MPa	24	20
Group 4	8.46	2.8 - 4.75	50.8 mm	10 MPa	23.7	10

Analysis of results with Fineness modulus: The Universal Testing Machine was used in getting the compressive strength of the concrete. The grades are usually described by the maximum aggregate size or the fineness modulus of the grade. The results will be compared to the fineness modulus of each group as well as the maximum size of each group in other to have a clearer view on the effect of these parameters on concrete property. Table 4 describes these grades under fineness modulus and aggregate maximum size. The more the volume of aggregate retained in the higher aggregate sieve size (50.8mm) the coarser the aggregate combination and hence the higher the fineness modulus value. Group 1 had a higher fineness modulus because 100% of the coarse aggregate content was retained on the 50.8mm sieve size. Group 2 had the second highest fineness modulus value because 100% of the coarse aggregate was shared equally between the 50.8.8mm and the next maximum sieve size of 38.1mm. Hence as less volume of aggregate was retained on the most coarse sieve sizes, the fineness modulus decreased. Delegating numbers to each sieve size from minimum to maximum such that 0.0212(1), 0.0425(2), 0.6(3), 0.85(4), 1.18(5), 1.7(6), 2(7), 2.8(8), 4.75(9), 12.7(10), 25.4(11), 38.1(12) and 50.8(13) indicates that a fineness modulus of 9.46 describes the grade as having an aggregate mean size between the number 9 and number 10 sieves which corresponds to a mean range between 4.75mm and 12.7mm aggregate size (refer to table 4).

As the fineness modulus increased, the compressive strength decreased meaning that the coarser the aggregate grade the lower the strength which to a large extent corresponds with the findings of Bloem & Walker (1963). The reduction in strength could be as a result of the gap graded areas in the coarse aggregate section which increased from group 4 to group 1. Group 1 had no aggregates sizes between 4.75mm and 50.8mm. Group 2 was gap graded between 4.75mm and 38.1mm. Other groups kept reducing in gap grade. This gap in aggregate grades would have created more voids in the concrete than the cement paste could cover. More voids mean less strength. It may be argued that the reduction in strength is as a result of having a stiff concrete mix with the cement paste being insufficient to surround the aggregates and bond them properly since 10mm to 40mm slumps are considered as concrete with low workability however this argument cannot be substantiated since the concrete strength reduced as the slump increased, if this were to be the case then the opposite response would have been expected. From the results it will be safe to state that the aggregate grades represented by the fineness modulus values had little or no effect in the density of the concrete since the density value remained largely the same through all the groups.

Conclusion: This study shows that concretes of the same mix ratio, maximum size of aggregate and water content will have their strength and workability properties differ if they are subject to a change in aggregate gradation. It shows that as the fineness modulus increases, the concrete becomes weaker but more workable. Finally the density of concrete in not affected by the maximum aggregate size or the grading of aggregates in the mix and could be the reason why the unit weight of mass concrete is usually specified as 24kN/m^3 irrespective of the concrete mix ratio.

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