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Effect of Coarse Aggregate Size and Gradation on Workability and Compressive Strength of Plain Concrete

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ABSTRACT: In this study effect of coarse aggregate size and gradation on workability and compressive strength of concrete was investigated. A mix ratio of 1:2:4 with a target strength of 20/25MPa, was adopted with a water-cement ratio of 0.6. Concrete cubes were produced with uniform coarse aggregate size of 4.75, 6.7, 9.5, 13.2 and 19mm respectively, with another set of samples produced with all the coarse aggregate sizes. Slump tests were carried out for all mixes and all sets of samples were tested for compressive strength after, 7, 14 and 28 days of curing. It was observed that workability was similar for all mixes with no well-defined pattern of relationship with size of coarse aggregate used. Compressive strength was observed to increase with increase in coarse aggregate size. Authors attributed this to the less quantity of water absorbed by larger size coarse aggregate during mixing which results in lesser quantity of capillary pores after curing. Maximum compressive strength was recorded for samples with 9.5mm coarse aggregate size. These show that quality concrete can still be produced with single-sized coarse aggregate as long as the optimum size can be determined for the particular mix.

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Every year, billions of tonnes of concrete is manufactured all over the world because of its ever-increasing demand in the construction industry (Ambrose *et al.*, 2018). This has made concrete the most consumed construction material and is simply due to its versatility and sustainability and the fact that concrete constituents can almost always be locally sourced. As put by Ambrose and Forth (2018), concrete is basically, a series of aggregates bonded together by hardened cement paste which is a product of hydration of cement. As such, aggregate usually occupies at least 75% of a typical concrete mix. With such high content, aggregate plays a vital role in determining properties of concrete at both fresh and hardened state. Apart from aggregate strength which is not usually a problem since it is often far higher than the required concrete strength, there are two categories of aggregate properties that influence concrete performance. The first category includes its shape, surface texture and cleanliness. These affect aggregate-cement paste bonding and consequently, the resulting concrete strength (Zegardlo *et al.*, 2018). Aggregates with angular or irregular shape and roughed surface texture produce stronger bonding with cement paste than aggregate with round shape and smooth surfaces. The other category of aggregate properties that affect concrete performance includes aggregate size and grading (Kabir *et al.*, 2019; Selvan *et al.*, 2021). These two properties affect workability and strength properties of concrete. Generally, a well graded aggregate produces better concrete in terms of strength and durability than a poorly graded or gap graded aggregate (Eme and Nwaobaka, 2019; Ukala, 2019). In a study by Ndon and Ikpe (2021), three different coarse aggregate gradings were investigated. These were aggregate of sizes 3.5-10mm, 13.2-19mm and 20-28mm. A constant fine aggregate grading was used for all the mixes, using a mix proportion of 1:2:4 being the proportions of cement, fine aggregate and coarse aggregate respectively. From the results, concrete mix with coarse aggregate grade 20-28mm produced higher slump height and compressive

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strength than mix with aggregate grade 13.2-19mm. Mix with aggregate size 3.5-10mm produced the lowest slump and compressive strength. This showed that compressive strength and workability were directly proportional to coarse aggregate nominal size. This was in line with the results of Kabir *et. al.* (2019) where aggregates of gradings 5-10mm and 14-20mm were investigated. Ogundipe *et al.*, (2018) investigated effect of aggregate size on compressive strength of concrete. For this study, concrete samples were produced using uniform coarse aggregate sizes of 6, 10, 12.5, 20 and 25mm respectively for two different mix proportions of 1:2:4 and 1:3:6 with a constant water-cement ratio of 0.55. Among the findings were that compressive strength increased with increase in coarse aggregate size up to 20mm aggregate size. Samples with 25mm aggregate size had lower compressive strength than those with 20mm for both mix proportions. Nevertheless, their compressive strengths were still higher than those of samples with the rest aggregate sizes. In another study, Vilane and Sabelo (2016) carried out an investigation using aggregate sizes 9.5, 13.2 and 19mm respectively and reported that workability and compressive strength increased with increase in aggregate size for a mix proportion of 1:2:4 and water-cement ratio of 0.5. Similar trend of compressive strength has also been reported elsewhere (Ekwulo and Eme, 2017; Ekwulo and Eme, 2017b). However, some other researchers have reported different trends of result. For instant, Ekwulo and Eme (2017) observed a different pattern of relationship between workability and aggregate size. In their study, coarse aggregate sizes of 9.5mm, 12.7mm and 19.1mm were used respectively with a mix proportion of 1:1.5:3 and a constant water-cement ratio of 0.6. Their results show that workability decreases with increase in aggregate size. Mix with graded aggregate made from a combination of the three sizes of coarse aggregates produced the least slump height. Another example could be seen in the work of Woode et. al. (Woode *et al.*, 2015). In their study, coarse aggregates of sizes 10, 14, and 20mm were used respectively with a constant mix of 1:2:3 and water-cement ratio of 0.63. Their results show that compressive strength decreases with increase in coarse aggregate size. With the reviewed literatures and other literatures available on this subject, it is clear that there is no general agreement on the influence of aggregate size on workability and strength of concrete. This has also been observed elsewhere (Ogundipe *et al.*, 2018). Some researchers have reported that strength and workability of concrete is directly proportional to aggregate size while others have reported otherwise. There is therefore a need for more research on this subject to ascertain these relationships. In this study, the aim is to determine effect of different aggregate sizes on workability and compressive strength of plain concrete.

MATERIALS AND METHODS

Materials: Materials used for the experiments in this study were cement, water, river sand and granite chippings. The cement used was Dangote brand of Ordinary Portland cement (CEM I) which was of strength class 32.5R and was in compliance to BS EN 197-1 (2011).It was purchased in 50kg bags from a dealer in Ibadan, Nigeria. Portable water was used as supplied on the campus of University of Ibadan, Ibadan. River sand was used as fine aggregate. It was obtained from a river sand mining site still in Ibadan. In place of coarse aggregate, granite chippings was used. It was purchased from a dealer in Ibadan who gets his supply from the nearest quarry. The chippings were sieved into 5 different uniform sizes of 4.75, 6.7, 9.5, 13.2 and 19mm respectively. A portion of the chippings containing all the five sizes was also used.

Preparation of Concrete Samples: A mix ratio of 1:2:4 (with a target strength of 20/25MPa) being the proportion of cement, fine aggregate and coarse aggregate respectively, was adopted for preparation of all concrete samples. A constant water-cement ratio of 0.6 was used. Six different mixes were used to produce six different sets of 100x100x100 mm^3 concrete cubes. For each mix, a uniform size of coarse aggregate was used. This was carried out for coarse aggregate sizes 4.75, 6.7, 9.5, 13.2 and 19mm respectively. Another set of samples was produced using coarse aggregate containing all the five sizes. Batching was by weight and mixing was carried out manually using shovel and hand trowel. The entire process of mixing and curing of samples were in compliance with BS EN 12390-2 (2009). All samples were cured by immersion in water at room temperature until their respective test dates.

Determination of Physical Properties of Materials: Tests were carried out on aggregates and cement used to determine their specific gravity and bulk density. Further tests were carried out to determine water absorption and particle size distribution of aggregates. Bulk density tests were carried out in accordance to BS 812-2 (1995) while particle size distribution tests were in accordance with BS 812-103.1 (1985).

Determination of Workability: Workability of each of the fresh concrete mixes was measured using slump test. A 300mm high fresh concrete frustum of a cone was prepared under the standard procedure of BS EN 12350-2 (2009) and allowed to subside under its self-weight. The reduction in height of the concrete, known as slump was measured to the nearest 5mm and taken as an indication of the workability of the concrete mix.

Determination of Compressive Strength: Compressive strength tests were carried out using a compression testing machine. Test samples were 100×100×100 mm^3 concrete cubes. For each test, the test sample was placed in between the machine's two steel platens of 30mm thickness and was subjected to progressive compressive loading till failure, following the procedures described in BS EN 12390-3 (2009). The maximum load sustained by the sample was recorded and compressive strength was computed using Equation 1. Where F is the load at failure (N), A_c is the cross-sectional area of sample (mm^2) and f_c is the compressive strength (N/mm^2).

$$f_C = \frac{F}{A_C} \qquad (1)$$

RESULTS AND DISCUSSION

Material Characterization: Selected physical properties of materials used for concrete mix in the experiment are presented in Table 1. Specific gravity and bulk density of sand were 2.60 and 1670kg/m^3 respectively while those of coarse aggregate were 2.52 and 1425kg/m^3 respectively. These values are within the range found in literature for fine and coarse aggregate materials used in normal weight concrete (Ambrose *et al*., 2021; Neville, 2011; Ambrose et al., 2021b). Water absorption results show that the sand have the capacity to absorb more water than chippings during mixing. The sand used can be classified as well graded since its coefficient of uniformity, C_u is greater than 4.0 and its coefficient gradation C_c is between 1 and 3 (Ambrose *et al.*, 2019). However, result shows that the coarse aggregate used was poorly graded.

Table 1: Physical Properties of OPC and Aggregates

Property	OPC	Sand	Coarse Agg. (All sizes)
Specific gravity	3.08	2.60	2.52
Bulk density (kg/m^3)	1513	1670	1425
Water absorption (%)		4.06	0.96
D_{10}		0.1	6.5
D_{30}		0.48	10
D_{60}		0.8	17.5
C_u		8.0	2.69
C_c		2.88	0.88

Workability: Results of workability tests for all the mixes, measured in terms of slump height, are presented in Figure 1. Surprisingly, there was no well-defined pattern of relationship between workability and coarse aggregate size. Slump of concrete made with all sizes of coarse aggregate (graded coarse aggregate) was the same with that made with 19mm aggregate size while those made with 13.2mm, 6.7mm and 4.75mm aggregate size respectively were slightly higher with the highest being on samples with coarse aggregate sizes of 6.7mm and 4.75mm respectively. Ordinarily, one would expect workability to reduce as the size of coarse aggregate used reduces. This is the trend in the works of Vilane and Sabelo (2016), Ukala (2019) and many others (Kabir *et al.*, 2019; Ndon and Ikpe, 2021; Ogundipe *et al.*, 2018). The explanation for such trend is that smaller coarse aggregate sizes have larger total surface areas to be wetted during mix (Vilane and Sabelo, 2016). However, for the workability results in this study, the slump values are all within a very small range of 10 to 25mm. These values are all within the "Low" workability category according to Neville (2011) and workability class S1 according to BS EN 206 (2013). With these, there is no significant difference between the workability of the mixes. This means that they could be said to be approximately the same.

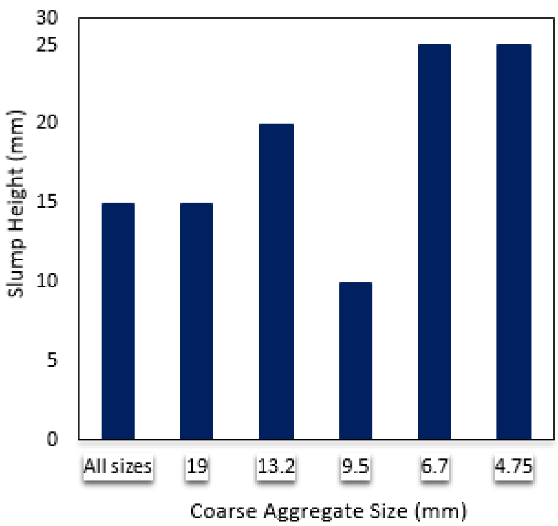

Fig 1: Slump of Mixes with Different Coarse Aggregate Size

Compressive Strength: Compressive strength results for all samples are presented in Figure 2. Obviously, for all the mixes, compressive strength increases with increase in curing age with maximum values at 28th day. This is due to continue hydration of cement which leads to gradual increase in strength of concrete but at a diminishing rate. Apart from samples with 9.5mm coarse aggregate size, compressive strength increases with increase in coarse aggregate size. However, the maximum compressive strength was achieved by samples with 9.5mm coarse aggregate size. Samples with graded coarse aggregate achieved compressive strength higher than those with 4.75mm and 6.7mm coarse aggregate size respectively, but lower than the rest of the samples. Increase in compressive strength with increase in coarse aggregate size has also been reported in earlier studies on this subject (Kabir *et al.*, 2019; Ndon and Ikpe, 2021; Ogundipe *et al.*, 2018; Vilane and Sabelo, 2016) Explanation for this trend is likely to be the same as that proposed by Vilane and Sabelo (2016) which is modified as follows. At constant mass, aggregate with smaller sizes have larger total surface area than aggregate with larger sizes. Therefore, during concrete mix, the quantity of mix water required to wet and lubricate the surfaces of aggregates is more for concrete with smaller aggregate sizes than for concrete with larger aggregate sizes. This water which is not used for hydration of cement – at least at the initial stage of hydration – will be collected at the capillary pores within the concrete matrix. It therefore follows that at the end of curing, concrete with smaller aggregate sizes will have more capillary pores and consequently weaker strength than concrete with larger aggregate sizes. This is evidenced in the density results of samples in Table 2. Apart from samples with 9.5mm aggregate size, density increases as aggregate size increases. This shows the present of more capillary pores in samples with smaller aggregate sizes. Maximum compressive strength was recorded for samples with 9.5mm coarse aggregate size. Again, from Table 2, these set of samples also recorded the highest density signifying a more condensed concrete mass. It has been mentioned that there is an optimum aggregate size for a given mix and a given water-cement ratio (Neville, 2011). It therefore seems that the optimum coarse aggregate size for the mix in this study is approximately 9.5mm. Moreover, the entire results show that quality concrete – or even better – in terms of strength can still be achieved with single-size coarse aggregate.

Table 2: Density of Concrete Samples after 28 days of Curing

Aggregate Size (mm)	Density (kg/m^3)
All Size	2560
4.75	2381
6.7	2445
9.5	2555
13.2	2518
19	2550

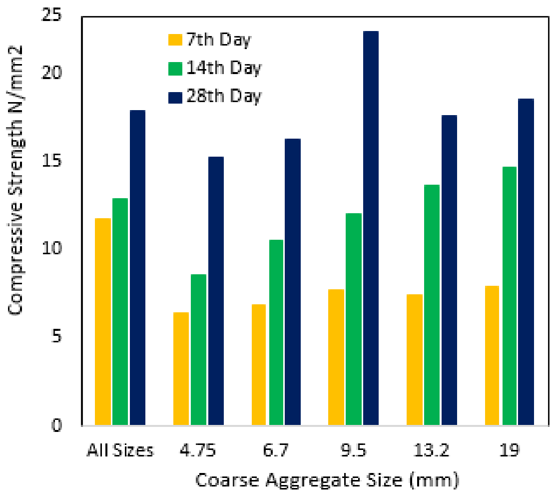

Fig 2: Compressive Strength of Concrete Samples with Different Coarse Aggregate Size

Conclusion: From this study, there was no well-defined relationship between workability and size of coarse aggregate used. Compressive strength increased with increase in coarse aggregate size and was attributed to the less quantity of mix water absorbed by larger coarse aggregate during mixing. Maximum compressive strength was recorded for samples with 9.5mm single-size coarse aggregate which seems to be the optimum size for that mix. The upshot of all these is that quality concrete can still be produced with single-sized coarse aggregate as long as the optimum size is determined for the particular mix and water-cement ratio.

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