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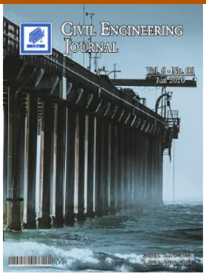

Effect of Maximum Aggregate Size on the Strength of Normal and High Strength Concrete

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Abstract

Aggregates form 60% to 75% of concrete volume and thus influence its mechanical properties. The strength of (normal or high-strength) concrete is affected by the maximum size of a well-graded coarse aggregate. Concrete mixes containing larger coarse aggregate particles need less mixing water than those containing smaller coarse aggregates, In other words, small aggregate particles have more surface area than a large aggregate particle. In this research, about twenty-two mixtures were covered to study the effect of the MSCA, on compressive strength of (normal strength concrete) and Sixteen mixtures to study the effect of the maximum size of coarse aggregate on compressive strength for (high strength concrete). The concrete mixture is completely redesigned according to the maximum size of coarse aggregate needs and maintaining uniform workability for all sizes of coarse aggregate. The American design method was adopted ACI 211.1, for normal concrete. ACI 211-4R, the design method was adopted for high strength concrete. And use the MSCA with dimensions (9.5, 12.5, 19, 25, 37.5, and 50) mm for normal strength concrete and the MSCA (9.5, 12.5, 19, and 25) mm for high strength concrete. The slump was fixed (75-100) mm for normal strength concrete. Slump is fixed to (25-50) mm for high strength concrete before added Superplasticizer high range water reducer (HRWR). With Fineness Modulus (F.M) fixed to 2.8 for both normal concrete and high-strength concrete. According to the results of the tests, the compressive strength increases with the increase in the MSCA, of the normal concrete and also high – strength concrete. And the effect of the MSCA, on the compressive strength of normal concrete, is higher than that of high-strength concrete.

Keywords: Maximum Size of the Coarse Aggregate (MSCA); Compressive Strength; High-Strength Concrete (HSC); High Range Water Reducer (HRWR); Fineness Modulus (F.M).

1. Introduction

Concrete is widely used in the construction of buildings, bridges and other infrastructure around the world. Concrete is affected by the components involved in production, and since coarse aggregate occupies a large part of the volume. The concrete is affected by the maximum size of a well-graded coarse aggregate, a concrete mixture containing large coarse aggregate particles has a small surface area compared to small coarse aggregate particles On the other hand, and the smaller coarse size aggregates give larger surface area for bonding with the mortar matrix. The study in this research completely redesigns the mixture according to the maximum size of the coarse aggregate used This method differs from previous research, as an increase in the value of the compression strength amount and maintaining the same average workability of mixtures Several researches had been done on the effect of the MSCA on concrete strength. Conclusions of these investigations differ from one to another as shown below.

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Aggregates are the most mined material in the world. They are a component of composite materials such as concrete and asphalt concrete. The aggregates are responsible for the unit weight elastic modulus and dimensional stability of concrete because these properties depend on the physical characteristics (strength and bulk density) of the aggregate [1]. Kozul and Drawin (1997) studied the compressive strength and fracture of concrete and how the aggregate type, size, and content affects these concrete properties. They used basalt or crushed limestone aggregate with sizes of 12 or 19 mm. They concluded that for both normal and high-strength concretes the compressive strength is little affected MSCA, while the flexure strength of the both concretes is not affected by the MSCA [2].

Krishna et al. (2010) investigated the effect of coarse aggregate sizes of (10, 12.5, 16, and 20 mm) on properties of both normal and self-compacting concrete. The main conclusions of them are that the all the strengths (compressive strength, split tensile strength, and flexural strength) of both normal concrete and (SCC) are achieved by using a coarse aggregate of 20 mm maximum size and the increase in strength of concrete is proportional to the size of coarse aggregate directly [3]. Tumidajski and Gong (2006) studied the variation of compressive strength and workability of concrete with the size of coarse aggregate. In their study the concrete was made by using different proportions of 37.5 and 19.5 mm stones as coarse aggregate. Their test results show that by using cement content of 160 kg/m^3 and (w/c) greater than 0.9, the compressive strength is maximum at 25 percent by weight of 37.5 mm stone. While for the cement content of 350 kg/m^3 and w/c ratios of less than 0.50, maximum compressive strength is substantively reduced [4]. Chen and Liu (2007) showed aggregate has a significantly influence on the fracture behavior of high performance concrete. The effects of aggregate size distribution on the fracture properties of high performance concretes with strength ranging from 50 to 80 MPa were investigated under three-point-bending tests. Acoustic Emission (AE) technique with three-dimensional orientation feature was applied to study the effect of maximum aggregate size (d_{max}) on fracture properties and the facture process zone (FPZ) at the crack tip. The results showed that the fracture energy of concrete increased with the increase of d_{max} [5].

For normal-strength concrete, at the same w/c ratio and with the same cement content, the larger the maximum sizes, the better the workability; at the same workability, the larger the maximum sizes, the higher the strength. A larger aggregate size also has some disadvantages. For instance, it makes the concrete look like nonhomogeneous, additionally it may causes a large interface which may effects the transport and the mechanical properties of concrete. Large sizes are rare in gravel deposits. In general, lean mixes benefit from a large aggregate size (up to 150 mm if available). For normal strength concretes, optimum maximum size usually lies between 20 and 40 mm. For very high strength concretes, 10 mm aggregate is best, probably due to improved bond [6].

Mehta et al. (1991) realized that size or type of coarse aggregate do not considerably influence the compressive strength of normal strength concert. While the strength and failure mode of high-strength concretes are affected by type and size of coarse aggregate. For high strength concrete made with weak coarse aggregate, crack is passing through the aggregates, as the aggregate itself is weaker than the bond of matrix-aggregate, leading to a trans granular failure type. When strong aggregate is utilized in high-strength concretes, both de bonding of matrix aggregate and trans granular failure happen. They concluded that cracks pass through the weaker aggregate particles portions and then spread into the paste of cement. Also, they realized that the flexural strength of high-strength concrete made in this research did not significantly influenced by sizes and types of coarse aggregate [7]. Musa and Aziz bin Saim (2017 conducted to find the effect of coarse aggregate size on concrete strength. Two maximum aggregates sizes were used which are (10, 20) mm. concrete strength was maintained without any additional materials or additives. Mixing ratio was (1:2:4) and ratio of water/cement was (0.5). Ordinary Portland cement was utilized in this concrete mixes. Three cubic samples were casted for each concrete mix with dimensions of (150×150×150) mm. The comparison cube test percentage was 47.6% after 28 curing days. It was noticed that concrete made with 20 mm maximum aggregate size has 45.7% compressive strength higher than that made with 10 mm maximum aggregate size [8].

Albarwary et al. (2017) investigated the impact of various maximum aggregate sizes on strength of concrete. Three different mixing proportions were tried in this investigation, which were 1:1.5:3, 1:2:4 and 1:3:6 (Cement: Sand: Gravel). Five various maximum aggregate sizes were utilized in each concrete mix which were (9.5, 12.5, 19, 25, and 37.5) mm, and all mixes slump results was fixed to be (25-50) mm. generally, results indicated that decreasing maximum aggregate sizes led to an increase in the compressive strength of concrete. The materials used in this study were ordinary Portland cement (specific gravity = 3.12), coarse aggregate and local river sand (fineness modulus = 2.6), which was obtained from Al-Khazer area. Utilized coarse aggregate was rounded river gravel with (37.5) mm maximum aggregate size. Results indicated that maximum aggregate size strongly effects compressive strength of concrete, as the strength increased when the maximum aggregate size decreased. For concrete mixes that having cement/aggregate ratio less than (6), the aggregate size has more effect on the compressive strength than content of cement [9].

Different recycled aggregates diameters (5-15), (15-20), and (20-30) mm were used in this study to evaluate the aggregate size influence on the concrete strength characteristics after 28 days of curing. The compressive strength of concrete samples increased with increasing aggregate size [10].

2. Materials and Methods

2.1. Materials

2.1.1. Cement

Ordinary Portland Cement (OPC) was used to prepare normal and high strength concrete mix, which was produced in Al-Sulaymaniyah city and supplied by Lafarge Company, commercially known as (Krista). And has a specific gravity of 3.15. The physical and chemical properties of ordinary Portland cement (OPC) Type I as shown in Table 1 which complies with the (ASTM C150-18) [11], and (EN, 2011) [12].

Table 1. Chemical and Physical properties of cement

Chemical composition (%)	Cement	Physical properties	
SiO2	62.2		
Al2O3	20.39	Specific gravity	3.15
Fe2O3	4.55	Specific surface (m^2/kg)	310
CaO	3.81		
SO3	2.36		
L.O.I	1.97		
CaO (free)	2.41		

2.1.2. Aggregate

Fine aggregates: Natural sand was utilized in this study to prepare the concrete mix, which is supplied from (Al-Akaeder) region in Karbala city. Physical properties of that sand were investigated; including gradation, specific gravity, sulfate content, and absorption. All the properties agreed with the limits of the American Standard (ASTM C33-03) [13] as shown in Figure 1.

Coarse aggregates: The used coarse aggregate in this study is a clean round aggregate from Al-Nebai (region) in Iraq; the max aggregate sizes were used in normal concrete mix were (9.5, 12.5, 19, 25, 37.5, and 50) mm, while they were (9.5, 12.5, 19, and 25) mm for high strength concrete. Graded according (ASTM C33-03) [13].

2.1.3. Water

Potable drinking water is used throughout this work.

2.1.4. Fly Ash

Fly ash (type F) was used in this study to prepare the concrete mix for investigating the effect of MSCA on high-strength concrete. It was brought from the local market, but it was produced in the United States; the physical and chemical characteristics of fly ash and they are compliant with the American standard (ASTM C-618) [14].

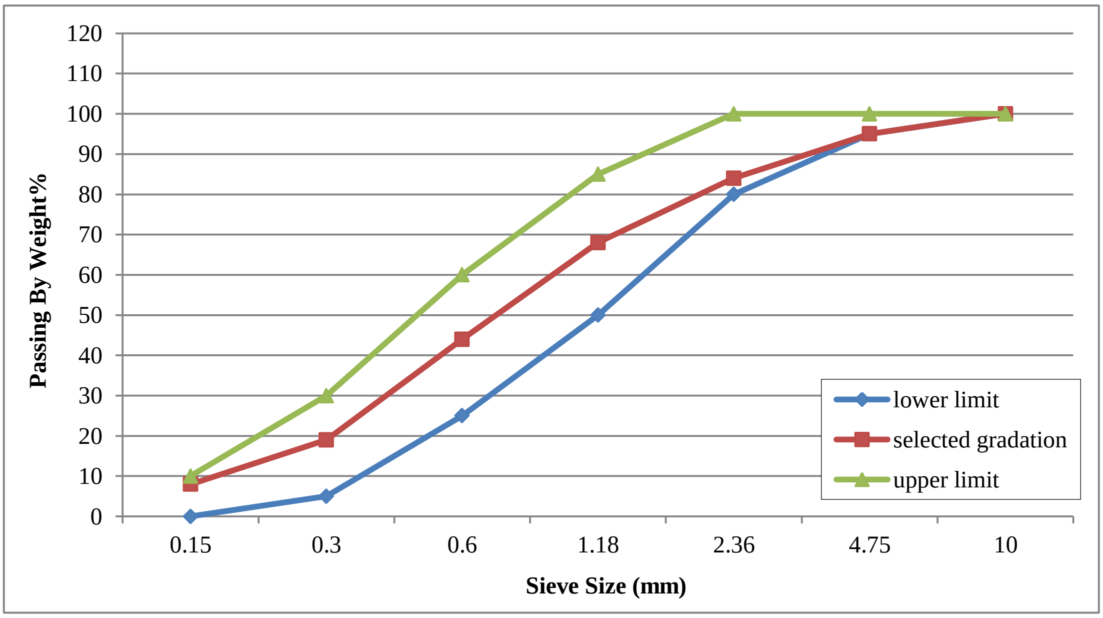

Figure 1. The grading curve of the original sand conform with (ASTM C33-03)

2.1.5. Super Plasticizer

To produce HSC with fly ash a High Range Water Reducer (HRWR) was used. It was based on polycarboxylic ether and had the trademark (VISCO CRETE 5930-L); VISCO CRETE 5930-L was complied with (ASTM C494-05) [15].

2.2. Method

2.2.1. Mixture Proportions

The concrete mix was designed depending on American Concrete Institute (ACI) methods for normal and high-strength concrete. To study the effect of aggregate size on compressive strength, two sets of cubic samples were prepared (15×15×15) cm and (20×20×20) cm.

The effect of different MSCA (9.5, 12.5, 19, 25, 37.5, and 50) mm was investigated for normal strength concrete and the fineness modulus of sand (F.M) (2.8). The slump range was, (75 – 100) mm and the cement weight was (250, 300, 350, 400, 450, and 500) kg/m^3. However, the tested MSCA for high strength concrete was (9.5, 12.5, 19, and 25) mm with F.M (2.8) of sand. The slump value was (25-50) mm before the addition of superplasticizer. Weights of cement content were (480, 540, 600, and 660) kg/m^3. The content of fly ash and superplasticizer was 20% and 0.5% of cement weight; respectively.

The concrete mix should be well designed before investigation the effect of MSCA on compressive strength. The normal strength concrete mix was designed by following (ACI 211.1) [16], while ACI 211.4R-08 [17] was adopted in designing high strength concrete mix.

The basis of work in this study is to redesign each mixture according to the MSCA. By using the American methods of design. The proportion of materials used in work is given in Table 2.for normal strength concrete. With F.M (2.8) and slump (75-100) mm. Also, the proportion of materials used in work is given in Table 3. For high-strength concrete. With F.M (2.8) and slump (25-50) mm before added superplasticizer.

2.2.2. Casting, Curing and Testing of Specimen

Concrete specimens were made according to BS 1881-108. [18]. The required weights of concrete ingredients were measured and mixing was done by an electrical mixer to ensure the homogeneity of the mixes, the degree of workability of all mixes was kept constant and measured by the slump test in accordance with (ASTM C143) [19]. Molds were cleaned and oiled to facilitate the extraction of the sample after hardening. Each mold was filled with concrete in three layers; then they vibrated using a laboratory table vibrator for about 1 minute and 30 seconds. Then the surface of the mold is adjusted manually, all molds with concrete were covered with plastic bags, and after 24 hours concrete samples were extruded and placed in curing bath filled with water at (21-27) Co until testing date as shown in Figure 2.

Table 2. Concrete mix proportions of mix normal strength concrete

Group/Mix Symbol	Cement (Kg/m^3)	Water (Kg/m^3)	Water/Cement Ratio	MACS (mm)	Coarse Aggregates (Kg/m^3)	Fine Aggregates (Kg/m^3)
A1	250	193	0.77	25	1052	833
A2	250	181	0.72	37.5	1111	819
A3	250	169	0.68	50	1155	820
B1	300	228	0.76	9.5	734	977
B2	300	205	0.68	19	977	822
B3	300	181	0.60	37.5	1111	777
B4	300	169	0.56	50	1155	778
C1	350	228	0.65	9.5	734	935
C2	350	216	0.62	12.5	872	842
C3	350	193	0.55	25	1052	750
C4	350	169	0.48	50	1155	737
D1	400	228	0.57	9.5	734	893
D2	400	205	0.51	19	977	738
D3	400	181	0.45	37.5	1111	694
D4	400	169	0.42	50	1155	695
E1	450	228	0.51	9.5	734	851
E2	450	216	0.48	12.5	872	758
E3	450	193	0.43	25	1052	666
E4	450	181	0.40	37. 5	1111	652
F1	500	228	0.46	9.5	734	809
F2	500	216	0.43	12.5	872	716
F3	500	205	0.41	19	977	654

Table 3. Concrete mix proportions of high- strength concrete

Group/Mix Symbol	Cement + Fly Ash (Kg/m^3)	Cement (Kg/m^3)	Fly Ash (Kg/m^3)	MSCA (mm)	Water (Kg/m^3)	W/C+F	Coarse-Aggregates (Kg/m^3)	Fine-Aggregates (Kg/m^3)	HRWR 0.5% by Wt ,cement
H-A1	480	384	96	9.5	184	0.38	1037	661	2.4
H-A2	480	384	96	12.5	175	0.36	1078	591	2.4
H-A3	480	384	96	19	169	0.35	1134	564	2.4
H-A4	480	384	96	25	166	0.35	1178	542	2.4
H-B1	540	432	108	9.5	184	0.34	1037	537	2.7
H-B2	540	432	108	12.5	175	0.32	1078	533	2.7
H-B3	540	432	108	19	169	0.31	1134	506	2.7
H-B4	540	432	108	25	166	0.31	1178	484	2.7
H-C1	600	480	120	9.5	184	0.31	1037	479	3
H-C2	600	480	120	12.5	175	0.29	1078	475	3
H-C3	600	480	120	19	169	0.28	1134	448	3
H-C4	600	480	120	25	166	0.28	1178	426	3
H-D1	660	528	132	9.5	184	0.28	1037	421	3.3
H-D2	660	528	132	12.5	175	0.27	1078	417	3.3
H-D3	660	528	132	19	169	0.26	1134	390	3.3
H-D4	660	528	132	25	166	0.25	1178	368	3.3

Figure 2. Filling moulds with concrete mixture and Specimens Curing

The concrete samples were tested for compressive strength at 28 days according to BS1881-116 [20]. For each variable, three samples were tested using a universal compressive testing machine and the average value for the three cubes was taken.

3. Results and Discussion

3.1. Normal Strength Concrete

Compressive strength of the concrete mixes (A, B, C, D, E, and F) with a constant fineness modulus of sand (2.8) and different weights of cement content are shown in Table 4 and Figure 3.

Table 4. Compressive strength test results of normal strength concrete group (A, B, C, D, E and F)

Group/Mix Symbol	Compressive Strength f_{cu} (MPa) of cubic samples at (28) day
A1	19.22
A2	19.98
A3	25.71
B1	19.04
B2	21.99
B3	28.74
B4	33.34
C1	25.12
C2	26.15
C3	31.50
C4	40.64
D1	28.60
D2	39.83
D3	43.55
D4	46.60
E1	36.19
E2	39.45
E3	45.68
E4	50.30
F1	42.78
F2	43.89
F3	47.25

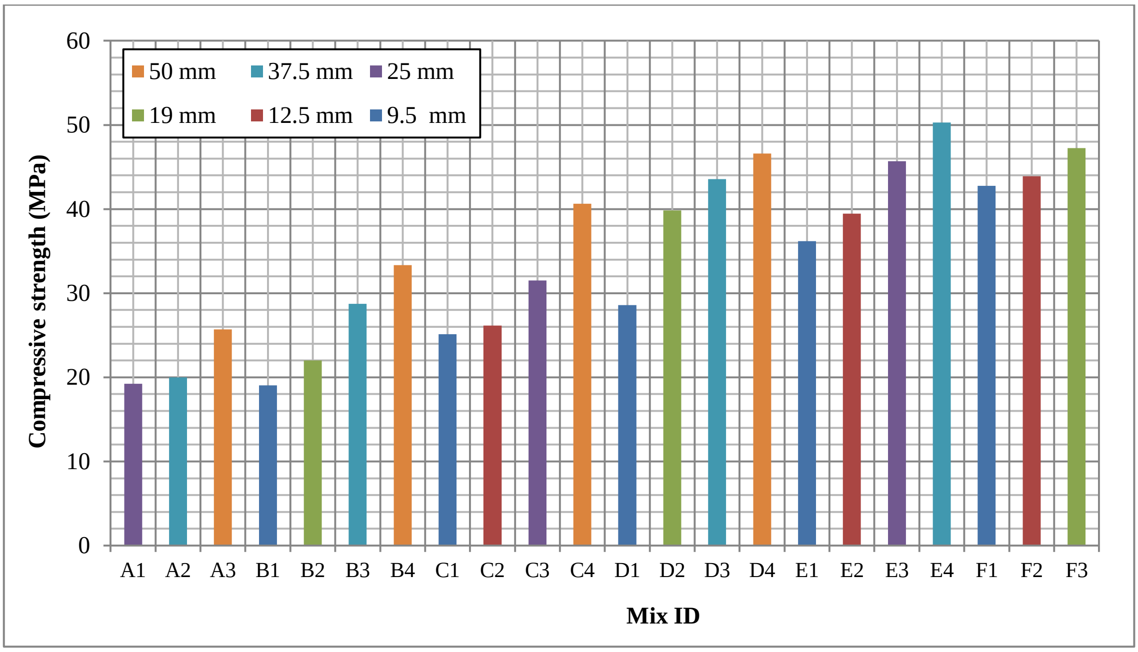

Figure 3. Compressive strength test results of normal strength concrete with constant fineness modulus of sand and varied cement content

3.2. High Strength Concrete

Compressive strength of the concrete mixes (H-A, H-B, H-C, and H-D) with a constant fineness modulus of sand (2.8) and different weights of cement content and slump within rate (25-50) mm before added Superplasticizer are shown in Table 5 and Figure 4.

Table 5. Compressive strength test results of high strength concrete (group H-A, H-B, H-C, and H-D)

Group/Mix Symbol	Compressive Strength f_{cu} (MPa) of cubic samples at (28) day
H-A1	57.40
H-A2	60.03
H-A3	64.23
H-A4	66.45
H-B1	61.33
H-B2	63.12
H-B3	65.40
H-B4	70.55
H-C1	67.14
H-C2	67.80
H-C3	70.31
H-C4	72.00
H-D1	72.12
H-D2	73.13
H-D3	74.84
H-D4	76.34

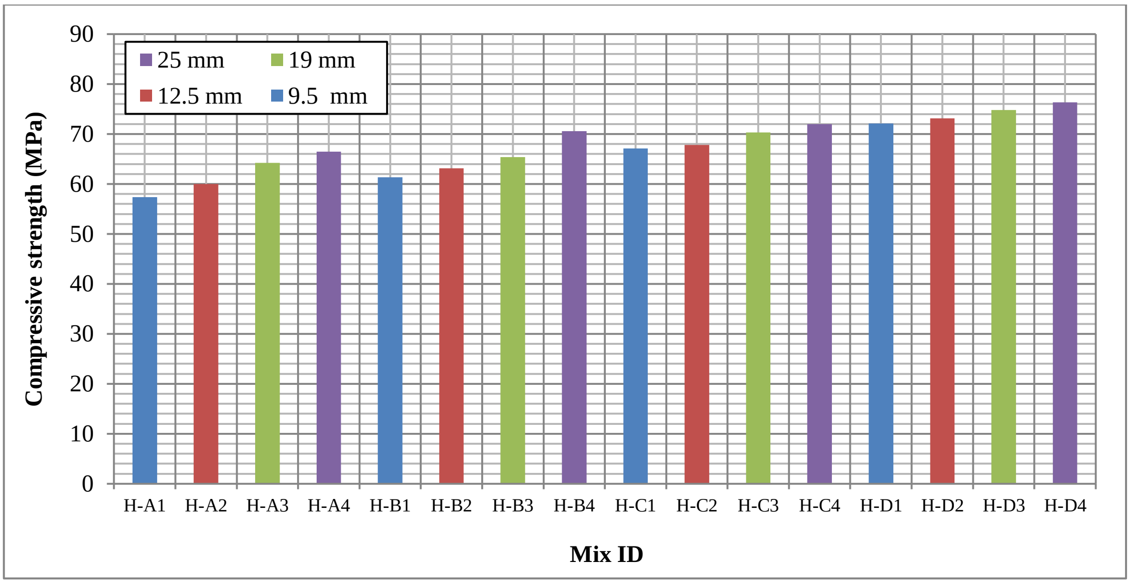

Figure 4. Compressive strength test results of high strength concrete

From Table 4 and Figure 3 for normal strength concrete, also Table 5 and Figure 4 for high strength concrete it appears that when the MSCA increases the compressive strength increases.

Figure 5. Failure mode of a sample of normal; Strength, concrete with MSCA (37.5 mm)

The increase in the strength is due to:

1. Concrete made with higher coarse aggregate size gives higher strength than concrete made with the smaller size of coarse aggregate due to the lager coarse aggregate have little surface area and you need less coverage than the mortar, in other words, you need less water and this leads to an increase in compressive strength;
2. Concrete batches of smaller aggregates have a larger wetted area than larger aggregates. When wetted area dries up during the curing process, it leaves pores where micro cracks start. This is the reason attributed to the low compressive strength associated with smaller sized aggregates compared to large-sized aggregates;
3. These results can be explained by the fact that the transition zone (Between coarse aggregate and mortar) is the weakest point in the stress matrix within the hardened concrete, Compared with the mortar and coarse aggregate. From this fact, the greater the transitional zone within the unit of volume, the more likely it is to fail. Large coarse aggregate particles have a smaller surface area than small aggregate particles and thus the formation of the transition zone is greater within the concrete matrix that contains small coarse aggregate particles;
4. When increases the maximum size of coarse aggregate leads to reduce water /cement ratio In order to maintain a certain slump. When the water /cement ratio decreases, the compressive strength increases.

3.3. Relationships between the Compressive Strength Concrete and Changing the Maximum Size of Coarse Aggregate

3.3.1. Relationships between the Compressive Strength of Normal Strength Concrete with the Maximum Size of Coarse Aggregate

The graph in Figure 6 links the relationship between the compressive strength of the concrete with the change in the maximum size of coarse aggregate for normal concrete strength. According to the results of the compressive strength of samples (A, B, C, D, E, and F). The constants of this relationship are:

1. Fixing the amount of cement entered in the volume unit;
2. Fixing slump (75-100) mm;
3. Fixing the F.M of sand (2.8).

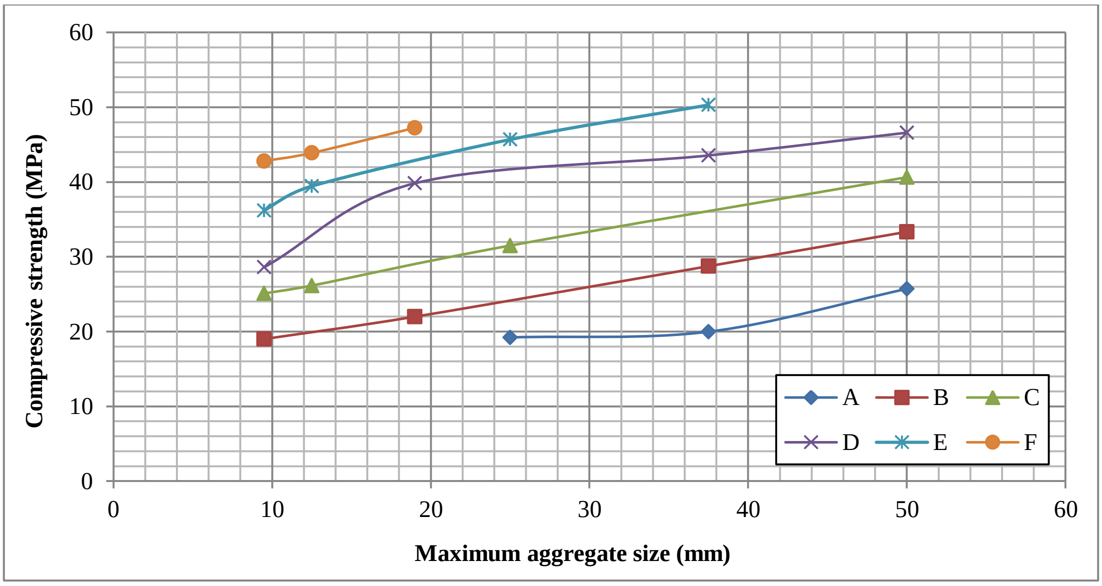

Figure 6. The relationship between compressive strength and the change in the maximum size of coarse aggregate with constant fineness modulus of sand and varied cement content (For normal strength concrete)

From this relationship, it is possible to choose the required strength with the maximum size of coarse aggregate, so that it does not conflict maximum size of coarse aggregate with the specification that defines the use of coarse aggregate in the field.

The ASTM318 specifies the use of the maximum size of coarse aggregate [21].

1. A, fifth of the distance between the two sides of the concrete mold inside;
2. One third of the depth of the concrete slab;

3. Three quarters of the net distance between the iron bars, beams of bars, pre-tensioned strings or channels.

This relationship gives you the freedom to choose the maximum size of coarse aggregate with a fixed amount of cement per unit volume with the required design strength.

3.3.2. The Relationship between the Compressive Strength of the High-strength Concrete with Maximum Size of Coarse Aggregate

The graph in Figure 7 links the relationship between the compressive strength of high-strength concrete with the change in the maximum size of the coarse aggregate. For high-strength concrete, according to the compressive - strength results of samples (H-A, H-B, H-C, and H-D).

The constants of this relationship are:

1. Fixing the amount of cement entered in the volume unit.
2. Fixing slump between (25-50) mm before adding the superplasticizer.
3. Fixing the proportion of fly ash substitutes 20% by weight of cement materials.
4. Fix the superplasticizer dose value to 0.5% by weight of cement materials.

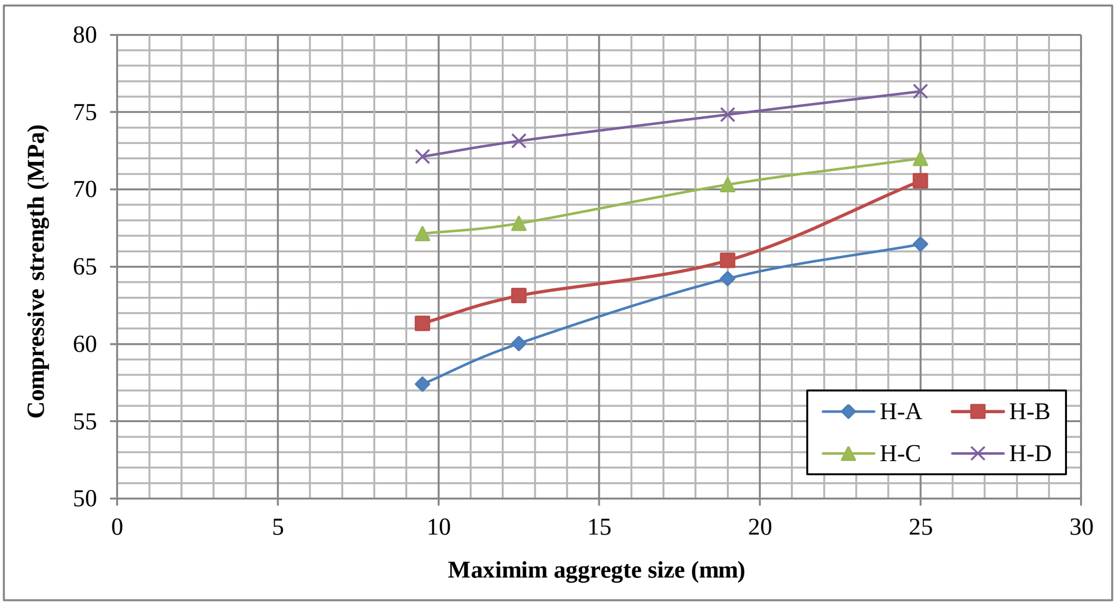

Figure 7. The relationship between the compressive strength of a high-strength concrete and the effect of changing the maximum size of the coarse aggregate

From this relationship, it is possible to choose the required strength with the maximum size of coarse aggregate, so that it does not conflict maximum size of coarse aggregate with the specification that defines the use of coarse aggregate in the field. Also the ASTM318 specifies the use of the maximum size of coarse aggregate [21]. For high strength concrete.

1. A, fifth of the distance between the two sides of the concrete mold inside;
2. One third of the depth of the concrete slab;
3. Three quarters of the net distance between the iron bars, beams of bars, pre-tensioned strings or channels.

This relationship gives you the freedom to choose the maximum size of coarse aggregate with a fixed amount of cement per unit volume with the required design strength.

4. Conclusions

The following conclusions can be drawn based on the test results of this study and within the limitations of the test parameters:

- The US Code Tables ACI 211.1 were used to obtain the requirements for the maximum size of coarse aggregate in a volume unit .for normal strength concrete;

- The US Code Tables ACI 211.R4.08 was used to obtain the requirements for the maximum size of coarse aggregate in a volume unit for high-strength concrete;
- The entire mixture is completely redesigned according to the maximum size of the coarse aggregate;
- The specific slump limits are maintained for all mixtures. (75-100) mm for normal strength concrete and (50-100)mm for high-strength concrete;
- The coarse aggregate is graded according to (ASTM C33-03), rounded and not broken;
- Results of compressive strength from (19.22 to 47.25) MPa at (28) day and water cement ratio from 0.40 to 0.79 for normal strength concrete;
- Results of compressive strength from (57.40 to 76.34) MPa at (28) day, and water cementitious ratio from 0.25 to 0.38. for high -strength concrete;
- The compressive strength increased with increasing the maximum size of the coarse aggregate for all mixtures an for the different quantities of cement entering in volume unit;
- Recommendations for future work Use the higher size of the maximum- size of coarse aggregate and finding design methods for high strength concrete using silica fume and Using late ages for examination and other strengths such as wear.

5. Acknowledgements

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6. Conflicts of Interest

The authors declare no conflict of interest.

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