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Effect of Aggregate Size and Water-to-Cement Ratio on the Mechanical Properties of No Fine Aggregate Concrete

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Keywords:
Coarse aggregate size; Compressive strength; No fine aggregate concrete; Splitting strength; Steel fiber; Recycled concrete aggregate.

Highlights:

- *Smaller aggregates (9.5mm) boost compressive strength by 42% vs 19mm.*
- *Recycled concrete reduces strength 54%; steel fiber restores 22-40%.*
- *Lower w/c ratio (0.4) increases density by 150 kg/m³ in no-fines concrete.*
- *Steel fiber (35kg/m³) counters RCA weakness, improving splitting strength.*

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Abstract: The mechanical properties of No-fine aggregate concrete are investigated. This paper consists of two parts: In the first part, three sizes of aggregates (9.5 mm, 12.7 mm, and 19 mm) with two water-to-cement ratios (0.4 and 0.45) were examined. In the second part, specimens made with recycled concrete aggregate with a replacement ratio of 30% by the weight of normal aggregate and a steel fiber of 35 kg/m³ were examined in two water-to-cement ratios (0.4 and 0.45), and an aggregate size of 12.7 mm. The effect of the cement-to-coarse aggregate ratio was also studied; three different ratios (1:2, 1:4, and 1:6) were examined. This study found that the increase in aggregate size and the water-to-cement ratio harmed the compressive, splitting tensile strength, and unit weight of the NO-fine aggregate concrete. The study also found that the compressive and splitting strength declined using recycled concrete aggregate; however, using steel fiber with recycled concrete aggregate improved both.

تأثير حجم الركام ونسبة الماء إلى الإسمنت على الخصائص الميكانيكية للخرسانة الخالية من الركام الناعم

سلوى مبارك عبدالله، منى مبارك عبدالله
قسم الهندسة المدنية / كلية الهندسة / جامعة الموصل / الموصل – العراق.

الخلاصة
يتناول هذا البحث دراسة الخصائص الميكانيكية للخرسانة بدون ركام ناعم. يتكون البحث من جزئين: في الجزء الأول، شملت الدراسة ثلاثة أحجام مختلفة من الركام (٩,٥، ١٢,٧، ١٩) ملميتر، مع نسبتين من الماء إلى الإسمنت (٠,٤ و٠,٤٥). في الجزء الثاني، تم استخدام حجم الركام البالغ ١٢,٧ مليميتر فقط مع نسبتين من الماء إلى الإسمنت (٠,٤ و٠,٤٥). كما تم استخدام ركام خرساني معاد تدويره بنسبة استبدال تصل إلى ٣٠٪ من وزن الركام العادي، بالإضافة إلى ألياف فولاذية بكمية ٣٥ كغم/م٣. استخدمت هذه الدراسة ثلاثة خلطات مختلفة (١:٢، ١:٤، و١:٦) من الإسمنت إلى الركام الخشن. تم التقييم من خلال فحص مقاومة الانضغاط والشد للنماذج بعد ٢٨ يومًا. بينت نتائج الفحص ان زيادة حجم الركام وايضا نسبة الماء إلى الإسمنت يؤدي الى انخفاض قوة الضغط والشد الانشطاري للخرسانة والكثافة. ايضا بينت الدراسة ان استخدام الركام المعاد يقلل من مقاومة الضغط والشد الانشطاري، ولكن استخدام الالياف يحسن كل منهما.

الكلمات الدالة: حجم الركام الخشن، مقاومة الانضغاط، والشد الانشطاري للخرسانة، الخرسانة الخالية من الركام الناعم، الالياف الفولاذية.

1.INTRODUCTION

No-fine aggregate concrete is a special concrete consisting of mixed cement, coarse aggregate, and water. This mix produces concrete with voids due to the absence of fine aggregate [1]. A uniform size of aggregate is usually used with No-fine aggregate concrete. The shrinkage of No-fine aggregate concrete tends to be low due to the absence of fine aggregates [2]. For the same reason, the compressive strength of No-fine aggregate concrete is lower than normal concrete [3]. As mentioned before, the absence of fine aggregate produces concrete with voids. The presence of prose in the structure of No-fine concrete aggregate provides lightweight concrete and exhibits low compressive strength. No-fine aggregate concrete is also called "zero-fine concrete," "pervious concrete," and "porous concrete" [4]. The presence of pores in No-fine aggregate concrete allows water to penetrate deep into the ground, causing an increase in the level of groundwater [5]. Many studies have investigated the No-fine aggregate concrete's properties, such as: Abadjieva et al. studied the density of No-fine aggregate concrete and how the aggregate-to-cement ratio impacts it. In their study, Abadjieva et al. investigated the effect of several aggregate-to-cement ratios ranging from 6:1 to 10:1 with a water-to-cement ratio of 0.45. Abadjieva et al. concluded that the density of the No-fine aggregate concrete decreased as the aggregate-to-cement ratio increased. They found that the highest density reached 1880 kg/m^3, while the lowest density was 1770 kg/m^3 [6]. Rehman [7] studied the effect of fiber on the properties of polypropylene and carbon fiber-reinforced No-fine aggregate concrete. Compressive strength, splitting tensile strength, and modulus of rupture tests were performed. Rehman [7] concluded that the splitting tensile strength and modulus of rupture improved by adding fiber to the No-fine aggregate concrete, while there was insignificant impact on the compressive strength. Thombre [8] studied the effect of coarse aggregate sizes and cement contents on the behavior of No-fine aggregate concrete. Coarse aggregate with a size varied from 10-20 mm and three cement contents, 250 kg/m^3, 275 kg/m^3, and 300 kg/m^3, were used. Thombre [8] concluded that workability and compressive strength increased with the decrease of the coarse aggregate size due to the reduction in the voids ratio. Patil et al. [9] performed an experimental study to produce sustainable No-fine aggregate concrete. Mixtures were made using ordinary Portland cement, coarse aggregates, water, and polypropylene. The specimens were tested for compressive strength, porosity, and slump. Patil et al. [9] found that compressive strength was affected by porosity. As the porosity increased, the compressive strength decreased. They also concluded that the durability of the No-find aggregate improved by adding polypropylene fibers. Al-Luhybi and Al-Sulayfani [10] evaluated the effect of using glass fiber reinforced polymer (GFRP) as an external wrapper to plain concrete beams. Fourteen plain concrete beams were used. These specimens were divided into five groups. The first group contained the control specimens that were not externally wrapped with GFRP sheets. The other four groups contained specimens wrapped with different numbers of GFRP layers (thickness of wrapping). The results showed that wrapping the specimens with GFRP sheets enhanced their capacity compared to the control specimens. The capacity of the prism wrapped with three layers increased at failure load by 342.5% compared to the control specimen (not externally wrapped with GFRP sheets) [10]. The objective of this research is to:

- Evaluate the effect of aggregate sizes, cement–to-aggregate ratios, and water-to-cement ratios on the behavior of No-fine aggregate concrete.
- Study the behavior of No-fine aggregate concrete using recycled concrete aggregate and steel fiber.

2.EXPERIMENTAL PROGRAM

2.1.Materials

- **Cement:** This research utilized Ordinary Portland Cement type (I) obtained from the Badush expansion factory in the Nineveh Governorate. The physical and chemical characteristics of this cement are listed in Table 1 and Table 2, meeting the requirements specified in IQS: 5/2010 [11].

Table 1 Physical Properties of Ordinary Portland Cement.

Characteristics	Units	Value	Specification (IQS:5/2010) [11]
Standard Consistency w/c	--	0.31	
Initial Setting	Minutes	120	≥ 45
Final setting	Minutes	240	≤ 600
Compressive Strength (3 days)	MPa	21.6	≥ 15
Compressive Strength (7 days)	MPa	32.7	≥ 23
Fineness (Sieve No.170)	%	4	≤ 10 (IS:12269)

Table 2 Chemical Properties of Ordinary Portland Cement.

Chemical Components	Value %	Specification (IQS:5/2010)	Chemical Components	Value %	Specification (IQS:5/2010) [11]
SiO2	20.8	-	C3S	39.7	-
AL2O3	4.8	-	C2S	29.6	-
Fe2O3	3.5	-	C3A	6.8	-
CaO	60.5	-	C4AF	10.7	-
MgO	2.9	≤ 5	L.S.F	88.9	-
SO3	2.3	≤ 2.5	Solid Solution	16.0	-
Free Lime	1.2	-			
Loss on ignition	3.0	≤ 4			
Insoluble residue	0.7	≤ 1.5			
Total	99.7	-			

- **Aggregate:** Coarse aggregate with a uniform size of 9.5 mm, 12.7 mm, and 19 mm locally available was used. Also, a recycled concrete aggregate with a uniform size of 12.7 mm and a replacement ratio of 30% by the weight of normal aggregate was used.
- **Steel Fiber:** Steel fibers are lengthy wire strands chopped and bent to specific lengths. They are employed to strengthen composite materials, such as concrete and mortar. Table 3 tabulates the physical properties of the steel fiber used in this study.

Table 3 Technical Data for Used Fiber.

Fiber Length (mm):	50 (2”)
Equivalent Diameter (mm):	1.0±0.03
Tensile strength: (MPa ±5%):	850
The thickness of fiber in mm	0.5
Width mm	1.4

- **Water:** For all mixtures, clean and drinkable water was used. This water was used for mixing and treatment, meeting the Iraqi Standard Specification (1703 for the year 1992, as well as its revisions in 2016) [12].

2.2.Laboratory Work Plan

1- **First Part:** Three mixtures, denoted as 1:2, 1:4, and 1:6 ratios of cement to coarse aggregate (c/a), were used with two water-to-cement ratios (w/c): 0.4 and 0.45 in this part. The details of these mixtures are listed in Table 4. A total of 54 standard cubes (100×100×100 mm) were used as test specimens. After casting, the specimens were demolded after 24 hours and then cured in water tanks for 28 days. These specimens were tested for compressive and splitting strength.

Table 4 Details of Concrete Mixtures.

Mix Proportions Cement -to -Coarse Aggregate (C/A)	W/C	Aggregate Size (mm)	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)
1:2	0.4	9.5, 12.7, 19	679.2	1358.5	271.7
1:4	0.4	9.5, 12.7, 19	449.1	1796.3	179.6
1:6	0.4	9.5, 12.7, 19	335.4	2012.6	134.1
1:2	0.45	9.5, 12.7, 19	656.9	1313.9	295.6
1:4	0.45	9.5, 12.7, 19	439.2	1756.8	197.6
1:6	0.45	9.5, 12.7, 19	329.8	1979.2	148.4

2- **Second Part:** The behavior of No-fine aggregate concrete using recycled concrete aggregate (RCA) and steel fiber was studied in this section. For normal and recycled aggregate, a uniform aggregate size of 12.7 mm was used with two water-to-cement ratios (w/c): 0.4 and 0.45. Ratios of cement to coarse aggregate (c/a) of 1:2, 1:4, and 1:6 were evaluated. Tables 5 and 6 list the details of these mixtures. A total of 48 standard cubes (100×100×100 mm) were cast and tested. These specimens were tested for compressive and splitting strength. Out of the 48 specimens, 24 cubs were made of recycled aggregate with a replacement ratio of 30% by the weight of normal aggregate weight used. While the remaining 24 specimens were made of recycled aggregate with a replacement ratio of 30% by the weight of normal aggregate and steel fiber of 35 kg/m3.

Table 5 Details of Concrete Mixtures with Recycled Aggregate.

Mix Proportions Cement -to -Coarse Aggregate (C/A)	w/c	M.A.Z (mm)	Cement kg/m^3	Coarse Aggregate (kg/m^3)	Recycled Coarse Aggregate (kg/m^3)	Water Kg/m^3
1:2	0.4	12.7	679.3	951.0	407.6	271.7
1:2	0.45	12.7	657.4	920.2	394.3	295.8
1:4	0.4	12.7	449.0	1257.3	538.7	179.2
1:4	0.45	12.7	439.3	1230.0	527.2	197.7
1:6	0.4	12.7	335.4	1408.7	603.7	134.1
1:6	0.45	12.7	329.7	1385.4	593.7	148.4

Table 6 Details of Concrete Mixtures with Recycled Aggregate and Steel Fibre.

Mix Proportions Cement -to -Coarse Aggregate (C/A)	w/c	M.A.Z (mm)	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Recycled Coarse Aggregate (kg/m^3)	Water (kg/m^3)	Steel Fibre (kg/m^3)
1:2	0.4	12.7	679.3	951.0	407.6	271.7	35
1:2	0.45	12.7	657.4	920.2	394.3	295.8	35
1:4	0.4	12.7	449.0	1257.3	538.7	179.2	35
1:4	0.45	12.7	439.3	1230.0	527.2	197.7	35
1:6	0.4	12.7	335.4	1408.7	603.7	134.1	35
1:6	0.45	12.7	329.7	1385.4	593.7	148.4	35

2.3.Preparing Mixes, Specimens, and Tests

No-fine aggregate concrete specimens were prepared. Concrete cubes (100×100×100) mm were used. Figure 1 shows the used molds.

Fig. 1 Used Molds.

All the mixtures were manually mixed. Initially, the saturated surface dry (SSD) aggregate was positioned in a container, as shown in Fig. 2(a). In the second group, the normal aggregate was mixed with the recycled aggregate and steel fiber for the specimens containing it. Subsequently, water was introduced to the cement and thoroughly combined to achieve a uniform cement paste, as illustrated in Fig. 2 (b). Following this, the cement paste was integrated with the aggregate, and the mixing process persisted until the mix reached a uniform state, as shown in Fig. 2 (c). Then, the molds were filled into two layers of concrete, each layer blown 25 times using a standard rolling pin. Then, the samples were covered, as illustrated in Fig. 2 (d), for 24 hours to retain their moisture. The samples were demolded and subjected to a 28-day curing process in a water tank.

Fig. 2 The Preparation and Packaging of the Specimens.

2.4.Concrete Tests

Unit weight of hardened concrete: The American standard (ASTM C642-13) [13] was used to establish the hardened density of the material.

1- Compressive strength: The concrete's compressive strength was assessed according to BS.1881 – part 116 – 1989[14]. A standard testing apparatus, with a 2000 kN capacity, applied load at a rate of 0.3 N/mm² per minute, as illustrated in Fig. 3.

2- Splitting strength test: The cubic specimens were tested for splitting strength, according to Geissert et al. [15]. Fig. 4 shows the splitting strength test.

3.RESULTS AND DISCUSSION

3.1.First Part

3.1.1.No-fine Aggregate Concrete Compressive and Splitting Strength

Table 6 summarizes the test results of No-fine aggregate concrete, representing the compressive strength, splitting strength, and hardened unit weight.

Fig. 3 Compressive Strength Test.

Fig. 4 Splitting Strength Test.

Table 6 The Concrete Compressive Strength, Splitting Strength, and Hardened Unit Weight.

Mix (Cement/ Coarse Aggregate)	w/c	M.A.S (mm)	Compressive Strength (MPa)	Splitting Strength (MPa)	Harden Unit Weight (kg/m³)
½	0.4	9.5	37	5	2460
		12.7	34	4.6	2410
		19	26	4.7	2387
	0.45	9.5	33	4.1	2420
		12.7	29	4.1	2400
		19	21	3.4	2323
¼	0.4	9.5	29	4.8	2401
		12.7	22	4.3	2349
		19	21	3.33	2298
	0.45	9.5	24	3.1	2392
		12.7	21	2.3	2345
		19	20	2.25	2293
1/6	0.4	9.5	15	2.98	2105
		12.7	14	2.8	2094
		19	14	2.6	2063
	0.45	9.5	14	2.6	2100
		12.7	13	2.6	2090
		19	12	2	2050

Figures 5 and 6 illustrate the compressive and splitting strength versus the maximum aggregate size of 28 days, respectively, for No-fine aggregate concrete specimens containing a w/c ratio of 0.4 and 0.45. In general, when the aggregate size increased, the compressive and splitting strength strengths decreased. It is noteworthy that Figs. 5 and 6 further reveal an upward trend in the compressive and splitting strength of No-fine aggregate concrete as the w/c ratio and cement-to-coarse aggregate ratio decrease. Figures 7 and 8 show the percentage increase in compressive and splitting strength versus the maximum aggregate size of 28 days, respectively, for No-fine aggregate concrete specimens containing a w/c ratio of 0.4 and 0.45. The increase could be due to the small size of the aggregate and the mixed proportion, providing dense concrete with less porosity.

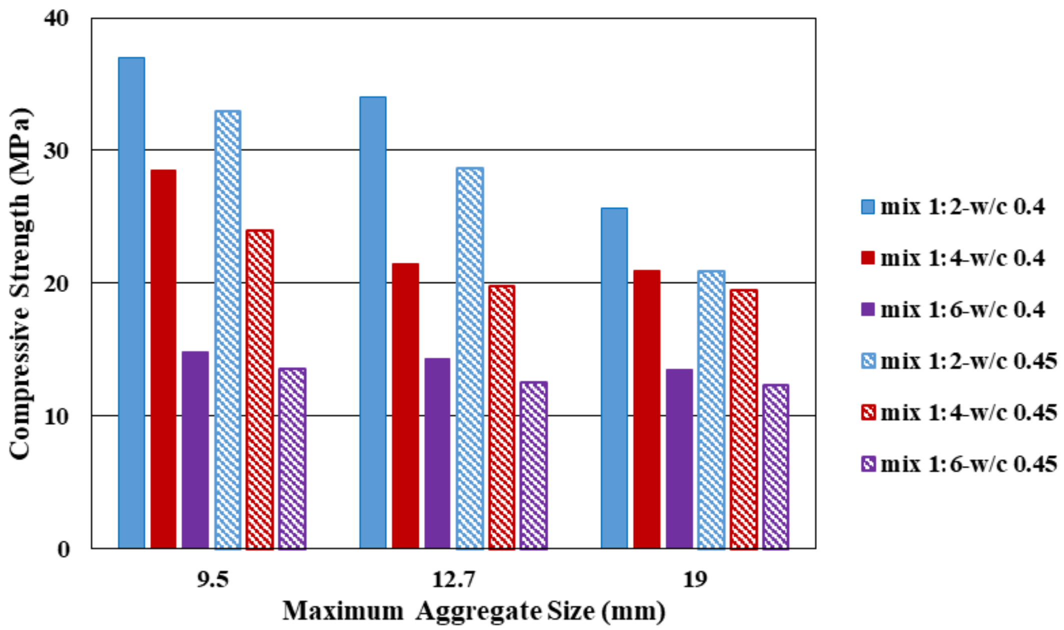

Fig. 5 Compressive Strength Versus Maximum Aggregate Size.

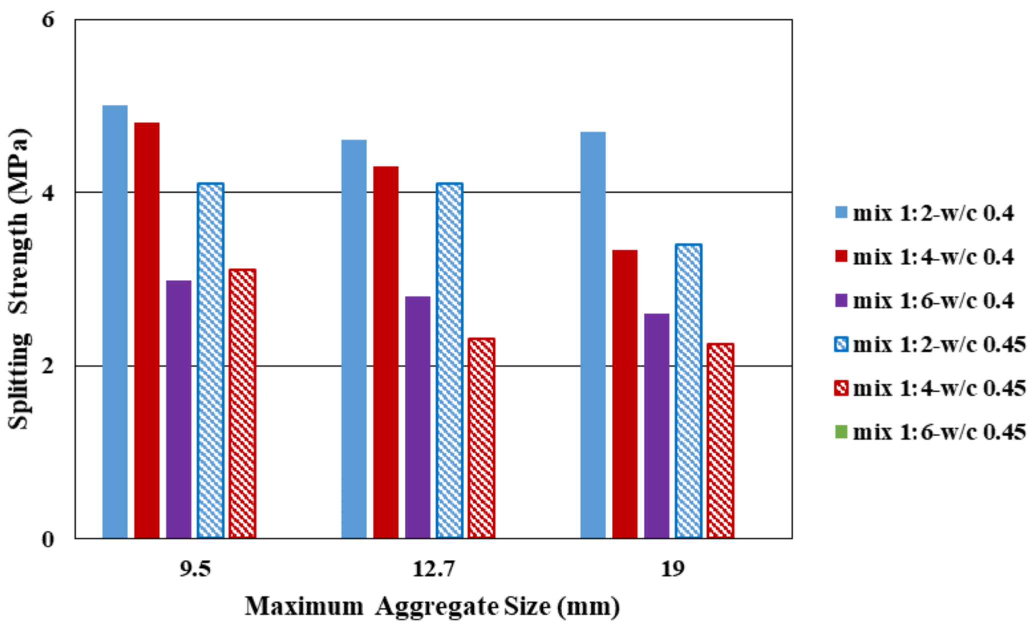

Fig. 6 Splitting Strength Versus Maximum Aggregate Size.

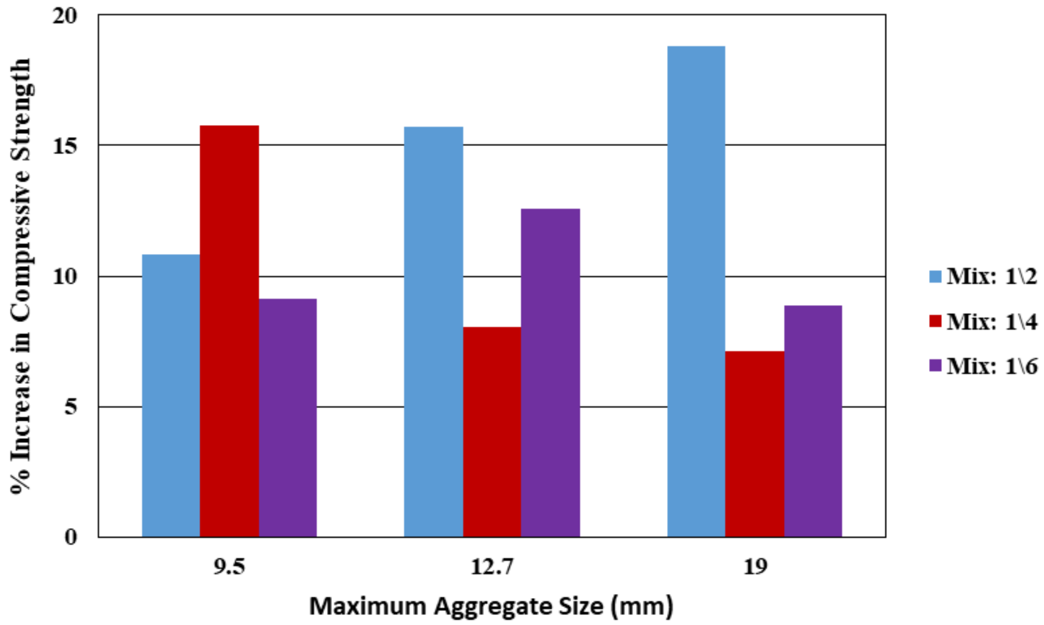

Fig. 7 Percentage Increase in Compressive Strength Versus Maximum Aggregate Size.

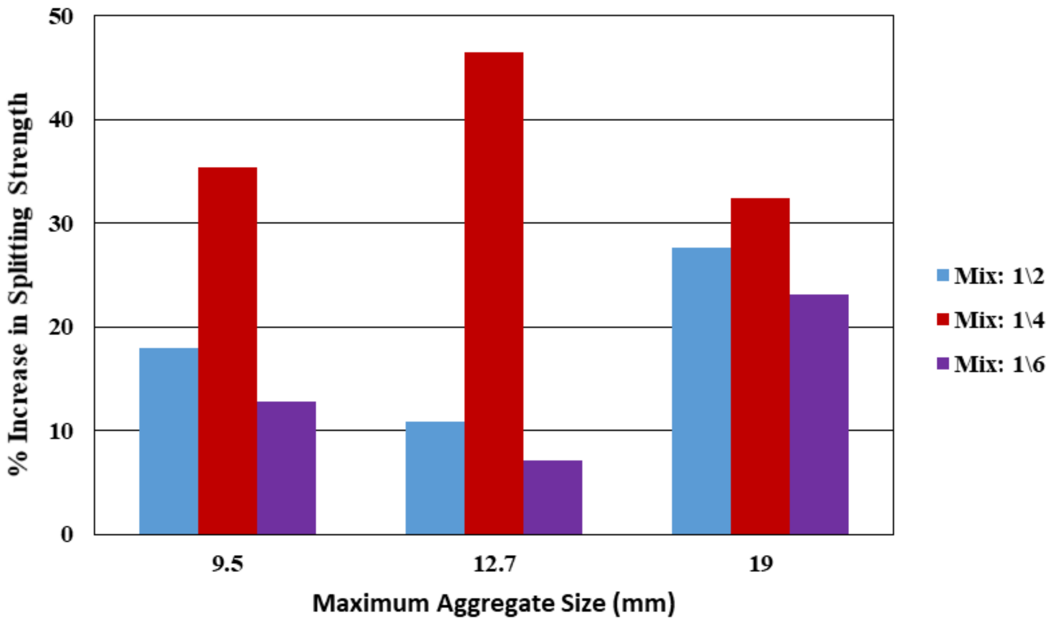

Fig. 8 Percentage Increase in Splitting Strength Versus Maximum Aggregate Size.

3.1.2. Unit Weight of No-Fine Aggregate Concrete

The results of the hardened unit weight are listed in Table 4. The relationship between the hardened unit weight and the maximum aggregate size is shown in Fig. 9. It can be observed that as the aggregate size increased, the unit weight decreased. Additionally, Fig. 9 illustrates that the unit weight experienced a decrease with the rise of the water-to-cement (w/c) ratio and the cement-to-coarse aggregate ratio (c/a). This phenomenon is attributed to the considerable porosity in the No-fine aggregate concrete, primarily due to the absence of fine aggregate. The No-fine aggregate concrete exhibited low values of hardened unit weight compared to the normal concrete except for the mix of (1:2) cement to coarse aggregate with an aggregate size of 9.5 mm. This mix showed a unit weight of (2460 and 2420) kg/m3 for w/c of 0.4 and 0.45, respectively. The behavior could be due to the small size of the aggregate and the mixed proportion, providing dense concrete with less porosity.

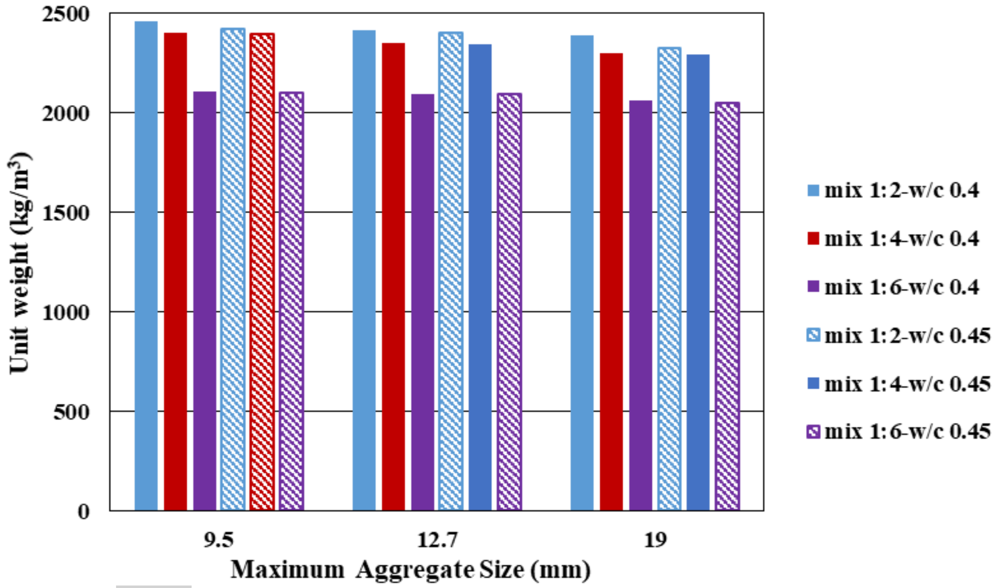

Fig. 9 Hardened Unit Weight Versus Maximum Aggregate Size.

3.2.Second Part

3.2.1.No-fine Aggregate Concrete Compressive and Splitting Strength

Table 7 summarizes the test results of No-fine aggregate concrete, representing compressive strength, splitting strength, and hardened unit weight for the specimens' containing recycled aggregate with a replacement of 30% by the weight of normal aggregate designated as (30% RCA) and 35 kg/m3 of steel fiber (SF) designated as (30% RCA+ steel fiber).

Table 7 The Concrete Compressive Strength, Splitting Strength, and Hardened Unit Weight.

Mix (Cement/ Coarse Aggregate	w/c	M.A.S (mm)	Compressive strength (30% RCA) (MPa)	Compressive strength (30%RCA+SF) (MPa)	Splitting strength (30 %RCA) (MPa)	Splitting strength (30 % RCA+SF) (MPa)	Harden unit weight(30 %RCA) (kg/m3)	Harden unit weight with (30 % RCA+SF) (kg/m3)
1\2	0.4	19	15.5	30.33	3.5	3.9	2290	2380
	0.45	19	8.83	23.06	3.1	3.28	2285	2335
1\4	0.4	19	7.5	15.4	1.5	2.45	2080	2155
	0.45	19	6.9	8.3	1.32	2.15	1995	2005
1\6	0.4	19	6.55	8.4	1.25	2.07	1840	1985
	0.45	19	6.4	7.9	1.145	1.555	1775	1955

Figures 10 and 11 illustrate the compressive and splitting strength versus the water-to-cement ratio of 28 days for No-fine aggregate concrete specimens with normal aggregate (designated as 1:2) and specimens containing recycled aggregate with a replacement ratio of 30% by the weight of normal aggregate (designated as a mix 1:2-30%RCA) and 35 kg/m3 of steel fiber and recycled aggregate with a replacement ratio of 30% by the weight of normal aggregate (designated as a mix 1:2-30% RCA+35% SF), respectively. Generally, when using 30%RCA, the compressive and splitting strength strengths decreased, and the reduction increased with the increase of the (w/c) ratio and the cement-to-coarse aggregate ratio (c/a). This behavior could be due to the weaker nature of recycled aggregate compared to the normal, as well as the increase of the cement-to-coarse aggregate ratio (c/a), which tends to provide concrete with less density and higher porosity. Based on the unit weight test, the specimens exhibited low values of hardened unit weight for specimens containing 30%RCA with steel fiber of 35 kg/m^3, followed by the specimens containing 30%RCA compared to the specimens containing normal aggregate without recycled aggregate or steel fiber (see Figure 12). Table 8 lists the percentage decrease in compressive and splitting strength for specimens containing 30%RCA and w/c of 0.4 and 0.45. Figures 10 and 11 also show that when using 30%RCA with steel fiber of 35 kg/m3, the compressive and splitting strength strengths decreased, and the reduction increased with the increase of the (w/c) ratio. However, the reduction was less than that of the same specimens without fiber. Table 9 details the percentage decrease in compressive and splitting strength for specimens containing 30%RCA with steel fiber of 35 kg/m3 for w/c of 0.4 and 0.45. Adding steel fiber exhibited a considerable enhancement in compressive and splitting strength.

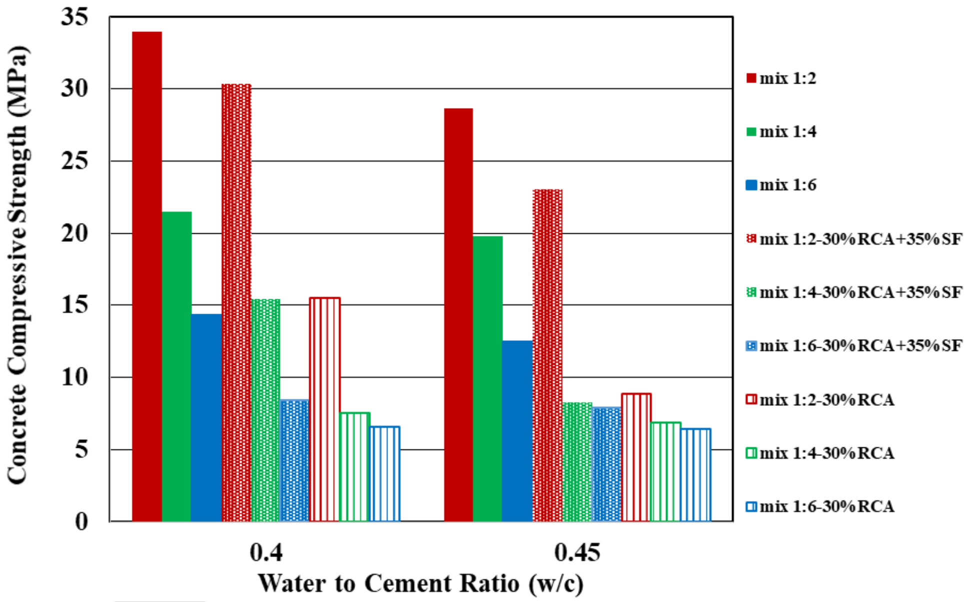

Fig. 10 Compressive Strength Versus Water-to-Cement Ratio.

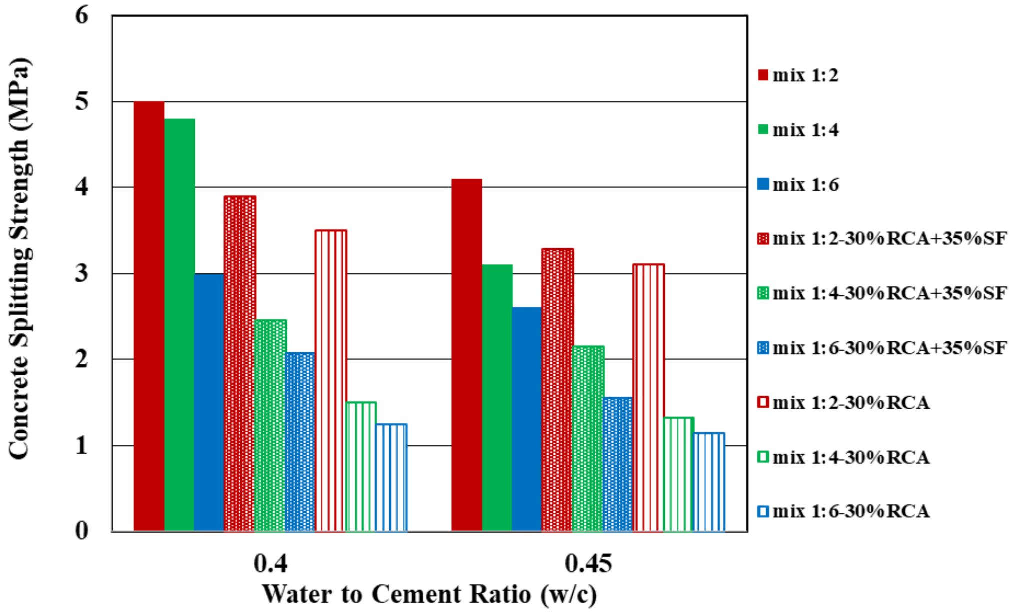

Fig. 11 Splitting Strength Versus Water-to-Cement Ratio.

Table 8 Percentage Decrease in Compressive and Splitting Strength for Specimens Containing 30%RCA.

Mix (Cement/ Coarse Aggregate	w/c	% Decrease in compressive strength	% Decrease in splitting strength
1\2	0.4	54.4	30.0
	0.45	69.2	24.4
1\4	0.4	65.1	68.8
	0.45	65.1	57.4
1\6	0.4	54.2	58.1
	0.45	48.8	56.0

Table 9 Percentage Decrease in Compressive and Splitting Strength for Specimens Containing 30%RCA with Steel Fiber of 35 kg/m3.

Mix (Cement/ Coarse Aggregate	w/c	% Decrease in compressive strength	% Decrease in splitting strength
	0.4	10.8	22.0
1\2	0.45	19.5	20.0
	0.4	28.4	49.0
1\4	0.45	58.0	30.6
	0.4	41.3	30.5
1\6	0.45	36.8	40.2

3.2.2.Unit Weight of No Fine Aggregate Concrete

The results of the hardened unit weight are listed in Table 7 and shown in Fig. 12. Figure 12 shows the hardened unit weight versus water-to-cement ratio relationship. Figure 12 illustrates that the unit weight decreased with the rise of the water-to-cement (w/c) ratio and the cement-to-coarse aggregate ratio (c/a). This phenomenon is attributed to the considerable porosity in the No-fine aggregate concrete, primarily due to the absence of fine aggregate. Figure 13 shows the high porosity of this type of concrete. The No-fine aggregate concrete exhibited low values of hardened unit weight for specimens containing 30%RCA with steel fiber of 35 kg/m^3, followed by the specimens containing 30%RCA compared to the specimens containing normal aggregate without recycled aggregate or steel fiber.

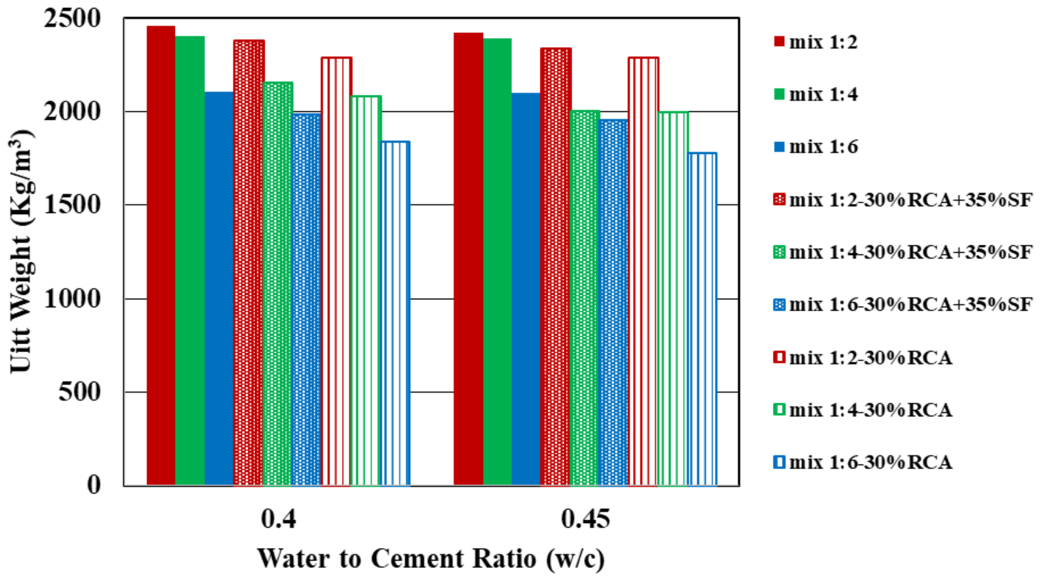

Fig. 12 Relationship of Hardened Unit Weight with Water-to-Cement Ratio.

Fig. 13 No-Fine Aggregate Concrete with High Porosity.

4.CONCLUSIONS

1- Aggregate size significantly affected compressive, splitting strength, and unit weight. As the aggregate size increased, compressive, splitting strength, and unit weight decreased. Also, the water-to-cement ratio (w/c ratio) was the factor that affected the compressive and splitting strength. When the (w/c) ratio increased, compressive and splitting strength decreased.

2- The water-to-cement (w/c) ratio and the cement-to-coarse aggregate ratio (c/a) notably affected the density of the No-fine-aggregate concrete. The density decreased with the increase of the water-to-cement (w/c) ratio and the cement-to-coarse aggregate ratio (c/a). The absence of fine aggregate produced concrete with high porosity, interpreting the decrease in the unit weight.

3- Compressive and splitting strength declined when recycled concrete aggregate was used with a replacement ratio of 30% by the weight of the aggregate. However, using steel fiber with recycled concrete aggregate improved both.

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