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Effect of Maximum Aggregate Size on the Mechanical Properties and Flexural Energy of FRC

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الملخص العربي

تتناول هذه الورقة دراسة تأثير المقاس الإعتباري الأكبر للركام على الخواص الميكانيكية للخرسانة المسلحة بالألياف. تمت دراسة تأثير أربعة مقاسات للركام الكبير (10 مم، 20مم، 25 مم، 40 مم) على الخواص الميكانيكية للخرسانة المسلحة بالألياف الحديدية. تم إعداد ثمانية خلطات، أربعة منها بدون إضافة ألياف والأربعه خلطات المتبقية تم تسليحها بالألياف الحديدية ذات النهايات المعكوفة بطول 35 مم ونسبة الطول إلى القطر 43,75. تمت إضافة الألياف بنسبة 1% من حجم الخرسانة. أشارت هذه الدراسة إلى تحسن ملحوظ في الخواص الميكانيكية للخرسانة (مقاومة الضغط ومقاومة الشدغيرالمباشرومقاومة الانحناء) للخرسانة العادية والليفية وذلك بزيادة المقاس الاعتبارى الاكبر للركام وأظهرت النتائج ايضا تحسن طاقة الانحناء مع زيادة المقاس الاعتبارى الأكبر للركام. تم حساب العلاقات بين مقاومة الشد والانحناء ومقاومة الضغط للأخذ فى الاعتبار المقاس الاعتبارى الأكبر للركام. أيضاً أشارت النتائج إلى زيادة كفاءة الألياف في تحسين الخواص الميكانيكية للخرسانة بزيادة النسبة بين طول الألياف الى المقاس الإعتباري الأكبر للركام.

ABSTRACT

This paper investigated the effect of maximum aggregate size (MAS) on the mechanical properties of fiber reinforced concrete (FRC). The effect of MAS of 10 mm, 20 mm, 25 mm and 40 mm on the mechanical properties of FRC was invoked. Eight mixes were prepared, four from which represented concrete with different MAS without fiber and the others represented concretes with different MAS and reinforced by 1% hooked ends steel fibers of 35 mm length and aspect ratio of 43.75. The results indicated that MAS caused a significant effect on the mechanical properties involving compressive strength, indirect tensile strength and flexural strength for both plain concrete and FRC. All mechanical strengths increased with increasing MAS but with a decreasing rate. With increasing fiber length/MAS ratio, the efficiency of fibers in enhancing the mechanical strengths increased. The strength relations were estimated and correlated. The addition of steel fibers to plain concrete showed a significant improvement in flexural energy.

1. INTRODUCTION

Plain concrete is brittle material and weak in tension. To overcome this problem, concrete is reinforced by fibers thus called as fiber reinforced concrete FRC [1]. The main components of FRC are similar to conventional concrete. The fresh and hardened properties are affected by the cement content, water/cement ratio and aggregate properties other than steel fibers [2, 3]. That performance and properties of concrete is greatly affected by particle size and distribution of aggregate. Moreover, maximum aggregate size (MAS) has a significant effect on the fresh and hardened properties of concrete [4, 6].

The grading means the distribution of aggregate particles with different sizes. Aggregate gradations also reflect the amount of voids and surface area of aggregate that needs to be that must be filled and coated by cement past. In addition, grading become important because the hardened properties of concrete cannot be fully realized if the concrete is unworkable and difficult to compact [7, 8]. Thus, the grading of the aggregate affects both the fresh and hardened properties of the concrete. According to previous study [9] carried out experimental on the effect of MAS on the mechanical properties of concrete, it was found that the tensile strength decreased as the aggregate size increased. This is because larger size of aggregates increased micro-cracks in the vicinity of the aggregate. Another studies [10, 11] carried out an experimental study on the effect of aggregate grading of FRC. They found that the effect of steel fiber (SF) on compressive strength is slightly influenced but highly effect on tensile strength. The compressive and tensile strengths increased with increasing MAS but with finer gradations. The fracture energy and fracture toughness related to the mechanical properties of concrete have been widely studied [11, 12]. These studies carried out an experimental work on the effect of MAS and found that both the fracture energy and fracture toughness increased with increasing MAS especially with finer gradation.

In this paper the effect of MAS on the mechanical properties (compressive, tensile and flexural strengths) flexural energy and strength relations of FRC was experimentally investigated.

2. EXPERIMENTAL WORK

2.1. Materials

Ordinary Portland Cement CEM I 42.5 N was used for all mixes. The coarse aggregate was crushed dolomite having MAS of 10, 20, 25 and 40 mm. The equation of Fuller and Thompson [13] was used to adjust the grading of the coarse aggregate according to the required MAS as follows: Passing percentage of aggregate = $(\frac{d}{D})^{0.5}$ where, d is the diameter of certain aggregate size and D is the MAS. The fine aggregate was natural siliceous sand having fineness modulus equals 2.55. The mixing water was tap water that free from any impurities. The fibers used were hook-ends steel fibers having 35 mm length and fiber aspect ratio of 43.75 added to concrete as volume fraction, V_f %, by the percentages of 0 and 1%. Super-plasticizer named ViscoCrete-3425 which complies with ASTM C-494 used for producing all mixes. The above materials were adjusted using the ACI method of mix design to produce eight concrete mixes, four from which were plain concrete and the other four were FRC) having MAS of 10, 20, 25 and 40mm. The quantities from each material to produce 1 m^3 from each type of concrete are given in Table 1.

Table 1: Materials in kg to produce 1 m^{3}from each mix.

Mix Code	**MAS, mm**	**Water content**	**Cement**	**Sand**	**Dolomite**	**Steel fiber volume fraction, V_f %**		**Super plasticizer**
						0%	**1%**	
D1	10	228	350	892.05	810	0	79	1.75
D2	20	205	350	700.29	1088.1	0	79	1.75
D3	25	193	350	653.10	1172.5	0	79	1.75
D4	40	181	350	620	1240	0	79	1.75

2.2. Test Specimens, Mixing Procedures, Casting and Curing

The studied mechanical properties were the compressive strength using cubes 150 mm side length, indirect tensile strength using cylindrical specimens of 150 mm diameter and 300 mm height and flexural strength using beams having square cross section of 100 mm side length and 500 mm total span and of 400 mm loaded span tested under 4-point bending. Eight concrete mixes were investigated. The materials were weighted and then placed in the mixer to be mixed in its dry state before adding the mixing water. For all mixes, two third of the mixing water was added to the dry materials. The estimated dosage of the super-plasticizer was added to the remaining third and added to previous mixture during mixing. For mixtures containing steel fibers, the required quantity of steel fibers was weighted and dispersed continuously to the homogeneous mix during mixing. The slump test was carried out on each mix before casting the mixture in the molds. After that, the concrete mix was poured in oiled coated steel molds. An electric vibrator was used to ensure good compaction. All specimens were remolded after 24 hours casting. Any deposits on the specimens' faces were removed before placing in the curing water. All specimens were cured in clean water at room temperature for 28 days.

2.3. Testing

The compression test and the indirect tension test were conducted on a compression testing machine of 3000 kN maximum capacity. In each test the fracture load was recorded and the fracture behavior was observed. The flexure test was carried out on 1000 kN maximum capacity universal testing machine. The deflection at mid span was recorded during loading using LVDT while the load was measured using load cell of 40 ton maximum capacity. The load versus mid span vertical deflection was drawn using data acquisition system as shown in Figure 1.

Fig. 1: Flexure test set up and data acquisition system.

3. RESULTS AND DISCUSSION

The mechanical properties including compressive strength, σ_c, indirect tensile strength, σ_t, and flexural strength, σ_f, for MAS of 10, 20, 25 and 40 mm at V_f % equals 0 and 1% are given in Table 2. The ratios of strengths of concrete specimens reinforced with fibers to that without fibers are also presented in Table 2.

Table 3: Mechanical properties of different concrete mixes.

Mix Code	MAS, mm	V_f %	σ_c, MPa	σ_c/σ_{co} %	σ_t, MPa	σ_t/σ_{to} %	σ_f, MPa	σ_f/σ_{fo} %
D1	10	0	24.88	100	2.26	100	3.54	100
		1	27.88	112.06	3.04	134.51	4.88	137.85
D2	20	0	30.45	100	2.75	100	4.2	100
		1	32.57	106.96	3.12	113.45	5.00	119.05
D3	25	0	32.81	100	2.89	100	4.91	100
		1	34.52	105.21	3.14	108.65	5.42	110.39
D4	40	0	35.50	100	3.53	100	5.49	100
		1	36.39	102.51	3.66	103.68	5.71	104

3.1. Compressive Strength Test Results

Fig. 2 presents the effect of MAS on compressive strength, σ_c, of plain concrete and FRC. Test results show that σ_c for plain concrete and FRC increases with increasing MAS. The increase in the compressive strength with the increase in MAS may be attributed to the increase in the volume of coarse per unit volume of mix as the MAS increases. These result in increasing the quantity of the hard phase in mixture which responsible for strength enhancement. The figure also shows higher σ_c values as a result of 1% addition of hook-ends steel fibers compared to concrete without fibers at different MAS. This may be attributed to the confining effect which created as a result of adding fibers to concrete [14]. It is also clear that the ratios of σ_c for concrete with fibers to σ_{co} decreases with increasing MAS. Maximum increase of 12.06% was recorded at MAS equals 10 mm while the minimum increase of 2.05% was recorded at MAS of 40 mm. This conflicts the higher efficiency of fibers in enhancing σ_c as the MAS decreases. Those results of compressive strength of FRC agree with previous studies [11, 10].

The ratios of compressive strength of concrete reinforced by 1% steel fibers to that without fibers (σ_c/σ_{co}) were drawn against the ratio of fiber length, L_f, to the MAS, L_f/MAS as shown in Fig. 3. It's clear that, with increasing L_f/MAS, the ratio σ_c/σ_{co} increases. The data in Fig. 3best fit the following relation between σ_c/σ_{co} and L_f/MAS:

$$\sigma_c/\sigma_{co} = e^{0.033\,(L_f/MAS)}$$

The boundary condition of the above equation is satisfied, i.e. $\sigma_c = \sigma_{co}$ at L_f=0.

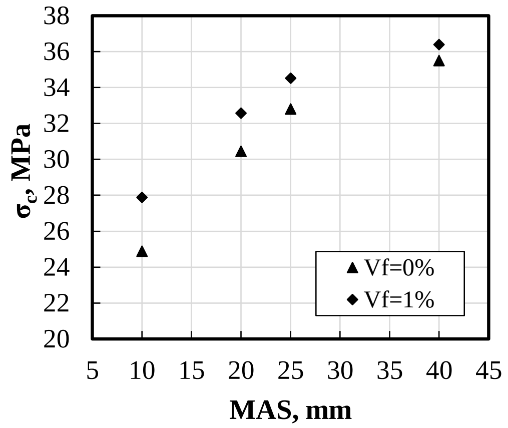

Fig. 2: Effect of MAS on the compressive strength of concrete with and without fibers.

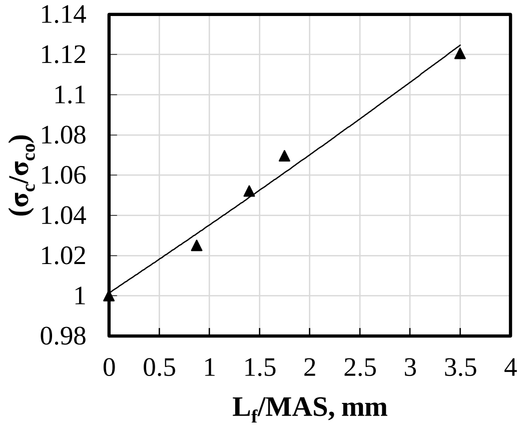

Fig. 3: Effect of ratios of L_f/MAS on the compressive strength.

3.2. Indirect tensile strength test results

The variation of tensile strength, σ_t, of FRC with different maximum aggregate sizes is shown in Fig. 4 and illustrated in Table 2.Test results show that σ_t for plain concrete and FRC increases with increasing MAS. The increase in the tensile strength with the increase in MAS may be attributed to the decrease in total specific area of aggregate with the MAS increases, which reduces the amount of cement mortar wrapping around the aggregate and increases the amount of cement mortar wrapping around the steel fiber. The bonding strength at fiber–matrix interface is improved, and thus the reinforcing the strength of SFRC is improved [10]. The figure shows that the addition of 1% SFs to plain concrete increases σ_t for all MAS. The maximum enhancement in σ_t due to adding SFs is about 34.51% was recorded at MAS equals 10 mm while the minimum increase of 3.68% was recorded at MAS of 40 mm. This conflicts the higher efficiency of fibers in enhancing σ_t as the MAS decreases. It is also clear that the ratios of enhancement in σ_t are higher than those of the σ_c for all different MAS. Thus we can state that the ratio of enhancement in the tensile strength increases for mix containing fibers to that without fibers with decreasing MAS. The enhancement in tensile strength with SFs can be attributed to the crack arresting effect produced by fiber bridging. The benefit of the fiber for the enhancement in the tensile strength of concrete is dependent upon the crack arrest and the fiber transferring energy. The results of tensile strength are consistent with previous study [10, 11].

The relation of tensile strength of concrete reinforced by 1% steel fibers to that without fibers (σ_t/ σ_{to}) was drawn against the ratio of fiber length, L_f, to the MAS, L_f/MAS as shown in Fig. 4. It's clear that, with increasing L_f/MAS, σ_t/σ_{to} increases. The data in the Fig. 4 best fit the following relation between σ_t/ σ_{to} and L_f/MAS:

$$(\sigma_t/\sigma_{to}) = e^{0.088\ (Lf/MAS)}$$

The boundary condition of the above equation is satisfied, i.e. $\sigma_t=\sigma_{to}$ at $L_f=0$.

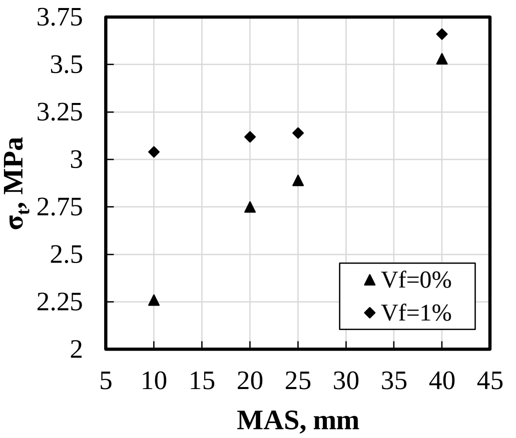

Fig. 4: Effect of MAS on the tensile strength of concrete with and without fibers.

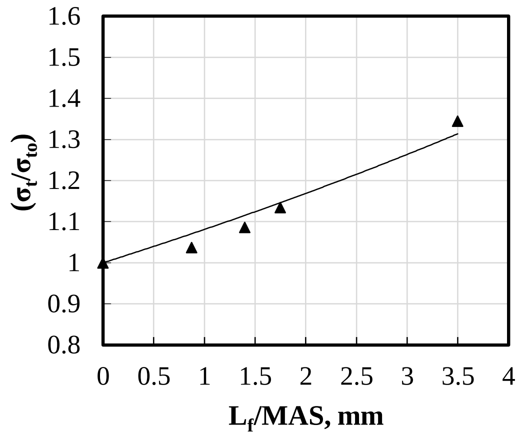

Fig. 5: Effect of ratios of L_f/MAS on the tensile strength.

3.3. Flexural strength test results

Fig. 6 shows the effects of MAS and *Vf*% on flexural strength, σ_f, of FRC. Test results show that σ_f for plain concrete and FRC increases with increasing MAS. The increase in the flexural strength with the increase in MAS may be attributed to the decreased of total specific area of aggregate with the MAS increases, which reduces the amount of cement mortar wrapping around the aggregate and increases the amount of cement mortar wrapping around the steel fiber. It can be seen that steel fibers added into the plain concrete significantly increases the σ_f. The enhancement in σ_f is ranged between maximum 37.85% was recorded at MAS of 10 mm and minimum 4% was recorded at MAS of 40 mm. This conflicts the higher efficiency of fibers in enhancing σ_f as the MAS decreases. It is also clear that the ratios of enhancement in the flexural strength are higher than those of σ_c and σ_t. It also clear that σ_f increases with increasing MAS up to 40 mm for plain concrete and FRC but the efficiency of fiber addition to concrete decreases with the increases in MAS. This may be due to the length of steel fibers of 35 mm compare to the MAS of 40 mm as illustrated in Table 2 and shown in Fig. 6. The increasing in the σ_f with the increase of MAS may be assign to increase the ratio of coarse aggregate to fine aggregate and fill all spaces by coarse aggregate with different sizes. Those results of flexural strength are consistent with the previous studies [10, 11].

The ratios of flexural strength of concrete reinforced by 1% steel fibers to that without fibers (σ_f / σ_{fo}) were drawn against the ratios of fiber length (L_f) to the MAS, L_f/MAS as shown in Fig. 7. It's clear that, with increasing L_f/MAS, σ_f/σ_{fo} increases. The data in the Fig. 7 best fit the following relation between σ_f / σ_{fo} and L_f/MAS:

$$(\sigma_f/\sigma_{fo}) = e^{0.096(Lf/MAS)}$$

The boundary condition of the above equation is satisfied, i.e. $\sigma_f = \sigma_{fo}$ at L_f=0.

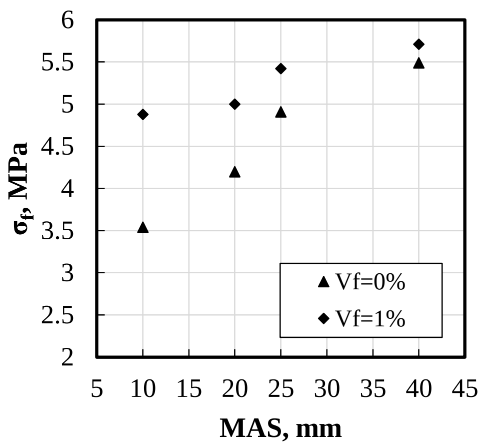

Fig. 6: Effect of MAS on the flexure strength of concrete with and without fibers.

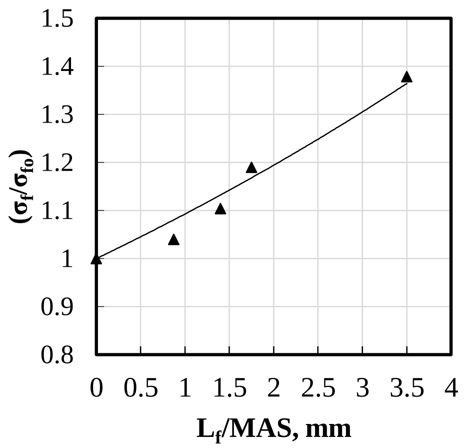

Fig. 7: Effect of ratios of L_f/MAS on the flexure strength.

3.4. Load-deflection behavior and flexural energy

The effect of V_f % on the load-deflection behavior for different MAS is shown in Fig. 8a to d. It is observed that the deflection corresponding to the ultimate load increases with the increase in MAS for plain concrete and FRC as shown in Fig. 9a and b respectively. It's also clear that, the deflection corresponding to the ultimate load increases with adding hooked end fibers. The enhancement in toughness for load-deflection curves was more pronounced at V_f equals 1% than that control mix (V_f =0%). The initial portion of the load deflection curves with different fiber contents is observed to be linear. It is also clear that the material can sustain additional load after maximum load increases as the ratio of L_f/MAS increases which reflect the positive effect of fibers in enhancing the mode of failure of FRC as the MAS decreases, see Fig 9(b). It's also clear that the stiffness of either plain concrete or FRC increases with increasing MAS. The load-deflection curves also show that the stiffness of FRC at V_f equals 1% is greater than that for concrete without fibers for all MAS [10, 11].

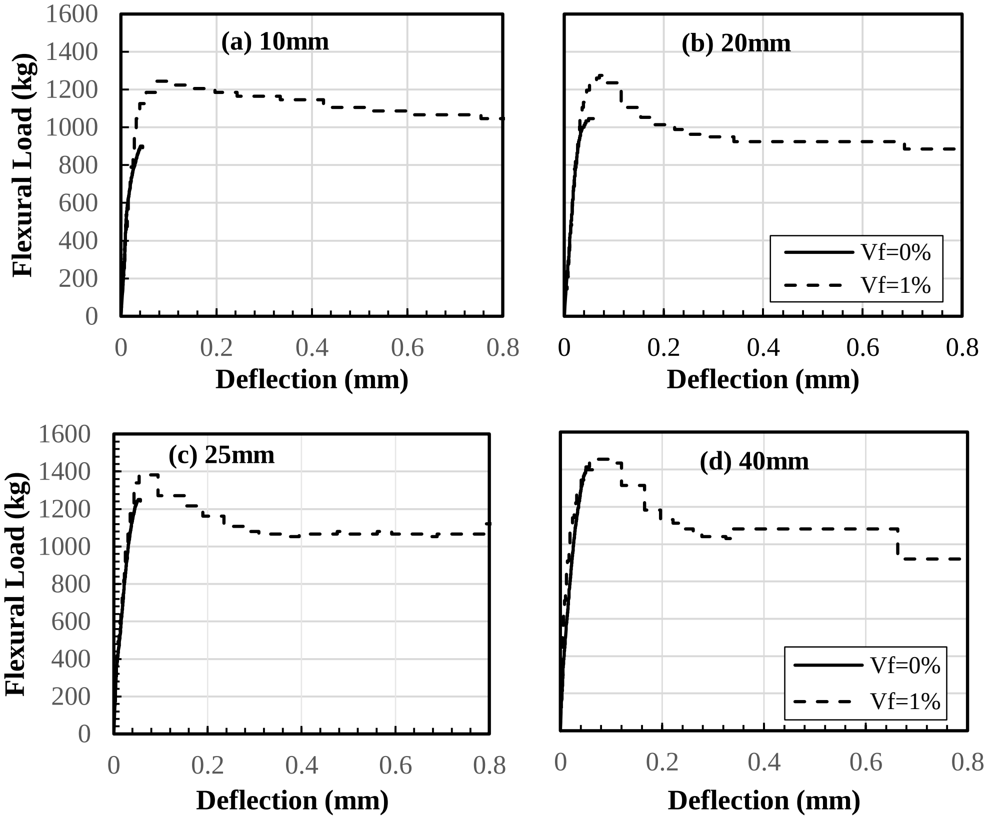

Fig. 8: Load-deflection curves for different MAS of concrete with and without fibers.

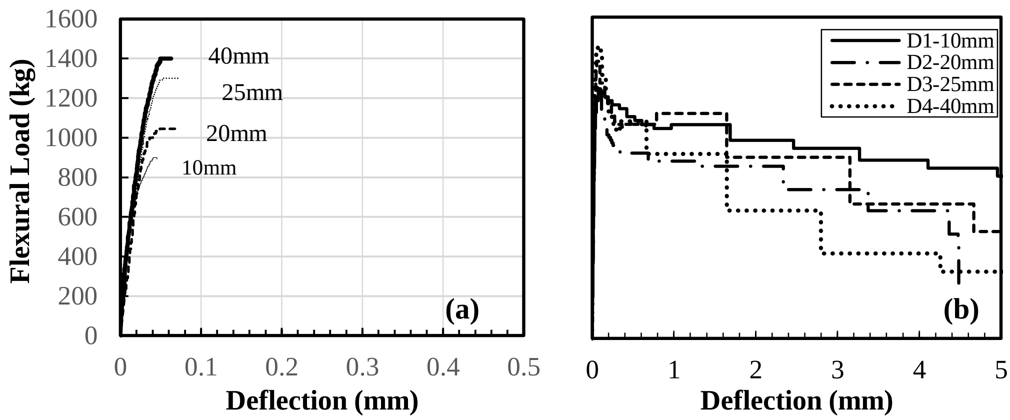

Fig. 9: Effect of MAS on the load-deflection curves for plain concrete and FRC.

The flexural energy was calculated for plain concrete at maximum flexure load and for FRCs at maximum flexure load and at deflection equals 3 mm by estimating the area under the curve corresponding to these points and dividing by specimen volume and the results are given in Table 3. It's clear that, the flexural energy increases with increasing MAS. For plain concrete, the flexural energy, modulus of toughness, increases by about 7.51% with increasing MAS from 10 mm to 20 mm and by 67.85% with MAS increases to 25 mm and by about 118.12% with MAS increases to 40 mm as compared to that of MAS equals 10 mm. For FRC, the flexural energy corresponding to maximum load, increases by increasing MAS. It also clear that, the flexural energy corresponding to deflection equals 3 mm decreases by increasing MAS. At V_f % equals 1%, the flexural energy corresponding to maximum load increases by about 3.135% with increasing MAS from 10 mm to 20 mm and by 5.60% with MAS increases to 25 mm and by 15.81% with MAS increases to 40 mm as compared to that of MAS equals 10 mm.

At deflection equals 3 mm and V_f% equals 1%, the flexural energy decreases by about 1.43% with increasing MAS from 10 mm to 20 mm and by 1.63% with MAS increases to 25 mm as compared to that of MAS equals 10 mm. At MAS equals 40 mm with V_f equals 1% the flexural energy index decreased by about 20.24% compared to that of MAS equals 10 mm this may be attribute to the efficiency of fiber addition to concrete decreases with the increases in MAS.

Table 3: Flexural energy at different MAS for plain and FRC

MAS, mm	At Maximum Load		At deflection equals 3mm
	V_f = 0%	V_f= 1%	V_f=1%
10 mm	0.706	2.43	76.10
20 mm	0.759	2.51	75.00
25 mm	1.185	2.57	74.85
25 mm	1.539	2.82	60.68

4. CONCLUSION

The results of the present work supported the following conclusions:

1. For plain concrete, the mechanical properties increased with increasing maximum aggregate size. The compressive strength increased by 22.4%, 31.87% and 42.68% for MAS of 20 mm, 25 mm and 40 mm respectively as compared to that of 10 mm. The tensile strength increased by 21.68%, 27.88% and 56.19% for MAS of 20 mm, 25 mm and 40 mm respectively as compared to MAS of 10 mm and the flexural strength increased by 18.64%, 38.7% and 55% for MAS of 20 mm, 25 mm and 40 mm respectively as compared to MAS of 10 mm.
2. For FRC by 1% fiber volume fraction, the compressive strength increased by 12.06%, 7%, 5.21% and 2.51% while the tensile strength increased by 34.51%, 13.45%, 8.65% and 3.68% compared to those of concrete without fibers for MAS of 10 mm, 20 mm, 25 mm and 40 mm respectively. On the other hand, the flexural strength increased by 37.85%, 19%, 10.4% and 4% for MAS of 10 mm, 20 mm, 25 mm and 40 mm respectively compared to those of concrete without fibers.
3. The effect of maximum aggregate size on the strength ratios of plain and reinforced concrete was estimated and correlated.
4. With increasing fiber length/maximum aggregate size, the efficiency of fibers in enhancing the mechanical strengths and flexural energy increased.
5. The flexural energy corresponding to maximum load increased with increasing maximum aggregate size for both plain and FRC.
6. For FRC, the flexural energy corresponding to deflection equals 3 mm increased by decreasing maximum aggregate size.

References

[1] Kaur, P. and Talwar, M., "Different Types of Fiber Used in FRC", International Journal of Advanced Research in Computer Science, Vol. 8, (2017).

[2] Açıkgenç, M., "A Graphic Based Approach for the Mix Design of Steel Fiber Reinforced Concrete", In: Civil Engineering Department, pp. 186, (2015)

[3] ACI 544.3R-93, "Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete" (Reapproved 1998), Michigan: Manual of Concrete Practice, (2005).

[4] ACI 544.1R-9 6, "State-of-the-art report on fiber reinforced concrete", Michigan: Manual of Concrete Practice, (Reapproved 2005).

[5] Banthia, N. and Sappakittipakorn, M., "Toughness Enhancement in Steel Fiber Reinforced Concrete Through Fiber Hybridization", Cement Concrete Research, Vol. 37, pp. 72-1366, (2007).

[6] Meddah, M. S., Zitouni, S. and Belâabes, S., "Effect of Content and Particle Size Distribution of Coarse Aggregate on the Compressive Strength of Concrete", Construction and building materials, Vol. 24, pp. 12-505, (2010).

[7] Mehta, P. K. and Monteiro, P. J. M., "Concrete: Microstructure, Properties and Materials",(New York: McGraw-Hill), (2006).

[8] Alexander, M. and Mindess, S., "Aggregates in concrete" (London: Taylor & Francis Group), (2005).

[9] Akcaoğlu, T., Tokyay, M. and Celik T., "Effect of coarse aggregate size on interfacial cracking under uniaxial compression", Materials Letters, Vol. 57, pp. 828-833, (2002).

[10] Han, J., Zhao, M., Chen, J., and Lan, X., "Effects of steel fiber length and coarse aggregate maximum size on mechanical properties of steel fiber reinforced concrete", Construction and Building Materials, Vol. 209, pp. 577-591, (2019).

[11] Ulas, M., Alyamac. K. and Ulucan, Z. C., "Effect of aggregate grading on properties of steel fiber reinforced concrete", Material Science and Engineering 246, pp.1-10, (2017).

[12] Chen B. and Liu J., "Effect of aggregate on the fracture behavior of high strength concrete", Construction and Building Materials, Vol. 18, pp. 585-590, (2004).

[13] Fuller W. B. and Thompson S. E., "The Laws of Proportioning Concrete", Transactions, American Society of Civil Engineers, Vol. 59, pp. 67,(1907).

[14] Abbas, W., Iqbal, M. and Mourad, S., "Evolution of Mechanical Properties of Steel Fiber reinforced concrete with different strengths of concrete", Construction and Building Materials, pp. 556-569, (2018).