Flexural Toughness Characteristics of Steel Synthetic Fibers-Lightweight Aggregate Concrete

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***Abstract*— In general, the steel synthetic fibers improve the durability of concrete by providing crack-arresting mechanism and minimizing it's possible to cracking. In this study, an experimental program was undertaken to investigate the effect of steel synthetic fibers content volume fractions on the compressive, tensile, modulus of elasticity, and flexural toughness of lightweight aggregate concrete (LAWC). The tested specimens were divided into five groups based on steel synthetic fibers content volume fractions (0, 0.3, 0.6, 0.9 and 1.2%). The experimental results show that steel synthetic fibers content volume fractions considerably enhanced the mechanical properties of concrete in terms of compressive strength (2.8 for 0.3% fiber to 11.3% for 1.2% fiber), splitting tensile strength (3.9 for 0.3% fiber to 35.9% for 1.2% fiber), and flexural strength (21.8 for 0.3% fiber to 56.8% for 1.2% fiber). Also, the tested results show that the flexural toughness indexes and post-cracking toughness especially on the first crack and failure deflections were extensively enhanced by the addition of fibers. The improvement in post-cracking toughness could be due to the crack arresting effect of steel synthetic fibers because it continued to exhibit residual strength after the first crack creation and needed higher energy for the fiber pull out.**

Keyword - Flexural Toughness, Characteristics, Steel Synthetic Fibers, Lightweight Concrete.

I. INTRODUCTION

The using of lightweight aggregate concrete (LWAC) has been utilizing effectively in the sustainable construction due to the numerous advantages such as a dead load reduction that eventually leads to flexibility in design and cost savings on the foundation construction and structural members as slabs, beams, and columns [1-2]. But, the splitting tensile strength of LWC can be considered lower than normal weight aggregate concrete (NWAC) up to a percentage of 30 [3]. Therefore, further attention is needed on the enhancement of the ductility and tensile strength the LWAC. The ductility, mechanical properties, and the post-cracking performance of LWAC can be enhanced effectively by adding fibers to the concrete mix [4-5]. The function of the fibers is to improve the post–cracking performance through bridging of the cracks as well as cement-fiber matrix interfacial bond [2, 5]. The enhanced properties due to adding of fibers include shrinkage [6], impact resistance [7], crack growth resistance [8], torsion and shear strengths [9-10], toughness [11], ductility [11-12] as well as basic mechanical properties [13].

Toughness enhancement is among the most important contributions of fibers to concrete. Toughness or energy absorption capacity is the area under a load deflection curve. This is especially important for structures subjected to large energy inputs such as earthquakes, blast loads, impact loads, and other dynamic loads. As fiber reinforced concrete beam or other structural element is loaded, the fiber bridges the cracks. Such bridging action provides the fiber reinforced concrete overlay with greater ultimate tensile strength and, more importantly, larger toughness and better energy absorption, that is, it retains some degree of structural integrity and post-cracking strength even when deformed to a considerable deflection [11, 14].

According to ASTM C1018-97 [15], the toughness or energy absorption is defined as the area under the load-deflection curve up to a specific deflection levels and was calculated at seven specified deflections of δ, 3δ, 5.5δ, 10.5δ, 15.5δ, 20.5δ and 25.5δ as shown in Fig 1. The toughness is calculated at the deflection δ (first-crack toughness), while the other six deflections at 3δ, 5.5δ, 10.5δ, 15.5δ, 20.5δ and 25.5δ are considered the post-peak toughness. The areas of OAB, OACD, OAEF, OAGH, OAIJ, OAKL, and OAMN are equal to the toughness at a deflection of δ, 3δ, 5.5δ, 10.5δ, 15.5δ, 20.5δ and 25.5δ, respectively, as shown in Fig 1. The toughness indices of I_5, I_{10}, I_{20}, I_{30}, I_{40} and I_{50} were calculated by dividing the total area (the post-peak toughness) up to the deflection of 3δ, 5.5δ, 10.5δ, 15.5δ, 20.5δ and 25.5δ by the area (pre-peak elastic toughness) under the curve up to the deflection at the first crack (δ), respectively, as shown in Fig 1. Therefore, the main objective of this study is to investigate the effect of steel synthetic fibers in improving flexural toughness, ductility, and mechanical properties of the lightweight aggregate fiber-reinforced concrete (LWAFRC).

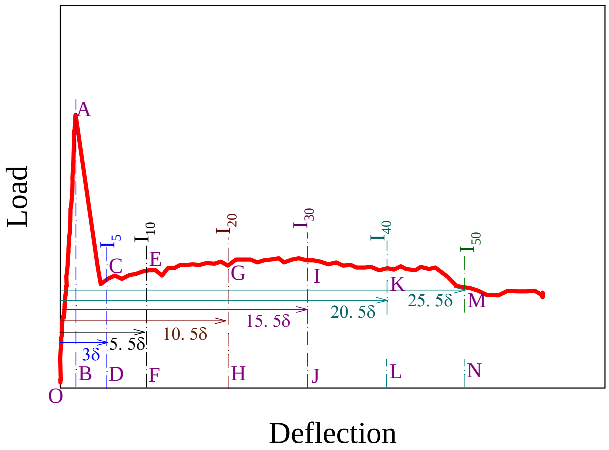

Fig. 1 The toughness indices according to ASTM C1018-97 [15]

II. DESCRIPTION OF EXPERIMENTAL PROGRAM

The LWAC mixture includes the following components: ordinary Type I Portland cement, lightweight coarse aggregates of a maximum size of 9.5 mm and specific gravity of 1.05, and normal weight crushed limestone sand with a specific gravity of 2.41. Based on ASTM C330-05 classification [15] for structural LWAC, the unit weight of the LWAC mixture was 1800 kg/m3. The Superplasticizer was added to enhance the workability of the LWAC mixture. The water, cement, lightweight coarse aggregate, and fine aggregate were mixed with proportions by weight of 0.40:1.0:1.2:3.0, respectively, by a tilting drum mixer with a capacity of 0.15 m3. The required steel synthetic fibers (The fiber is 40 mm long with an aspect ratio of 90 and composed of polypropylene and polyethylene blend) content volume was the last ingredient to be added and mixed for about five minutes to ensure uniform fiber distribution before pouring. The specimens were de-molded after 24 hours and covered with wet burlap and plastic sheet for 28 days for curing. The specimens then were taken to the open laboratory environment before being transported for testing.

In this study, a total of five LWAC mixes were prepared with different fiber dosages; i.e. 0 kg/m3 (0%), 2.73 kg/m3 (0.3%), 5.45 kg/m3 (0.6%), 8.18 kg/m3 (0.9%), 10.91 kg/m3 (1.2%). For each mix, three cylinders of 150×300 mm, three cylinders of 150×300 mm, three cylinders of 150×300 mm, three prisms of 100×100×350 mm, and three prisms of 100×100×350 mm were prepared for compressive strength (ASTM: C39/ C39M-16) [15], splitting tensile strength (ASTM: C496/C496 M-11) [15], modulus of elasticity (ASTM: C469-10) [15], flexural strength (ASTM: C78-10) [15], and flexural toughness (ASTM: C1018-97) [15], respectively. Page Layout

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Workability

Table 1 shows the mechanical properties of the tested LWAFRC. Inspection of Table 1 reveals that the slump of the control specimen without fiber is 70 mm and the slump decreased with the increase of the fiber content fractions. The addition of 0.3%, 0.6%, 0.9%, and 1.2% fiber decreased the slump (Workability) with a percentage of 28.6, 50.0, 57.1, and 64.3, respectively, with respect to the control one without fiber. This considerable reduction in the slump (Workability) is due to the large surface area of steel synthetic fibers that needs more cement mortar around the fibers which is significantly increased the concrete viscosity [16].

B. Compressive, splitting tensile and flexural strengths

On the other hand, the compressive, splitting tensile and flexural strengths increased with the increase of the fiber content fractions. The addition of 0.3%, 0.6%, 0.9%, and 1.2% fiber had a diminutive impact on the compressive strength with an improvement percentage of 2.8, 50.0, 57.1, and 64.3, respectively, with respect to the control one without fiber. But, the fiber content fraction had significant impact on the splitting tensile strength (3.9 for 0.3% fiber to 35.9% for 1.2% fiber) and flexural strength (21.8 for 0.3% fiber to 56.8% for 1.2% fiber). Based in the regression analysis of the tested results, the following equation can be used to predict the splitting tensile strength of LWAFRC as a function of concrete compressive strength (MPa) at 28 days and fiber volume fraction (V_f) as shown in Fig 2.

$$f_t = 0.467 e^{0.2224 V_f} \sqrt{f_c^{/}} \qquad (1)$$

TABLE I. Mechanical properties of tested LWAFRC specimens

Fibers Volume Fraction, %	Slump, mm	Compressive Strength, MPa	Splitting Tensile Strength, MPa	Flexural Strength, MPa
0	70 (0%)	43.1 (0%)	3.06 (0%)	3.81 (0%)
0.3	50 (-28.6%)	44.3 (2.8%)	3.18 (3.9%)	4.65 (21.8%)
0.6	35 (-50.0%)	45.3 (5.1%)	3.50 (13.9%)	5.05 (32.5%)
0.9	30 (-57.1%)	46.5 (7.8%)	3.82 (24.8%)	5.48 (43.7%)
1.2	25 (-64.3%)	48.0 (11.3%)	4.16 (35.9%)	5.98 (56.8%)

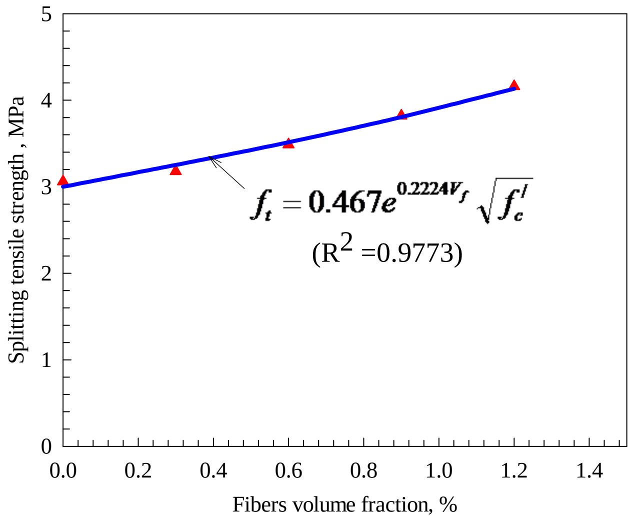

Fig. 2 Splitting tensile strength versus fiber volume fraction

C. Characteristics of concrete compressive stress-strain behaviour

Fig *3* shows the stress-strain diagrams for the LWAFRC with different fiber volume fractions. The initial tangent modulus and secant modulus of LWAFRC listed in Table 2 are calculated from the slope of the linear portion of the stress-strain diagram and the slope of a line drawn from the origin to a point on the curve corresponding to a 40% of the failure stress, respectively. Also, the energy absorption is defined as the area under the load-deflection curve. Inspection of Table 2 reveals that the initial tangent modulus and secant modulus decreased with the increase of the fibers volume fraction. While, the energy absorption increased with the increase of the fibers volume fraction. The decrease in the initial tangent modulus with respect to concrete mix without fibers is 4.8%, 10.4%, 15.3% and 21.8% for the concrete mix with fiber volume fractions of 0.3%, 0.6%, 0.9 and 1.2%, respectively. In addition, the percentage effect of fiber volume fractions on the secant modulus is almost the same as on the initial tangent modulus as shown in Table 2. The increase in the energy absorption with respect to concrete mix without fibers is 11.9%, 22.8%, 36.5% and 57.1% for the concrete mix with fiber volume fractions of 0.3%, 0.6%, 0.9 and 1.2%, respectively. Based in the regression analysis of the tested results, the following equation can be used to predict the tangent and secant modulus of LWAFRC as a function of concrete compressive strength (MPa) at 28 days and fiber volume fraction (V_f) as shown in Fig 4.

$$E_{Tangent} = 5173.4e^{-0.247V_f}\sqrt{f_c^{/}} \qquad (2)$$

$$E_{Secant} = 5793.6e^{-0.24V_f}\sqrt{f_c^{/}} \qquad (3)$$

TABLE II. Characteristics of stress-strain diagram of LWAFRC

Fibers Volume Fraction, %	Initial Tangent Modulus, MPa	Secant Modulus, MPa	Energy Absorption, MPa
0	33711 (0%)	37766 (0%)	0.1093 (0%)
0.3	32080 (-4.8%)	35991 (-4.7%)	0.1223 (11.9%)
0.6	30205 (-10.4%)	33952 (-10.1%)	0.1341 (22.8%)
0.9	28560 (-15.3%)	32162 (-14.8%)	0.1492 (36.5%)
1.2	26348 (-21.8%)	29755 (-21.2%)	0.1716 (57.1%)

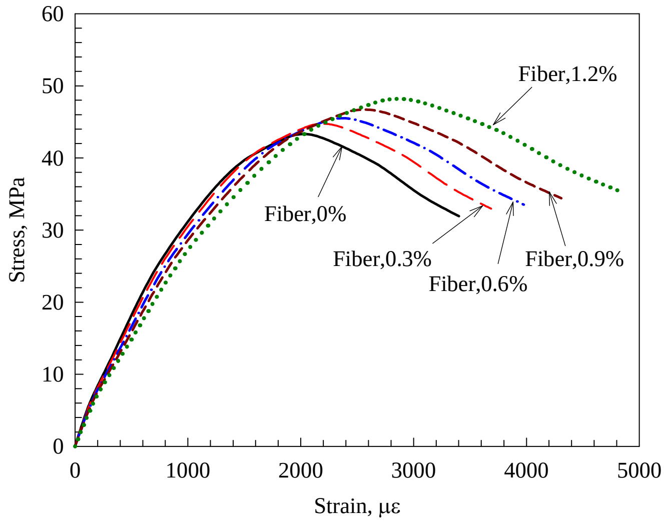

Fig. 3 Stress-strain diagrams of tested LWAFRC cylinders

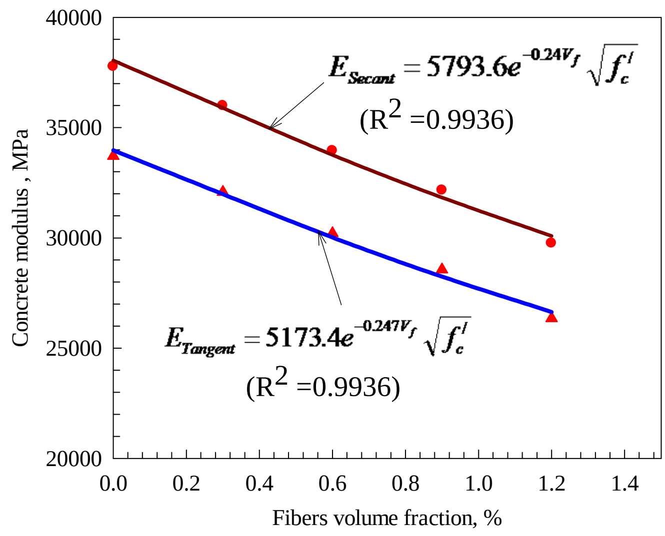

Fig. 4 Tangent and secant modulus versus fiber volume fraction

D. Flexural toughness

1) *Load Deflection Behaviour:* Fig 5 shows the load deflection of the tested specimens under flexural loading according to ASTM C1018-97 [15]. Comparing plain and fibrous concrete beams, it was clear that the post-peak behaviour differentiated the plain concrete from the fibrous concrete beams. The behaviour of a plain concrete beam was more in a brittle manner. Once the strain energy was high enough to cause the crack to self-propagate, fracture occurred almost instantaneously once the peak load was reached due to the tremendous amount of energy being released. For fibrous concrete beams, the fibers bridging effect helped to control the rate of energy release. Thus, fibrous concrete maintained its ability to carry load after the peak (first crack). In the

case of fibrous concrete (Fig 5), the behaviour was a so-called 'single-peak' behaviour. Prior to the peak, the load increased proportionally with increasing deflection and then the flexural beams exhibited an abrupt load decrease immediately after first cracking before fibers began to take over. The fibrous concrete beams were able to maintain the load carrying ability even after the concrete had been cracked as shown in the descending long post-cracking behaviour. Fig 6 shows the mode of failure of tested prisms.

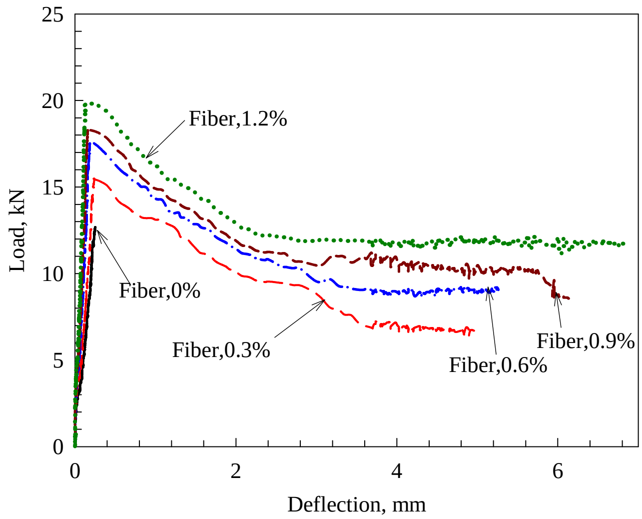

Fig. 5 Load deflection behaviour

Fig. 6 Modes of failure

Toughness or Energy Absorption: According to ASTM C1018-97 [15], the toughness or energy absorption is defined as the area under the load-deflection curve up to a specific deflection levels and was calculated at seven specified deflections of δ, 3δ, 5.5δ, 10.5δ, 15.5δ, 20.5δ and 25.5δ as shown in Table 3. The toughness is calculated at the deflection δ (first-crack toughness), while the other six deflections at 3δ, 5.5δ, 10.5δ, 15.5δ, 20.5δ and 25.5δ are considered the post-peak toughness. The areas of OAB, OACD, OAEF, OAGH, OAIJ, OAKL, and OAMN are equal to the toughness at a deflection of δ, 3δ, 5.5δ, 10.5δ, 15.5δ, 20.5δ and 25.5δ, respectively, as shown in Fig 1. The toughness indices of I_5, I_{10}, I_{20}, I_{30}, I_{40} and I_{50} were calculated by dividing the total area (the post-peak toughness) up to the deflection of 3δ, 5.5δ, 10.5δ, 15.5δ, 20.5δ and 25.5δ by the area (pre-peak elastic toughness) under the curve up to the deflection at the first crack (δ), respectively, as shown in Table 3. Inspection of Table 3 reveals that the peak load and the stiffness of the load pre-crack behaviour of the load deflection curve increased with the increase of the fiber volume friction.

The residual strength factors represent the average level of strength retained after the first crack as a percentage of the first crack strength for the specific deflection as shown in Fig 5. Residual strength factors of 100 correspond to perfectly plastic post-cracking behaviour, while lower values indicate inferior performance. Inspection of Table 3 reveals that an average percentage of recovering strength after first crack for synthetic fibrous concrete beam. Considering the post-cracking toughness of 3δ, 5.5δ, 10.5δ, 15.5δ, 20.5δ and 25.5δ by looking at the toughness indices, at small deflection of 3δ and 5.5δ higher volume percentage synthetic fibers seemed to be more effective than lower volume percentage as indicated by the larger values of I_5 and I_{10}. However, at large deflections of 20.5δ and 25.5δ, the load started to recover, especially for higher volume percentage synthetic fibers where the toughness index of synthetic fibrous concrete beam was two times the toughness index of lower volume percentage at failure. Also, the results reveal that the toughness indices of higher volume percentage synthetic fibers mixtures achieved the toughness indices of I_{50}. While, the lower volume percentage synthetic fibers mixtures achieved the toughness indices of I_{40} In addition, the values of residual strength factors reflect the same fact that the higher volume percentage synthetic fibers were much better in recovering the load in post-cracking behaviour than the lower volume percentage as shown in Table 3.

TABLE III. Characteristics of flexural toughness of LWAFRC

Fibers Volume Fraction, %	**0**	**0.3**	**0.6**	**0.9**	**1.2**
Peak Load, kN	12.68	15.49	17.51	18.27	19.79
Deflection, mm	0.2517	0.2397	0.1844	0.1586	0.1300
Stiffness, kN/mm	50.38	64.63	94.97	115.22	152.20
Area under the curve (kN.mm)					
δ	1.638	1.906	1.685	1.512	1.343
3δ	---	6.966	7.155	7.708	7.702
5.5δ	---	10.240	11.983	13.597	15.020
10.5δ	---	18.544	22.454	26.554	30.956
15.5δ	---	27.004	33.228	39.270	43.582
20.5δ	---	35.396	44.186	52.108	52.647
25.5δ	---	---	---	63.711	63.045
Toughness Index					
I5	---	3.654	4.247	5.099	5.736
I10	---	5.372	7.112	8.994	11.185
I20	---	9.728	13.327	17.564	23.052
I30	---	14.166	19.722	25.975	32.455
I40	---	18.569	26.226	34.467	39.206
I50	---	---	---	42.141	46.949
Residual Toughness Index, %					
I5-10	---	34.3	57.3	77.9	109.0
I10-20	---	43.6	62.2	85.7	118.7
I20-30	---	44.4	63.9	84.1	94.0
I30-40	---	44.0	65.0	84.9	67.5
I40-50	---	---	---	76.7	77.4

IV. CONCLUSIONS

Based on the experimental results the following conclusion can be drawn: The steel synthetic fibers content volume fractions considerably enhanced the mechanical properties of concrete in terms of compressive strength (2.8 for 0.3% fiber to 11.3% for 1.2% fiber), splitting tensile strength (3.9 for 0.3% fiber to 35.9% for 1.2% fiber), and flexural strength (21.8 for 0.3% fiber to 56.8% for 1.2% fiber). Also, the tested results show that the flexural toughness indexes and post-cracking toughness especially on the first crack and failure deflections were extensively enhanced by the addition of fibers. However, at large deflections, the load started to recover, especially for higher volume percentage synthetic fibers where the toughness index of synthetic fibrous concrete beam was two times the toughness index of lower volume percentage at failure. The improvement in post-cracking toughness could be due to the crack arresting effect of steel synthetic fibers because it continued to exhibit residual strength after the first crack creation and needed higher energy for the fiber pull out.

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