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Compressive Toughness of Lightweight Aggregate Concrete Containing Different Types of Steel Fiber under Monotonic Loading

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ABSTRACT: The noticeable brittleness of lightweight aggregate concrete limits its vast application. Using steel fibers will improve the disadvantage contrived in this type of concrete. Steel fiber increases the ductility and prevention of brittle failure of the concrete. In this paper, the influence of steel fiber on the ability of lightweight concrete to absorb energy during the response in compression has been investigated. For this purpose, steel fiber ratios of 0, 0.5, 1 and 1.5 percent by the volume of the sample were used. The sample with 0.0 percent steel fiber ratio was used as a reference to be compared with other samples. Two types of steel fibers, including hooked-end and crimped, were used. All of the fine and coarse aggregates were lightweight. The results show that there is no noticeable improvement in the pre-peak energy absorption by adding steel fiber to the composite. The increase of steel fiber ratio changes the shape of the descending branch of the stress-strain curve in compression and increases the compressive toughness of lightweight aggregate concrete. Furthermore, based on the experimental data, the relationship between compressive strength and steel fiber volume fraction was derived.

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1- Introduction

Lightweight concrete (LWC) is a type of concrete with a lower density compared with that of normal weight concrete because of air-filled voids, either in the mortar, in the aggregate or in the interstice between the coarse partials [1]. Furthermore, based on the purpose of application, LWC is also classified as structural lightweight concrete, concrete used in masonry units and insulating concrete. In this research the structural lightweight aggregate concrete (LWAC) was investigated. For structural lightweight concrete, the 28-day cylinder compressive strength should not be less than 17 MPa and the density should not exceed 1840 kg/m^3 [2]. This type of concrete has many benefits such as good thermal insulation, reduction in the dead load consequently, smaller foundation size, saving on formwork [1], better fire resistance [3], satisfactory durability [4], etc. Therefore, it has been utilized for structural intentions for many years due to its some excellent properties [5-8].

LWAC has some disadvantages, including low flexural and tensile strength and fracture toughness. These disadvantages and the brittleness of LWC limit the vast application of this type of concrete [9-11]. One method to increase the mechanical properties of LWAC is the use of steel fiber [12]. The addition of steel fiber as a ductile material, enhances many of the mechanical properties of concrete and mortar, tensile, flexural and impact strength and flexural toughness are significantly affected by steel fiber [13-15]. Furthermore, the addition of steel fiber changes the behavior of LWAC as a brittle into the more ductile material. This transformation occurs because of the fibers role and makes the concrete more homogeneous and isotropic [16].

Modeling and simulation of the response of a structure under different conditions require statistical data from the material behavior. Hence, in order to accurately predict the structural response of concrete members, the effect of materials used on the behavior of concrete under monotonic loading conditions should be determined and it is important to investigate the compressive stress-strain curve of concrete [17-19]. Moreover, during deformation in compression, to describe the ability of concrete to absorb energy, the term compressive toughness has been defined as the area under the stress-strain curve [20-22]. There are several experimental studies in the literature which have studied the effect of steel fiber on the compressive toughness and the considerable improvement in compressive toughness has been reported [15, 23, 24].

Most of the studies on the application of steel fiber in LWC and changing of compressive toughness refer to the concrete with Pumice, fly ash or oil palm shell [15, 24-26]. While, because of the wide existence of the Scoria aggregate in Iran and the limited research in this field, it is important to investigate the behavior of Scoria lightweight aggregate concrete with the steel fiber. Both of the fine and coarse aggregates are Scoria in this experimental study.

In the steel fiber, reinforced concrete the behavior of concrete is affected by both fiber aspect ratio (*l/d*) and the fiber content (V_f). The *l/d* ratio is significant at mixing and replacement stages of concrete production. With the increase of *l/d* ratio, heterogeneous distribution of fibers in the concrete mixture is increased Moreover, V_f has an effect on workability [27, 28].

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Thus, in this study the optimum combination of two types of steel fibers, i.e. hooked-end and crimped with aspect ratio of 50 and 30, respectively were used [29] and different volume fraction of fibers, including 0%, 0.5%, 1% and 1.5% by the volume of the sample were added to samples.

This research was conducted to investigate the effect of different volume contents of steel fiber on the stress-strain curve and the compressive toughness of steel fiber reinforced lightweight aggregate concrete (SFRLWAC).

2- Experimental Program

To investigate the effect of steel fiber on the stress-strain curve and the behavior of lightweight aggregate concrete, an experimental program was designed and the uniaxial compressive test was conducted. Complete details of the experimental study are given in following.

2- 1- Material

The scoria aggregate was used as fine and coarse lightweight aggregate in preparing the specimens. The maximum size of aggregate was 12.5 mm and the aggregate was in a saturated surface dry (SSD) condition. Table 1 presents the properties of aggregate. .The ordinary Portland cement (Type I) was used in this experimental research. The two types of steel fibers used in this study were straight hooked-end steel fiber (SF1) and crimped steel fiber (SF2), as shown in Figure 1. Steel fibers with the contributing content of 30% crimped and 70% straight hooked-end fiber were added to the mix to make the optimum mix design [29].

The fiber volume fractions of 0.5%, 1%, and 1.5% were used for mixes containing steel fiber. Also, in order to achieve the desired workability level, a superplasticizer based on Polycarboxylic ether was added to the mix. Additional information about the materials employed is shown in Table 1. The volumetric method, ACI 211.2 [30], was adopted

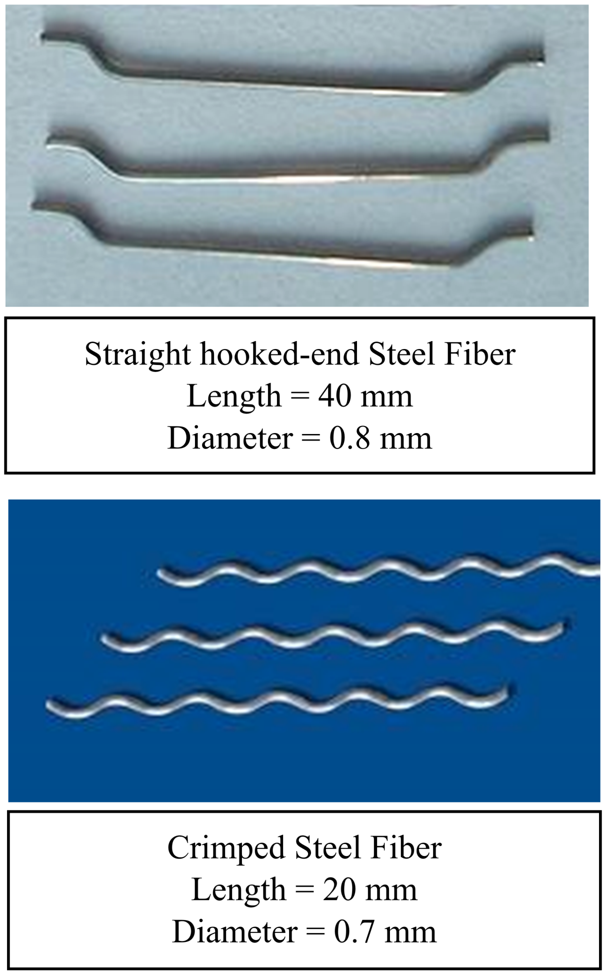

Fig. 1. Steel fibers used in this study

Table 1. Materials properties

Materials	Type	Specific density [kg/m³]
Cement	Ordinary Portland (Type I)	3150
Fine lightweight aggregate	Scoria	Bulk density: 772 Apparent specific gravity :1650 Water absorption in 24 hours: 16%
Coarse lightweight aggregate	Scoria	Bulk density: 680 Apparent specific gravity :1530 Water absorption in 24 hours: 12%
Superplasticizer	Polycarboxylic ether	1080
Fiber-1(SF_1)	Straight-hooked end Steel fiber	7800
Fiber-2(SF_2)	crimped steel fiber	7800

Table 2. Mix proportions

Samples	C [kg/m³]	CA [kg/m³]	FA [kg/m³]	W/C ratio	SP [kg/m³]	SF [vol %]	
						SF_1	SF_2
Ref	460	528	584	0.31	2.4	-	-
0.5% Fiber	460	528	584	0.31	2.5	0.35	0.15
1% Fiber	460	528	584	0.31	2.6	0.7	0.3
1.5% Fiber	460	528	584	0.31	2.8	1.05	0.45

C: Cement, CA: Coarse aggregates, FA: Fine aggregates, W: Water, SP: Superplasticizer, SF: Steel fiber.

to design the concrete mix. Composition and properties of mixtures are shown in Table 2.

2- 2- Test Specimens

In this investigation, four mixes containing 0%, 0.5%, 1% and 1.5% steel fiber ratios by the volume of the sample were prepared. First, the fine lightweight aggregate was mixed with coarse lightweight aggregate. Then, cement, fibers, and water blended with superplasticizer were added gradually to the aggregate. Once the mixing process was completed, the samples were cast into molds and then placed on the shaking table for compaction. Three 150×300 mm cylinders were produced for each mix to achieve the stress–strain curve of steel fiber reinforced lightweight concrete in compression and the average of each three specimens was presented as the test result. After casting, the polyethylene sheets were used to cover the surface of the specimens. Therefore, the loss of humidity by evaporation was avoided. The next day, test specimens were removed from the molds and placed in water at 23 ± 2 °C until the specified testing age (28 days). Prior to the testing, the cylindrical specimens were capped with sulfur capping compound to provide a smooth surface so that the load could be transferred uniformly.

2- 3- Test Procedure and Setup

A schematic arrangement of the test set-up is shown in Figure 2. In order to determine the stress–strain curves, specimens were tested by a 3000 kN hydraulic compressive testing machine. The control criterion was the force control and all specimens were loaded at the steady rate of 4.4 kN/s. The loading assembly included the 50-mm maximum ram travel hydraulic jacks, the load spreader and the bottom platen marked for the centering of cylindrical specimens. To achieve the stress–strain curves, displacement was measured by two Linear Variable Differential Transducers (LVDTs) which were parallel to the specimens (Figure 2) and circular steel frame was built to grip LVDTs. We/I monitored the vertical movement of the uniaxial load assembly by LVDTand a data logger captured the data from them. The outputs of data logger were averaged for the more accurate results. As the loading progressed, the uniaxial load was kept concentric to the cylindrical specimens. The process of loading results in the access of complete stress-strain curve of concrete, including ascending and descending (softening) branches. The limitation of LVDTs determines the measurement of the softening response. The used LVDTs in this study displace equal to 10 mm.

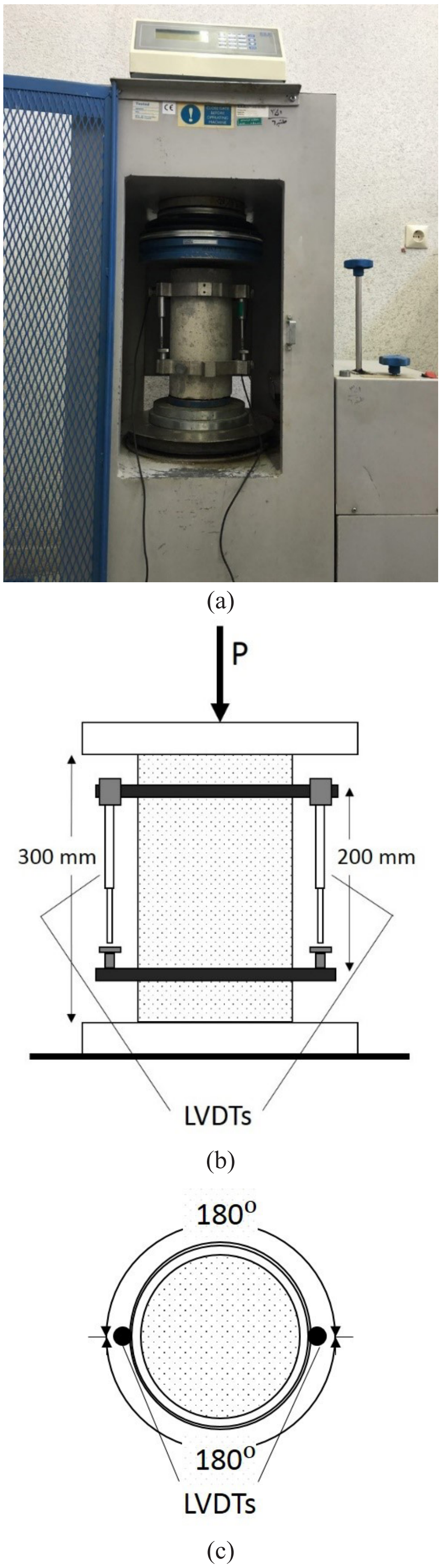

Fig. 2. Test Setup for generating stress-strain curve

3- Experimental Results and Discussion

3- 1- Density

Adding steel fiber to LWAC increases its density because of the steel fiber high specific gravity. The test results in the literature show that a high dosage of steel fiber causes heavier lightweight concrete [15, 31]. Enhancement of density is one of the drawbacks of steel fiber application in lightweight concrete. The designer should notice this happening particularly when a high steel fiber volume fraction is in use. Researchers have reported that low fiber content (less than 1%) does not significantly affect the density. The test results of the study carried out by Gao et al. [32] showed that the inclusion of steel fiber with different volume fraction in an expanded clay high strength LWAC, the density was mainly influenced by the steel fiber volume fraction. The density of hardened steel fiber reinforced lightweight aggregate concrete (SFRLWAC) was measured and for mixtures comprising 0%, 0.5%, 1% and 1.5% steel fiber, the densities were 1736, 1775, 1810 and 1845 Kg/m^3, respectively. These values for 0%, 0.5% and 1% fiber are at the range of lightweight concrete defined by ACI 318, while the density of 1.5% steel fiber is beyond the determined restriction. ACI 318-11 defines lightweight concrete with only lightweight aggregate as a concrete with a unit weight between 1440 and 1840 kg/m^3.

3- 2- Stress-Strain Curve under Monotonic Loading

The behavior of concrete in uniaxial compression affects the design and analysis of both compressive and flexural members. For a flexural member, a singly reinforced rectangular beam is subjected to a normal bending moment Mn at ultimate load stage (Figure 3a). The fundamental assumption relating Mn to φu is the well-known Bernouli compatibility hypothesis. The equilibrium condition can be derived from the distribution of stresses along the depth of the cross-section, as given in Figure 3c. Above the neutral axis is a compressive stress block sketched by a curve. The stresses in the compressive stress block are related to the strain in Figure 3b through the stress-strain relationship of the concrete. The stress-strain relationship of concrete is assumed to be identical to the stress-strain curve obtained from the compression test of a standard concrete cylinder, shown in Figure 3e. To simplify the analysis and design, ACI 319-08 allows the curved concrete stress block to be replaced by an equivalent rectangular stress block as shown in Figure 3d. The replacement is such that the magnitude and the location of the resultant C remain unchanged [33]. Parameter C is calculated from the area under the stress-strain curve in compression. The changing in the area under the stress-strain curve by adding a new material to the concrete should be investigated by the researchers.

The monotonic compressive loading test was carried out for all specimens to determine ascending and descending parts of the stress-strain curve. The major experimental parameters to investigate the monotonic stress-strain curve are maximum compressive strength, modulus of elasticity and strain at peak stress which are presented in Table 3. As can be seen in Figure 4, in all specimens, the ascending part of the stress-strain curve is linear close to the maximum compressive strength. The addition of steel fiber to LWAC has a negligible effect on the ascending part of the stress-strain curve. Fiber addition increases the compressive strength and the strain at peak stress almost by the same percentage and has the least effect on the modulus of elasticity. Based on the results presented in Table 3, the compressive strength of fiber reinforced lightweight aggregate concrete for 0.0%, 0.5%, 1% and 1.5% steel fiber ratios by volume of the sample are 28.2, 28.9, 29.6 and 30.2 MPa and the modulus of elasticity are 12.18, 12.32, 12.48 and 12.67 GPa, respectively (measurement of modulus of elasticity was based on AStM C469-02). The descending part of the stress-strain curve is more significantly affected by adding steel fibers. By increasing fiber content, strength reduction of the descending branch of the stress-strain curve is reduced which indicates a higher energy absorption. Thus, lightweight concrete shows a less brittle behavior. The inconsiderable influence of steel fiber on the compressive strength has been reported by other researchers [20, 34], in which they mentioned two reasons for this happening. 1- The addition of steel fiber reduces the workability of concrete results in producing more entrapped air after compacting, 2- the fiber orientation is affected by the aggregate and bulking of the fibers that are parallel to the load direction that may prevent the increase in compressive strength due to the added fiber.

At the level of ultimate load, cracks are created in the cylinders because of lateral expansion of the concrete. Steel fibers by making the lateral limitation and arresting the cracks propagation, produce a little improvement in the compressive strength of concrete.

3- 3- Compressive Strength

There are different results in the literature about the effect of steel fiber on the compressive strength of samples.

Table 3. Experimental results

Samples	Compressive strength [MPa]	Modulus of elasticity [GPa]	Strain at peak stress [mm/mm]
Ref	28.2	12.18	0.00274
0.5% Fiber	28.9	12.32	0.00283
1% Fiber	29.6	12.48	0.00290
1.5% Fiber	30.2	12.67	0.00298

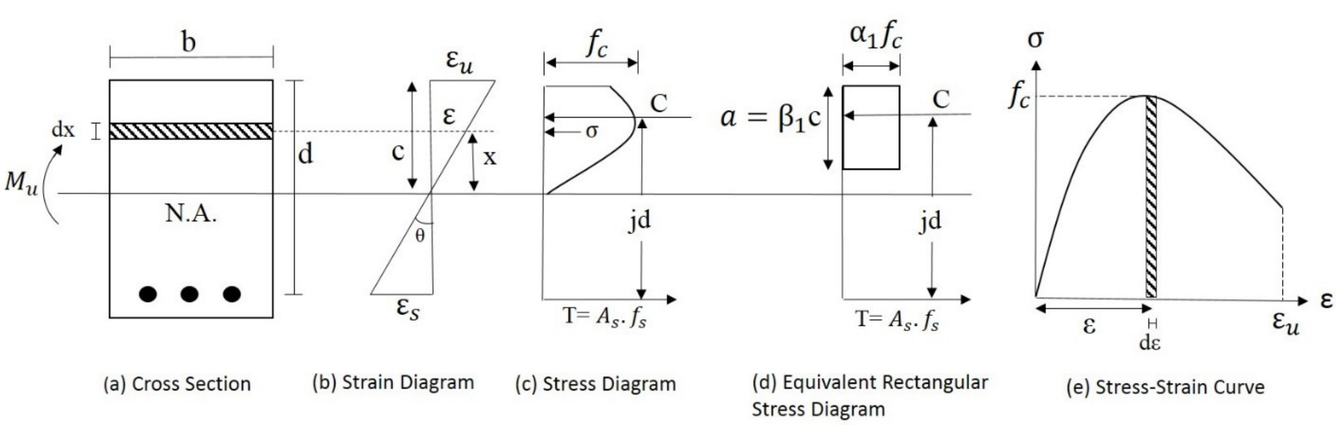

Fig. 3. Singly reinforced rectangular sections at ultimate

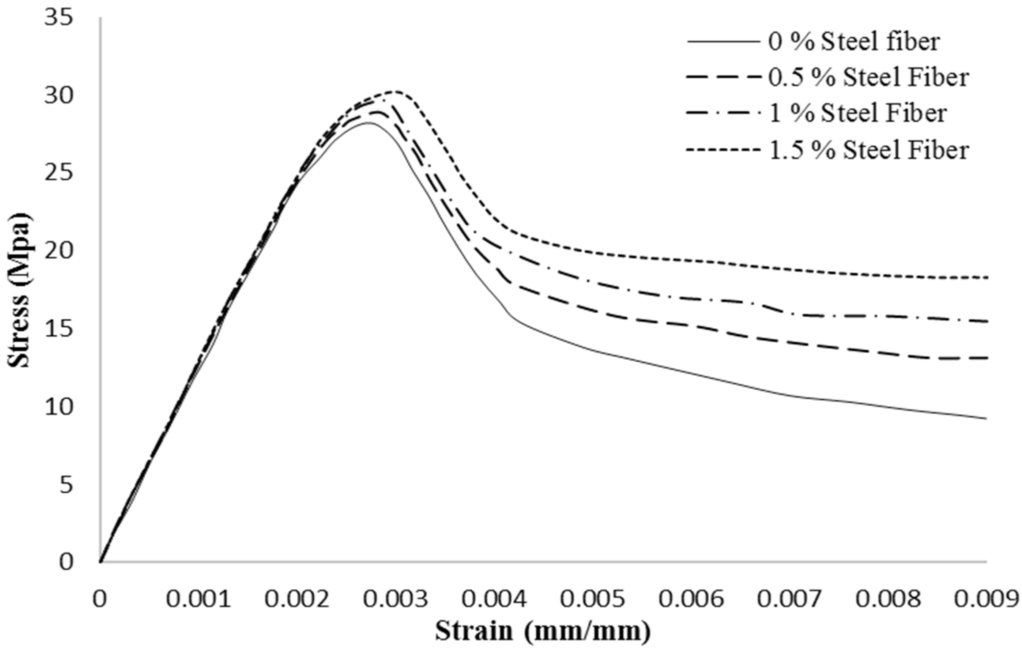

Fig. 4. Stress-Strain curve of steel fiber lightweight aggregate concrete

Several authors have reported that adding steel fiber to high strength LWAC does not affect the compressive strength [13, 35], or, even has a negative effect [36]. G. Campione et al. [14] mentioned the unfavorable effect of steel fiber on the properties of cylinders in compression that is probably due to the steel fiber length/maximum aggregate size ratio (aspect ratio *l/d* = 60 and maximum aggregate size was equal to 10 mm). However, in this study probably the use of optimum combination of two types of steel fiber and lower steel fiber length/maximum aggregate size ratio (crimped fiber aspect ratio *l/d* = 30, straight hooked-end fiber *l/d* = 50 and 12.5 mm for maximum aggregate size) led to the improvement in compressive strength. Also, the considerable effect of steel fiber on the compressive strength has been mentioned in the literature. Enhancement up to 14% [37], , 21% [31], 22% [32] and 30% [38] for steel fiber reinforced lightweight concrete has been reported.

Figure 5 and Table 3 show the development of the 28-day compressive strength of SFRLWAC at various volume fractions. Each point in Figure 5 is the average of three specimens. Compared to the plain concrete, the compressive strength improves 2.5%, 4.96% and 7.1% for 0.5%, 1% and 1.5% steel fiber, respectively. The compressive strength value of SFRLWAC is related to the fiber volume fraction and based on experimental data the following equation is derived:

$$f_r = 134\, V_f + f_c' \quad , R^2 = 0.99 \tag{1}$$

Where, f_c is compressive strength in MPa, f_c' is the compressive strength of plain lightweight concrete in MPa and V_f is steel fiber volume fraction.

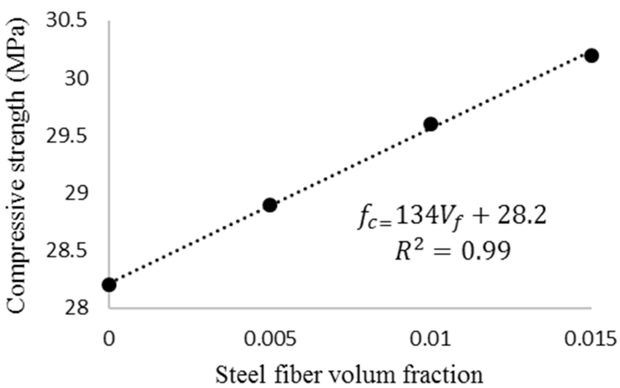

Fig. 5. Relationship between steel fiber volume fraction and compressive strength

3- 4- Compressive Toughness

The researchers have recognized the importance of reaching a certain degree of ductility in concrete structure elements. And, it is significant to limit the brittleness of lightweight concrete by improving the concrete ability to absorb energy. During the deformation in compression, to describe the ability of concrete to absorb energy, the term compressive toughness; in other words, the strain energy density, has been defined as the area under the stress-strain curve.

Based on the results presented in Table 4, there is no noticeable improvement in pre-peak energy absorption by adding steel fiber to the composite. The main goal of this study is to improve the ability of concrete to absorb energy by adding steel fiber and calculating the compressive toughness until a noticeable strain beyond the strain at the maximum stress. Thus, the important value is the total compressive toughness listed in Table 4. The value of the strain energy density of the plain lightweight aggregate concrete at the strain of 0.009 is about 132 kJ/m^3. While for 0.5%, 1% and 1.5% steel fiber volume fraction, the values are 151, 166 and 176 kJ/m^3, respectively.

Table 4. Compressive Toughness

Samples	Pre-Peak Energy [kJ/m^3]	Total Energy [kJ/m^3]
Ref	46.5	132
0.5% Fiber	47.3	151
1% Fiber	48.2	166
1.5% Fiber	49.9	176

3- 5- Toughness Index

A useful way to calculate the value of increase in toughness is to use the toughness index (TI) explained as the area under the stress-strain curve of SFRLWAC – area under the stress-strain curve of LWAC up to the particular strain [20]. In this study, the particular strain is 0.009.

$$\text{T.I.} = \frac{\text{area under the stress-strain curve of SFRLWAC}}{\text{area under the stress-strain curve of LWAC}} \quad (2)$$

Figure 6 presents the toughness index versus the reinforcing index in which the reinforcing index is calculated in Eq. (3). In this paper, utilizing two different types of steel fiber with different aspect ratios (*l/d*) results in transforming Eq. (3) into Eq. (4). The toughness index is calculated in Eq. (5).

$$R.I = V_f \times (l/d) \quad (3)$$

$$R.I = (V_f)_1 \times (l/d)_1 + (V_f)_2 \times (l/d)_2 \quad (4)$$

$$T.I = 0.5057(R.I) + 1.0167 \qquad R^2 = 0.98 \quad (5)$$

Where *R.I* is the reinforcing index, *T.I.* is toughness index, *l/d* is the aspect ratio of steel fiber and V_f is steel fiber volume fraction.

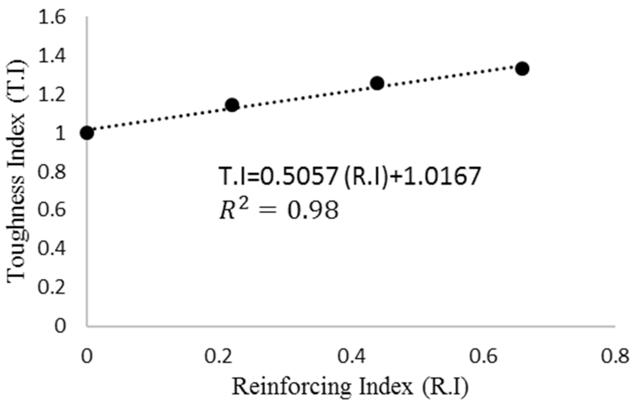

Fig. 6. Variation of toughness index with reinforcing index

4- Conclusion

In this study, the effect of steel fiber on the behavior of lightweight aggregate concrete under monotonic loading in compression was evaluated. Based on the experimental investigation presented above the following conclusions can be drawn:

1. Monotonic loading results show that the addition of fiber hardly affects the linear ascending part of the stress-strain curve. Adding steel fibers has an insignificant effect on the compressive strength, strain corresponding with the peak stress and modulus of elasticity. Thus, there is no noticeable improvement in pre-peak energy absorption by adding steel fiber to the composite.
2. The addition of steel fiber has a considerable influence on the descending part of the stress-strain curve and the rate of reduction in compressive strength after the peak stress decreases. Furthermore, compressive toughness up to the sizeable value of strain beyond the strain at peak stress significantly improves by adding steel fiber.
3. Based on the experimental data, the relationship between compressive strength and steel fiber volume fraction and that of compressive toughness and reinforcing index were built.

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