Experimental investigation of the effect of high strain rate loading on the compressive behaviour of the steel fibre-reinforced concrete

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Abstract

This research investigates the effect of loading rate on the compressive behaviour of steel fibre reinforced concrete (SFRC) designed to be used in prefabricated urban protective furniture. Although SFRC is known as a rate sensitive material and its dynamic and static compressive behaviour can be significantly different, the experimental studies on the loading rate sensitivity of SFRC in the range of impact have been rarely done compared to quasi-static. In the present study, the inertia effect in the range of impact as an important parameter for dynamic analysis of SFRC is considered. For this purpose, the SFRC mixture developed includes 1% hooked end steel fibres with length of 30 mm and aspect ratio of 80. The drop-weight impact tests were performed with three different drop heights, corresponding to maximum strain rates that range from 1 to 50 s^{-1}. Using a servo-hydraulic testing machine, the quasi-static tests with four different loading rates were also performed with strain rates ranging from 10^{-6} to 10^{-2} s^{-1}. The impact forces on top (impact force) and bottom (reaction force) of specimens were recorded in order to evaluate the inertia force and the stress wave propagation in the direction of the applied load. The strain and the strain rates were directly measured by three strain gauges installed on the specimens' mid height and also indirectly measured using a high-speed video camera during the impact loading. The results show that, by increasing the strain rates, compressive strength, modulus of elasticity and energy absorption capacity of SFRC were increased. The dynamic to static ratios established for SFRC main properties are discussed and compared with those proposed by other researchers and recommended by CEB-FIP 2010. The models proposed by CEB-FIP describe quite well the dynamic increasing factor for the compressive strength of SFRC, at the measured strain rate range. The CEB-FIP models seemed to underestimate the increase in the modulus of elasticity experimentally measured for SFRC under impact loading.

Keywords: *Steel Fibre reinforced concrete, drop-weight test, compressive behaviour, impact load, strain rate.*

1. Introduction

In recent years, steel-fibre reinforced concrete (SFRC) has been increasingly used in construction. SFRC includes discontinuous discrete steel fibres that increase its structural integrity (ACI-Committee 1996). The addition of steel fibres generally improves the concrete properties such as static tensile and flexural strength, ductility, and flexural toughness by controlling the crack propagation due to its bridging and pulling effects (Barros et al. 2005). Many studies report that steel fibres can also significantly improve impact resistance and energy dissipation capacity when compared to plain concrete (Banthia and Mindess 1996, Zhang et al. 2014). Therefore, SFRC has been considered as a suitable material for protective structures, transportation structures such as bridge decks, pavements, highways, airport runways overlays, as well as in structures designed to resist impact or explosive loads (Xu et al. 2012).

The properties of concrete under dynamic and static loading are different. In this regard, Bischoff and Perry (Bischoff and Perry 1991) investigated the effect of strain rate on the compressive behaviour of plain concrete and adopted different test procedures to determine the dynamic characteristics of the tested materials. The majority of the research developed on the dynamic material properties of SFRC is based on experimental tests, and several experimental techniques have been developed for investigating the mechanical properties of concrete under impact loading.

Loading time is very short during impact, and therefore measuring deformation on the specimens is quite different from what is usually done in conventional tests, requiring special equipment and adequate methodologies. The effect of strain rate on the mechanical behaviour of SFRC has been investigated by different researchers (Banthia and Mindess 1996, Lok et al. 2003, Lok and Zhao 2004, Wang et al. 2011, Wang et al. 2011). Wang et al. (2011) used the SHPB test (Split Hopkinson Pressure Bar test) to investigate the effect of strain rate on the compressive behaviour of plain concrete and FRC with steel and polyethylene (PE) fibres. They reported that the compressive strength of SFRC increases with strain rate. Moreover, by increasing the strain rate, the failure mode of the steel fibre in the SFRC has changed from pull-out to fracture. Therefore, the maximum impact force has increased with the number of fractured steel fibres, but the ductility of post-peak behaviour of SFRC has decreased. In another research, Wang *et al*. (2011) performed some compressive tests on plain concrete and SFRC specimens with three different volume fractions of very short straight steel fibres (1.5%, 3% and 6%). The results showed that the compressive strength of SFRC has increased with both the strain rate and the volume fraction of steel fibres. Furthermore, the compressive toughness at higher strain rates has improved by using up to 3% of steel fibres volume fraction. Lok and Zhao (2004) investigated the dynamic compressive behaviour of SFRC with hooked end fibres, using the SHPB test. They found that the compressive strength of SFRC has increased with the strain-rate. Using the non-instrumented drop weight impact test, Swami and Jojagha (1982) studied the effect of shape, volume fraction and aspect ratio of steel fibres on the number of blows needed to form the first crack. This study indicated that crimped and hooked end fibres were more effective than smooth fibres in increasing the first crack strength of SFRC. Moreover, the number of blows needed to form the first crack and the dissipation energy capacity have increased with the volume fraction and aspect ratio of steel fibres. Although there is no standard test for SFRC cylinders under compressive impact loading, instrumented drop weight tests were carried out by Xu et al. (2012) on standard SFRC cylinders to study their compressive behaviour under impact loading. These authors used synthetic fibres, undulated, cold rolled, flattened, hooked end, and two new spiral shape steel fibres in their experimental study. Regarding the dynamic compressive behaviour of SFRC, many researchers consider the compressive dynamic increase factor (DIF) as a principal parameter (Wang et al. 2011, Wang et al. 2011, Zhang et al. 2014, Yang et al. 2018, Othman et al. 2019). Several models based on the strain rate value have been suggested for predicting the DIF of concrete compressive strength (Lok and Zhao 2004, CEB-FIP 2010, Wang et al. 2011, Hao and Hao 2013, Yang et al. 2018). The most common empirical DIF model for concrete under compression is proposed in CEB-FIP Model Code (CEB-FIP 2010). Wang et al. (2011) research showed that the DIF associated to SFRC compressive strength is underestimated by the CEB-FIP model.

Despite the dynamic and static compressive behaviour of SFRC can be significantly different, the experimental studies on the loading rate sensitivity of SFRC in both ranges of quasi-static and impact are still scarce. Various valuable research works were reviewed above, but so far, the investigation regarding the effect of strain rate on the compressive behaviour of SFRC has not been systematic. The purpose of the present research is to study the effect of strain rate on compressive strength, on strain at compressive strength, and on the energy absorption capacity of SFRC with hooked end fibres. The SFRC mixture developed includes 1% volume fraction of hooked end steel fibres with length of 30 mm and aspect ratio of 80. The hooked end fibre due to its relatively high reinforcement performance demonstrated in several experimental works. An instrumented drop-weight impact test setup was designed for the experimental analysis. Drop-weight impact tests were performed with three different drop heights, corresponding to maximum strain rates ranging from 1 to 50 s^{-1}. Moreover, four different loading rates for quasi-static tests with strain rates ranging from 10^{-6} to 10^{-2} s^{-1} were selected. At least three cylindrical specimens were tested for each rate of loading and each height of the impactor. Based on the test results of SFRC specimens, the dynamic to static properties ratios of SFRC are discussed and compared with those recommended by CEB-FIP model code.

2. Experimental procedure

2.1. Materials

A single type of SFRC was used throughout the experiments, made with EN 197-1 (2011) type I cement, 42.5R with a specific density of 3.15 gr/cm^3, and fly ash Type II according to EN 450-1 (2012) requirements. Normal-weight fine and coarse aggregates of this study were natural river sand and gravel, whose saturated-surface-dry (SSD) densities were 2.60 and 2.64 g/cm^3, respectively, and the maximum size was 12 mm. The superplasticizer SIKA ViscoCrete 5920 was used. The mixing proportions by weight were 1: 0.43: 0.5: 2.2: 1.5: 0.012 (cement: water: fly ash: sand: coarse aggregate: superplasticizer). 75.8 kg/m^3 of hooked-end steel fibres were added as the reinforcement, equivalent to the volume fraction of 1% (Table 1).

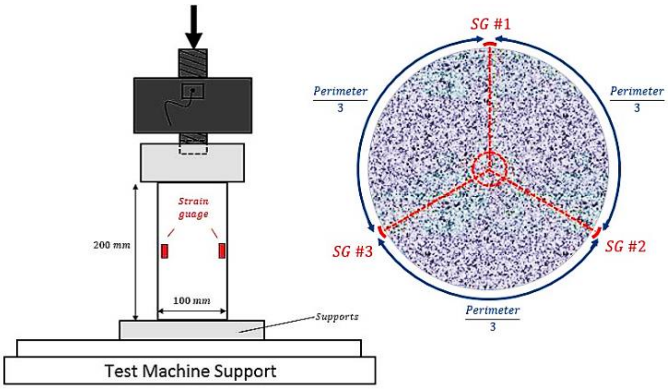
Table 1. Properties and amount of utilized steel fibre.

Volume [%]	**Mass [kg/m^3]**	**Diameter [mm]**	**Length [mm]**	**L/D**	**Modulus of elasticity [GPa]**	**Tensile strength [MPa]**
1	75.8	0.38	30	80	210	2300

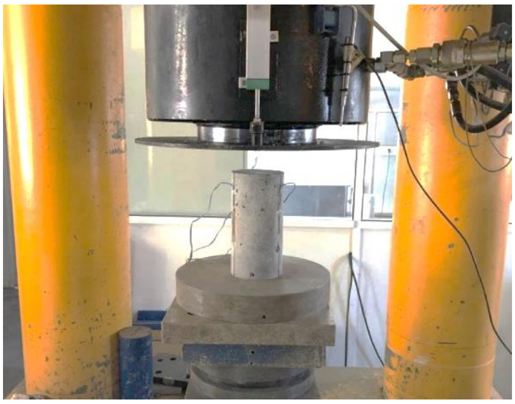
2.2. Test program

2.2.1. Quasi-static tests

Tests to evaluate compressive strength and modulus of elasticity were conducted according to EN 12390-3. Cylindrical specimens with 100 mm diameter and 200 mm height were chosen, according to the recommendation of EN 12390-3 with a reducing factor of 1.6. Three specimens were tested for each strain rate level. To perform the compressive tests under quasi-static loading, a servo-hydraulic testing machine with a maximum load capacity of 3000 kN was adopted. Three linear variable differential transducers (LVDTs) were installed at the mid height of the specimen to measure the average compressive strain and modulus of elasticity under static loading (lowest rate of quasi-static loading). In quasi-static compressive tests, three strain gauges were used for measuring the strain rate and comparing it with the displacement rate measured by LVDT. The effect of strain rate on the compressive behaviour of SFRC was investigated on specimens with 28-days of age. Relevant parameters, such as compressive strength, elastic modulus, and energy absorption capacity were measured for each rate of loading. Figure 1 shows the positions of the strain gauges on the specimens prepared for compressive loading and the loading setup. As listed in Table 2, four different series of compressive strength tests were carried out, which correspond to four different strain rates in the range of quasi-static loading. To establish the DIF for strain rate, all the results obtained in the experiments conducted at different strain rates were related to a static strength measured at a specific quasi-static strain rate. In addition, the experimental data was also compared to the DIFs proposed by CEB-FIP model code (CEB-FIP 1990, CEB-FIP 2010) and other researchers (Malvar 1998, Fujikake et al. 2001, Wang et al. 2011, Hao and Hao 2013) that investigated the topic. The displacement rate measured by the LVDTs placed in the specimens with gauge length of 100 mm are considered as 1 mm/min that almost directly corresponds to the basic CEB-FIP quasi-static strain rate of $30\times10^{-6}\ s^{-1}$. Also, the maximum displacement rate is selected 500 mm/min that matches a strain rate of $5.6\times10^{-2}\ s^{-1}$.



(a)



(b)

Figure 1. (a) Schematic diagram of a compressive specimen and (b) test set-up.

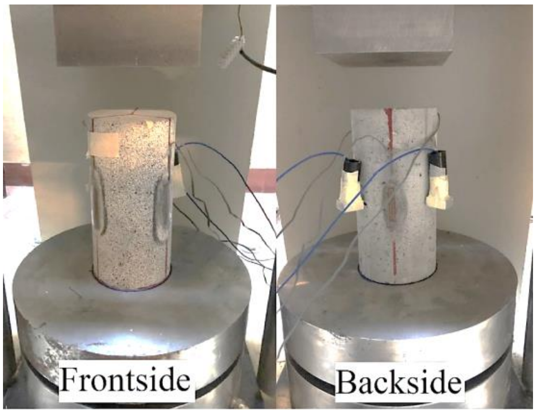
Table 2. Cylindrical specimens at different loading rate.

Specimen ID	Displacement rate (mm/min)	Height of impactor (mm)
S	1	-
Q1	10	-
Q2	100	-
Q3	500	-
HS1	-	1500
HS2	-	2000
HS3	-	2500

2.2.2. Impact tests

The instrumented drop-weight system used in the compressive tests was located in the Department of Mechanical Engineering at the University of Minho. This system was developed to apply compressive impact loads with varying heights and masses, as shown in Figure 2a. It has the capacity to drop a maximum mass of 260 kg up to a height of 9 m, which corresponds to a theoretical maximum impact velocity of 13.3 m/s. The impact forces on top (impact force) and bottom (reaction force) of the specimens were recorded by two load cells with capacity of 1000 and 2000 kN, respectively (Figure 2b). The inertia force may be calculated from the difference between the top and bottom impact forces. The load cells were connected to a data acquisition system with a SCXI-1000DC card with three input modules (National Instruments, Austin, Texas) and this control card was connected to a PC. The recording rate capacity of this control card is 50 samples per millisecond when multiple channels are used simultaneously, and results show that the recording rate was sufficient. The failure process, crack velocity, and deformation of specimens were measured with a high-speed video camera. These measurements were used to calculate strain values and strain rates in the tested specimens, during the impact loading process. The strain and the strain rates were also directly measured by three strain gauges installed at the specimen’s mid height.

(a)



(b)

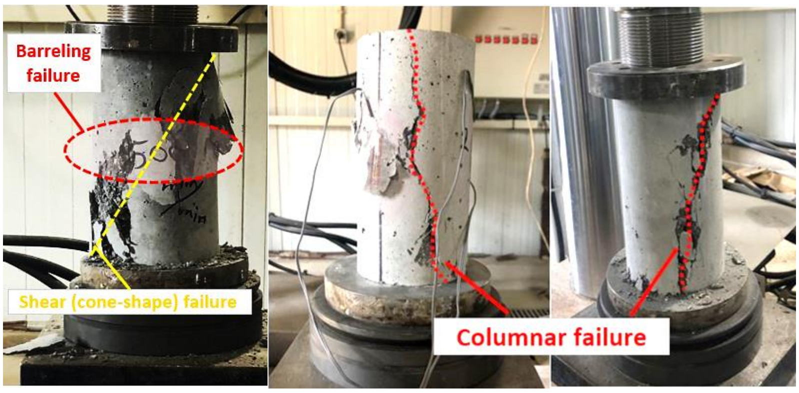
Figure 2. (a) The drop weight impact machine and (b) compressive specimens under impact test.

Two approaches were considered for measuring the deformation of the specimens: (1) use of a high-speed video camera, and (2) strain gauges. In the first approach, a PHOTRON FastCam APX-RS (PHOTRON, Japan) with the capability of recording up to 50,000 frames per second (fps) to measure surface deformations of cylindrical specimens ignoring the effect of curvature, was used, together with halogen lights that were installed to provide the lighting required for recording high speed videos. The recorded videos were analyzed by *GOM Correlate* software for digital image correlation (DIC). In the second approach, three strain gauges were installed around the cylindrical specimen's mid height, with 120-degree of radial distance (Figure 2b). Strain gauges of type PFL-30-11-3LJC-F from TML company (Japan) were used and connected to the data acquisition system. In total, 12 cylinders were tested with three different heights of impactor (1500, 2000, and 2500 mm) in order to determine the effect of the strain rate on compressive strength, modulus of elasticity, and peak strain at the compressive strength.

3. Results and discussion

3.1. Failure patterns and fracture surfaces

As the concrete matrix properties and the shape of steel fibres were kept the same, the loading strain rate applied in the performed experimental tests is the main parameter influencing the compressive failure mode of specimens. In the specimens tested under the quasi-static range (low strain rates), micro cracks propagate mainly parallel to the direction of loading. For this loading situation, cracks progressed roughly in the axial direction of the specimen and a cone-shape failure was observed (Figure 3a). In this mode, the cylinders failed by splitting in the lateral sides and two cones were formed at the top and the bottom of the specimens, forming an hourglass shape. By increasing the loading rate, compressive barreling and columnar failure were also identified (Figure 3a) in addition to the shear (cone-shape) failure previously observed. Therefore, when the rate of loading in the quasi-static range increased, the failure mode of specimens changed from cone-shape to barreling mode. This phenomenon led to an increase in the axial compressive force, as it contributes to the improvement of cylindrical specimens' capacity to resist the compressive load. On the other hand, under impact loading, observations indicated that a large number of micro cracks were formed and then propagated along the cylinders. By increasing the height of the impactor, an increase in the number of fractured pieces was observed in the tested specimens, showing the effect of strain rate on the failure of SFRC cylinders (Figure 3b). The increase in the number of fractured pieces is an indication of a higher energy dissipation capacity of the specimen. Moreover, the pull-out was the dominant mechanism for hooked end fibers in SFRC cylinders tested in this series.



(a)

(b)

Figure 3. Failure modes of SFRC cylinders under compressive (a) quasi-static and (b) impact loading.

3.2. Effect of strain rate on compressive behaviour of SFRC

3.2.1. Compressive strength and Young's modulus

The ratio between the impactor velocity at the instant of contact and the length of the specimen is generally accepted as an estimation of strain rate (Bischoff and Perry 1991). This value of strain rate is not consistent with the real strain rate registered in the specimen during loading, due to the difference between the stiffness of the impactor and the stiffness of SFRC. The high-speed camera was able to record the impact process with a rate of 15,000 frames per second and a resolution of 128×256 pixels. During loading of both quasi-static and impact loading tests, the average strain and the strain rate of specimens were measured with the high-speed camera and by three strain gauges installed at the mid height of the SFRC cylinders. Due to the possibility of having cracks passing near the strain gauge, the adoption of three strain gauges was aimed at minimizing the likelihood of this disturbance.

In the present research, the maximum reaction force recorded by the bottom load cell was considered to determine the compressive strength of SFRC (Bischoff and Perry 1991, Xu et al. 2012). The compressive strain was obtained by computing the average of the aforementioned three strain gauges. The mechanical results obtained for the specimens tested at the lowest strain rate (as the static strain rate) are shown in Table 3. Three specimens were tested at the static compressive strain rate of 1.33E-05.

Table 3. Cylindrical specimens at static strain rate.

Type ID	**Compressive strength (MPa)**	**Elastic modulus (GPa)**	**Toughness (kJ/m^3)**
S-1	73.07	41.72	99.96
S-2	76.72	42.40	124.24
S-3	67.09	40.55	126.28
Average	72.29 (5.5)	41.56 (1.8)	116.83 (10.2)
Note: values in parentheses are the coefficient of variation (in percentage).			

Twenty-one cylinders were tested to determine the effect of the strain rate on compressive strength and modulus of elasticity. The results shown in Table 4 evidence that the compressive strength, the elastic modulus, and toughness of SFRC specimens are sensitive to the imposed strain rate. The DIF of compressive strength (DIF_C), modulus of elasticity (DIF_Y), and toughness (DIF_T) for each specimen were calculated and compared with existing DIF models to investigate which model can predict the effect of strain rate on compressive strength, modulus of elasticity, and toughness of hooked end SFRC in a more precise manner (Figures 4, and 5).

As expected, the strain rate influences the compressive strength, the peak strain and the modulus of elasticity of SFRC specimens. It is obvious that the compressive strength and modulus of elasticity have increase with the strain rates. The values of strain rate are represented in a logarithmic scale because the data range is very large in comparison to the range of the DIF values. Therefore, the log-linear graph was used to represent the relationship between DIF and strain rate. Figure 4 shows an almost linear relationship between the logarithmic values of strain rate applied and the DIF values associated to compressive strength and modulus of elasticity of SFRC, at the considered range of quasi-static strain rates. Furthermore, the evolution of DIF is different for compressive strength and elastic modulus. The models proposed by CEB-FIP describe quite well the DIF of compressive strength of SFRC, at the measured strain rate range, but underestimate the modulus of elasticity. It must be noted that both CEB-FIP models (CEB-FIP 1990 and CEB-FIP 2010) use the same equation to estimate the DIF of the modulus of elasticity.

The results were also compared with models that evaluate the influence of strain rate on compressive strength, such as the ones proposed by CEB-FIP (CEB-FIP 1990, CEB-FIP 2010) and other researchers (Fujikake et al. 2001, Hao and Hao 2013, Krahl et al. 2018). The DIF values for the compressive strength of SFRC ranged between 1.02 and 1.32. The results associated with specimen HS3-2 are out of this range, as shown in Figure 4, and therefore this specimen was considered as an outlier. The maximum DIF obtained for the modulus of elasticity was 1.58. As shown in Figure 4, both CEB-FIP models (CEB-FIP 1990, CEB-FIP 2010) predict the increase of compressive strength more precisely than the other considered models, both in quasi-static and in impact range of strain rate. These models are proposed for either plain concrete or SFRCs. For example, CEB-FIP model is appropriate for plain concrete. Krahl et al. (2018) proposed an alternative model based on the experimental results obtained using smooth steel fibres. Hao and Hao (2013) proposed another model based on experimental results obtained with spiral fibres and SHPB testing. This difference among proposed models can be attributed to the fact that the strain rate sensitivity of SFRC is influenced by parameters such as shape, volume fraction, aspect ratio, tensile strength of steel fibres, and type of test setup for compressive loading (Instrumented Drop Weight Test or SHPB test) as well.

Table 4. Cylindrical specimens at different loading rate.

Sample	Strain rate (s^{-1})	Compressive strength (MPa)	Young modulus (GPa)	Toughness ($kJ.m^{-3}$)	DIF_c	DIF_Y	DIF_T
S (Average)	1.33E-05	72.29	41.56	116.83	1.000	1.000	1.000
Q1-1	1.33E-04	75.65	42.21	102.74	1.047	1.080	0.879
Q1-2	1.33E-04	74.83	42.39	122.28	1.035	1.086	1.047
Q1-3	1.33E-04	73.68	43.06	125.14	1.019	1.103	1.071
Q2-1	1.33E-03	76.97	43.04	120.45	1.092	1.170	1.031
Q2-2	1.33E-03	75.55	42.08	114.24	1.045	1.146	0.978
Q2-3	1.33E-03	77.91	43.32	127.75	1.078	1.179	1.093
Q3-1	6.67E-03	76.03	43.83	126.40	1.093	1.194	1.082
Q3-2	6.67E-03	74.58	44.51	137.93	1.170	1.212	1.181
Q3-3	6.67E-03	79.53	44.19	130.10	1.100	1.204	1.114
HS1-1	18.65	77.79	61.40	166.50	1.068	1.478	1.425
HS1-2	25.18	79.85	59.63	207.40	1.096	1.435	1.775
HS1-3	19.50	80.58	52.40	185.50	1.106	1.261	1.588
HS2-1	29.28	81.55	59.26	212.53	1.119	1.426	1.819
HS2-2	36.17	89.48	63.29	285.03	1.228	1.523	2.440
HS2-3	34.60	82.71	65.46	216.58	1.135	1.575	1.854
HS3-1	27.27	91.29	60.91	227.79	1.253	1.466	1.950
HS3-2*	41.34	143.08	67.77	286.51	1.964	1.631	2.452
HS3-3	37.94	96.27	61.47	240.67	1.321	1.479	2.060

* The results obtained with specimen HS3-2 are considered as outliers

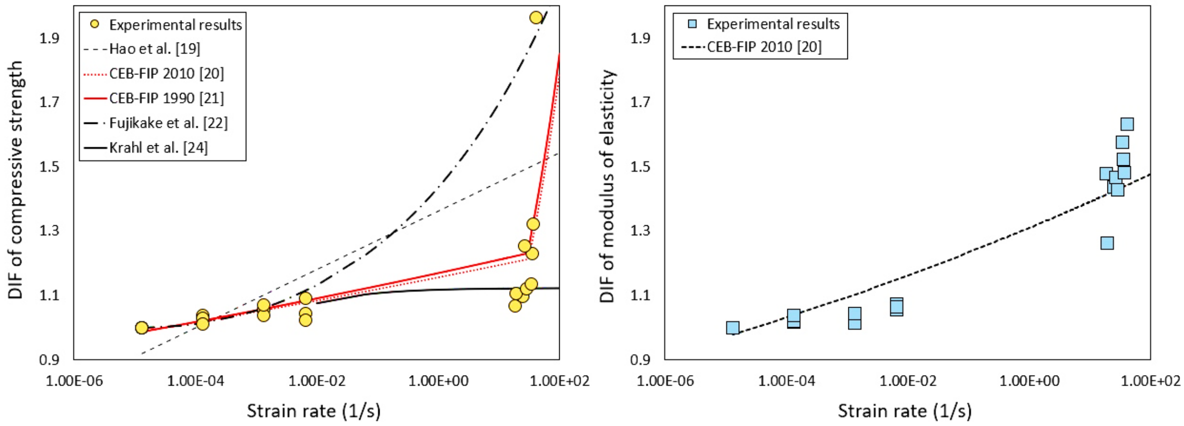


Figure 4. DIF for compressive strength and modulus of elasticity of SFRC.

3.2.2. Energy absorption capacity (Toughness)

In the present study, toughness was calculated as the total area under the stress-strain curve up to failure. This parameter was used to characterize the energy absorption capacity of SFRC specimens. Under quasi-static loading, it is considered that the failure point in the compressive stress-strain curve corresponds to a strain value of 0.005. The ratio of dynamic to static toughness for all SFRC specimens is listed in Table 4. The maximum DIF for toughness was 2.44, showing that the strain rate can significantly influence the toughness of SFRC. According to (Xu et al. 2012), hooked end fibres have a comparatively weaker mechanical contribution in impact loading, due to a limitation in the displacement of fibres and the local damage that takes place near the hooks, as opposed to other types of steel fibres. Consequently, the toughness of SFRC under impact loading mainly depends on the anchorage of the fibres hooked end (Banthia and Trottier 1991). It should be noted that the hooked end fibre in SFRC depends on its mechanical bond with concrete and its two end's anchorage. Based on the strain rate, the contribution of each of them in energy dissipation can be different.

The pull-out load of hooked end fibres, together with its own mechanical properties, are the most important parameters influencing SFRC toughness. Likewise, the pull-out load and the mechanical properties of hooked end fibres are also determinant on the toughness of SFRC specimens subjected to different loading rates. In the present study, one type of hooked end fibre with specific mechanical properties was used for all specimens. Due to use one type of fibre (hooked end steel fibre) with specified mechanical properties, aspect ratio, and volume fraction in the present study, the effect of fibre is ignored and the effect of strain rate on toughness could be appropriately evaluated with DIF. Figure 5 shows the DIF values associated to toughness for the loading rates tested within the present research, and compares these with the ones obtained with the model proposed by Ibrahim et al. (2016).The model underestimates the present experimental results, perhaps because Ibrahim et al. (2016) have used the hybrid fibres (steel, polypropylene, and Kevlar fibres) and SHPB testing to calibrate their model. As shown in Figure 5, by increasing the strain rate, the underestimation of the results by this model is even more visible.

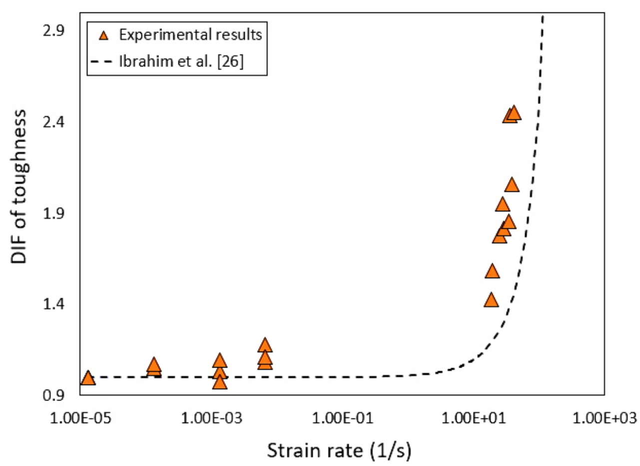


Figure 5. DIF of toughness of SFRC up to fracture.

4. Conclusion

This paper investigated the effect of strain rate on the compressive behaviour of hooked end steel fibre reinforced concrete (SFRC). For this purpose, an experimental study was performed on 21 SFRC cylinders under compressive loading. Compressive strength, modulus of elasticity and toughness were investigated under seven different strain rates, ranging from the quasi-static, (between 10^{-6} and 10^{-2} s^{-1}) to the impact level (between 1 to 50 s^{-1}). The investigation on the strain rate effect was based on the dynamic increase factor (DIF), and this parameter was analysed and calculated for compressive strength, modulus of elasticity and toughness. In addition, the calculated DIFs based on the experimental results were compared with DIF models proposed by CEB-FIP model codes and other researchers to evaluate their applicability in predicting the influence of high strain rates on the abovementioned SFRC properties. Based on the results and observations of this study, the following conclusions were reached:

1- Compressive strength, modulus of elasticity and toughness of SFRC increase with the strain rate. The effect of strain rate in the range of impact is more significant than in the range of quasi-static loading. For the highest strain rate tested, maximum DIF values of 1.32, 1.58, and 2.44 were obtained for the compressive strength, modulus of elasticity and toughness, respectively. The maximum DIF values of these parameters show that the strain rate can significantly influence the mechanical properties of SFRC.

2- The DIF models of compressive strength proposed by CEB-FIP 1990 and CEB-FIP 2010 can predict DIF values of SFRC with more accuracy than the other considered models.

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