Repeated drop-weight impact tests on self-compacting concrete reinforced with micro-steel fiber

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ABSTRACT

Steel fiber has become a proven material that can significantly alter the behavior of different types of concrete mixtures from brittle to more ductile ones. Rich literature is currently available on the mechanical properties of steel fiber-reinforced self-compacting concrete. However, the investigation of the impact resistance of this material to drop weight is still required to enrich the knowledge about its behavior under different loading conditions. An experimental work was conducted in this research to evaluate the performance of steel fiber-reinforced self-compacting concrete under repeated impact loading using the repeated blows test recommended by ACI 544-2R. The tests investigated the effect of drop weight and drop height in addition to fiber content. Straight micro-steel fibers were incorporated in three volumetric contents of 0.5, 0.75 and 1.0% and were compared with a similar plain mixture. The test equipment was adjusted to conduct repeated impact loading from different drop-heights and using different drop-weights. The adopted drop-heights were 450, 575 and 700 mm, while the adopted drop-weights were 4.5, 6.0 and 7.5 kg. The combination of the adopted drop-heights and weights composes four loading cases in addition to the standard loading case with a drop-weight and drop-height of 4.5 kg and 450 mm. The inclusion of micro steel fiber was found to significantly increase the impact resistance of self-compacting concrete with percentage developments ranging from 150 to 860% compared to plain samples. The specimens tested under 4.5 kg and 450 mm drop weight and height exhibited the highest percentage improvement in impact resistance among the five loading cases. The results also showed that the impact ductility of fibrous specimens was up to 24% higher than that of plain specimens.

1. Introduction

Many structures and structural members are probable to be subjected to impact forces or even repeated impacts during their functional life. Impact forces can be of many forms and due to different reasons. The accident impact of moving vehicles on columns and walls of structures is one example of which [1]. Other examples may be the impact of dropping objects from higher altitudes, impact of projectiles in wars or terrorist attacks [2, 3], impact of water on hydraulic structures and offshore structures or even bridge piers [4, 5]. Impact forces subject short term dynamic loads that subject the material to unusual and undesirable stresses especially for brittle materials like concrete. To be effectively absorbed, such type of loading requires better microstructural performance. The use of steel and synthetic fibers in concrete mixtures was introduced during the last decades as a candidate solution for such a case. One of the major characteristics of Fiber Reinforced Concrete (FRC) is its significantly improved impact resistance. Higher impact resistance means both higher impact energy absorption and higher dynamic strength. FRC is being widely used recently in several types of civil and military structural applications. Examples of these applications are the channel lining, bridge decks, industrial flooring, pavements of airports, offshore and military infrastructures [6, 7].

To obtain a suitable measurement of impact resistance of FRC, several testing methods were proposed by related researchers and standards. According to each type of these tests, the investigated parameters are different and the mechanism of impact load application is of course different. Among these tests are the Charpy pendulum, drop-weight, projectile impact, the explosive and the Repeated Blows Drop-Weight Impact (RBDWI) tests [8, 9]. The RBDWI test is considered as the simplest test to evaluate the impact resistance of fibrous concrete as introduced by ACI 544-2R [9]. However, the results of the RBDWI test are widely scattered, which makes the analysis of the obtained results a difficult task [9, 10, 11, 12].
Several researches were conducted using the RBDWI test on different types of concrete reinforced with different types of fibers. Natajada et al. [13] investigated the impact resistance of SCC reinforced with crimped steel fiber with fiber length of 27.5 mm. Nili and Aroughsabet [1] studied the influence of the inclusion of silica fume on the impact resistance of concretes reinforced with polypropylene fibers. Their test results showed that the inclusion of silica fume and polypropylene fibers enhanced the impact resistance, especially when 0.5% fiber content was used. In another research by the same authors [14], hooked end steel fibers with length of 60 mm were used instead of the polypropylene fibers with dosages of 0.5 and 1.0% by volume. Their results showed that impact resistance increases significantly as the steel fiber content increases. Nia et al. [15] evaluated the test results and the failure mechanisms obtained from the previous two researches [1, 14] using the finite element method. Yıldırım et al. [16] investigated the impact resistance of concretes reinforced with different types of fibers using the RBDWI test method. Chen et al. [17] tried to experimentally evaluate the improvement in impact resistance gained from the combined use of steel reinforcing bar and steel fibers. They used the ACI 544-2R RBDWI testing technique on high performance concrete reinforced with 12 mm diameter bars and 35 mm length steel fibers. Rahmani et al. [18] investigated the performance of concrete incorporating cellulose, polypropylene and steel fibers under the repeated impact loading. Khalil et al. [19] and Mastali and Davland [20] used the RBDWI test method to evaluate the impact resistance of Self-Compacting Concrete (SCC) containing crumb rubber. Most recently, several researches [2, 6, 21, 22, 23] were conducted to evaluate the impact resistance of layered fibrous concrete. In these researches, the course aggregate along with large amount of fibers were firstly mixed and placed in the molds, then after followed by the adding of a flowable cementitious grout that ingress inside the molds by means of gravity and fill voids between the aggregate and fibers. Concrete samples were prepared in single or multi layers, with different fiber configurations and contents. Crimped and hooked-end steel fibers with different lengths were used in these mixtures with fiber volumetric contents up to 4, 5 or 6% [2, 6, 23] or even up to 10% in others [21]. The authors concluded that the proposed layered fibrous sections were of much superior impact resistance compared to normal concrete [2, 6, 23]. They revealed that the impact resistance, in terms of number of blows, of some of these mixtures exceeded 30 times that of normal concrete and was also much superior to that of normal fibrous concrete [21].

Self-compacting concrete is like any ordinary concrete known to be of low tensile strength and impact performance. However, including fibers would enhance these properties significantly [15, 16, 17, 18, 19, 20, 24]. Yet, as the use of fibers has its advantages in improving the strength and structural performance, it also has the disadvantage of adversely affecting the workability of concrete mixtures. Considering SCC that should be a flowable fibrous concrete with special characteristics of suitable filling ability, passing ability and segregation resistance [9], the adverse effect of fiber inclusion on these characteristics may be more pronounced. Therefore, fiber contents must be adjusted carefully in SCC mixtures. In their work to introduce mixture design procedure for fiber-reinforced SCC, Khayat et al. [25] concluded that a fiber volume fraction of 0.5% can be considered as the upper limit to produce SCC without significantly affecting its fresh properties. On the other hand, a recent study by de la Rosa et al. [26] introduced a new mixture design procedure for steel fiber-reinforced SCC with fiber volume fractions up to 1.0%. They stated that beyond this fiber content, the practical producing of SCC with the desirable fresh properties that fall within the limits of modern SCC standards [27] becomes not easy. Khayat et al. [25] stated that in most construction projects where fibers are used, the volume fraction of fiber is limited to 1.0%. This limit was also supported by recent studies [7, 28]. Aydin [29] concluded that SCC with fiber contents up to 2.0% can be produced without serious mixing difficulties, however, the author revealed that all mixtures with high fiber volume fractions failed to satisfy the limits of SCC fresh properties specified by EFNARC [27].

Some previous studies have attempted to evaluate the impact resistance of SCC reinforced with different types of synthetic and metallic fibers. Mastali et al. [30, 31] conducted impact tests on SCC incorporating CFRP and glass fibers. Ding et al. [32] evaluated the use polypropylene fibers on the impact resistance of SCC, while AbdelAleem et al. [33] used two types of synthetic fibers, rigid and flexible. On the other hand, steel fibers were also used by some previous researchers aiming to investigate their effect on the impact resistance of SCC. AbdelAleem et al. [33] and Ismail and Hassan [34] used hooked end steel fibers with lengths of 35 and 60 mm, while Ding et al. [32] used 35 mm hooked end fibers. Most recently, the influence of the use of hybrid combination of crimped and hooked-end steel fibers on the impact resistance of SCC was investigated by Mahakavi and Chithira [35]. They used 70 mm length fibers in dosages of up to 0.75% of hooked-end fiber and up to 0.5% of crimped fiber. They showed that a maximum improvement in impact resistance of 100% over plain concrete was achieved when 0.75% of hooked-end fibers was used together with 0.5% of crimped fiber. SCC has been widely used in Japan, North America and Europe in several types of structures where external vibration of deep reinforced structural sections is a difficult task. Example of the applications of SCC are bridge towers, repair of bridge elements, tunnel lining, building structures and parking garages, architectural panels and many special structural elements where external vibration of the formwork cannot be easily performed [36].

According to ACI 544-2R, a drop-weight of approximately 4.5 kg should freely fall from a drop-height of approximately 450 mm on a test specimen. The standard ACI 544-2R test specimen is a disk with a diameter of approximately 150 mm and a thickness of approximately 64 mm. Some previous researchers attempted to investigate the influence of drop-weight or drop-height on the impact resistance of fibrous concrete. However, their works did not follow the ACI 544-2R strictly, where they either used different test specimen types or different test configuration. Zhu et al. [37] conducted drop-weight tests using U-shaped test specimens. In their tests, the drop-height was 400 mm, while the considered drop-weights were 0.5, 0.675, 0.8 and 0.875 kg. Wang and Chouw [38] used 100 mm diameter and 200 mm depth cylinders to conduct impact tests under a drop-weight of 40 kg, yet, the drop-height was variable. They adopted drop-heights of 500, 1000, 1500 and 3000 mm. On the other hand, other researchers conducted flexural drop-weight impact tests, in which the used drop-weights and heights were different among the different researches [33, 39, 40, 41]. Some other researchers investigated the effect of drop-height or the drop-weight using the flexural drop-weight impact test on beam specimens. Zhu et al. [42] conducted flexural impact tests on glass fiber-reinforced beams. The drop-weight was approximately 13.6 kg, while different drop-heights of 50, 100, 200 and 250 mm were tested. Dey et al. [43] used different drop-heights of 25, 75 and 150 mm in their flexural impact tests considering different beam cross-sections. Zhang et al. [44] investigated the effect of drop-weight and drop-height on fibrous concrete using the flexural impact test. In their tests, the drop-weight was variable from 1 kg to 9 kg and the drop-height was variable from 100 mm to 900 mm.

The above literature review shows that although extensive research works are available on the impact resistance of fibrous concretes and on the mechanical properties of SCC, in general, the works available on drop-weight impact resistance of steel fiber-reinforced SCC are limited. Moreover, it is also revealed that few researches have investigated the effect of drop-weight and drop-height, however, none of which was conducted on the ACI 544-2R disk specimens. According to the best of the authors’ knowledge, no previous research has attempted to evaluate the drop-weight impact resistance of SCC incorporating micro steel fibers using the ACI 544-2R test method. This research was directed to fill this gap of knowledge by studying the impact resistance of SCC reinforced with micro steel fibers using the RBDWI test. Moreover, the drop-weight and drop-height were also investigated among the test parameters. For this purpose, an adjusted impact testing apparatus was fabricated and used in this study.
2. Experimental work

The current experimental work includes the testing of shallow cylinders to evaluate the repeated impact resistance of Steel Fiber-Reinforced Self-Compacting Concrete (SFRSSC) using the RBDWI test. Six cylinders with 150 mm diameter and 65 mm thickness were cast for each test. In addition, standard 150 mm cube specimens were used to evaluate the compressive strength and to conduct the ultrasonic pulse velocity nondestructive test, which was conducted using the PUNDIT ultrasonic pulse velocity tester. Moreover, three 100 mm diameter and 200 mm length cylinders were used to conduct splitting tensile strength test.

Normal strength SCC mixtures with different micro steel fiber contents of 0, 0.5, 0.75 and 1.0% by volume were adopted in this study. The nominal diameter and length of used straight micro steel fibers were 0.2 and 15 mm, respectively, while the nominal tensile strength and modulus of elasticity of the fibers were 2600 and 200000 MPa, respectively. Due to its straight configuration and smaller size, micro steel fiber can be more easily handled in SCC mixtures than macro steel fibers. An upper limit of 1.0% of steel fiber in SCC was advised to be used by previous studies [25, 26]. Based on which and on several trial mixtures, it was found in this study that a steel fiber content of 1.0% is quite acceptable to achieve SCC mixtures without significantly influencing the required fresh properties. Type 42.5 Portland cement and well-graded local siliceous gravel and sand from Wasit province/Iraq were used in all mixtures in addition to a fixed content of lime stone powder. Table 1 shows the chemical composition of the used Portland cement and limestone powder, while Table 2 shows the grading of the used fine and coarse aggregates. The maximum size of coarse aggregate was 12.5 mm, while the specific gravity values of the fine and coarse aggregates were 2.6 and 2.64, respectively. To achieve the required mixture workability, Sika ViscoCrete-5930 superplasticizer was used with the mixtures.

In the design of the SCC mixtures, the requirements of ACI 237-R [36] and ASTM standards [45, 46, 47] were considered to accept the fresh properties of the mixtures. According to SCC standards, filling and passing abilities in addition to segregation resistance are three key characteristics that should be verified for any SCC. Therefore, a basic design mixture was first adopted and trials were then made for each fiber content. The final weight proportions of the adopted SCC mixtures are shown in Table 3. The tests that were adopted to evaluate the fresh properties of the prepared fibrous SCC are slump flow, T50, J-ring and the rapid penetration tests. Three different drop-heights of 450, 575 and 700 mm with constant drop-weight of 4.5 kg, and two more drop-weights of 6.0 and 7.5 kg with a drop-height of 700 mm were designed as investigation targets. Thus, the number of impact cylinders becomes (5 × 6 = 30) specimens per fiber content. Considering four different fiber contents of 0, 0.5, 0.75 and 1.0%, the total number of cylinders prepared for impact test in this study is 120 specimens.

The repeated blows impact test was conducted using a testing apparatus conforming the requirements of ACI 544-2R [9]. The design and manufacturing of the testing apparatus was controlled by two bases. These are the recommendations of the ACI 544-2R RBDWI testing equipment and the additional requirements to investigate the parameters designed in the current research. It should be mentioned that the RBDWI test is a simple test that requires no vibration, strain or other measurements besides recording the number of repeated blows. As stated by ACI 544-2R [9], this test is a conventional qualitative test that can be useful to compare among different concrete mixtures or different material thicknesses in terms of impact resistance. This test can also be beneficial to demonstrate the improvement due to fiber inclusion in impact energy absorption of these mixtures.

A thin grease layer was applied on the bottom surface of the test specimen before positioning between the base lugs, and then the specimen was bolted using the positioning brackets. After the specimen was held in place, a 63 mm diameter steel ball was placed within the circular bracket on the top surface of the test specimen as shown in Figure 1. Elastomer pieces were inserted between the specimen and the lugs to prevent the specimen movement during the test. The test was then started by dropping the free drop weight repeatedly until causing the first visible crack, at which the number of blows was recorded. Then, after the elastomers were removed and the test was continued until failure, where the number of blows was also recorded. According to ACI 544-2R, the standard drop-weight and drop-height are 10 lb (4.54 kg) and 18 inches (457 mm), respectively. However, one of the aims of this study is to evaluate the effect of the variation of both drop-weight and drop-height. Therefore, the testing equipment was manufactured to perform impact testing with different drop-heights of 450 (which is approximately equal to the standard 457 mm), 575 and 700 mm and different drop-weights of 4.5 (which is approximately equal to the standard 4.54 kg), 6.0 and 7.5 kg.

### Table 1. Chemical composition of Portland cement and limestone powder.

| Compounds (%)          | Portland Cement | Limestone Powder |
|------------------------|-----------------|-----------------|
| Silica (SiO2)          | 21.04           | 1.38            |
| Iron Oxide (Fe2O3)     | 5.46            | 0.12            |
| Alumina (Al2O3)        | 2.98            | 0.72            |
| Lime (CaO)             | 63.56           | 56.1            |
| Magnesia (MgO)         | 2.52            | 0.13            |
| Sulphur Trioxide (SO3)| 2.01            | 0.21            |

### Table 2. Grading of the fine and coarse aggregates.

| Sieve size (mm) | Fine (% Passing) | Coarse (% Passing) |
|-----------------|------------------|--------------------|
| 19              | 100              | 100                |
| 12.5            | 100              | 68                 |
| 9.5             | 100              | 30                 |
| 4.75            | 93.2             | 0                  |
| 2.36            | 65               | -                  |
| 1.18            | 50.6             | -                  |
| 0.6             | 42               | -                  |
| 0.3             | 12               | -                  |
| 0.15            | 0                | -                  |

### Table 3. Weights per cubic meter of the SCC mixtures.

| Gradient (kg/m³) | M0   | M0.5  | M0.75 | M1.0 |
|------------------|------|-------|-------|------|
| Cement           | 392  | 412   | 412   | 417  |
| Sand             | 1063 | 1063  | 1063  | 1052 |
| Gravel           | 574  | 503   | 503   | 468  |
| Lime stone powder| 67   | 67    | 67    | 67   |
| Water            | 181.3| 190   | 190   | 204  |
| Superplasticizer | 9.3  | 13    | 13    | 14.3 |
| Micro-steel fiber| 0    | 39    | 58.5  | 78   |

![Figure 1. Section through the lower part of the drop-weight impact testing apparatus.](image-url)
3. Results of fresh SCC tests

Table 4 shows the acceptable limitations of the four selected fresh SCC tests according to ACI 237-R [36] and ASTM standards (ASTM C1611, ASTM C1621 and ASTM C1712) [45, 46, 47], while Table 5 summarizes the fresh test results of the four SCC mixtures. As mentioned in the previous section, the conducted fresh tests were the slump flow, T50, J-ring and the rapid penetration tests. The test results show that the slump flow of all mixtures ranges from 630 to 755 mm. The slump flow values of the fibrous mixtures are within the accepted limitations of ACI 237-R and ASTM C1611 [45] as shown in Table 5, while although the slump flow of the basic mixture was slightly higher than the limitation of ASTM C1611, it still within the limitations of ACI 237-R. The T50 records of all mixtures are also more than the lower limit (2 s) and less than the upper limit (5 s) of the ACI 237-R. These measurements mean that the adopted mixtures have good filling ability and acceptable viscosity.

The J-ring test measures the passing ability of the flowable SCC concrete through reinforcing bars. The acceptable SCC concrete should flow smoothly across the reinforcing bars. ∆J-Ring represents the recorded flow diameter through the J-ring minus the recorded slump flow, which is considered by ASTM C1621 [46] to measure the degree of passing obstruction through the steel reinforcement. Table 5 shows that all of the four mixtures show acceptable passing ability with ∆J-Ring values ranging from 5 to 20 mm.

The fourth SCC fresh test is the static rapid penetration test recommended by ASTM C1712 [47]. This test aims to evaluate the segregation tendency of aggregate. The apparatus of this test composes mainly of a vertical metal rod that is attached to a hollow cylinder. The apparatus is placed on an inverted cone of fresh SCC and released freely to penetrate. The stability against segregation is then evaluated using the penetration depth inside the fresh SCC. The test results shown in Table 5 reveal that the four adopted SCC mixtures are resistant to segregation, where the penetration records ranged from 4 to 5.5 mm.

4. Results of compressive strength, splitting strength and UPV

As mentioned previously, 150 mm cubes were cast from each mixture to evaluate the compressive strength and the ultrasonic pulse velocity of the SCC mixtures. The test results are shown in Table 6. It is shown that the compressive strength of the four mixtures is quite similar with minor differences. The compressive strength of the four mixtures was in the range of 43–46.3 MPa and was independent of the steel fiber content. This result reflects the negligible effect of the steel fiber usage on compressive strength of normal strength SCC, which agrees with results obtained in previous studies [53, 54, 55]. Table 6 also lists the results of the splitting tensile strength. It is clear that increasing the fiber content leads to the increase of splitting tensile strength. This result is frequent in the literature [52, 56, 57, 58] as fibers noticeably enhance tensile resistance of concrete by bridging the two sides of cracks. Oppositely, the ultrasonic pulse velocity (UPV) showed continuous decrease as the fiber content increased. The negative effect of steel fiber on UPV can be attributed to the scattering of the ultrasonic waves when travelling through different layers of concrete containing different amounts of randomly distributed and oriented fibers.

5. Results of the RBDWI test

Figure 2 shows the variation of impact resistance of SCC in terms of the number of blows at first crack stage with the volumetric content of micro steel fiber, while Figure 3 shows this variation in terms of the number of blows at failure stage. The two figures also show the effect of the drop-height of the 4.5 kg drop-weight on impact resistance of the four SCC mixtures. The positive effect of steel fiber on the development of impact resistance is obvious in both stages. Figures 2 and 3 show that the impact resistance of SCC clearly increases with the increase of fiber content. This reflects the higher potential to absorb the impact energy due to fiber inclusion. This is attributed to the active bridging action of steel fiber during the load transferring along the crack, where these fibers arrest or slowdown the growth of the crack leading to the absorption of higher number of impact blows [7]. This is an expected positive action as fibers are known of their ability to improve the tensile strength of concrete.
concrete via crack controlling leading to more ductile behavior under tensile, flexural and dynamic loads [59, 60, 61].

Figures 2 and 3 also show that regardless of fiber content, specimens exposed to higher drop-heights retained significantly lower number of blows at both first crack and failure stages. This is an expected result because the impact force increases as the height of the drop-weight increases. Hence, specimens exposed to repeated impacts from shallower drop-heights are exposed to lower impact forces, which makes them last longer till cracking and failure compared to those exposed to higher impact forces. The recorded numbers of blows at first crack stage for specimens exposed to a repeated 4.5 kg drop-weight from 450 mm were 79, 350, 498 and 672 for fiber contents of 0, 0.5, 0.75 and 1.0%, respectively, while their corresponding values at failure stage were 82, 381, 611 and 789 blows, respectively. Similar sequences of results were recorded for drop-heights of 575 and 700 mm but with smaller values. The first crack stage records for 700 mm drop-height and 4.5 kg drop-weight were 42, 106, 177 and 245 for fiber contents of 0, 0.5, 0.75 and 1.0%, respectively, while their corresponding values at failure stage were 43, 120, 212 and 293, respectively. These values reflect the amount of development in impact resistance due to fiber inclusion. Similarly, the abovementioned test results reflect the harsh effect on number of blows due drop-height increase. Figure 4 shows the cracking of a cylindrical specimen tested under repeated impact.

To better evaluate the effect of drop-height on impact resistance, the comparison should be in terms of impact energy absorption capacity. This is because the number of blows measures the resistance to repeated impact load regardless of the applied impact force, while converting the number of blows to the absorbed energy would better compare all specimens. The impact energy resistance of a specimen subjected to number of blows (N) of a drop mass (W) from a drop-height (H) is calculated as:

$$E_i = N \cdot \frac{Wv^2}{2} = N \cdot (WgH)$$

where $v$ is the impact velocity of the drop-weight, while $g$ is the gravity acceleration.

The absorbed energy capacity reduces as the height of the drop-weight increases as shown in Figures 5 and 6 for both the first crack and failure stages. The figures show that this behavior is clear for fibrous SCCs, while it is not a behavior trend for plain SCC. This can be attributed to the higher impact forces of higher drop-heights, which impose more significant effects on the microstructure of the tested specimens after each impact blow. Thus, the microstructure starts to crack and fracture at higher rates when exposed to higher repeated forces. Consequently, the recorded first crack and failure absorbed energies for each specimen decreases with the increase of drop-height. However, it is also obvious in Figures 5 and 6 that the absorbed impact energy jumps noticeably as the
steel fiber content increases from 0 to 1.0%, which again shows the significant effect of steel fiber inclusion on the development of impact resistance of SCC. The presence of fibers along the crack leads to effectively improve the stress transfer along this crack, which is translated into much higher resistance to crack widening. Hence, higher impact loads (number of blows) are required to impose effective stresses that can break the bond between the fibers and the surrounding concrete media. The bond breaking leads to the pullout of these fibers and the consequent failure of the specimen [21]. The absorbed impact energies for specimens reinforced with 0.5, 0.75 and 1.0% of micro steel fiber were approximately 7.0, 9.9 and 13.4 kJ, respectively, for a drop-height of 450 mm compared to only approximately 1.6 kJ for plain specimens. Similarly, for a drop-height of 700 mm and for fiber contents of 0, 0.5, 0.75 and 1.0%, the absorbed impact energies at first crack stage were approximately 1.3, 3.3, 5.5 and 7.6 kJ, respectively. Comparing the two sequences of results, it can be said that the absorbed energy was approximately reduced to the half when the drop-height was increased by slightly more than 50%.

Figures 7 and 8 compare the number of blows retained from specimens exposed to different drop-weights that fall from a fixed drop-height of 450 mm. The figures show that the number of blows required to cause the first crack and failure of the tested specimens decreases as the drop-weight increases. This behavior can be attributed to the same reason discussed for Figures 3 and 4. After crack formation, the impact resistance of the fibrous specimens relies on the tensile strength of fibers and the bond strength between the fibers and concrete, where the fibers dominate the crack opening restricting due to the dowel action that prevent the crack widening [6]. As the repeatedly applied stresses become larger due to the larger impact energy that results from increasing the drop mass, the number of repetition (blows) of these stresses required to break the bond becomes lower. The retained numbers of blows for the 4.5 kg were addressed in the previous paragraph. For fiber contents of 0, 0.5, 0.75 and 1.0%, the recorded number of blows at first crack stage were 67, 172, 211 and 350, respectively, for a drop-weight of 6.0 kg, while for a drop-weight of 7.5 kg, these records were 32, 97, 110 and 130 blows, respectively.

Figures 9 and 10 show the absorbed impact energy at first crack and failure stages for specimens impacted from a height of 450 mm but with different impact weights of 4.5, 6.0 and 7.5 kg. It is known that the increase of drop-weight directly increases the impact force. The figures show obviously that the absorbed energies decrease with the increase of the drop-weight for the same fibrous SCC specimens. This result confirms the results obtained from the increasing of drop-height shown in Figures 5 and 6, and can be explained similarly. The increase of the drop-weight or drop-height increases the drop force. Exposing a specimen to higher repeated impact forces would accelerate the deterioration of the microstructure and thus would reduce the absorbed energy till cracking or failure.
6. Development of impact resistance due to fiber inclusion

Figures 11, 12, 13, and 14 show the development of impact resistance due to the addition of the micro steel fiber in terms of number of blows. Figures 11 and 13 show this development at first crack stage for variable drop-heights and variable drop-weights, respectively, while Figures 12 and 14 show their corresponding values at failure stage. It is obvious from the observation of the figures that the inclusion of micro steel fiber significantly increases the impact resistance by not less than 150% in worst cases compared to plain concrete, while this increase jumps to more than 800% in best cases. It is also obvious in the figures that regardless of the drop-weight or height, the percentage increase in impact resistance increases with the increase of fiber content, and for cracking and failure stages. Comparing the four figures, it can be said that the standard loading condition with 4.5 kg drop-weight and 450 mm drop-height shows the best development results for all fiber contents and at both the first crack and failure stages. On the other hand, the other four loading cases show comparable results with minor deviations. Considering Figure 11, the percentage increases in retained number of cracking blows for the standard loading case were 343, 530 and 750% for fiber contents of 0.5, 0.75 and 1.0%, respectively, compared to plain specimens. For specimens loaded with 4.5 kg falling from 700 mm, the recorded sequence was 152, 321 and 483%, respectively. Similar results can be observed in Figures 12, 13, and 14.

7. Failure patterns and impact ductility

Figure 15 shows the observed fracture patterns of the plain and fibrous mixtures. The plain specimens exhibited much lower impact resistance regardless of the loading condition (drop weigh and drop height) compared to fibrous specimens as discussed earlier. The failure of these specimens was sudden directly after the formation of the first crack, reflecting the brittle behavior of these specimens under impact load. As the cracking capacity reached, a diagonal line crack formed as shown in Figure 15(a). After one to three more blows, this crack became wider and reached the cylinder edges, extended down to the bottom surface and splitting the specimens into two parts. This is the most common noticed brittle failure of plain cylinders, which agrees with most of the available literature [1, 14, 17, 31, 32, 33, 34]. However, it was also noticed that a minor crack may form before the failure of the specimen as shown in Figure 15(b). It should also be addressed that fewer number of specimens exhibited brittle failure but were fractured into four parts. The brittle behavior is attributed to the brittle nature of concrete and the absence of any bridging elements that keep the bond along the two sides of the formed crack. As impact load is transferred concentrically from the steel ball to the center of the cylinder’s top surface, the stresses are expected to transfer diagonally in all directions. Hence, cracks may form along any direction that might be weaker than others owing to the heterogeneous nature of concrete. Consequently, two or more cracks may form and extend along any diagonal directions.
Fibrous specimens exhibited differently where the impact capacity was significantly improved due to fiber inclusion. Because of the higher number of absorbed impact blows, a central circular fracture zone was formed beneath the steel ball. The area of this zone increased with the increase of number of blows leading to the fracture of the surface showing small size surface cracks. Figure 15(c)–(e) show the fracture surfaces of the fibrous specimens. These cracks opened wider as the number of blows increased, while only one of which reached the outer perimeter and extended to the bottom surface. The fibers continue bridging the two sides of the cracks, while the bond was lost gradually between these fibers and the surrounding matrix leading to the failure of the specimens by fiber pullout as shown in Figure 15(f). This type of failure is attributed to the length and configuration of the used steel fibers, where the short length of the fibers and its straight configuration allowed for the fiber to lose bond before being effectively stressed.

Ductility is known as the ability of the material to withstand plastic deformations under loading, which is normally used with tensile and flexure tests [59, 61]. However, this definition can be generalized to the repeated impact test as the ratio of number of impact blows at failure to that at cracking stage (ductility ratio). Several previous researches [2, 6, 21, 22, 23] used this definition to observe the ability of fibers to alter the behavior of concrete from brittle to more ductile under impact loading. In this study, it was found that the ductility ratio of the plain specimens was approximately 1, where all plain specimens failed at only 1 to 3 blows after cracking. On the other hand, the fibrous specimens exhibited more ductile behavior showing average ductility ratios of approximately 1.17, 1.24 and 1.19 for fiber contents of 0.5, 0.75 and 1.0%, respectively. The increase of ductility is of course attributed to the bridging action of the steel fibers that increases the overall impact capacity and allows for
absorbing higher impact energy after cracking. Hence delays the failure and increase the absorbed number of blows after cracking. Considering the 4.5 kg drop weight and 450 mm drop height loading case, the fibrous specimens with 0.5, 0.75 and 1.0% fiber failed at 31, 113 and 117 blows after cracking.

Comparing the obtained ductility ratios with several previous studies on fibrous concrete, self-compacting concrete and high performance concrete, three notes can be addressed. First, all researches agreed that ductility ratio equals approximately 1.0 for plain concrete. Second, most of the reviewed literature [1, 10, 11, 12, 13, 14, 16, 17, 33, 34] showed that for concrete reinforced with steel fibers (mostly crimped and hooked-end), the ductility ratio ranges between 1.1 and 1.4, which agrees well with the obtained results in this study. However, few researches [18, 32] showed that steel fiber-reinforced concrete and steel-fiber reinforced high performance concrete can reach ductility ratios up to slightly lower than 2.0. The third note is that increasing fiber content would normally result in higher impact capacity (higher number of blows), yet it is not necessary that mixtures with higher volume fractions would have higher ductility ratios. This result was noticed in this research and several previous researches [14, 32, 34, 62]. It is worth to mention that much higher ductility ratios reaching 5.0 were recorded for special types of concrete like engineered cementitious composites (ECC) [63] and layered fibrous concrete with very high fiber contents [2, 6, 21, 22, 23].

8. Relationship between impact resistance and UPV

Nataraja et al. [13] in their experimental investigation tested the ultrasonic pulse velocity (UPV) in conjunction with the number of impact blows for 32 fibrous impact specimens having the same mix properties and under the same test environment. Their test results showed that the number of blows at first crack and failure stages is independent of the recorded UPV. Yildirim et al. [16] tested both the impact resistance and the UPV for different types of mono and hybrid fiber reinforced specimens. They used the ACI 544-2R [9] test technique and recorded the UPV after each six impact blows for the same disk specimens. They showed that independently of the used fiber type and fiber content, UPV decreases with the increase of number of blows.

In the current research, the UPV was conducted on cube specimens cast from the same mixture batches of the impact specimens as discussed previously. The UPV test was conducted only before the destructive test. Figures 16 and 17 show the linear relationships between the returned number of blows and UPV, while Table 7 lists these linear relationships. It is obvious in both figures that inverse correlations were obtained between the number of retained blows and UPV for all of the five loading cases. Actually, this result does not reflect the direct relation between the impact resistance and UPV. As listed in Table 6, UPV values decreased as the fiber content increased, while the impact resistance showed noticeable increase with the increase of fiber content. The opposite relations of both of which with fiber content explains the indirect inverse relationship between UPV and impact resistance.

9. Conclusions

In this study, the response of steel fiber-reinforced self-compacting concrete to drop weight impact was experimentally investigated. The test procedure of the ACI 544-2R repeated drop weight test was followed but with variable drop weights and drop heights. Within the limitations of the investigated parameters, followings are the most important results and concluding remarks obtained from the experimental work of this study.

1. The inclusion of micro steel fibers increases the retained number of impact blows of SFRSCC at first crack and failure stages (N₁ and N_f) compared to plain SCC. Both N₁ and N_f increase with the increase of fiber content. For specimens impacted with 4.5 kg from 450 mm (standard loading case), N₁ records were 79, 350, 498 and 672 for fiber contents of 0.5, 0.75 and 1.0%, respectively, while their corresponding N_f values were 82, 381, 611 and 789, respectively.

2. Specimens exposed to similar drop-weight from higher falling altitudes retained lower N₁ and N_f values. Similarly, N₁ and N_f decrease as the drop-weight increases at fixed drop-height. This trend of results is attributed to the increase in the impact force due to the increase of drop-height or drop-weight. Considering the specimens with 1.0% steel fiber content, the retained N₁ values were 672, 389 and 245 blows for a drop-weight of 4.5 kg and drop-heights of 450, 575 and 700 mm, respectively, while for drop-weights of 6.0 and 7.5 kg from 450 mm, N₁ records were 350 and 150.

3. For similar fibrous SCC specimens exposed to different drop-weights and different drop-height, the absorbed impact energy showed continuous decrease as the drop-weight or drop-height increase. This result is attributed to the accelerated deterioration of the material microstructure due to the exposure to higher repeated impact forces.

4. High percentage developments in impact resistance were gained when micro steel fiber was added to the SCC mixtures. The percentage development increases as the fiber content increases regardless of the loading case and it was in the range of approximately 150–860% compared to plain specimens.

5. The highest percentage development in impact resistance was obtained when the standard loading case of a drop-weight and drop-height of 4.5 kg and 450 mm was considered, while the percentage developments were approximately comparable when the other four loading cases were considered.

6. The impact ductility in terms of the ratio of number of blows at failure to that at cracking was calculated for all mixtures. The average ductility ratios of the fibrous specimens with fiber contents of 0.5, 0.75 and 1.0% were approximately 1.17, 1.24 and 1.19, respectively, while that of plain specimens was approximately 1.0. Such results agree with ductility ratios calculated for data from most of the available literature on fibrous concretes, in which ductility ratios of 1.1–1.4 were recorded for steel fiber-reinforced concrete.

Declarations

Author contribution statement

Sallal R. Abid: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.
Munther L. Abdul-Hussein: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.
Nadheer S. Ayooob: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Sajjad H. Ali & Ahmed L. Kudham: Performed the experiments.

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