Low-velocity impact tests on self-compacting concrete prisms

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Abstract. Several structural members like columns and walls can be under the effect of accidental strikes from falling objects or collision of moving vehicles. Several researches are available in the literature on impact tests on different types of concrete, while those on Self-Compacting Concrete (SCC) reinforced with steel fiber are very limited. In this research, repeated impact tests were conducted on normal strength and high strength SCC reinforced with micro-steel fibers. Four fiber fractions of 0, 0.5, 0.75 and 1.0% by volume were investigated, while two design strength of 30 and 50 MPa were considered as normal and high strength SCCs. The test procedure was similar to the repeated impact test technique of ACI 544-2R but with a drop height of 100 mm and using prism specimens. The test results showed that micro-steel fiber can increase the impact resistance of SCC significantly. The inclusion of 1.0% fiber led to up to approximately 500% increase in the retained number of impacts at cracking stage, while the percentage increase at failure was much higher which reached approximately 2100%. On the other hand, the adopted high strength SCC could retained only up to approximately 30% higher number of impacts compared to normal strength SCC.

1. Introduction
In structural members like deep walls or heavy reinforced members, the achievement of adequate compaction of concrete is not an easy task. The Self-Compacting Concrete (SCC) as a new material was invented in Japan as a successful solution for this problem [1-3]. The SCC is a concrete that have superior fresh properties without causing any negative influence on the strength of the material or its durability. According to ACI 273R [3] and EFNARC [4], any flowable concrete should possess three major characteristics to be considered as SCC. Self-compacting concretes must have the ability to fill the formworks without the need of any means of external vibration. SCC should also passes smoothly across heavy reinforcements and shows no segregation tendency. Hence, it should be flowable with adequate passing ability and segregation resistance [3, 4].
Several literature research works were found on the mechanical properties and structural performance of SCC reinforced with steel fiber. Steel fibers are used with the different concrete types to improve the capability of concrete to withstand tensile stresses that arise from the different loading cases. It is proven that steel fibers can significantly improve the flexural strength of concrete, ductility and shear resistance of structural members [5-7]. The significant improvement of strain energy absorption under dynamic and impact loads is also one of the superior features of steel fibers [8-9]. As for other types of concretes, steel fiber can also positively affect the mechanical properties and durability of SCC [10-11]. However, the use of steel fiber can negatively influence the fresh properties of SCC, which requires more careful mixture design and optimization [12-13].
In addition to the typical gravity loads, structures are mostly designed to be safe enough under the action of some probable short duration effective loads like seismic loads. However, most of the typical structures are not designed for accidental impact forces that occur within very short time. Impact loads can be due to the direct collision of moving vehicles, direct or indirect hits of projectiles or explosions, especially in war regions or due terrorist attack [14-16]. On the other hand, other structural members are usually designed for such type of loads. For instance, concrete pavements of airports runways are designed to withstand repeated impacts from the wheels of the landing aircrafts [17, 18]. Chute blocks in spillway hydraulic structures are another example of structures that are designed for repeated impacts of water and waterborne materials [19, 20]. Several testing procedures were used to evaluate the different impact scenarios, among which is the drop-weight impact test. The testing procedure of the repeated drop-weight impact test introduced by ACI 544-2R [21] is a simple technique that can be conducted in laboratory or in the field. This test is manual and requires only one person to perform repeated lift-and-leave impacts on small concrete specimens without the need of any sophisticated measurements. Experimental research works on SCC impact resistance can be found in the literature [22-29]. Most of these researches were conducted on macro steel fibers with hooked-end configuration and fiber lengths of 30 to 60 mm. However, except a previous study [30], no experimental works were found on micro-steel fiber reinforced SCC using the ACI 544-2R repeated low-velocity impact test procedure. Moreover, in the current investigation, beam specimens were tested under impact loads instead of the typical cylindrical discs.

2. Experimental work
Two concrete grades of SCC mixtures were adopted from previous works [11, 30], one with design strength of 30 MPa to represent normal strength SCC, while the second with design strength of 50 MPa that is considered as high strength SCC. For each of the two SCC grades, mixtures including three different steel fiber contents were prepared in addition to the fourth reference mixture that contains no fiber. The adopted fiber contents were 0.5, 0.75 and 1.0%. Thus, eight SCC mixtures were adopted in this study. Table 1 lists the details of the eight SCC mixtures. The cement used in all mixtures of this study is type R42.5 Portland cement, while silica fume from Sika was also used as partial substitution in the high strength mixtures only. In addition, 67 kg/m³ of lime stone powder was used with all mixtures. Crushed gravel from Wasit/Iraq province was used as coarse aggregate, while sand from the same location was used as fine aggregate. The maximum size of the gravel was 12.5 mm. To facilitate achieving the required SCC, Sika produced superplasticizer, ViscoCrete-5930, was used with all mixtures, but with different dosages. The used straight steel fiber was 15 mm long and 0.2 mm in diameter and was cooper coated. The nominal tensile strength of the used steel fiber was 2600 MPa. Two SCC fresh tests were considered for the verification of the adopted mixtures. These tests are the slump flow in accordance with ASTM C1611 [31] and the rapid penetration test in accordance with ASTM C1712 [32]. The carried out fresh tests were adopted to estimate the acceptability of the filling ability and segregation resistance of the SCC mixtures. The results of the two tests for the eight SCC were within the limitations of the ASTM standards. The slump flow of all mixtures was in the range of 615 to 755 mm. Similarly, the results of the rapid penetration test showed that all mixtures have good resistance against segregation where the test records were in the range of 0.5 to 9 mm. To evaluate the compressive strength of the adopted mixtures, 70 mm cubes were prepared and tested at an age of 28 days. The compressive strength results of the eight mixtures are shown in Table 1. NS in the identification number of the mixtures in Table 1 refers to normal strength mixtures, while HS refers to high strength mixtures. The following number refers to the volumetric content of steel fiber. The free-falling drop weight technique was used in the impact tests of this study. The testing procedure was similar to that of the ACI 544-2R [19] repeated drop-weight test, but with some differences. The ACI 544-2R testing procedure requires that a weight of 4.57 kg is freely and repeatedly falls from a height of 457 mm on a disc specimen that has 150 mm diameter and a thickness of 63 mm. In the current work, 70x70x260 mm prisms were used instead of the disc specimens. Moreover, the height of the drop
mass was reduced to 100 mm only to better evaluate the effects of the investigated parameters, while the drop weight kept as recommended by ACI 544-2R (4.57 kg). The prism was restricted to the base plate to prevent the movement after each impact. The number of impacts required to cause the first visual crack was recorded as the cracking number (Ncr), while the number required to fail the prism was recorded as the failure number (Nf). Figure 1 shows the details of the testing procedure. Six prisms were tested from each mixture, and their average records are presented as Ncr and Nf for each mixture in the following section.

Table 1. Details of the eight SCC mixtures.

| Mixture | C (kg/m³) | S (kg/m³) | G (kg/m³) | SF | W (kg/m³) | SP (kg/m³) | Vf (%) | F cu (MPa) |
|---------|-----------|-----------|-----------|----|-----------|-----------|--------|-----------|
| NS0.00  | 392       | 1039      | 574       | -  | 181.3     | 9.3       | 0      | 54.85     |
| NS0.50  | 412       | 1063      | 503       | -  | 190       | 13        | 0.5    | 51.02     |
| NS0.75  | 412       | 1063      | 503       | -  | 190       | 13        | 0.75   | 56.5      |
| NS1.00  | 417       | 1052      | 468       | -  | 204       | 14.3      | 1.0    | 55.6      |
| HS0.00  | 525       | 907       | 518       | 67 | 190       | 17        | 0      | 83.5      |
| HS0.50  | 525       | 907       | 518       | 67 | 209       | 17        | 0.5    | 85.7      |
| HS0.75  | 525       | 931       | 486       | 67 | 209       | 17        | 0.75   | 84.9      |
| HS1.00  | 525       | 931       | 486       | 67 | 209       | 17        | 1.0    | 88.2      |

Figure 1. Details of the repeated impact test.

3. Results and discussion

3.1. Effect of micro-steel fibers

The test records of the cracking number of impacts (Ncr) and failure number of impacts (Nf) of the normal strength specimens (first four mixtures in Table 1) are visualized in Figure 2. It is evident from the figure that the inclusion of short micro-steel fibers led to significant development in impact resistance. The number of impacts carried by the prism specimens is obvious to be increased with the increase of fiber content. The number of impacts required to crack the specimens (Ncr) increased from only 3.5 impacts for the plain specimens to 15, 16 and 21.7 impacts for beam specimens containing 0.5, 0.75 and 1.0% by volume contents of micro-steel fibers, respectively. These results mean that, at the cracking stage, the inclusion of micro-steel fibers with volumetric contents of 0.5, 0.75 and 1.0% led to percentage improvements in the impact resistance of approximately 330, 360 and 520%, respectively, compared to the plain specimens, which is obvious and better visualized in Figure 3. As for the normal strength specimens, Figures 4 and 5 show that micro-steel fibers has the same positive affectivity on impact resistance. It is shown in Figure 4 that both numbers of impacts increased with the increase of

![Figure 1](image-url)
fiber content. The cracking number of impact increased from 4.5 for the plain specimens to 15, 18.7 and 27 for the micro-steel fiber fractions of 0.5, 0.75 and 1.0%, respectively. On the other hand, the recorded failure numbers of impact for fiber contents of 0, 0.5, 0.75 and 1.0% were 5.7, 57.8, 93.7 and 104.7, respectively.

It is also noticed for normal-strength SCC (Figure 2) and high-strength SCC (Figure 4) that the slope of the number of impact-fiber content relation was higher at failure stage than at cracking stage. This means that the influence of the used micro-steel fibers fiber was more functional within the post cracking stage than before cracking initiation. This result is also shown in Figures 3 and 5 where the percentage improvements due to fiber inclusion, for normal strength SCC and high strength SCC, were apparently higher for failure number than for cracking number of impacts. For the normal strength SCC, Figure 3, the percentage improvement was in the range of approximately 330 to 520% at cracking stage, while it was in the range of approximately 1040 to 2120% at failure.

![Figure 2. Cracking and failure numbers of impacts of normal strength SCC with different fiber contents.](image)

![Figure 3. Improvements in cracking and failure numbers of impacts of normal strength SCC due to fiber inclusion.](image)
Figure 4. Cracking and failure numbers of impacts of high strength SCC with different fiber contents.

Similarly, the percentage increases for the high strength SCC, Figure 5, where in the ranges of approximately 230 to 500% and 920 to 1750% at cracking and failure, respectively. Figure 6 reinforces this conclusion as the difference between the failure and cracking numbers jumped as fiber was included. This difference is obvious to exhibit continuous increase as the volumetric content of fiber get higher. This is an expected result as the capability of fiber in strength improvement is attributed to its bridging activity. Before the initiation of the first crack, microcracks are formed inside the matrix under the effect of repeated impacts. However, due to the size ratio of these cracks to fibers, the effect of fibers on restricting such cracks still very limited. Oppositely, after the formation of visual cracks, the interior microcracks become wider and the fibers start to bridge the two sides of these cracks. In turn, the material could withstand higher impact loads before failure. The vast available literature showed that the bridging activity of fibers has apparently positive imprint on the strength, ductility, strain energy absorption and impact resistance under the different loading scenarios [6, 15, 33, 34].

Figure 5. Improvements in cracking and failure numbers of impacts of high strength SCC due to fiber inclusion.
Figure 6. $N_f - N_{cr}$ of the two tested groups of SCC.

3.2. Effect of SCC compressive strength

Figure 7 compares the number of impacts at cracking stage for the two tested groups of SCC specimens with various micro-steel fiber volume contents. It is obvious in the figure that minor differences are shown between the numbers of impacts of the two concrete grades. The cracking impact number increased by not more than 29% when the design strength was increased by approximately 20 MPa. On the other hand, it was discussed earlier that 1.0% volume fraction of micro-steel fibers resulted in an up to 500% increase. This means that the effect of concrete strength on the retained number of impacts, and hence on the impact resistance, is very limited compared to the effect of fiber inclusion. This result is also noticed in Figure 8 for the number of failure impacts, where the maximum percentage increase was 31% as the mixture changed from normal to high strength, while the maximum percentage gain due to 1.0% fiber was more than 2100%. It should be reminded herein that the term high strength used here refers to the design strength of 50 MPa, while much higher strengths can also be addressed under the same definition. Therefore, it should be addressed that, in this study, the presented comparison between the two groups of SCC is limited to the investigated range of concrete strengths.

Figure 7. Comparison of cracking number of impacts of the two tested groups of SCC
4. Conclusions
In this study, repeated impact tests were conducted on normal and high strength SCC prisms reinforced with different contents of micro-steel fibers. Based on the test results obtained and within the limitations of the investigated test parameters, the followings can be drawn as the most important conclusions:

1- Adding micros-steel fiber to SCC can improve the impact resistance of the material at cracking stage, regardless of the concrete strength. For normal strength SCC, the number of cracking impacts retained were 15, 16 and 21.7, when fiber volume fractions of 0.5, 0.75 and 1.0% by volume were incorporated, while it was 3.5 for the zero-fiber specimens. Similar sequence of results was also obtained for high strength SCC. This means that percentage improvements up to 500% were gained in the cracking number of impacts when 1.0% fiber was included.

2- The effect of micro-steel fiber was much higher after cracking than before cracking, where more effective fiber improvement in impact resistance at failure stage was recorded compared to at cracking stage. For normal strength SCC, the use of 1.0% micro-steel fiber increased the retained number of failure impacts from 4.5 to 100 with an improvement of approximately 2100%. Similarly, for high strength SCC, the failure number of impacts increased from 5.7 for plain specimens to 104.7 for specimens reinforced with 1.0% of micro-steel fibers. The superiority of improvement in failure stage compared to cracking stage is because that fiber bridging becomes more dominant after cracks formation.

3- Comparing to the contribution of steel fibers in impact strength development, the increase of concrete strength has much lower effect. The number of recorded impacts was increased by a maximum of approximately 30% as the design strength was increased by 20 MPa, both at cracking and failure stages, while adding 1.0% micro-steel fiber could increase the impact resistance by up to approximately 2100%.

5. References
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