Magazine of Civil Engineering. 2021. 105(5). Article No. 10504

Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

DOI: 10.34910/MCE.105.4

Impact resistance of steel fiber-reinforced self-compacting concrete

S.R. Abid*, S.H. Ali, H.A. Goaiz, T.S. Al-Gasham, A.L. Kadhim
Wasit University, El'-Kut, Iraq
**E-mail: sallal@uowasit.edu.iq*

Keywords: concrete, steel fibers, self-compacting concrete, fiber-reinforced concrete, impact

Abstract. Among the adopted test methods to evaluate the impact resistance of materials and structural members is the drop-weight impact test. The ACI 544-2R repeated drop-weight impact testing technique was used in this research to evaluate the impact resistance of Self-Compacting Concrete (SCC) reinforced with micro-steel fibers. SCC concrete sample were made with two concrete grades and four fiber volumetric contents of 0, 0.5, 0.75 and 1.0 %. Another investigated parameter is the shape of the test specimen, where disk specimens (150 mm diameter and 65 mm thickness), 70 mm cubes and 70×70×260 mm beams were tested. The experimental results showed continuous improvement of impact resistance of SCC as the fiber content increased with percentage improvements ranging from 110 to 1200 % compared to the plain SCC. The failure impact resistance of the high strength SCC was higher than that of normal strength SCC regardless of specimen type and fiber content. The test results also showed that the impact resistance of disk specimens were clearly higher than those of cubes and beams and has more uniform variation with fiber content.

1. Introduction

Self-Compacting Concrete (SCC) can be described as a special type of flowable concrete that is consolidated due to its own weight without any signs of undesirable segregation or bleeding. Such property can save both time and cost by eliminating the effort required for external vibration. Moreover, it reduces the site noise leading to a better work environment. The flowability of concrete can also lead to better surfacing of the structural elements resulting in enhanced durability [1]. According to EFNARC [2] and ACI 273R [1], a concrete should pass the required limitations of the tests of three properties to be considered as a successful SCC. Filling ability, passing ability through steel reinforcement and segregation resistance during casting are the desired properties of SCC. Several tests were developed by researches and adopted by different standards to examine the required properties. Like the ordinary concrete, SCC is relatively a brittle material that shows weak behavior under tensile loads. This brittleness also leads to low dynamic response and impact resistance. Steel and synthetic fibers can be added to SCC to make it more ductile, which enhances the structural behavior both under static and dynamic loads. However, such fibers significantly reduce the flowability of SCC mixtures, which imposes the use of more liquidity and viscosity enhancement agents. The effect of different types and sizes of steel fibers on the fresh properties and mechanical properties of Steel Fiber-Reinforced Self-Compacting Concrete (SFRSCC) were investigated by many previous researchers [3–7] who revealed the adverse effect of steel fiber on workability and fresh poperties of concrete.

One of the loads that concrete structures are possible to suffer is the short duration dynamic load. Such load can be imposed by accidental impacts of moving objects, projectiles, or even wind gusts [8–11]. The influence of using steel fiber with different types of concretes on the impact resistance was investigated by many studies using different testing techniques. The most widely used of impact loading tests are the

Abid, S.R., Ali, S.H., Goaiz, H.A., Al-Gasham, T.S., Kadhim, A.L. Impact resistance of steel fiber-reinforced self-compacting concrete. Magazine of Civil Engineering. 2021. 105(5). Article No. 10504. DOI: 10.34910/MCE.105.4

Charpy pendulum test and the drop weight test. In addition, other test methods like the projectile impact and explosive tests were also considered to evaluate the impact resistance of concrete. Among these tests, the repeated drop weight impact test is considered as a simple and low-cost alternative for this purpose. This test is recommended by ACI 544-2R [12], which uses the recorded number of impact blows till cracking and failure as measurements of the impact resistance of the tested specimen. This test was used by many previous studies to evaluate the impact resistance of concretes incorporating steel or other types of synthetic fibers [8, 13–23]. Other studies utilized the procedure of ACI 544-2R [12] to conduct repeated flexural impact tests on concrete beams [24–29]. In these studies, the drop weight, drop height, the geometry of the test specimen and the flexural span differed from study to another.

Few studies were found in the literature on the repeated impact resistance of SFRSCC [30–36]. Using the ACI 544-2R [12] drop-weight impact method, Khalil et al. [30] studied the impact performance of rubberized SCC containing different contents of crumb rubber, while Ismail and Hassan [31] investigated the impact resistance of steel fiber-reinforced rubberized SCC. Khalil et al. [30] and Ismail and Hassan [31] used different replacement levels of the fine aggregate by crumb rubber and steel fiber volume fractions up to 1 %. Hooked end steel fibers were used with fiber lengths of 35 and 60 mm. The test results revealed that both crumb rubber and steel fiber enhance the impact resistance. Another study by AbdelAleem et al. [32] conducted experimental impact tests to investigate the impact resistance of rubberized SCC containing flexible and rigid synthetic fibers. Two test procedures were utilized in the study, the ACI 544-2R drop-weight impact method and the flexural impact test. Ding et al. [33] also used the ACI 544-2R drop-weight impact method and the flexural impact test to study the combined effect of steel bars and fibers on the impact resistance of SCC. Polypropylene and steel fibers were used with lengths of 30 and 35 mm, respectively. The test results showed that the combined effect of steel bars and fibers are superior to the superposition of their individual effects by approximately 30 to 200 %. Mastali et al. [34–36] used the ACI 544-2R [12] method to evaluate the impact resistance of SCC incorporating different types of recycled fibers (glass and carbon fibers).

The previous studies were found in the literature on the impact resistance of steel fiber reinforced concretes or on SCC incorporating synthetic and steel fibers using the ACI 544-2R drop-weight impact method. However, no study was found on the impact resistance of normal and high strength SCC incorporating micro steel fibers. Thus, an experimental program was directed in this study to examine the impact resistance of SFRSCC using the repeated drop-weight impact loading test. In addition, the effect of the specimen shape on the test measurements was also investigated using three different types of test specimens.

2. Methods

The experimental program of this study was directed to examine the impact resistance of SFRSCC. Mainly, two basic SCC mixtures were designed to obtain a nominal compressive strength of 30 MPa as normal strength SCC (NS-SCC) and 50 MPa as high strength SCC (HS-SCC). For each of which, four fiber volumetric contents of 0 %, 0.5 %, 0.75 % and 1.0 % of micro-steel fibers were adopted. For each SCC grade, the zero-fiber specimens were prepared for comparison purposes. The shape of the test specimen was also one of the main investigated parameters in this study. In addition to the impact resistance, the compressive strength was obtained using 70 mm concrete cubes, while the modulus of rupture was obtained using the four-point bending test on 70×70×260 mm beams with a span of 210 mm and shear spans of 70 mm. To evaluate the fresh properties of the SCC mixtures, three fresh concrete properties were tested. For the slump flow, the T50 tests as per the requirements of ASTM C1611 [37] was followed. For the penetration ability, the rapid penetration test procedure recommended by ASTM C1712 [38] was adopted. Also, the slump flow and the T50 tests are recommended by EFNARC [2] to evaluate the acceptability of the SCC. The accepted values of the three tests are shown in Table 1 according to the requirements of ASTM and EFNARC standards.

Table 1. Accepted values of slump flow, T50 and rapid penetration tests.

Test	Limitations		ASTM Standard
	EFNARC	ASTM	
Slump flow (mm)	650–800	480–680* Or 530–740**	ASTM C1611
T50 (sec)	2–5		
Rapid Penetration (mm)		0–10 † 10–25††	ASTM C1712

* Single-operator precision; ** Double-operator precision; † Resistance to segregation; †† Moderately resistance to segregation

The impact tests were carried out using the repeated drop-weight test recommended by ACI 544-2R [12]. This testing technique uses the number of impact blows absorbed by the test specimen as an index for impact resistance. Based on the recommendations of ACI 544-2R [12], a drop weight of approximately 4.5 kg should fall freely from a drop height of approximately 450 mm on a steel ball of 63 mm diameter placed on the center of the surface of the test specimen. The impact loading is repeated until a visible crack is shown along the full diameter length of the top surface. During the test, the specimen is restricted in place using four steel lugs and two elastomer pieces on a stiff steel base. After cracking, the elastomers are removed and the impact test continues until failure. The number of blows required to cause the specimen to crack and fracture is then recorded. Fig. 1 shows the details of the testing apparatus.

In this study, the impact load was 4.5 kg and was dropped from a height of 700 mm. The drop height was increased from 450 mm to 700 mm in order to reduce the number of blows in each test due to the high strength characteristic of the SCC used in this study. The test specimen is a concrete disk having a diameter of 150 mm and a thickness of approximately 65 mm. However, as the shape of the specimen is one of the studied variables in this research, different shapes of specimens were tested under repeated impact loading. In addition to the disks, cube specimens of 70 mm side length and beam specimens of 70×70×260 mm were used to evaluate the impact resistance. To evaluate the shape effect, the thickness of all specimens was kept approximately equal which were 65 mm for the disks and 70 mm for the other specimens.

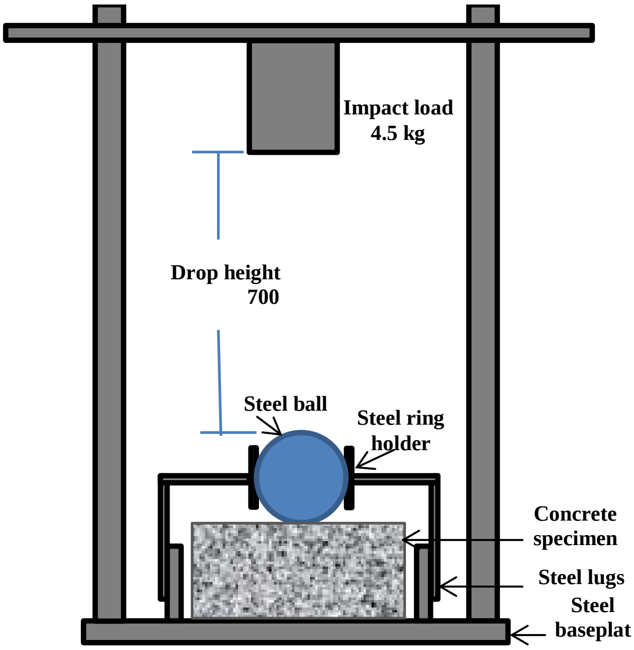


Figure 1. Apparatus of the repeated drop-weight impact test.

As mentioned above, two concrete design grades of 30 MPa (NS-SCC) and 50 MPa (HS-SCC) were adopted with four different fiber contents. Thus, a total of eight SCC mixes were adopted with weight proportions as listed in Table 2. The cement used in all mixtures was type R42.5 Portland cement, while the aggregate of the mixtures were crushed gravel and sand with grading, as shown in Fig. 2. The silica fume was used only with the high strength mixes as shown in Table 2 and 67 kg/m^3 of limestone powder was used with all SCC mixes. Cooper-coated straight micro steel fiber were used in this study with diameter and length of 0.2 mm and 15 mm and a tensile strength of 2600 MPa according to properties provided by the manufacturer. Also, the production of the SCC cannot be achieved without using of a high range water reducing agent (super plasticizer), for this reason Sika ViscoCrete-5930 was used in this study. To evaluate the impact resistance of the SCC mixes, six cubes, twelve beams, and six disks were cast from each concrete mix. Four cubes were also cast and tested to evaluate the compressive strength and eight beams were cast and tested to evaluate the modulus of rupture. Thus, a total number of 80 cubes, 160 beams, and 48 disks were cast and tested in this study. All specimens were cured in temperature-controlled water tanks for 28 days at a temperature of approximately 23 ^{o}C until testing date. Fig. 3 shows one SCC batch of specimens before and after demolding.

Table 2. Mix proportions per cubic meter of the SCC mixtures.

Mix	Design Grade (MPa)	Fiber volume Content (%)	Cement (kg/m³)	Sand (kg/m³)	Gravel (kg/m³)	Silica fume (kg/m³)	Water (kg/m³)	Water/Binder (W/B)	Superplasticizer S.P. (kg/m³)
M1	30	0	392	1039	574	–	181.3	0.395	9.3
M2	30	0.5	412	1063	503	–	190	0.397	13
M3	30	0.75	412	1063	503	–	190	0.397	13
M4	30	1.0	417	1052	468	–	204	0.42	14.3
M5	50	0	525	907	518	67	190	0.288	17
M6	50	0.5	525	907	518	67	209	0.317	17
M7	50	0.75	525	931	486	67	209	0.317	17
M8	50	1.0	525	931	486	67	209	0.317	17

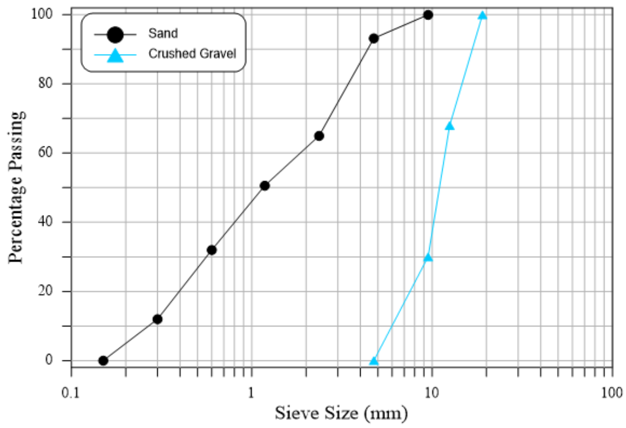
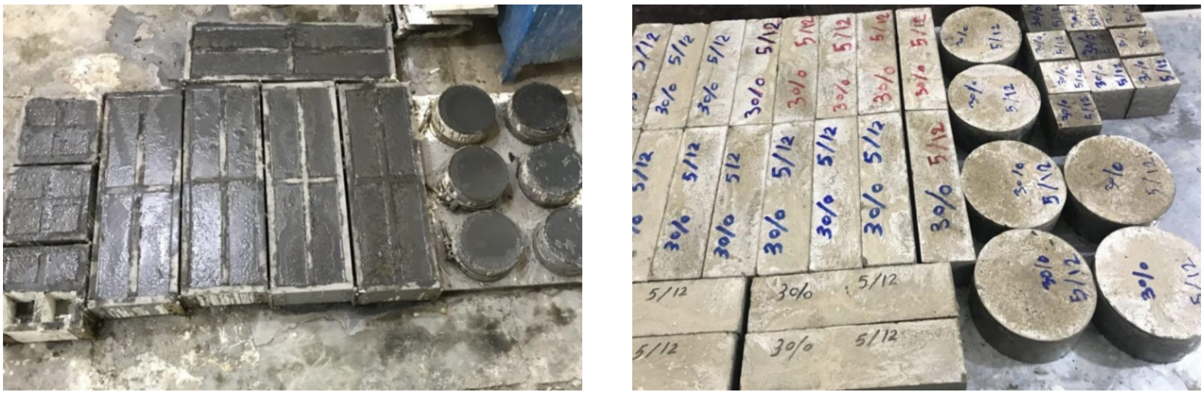


Figure 2. Seive analysis of sand and crushed gravel.



(a) **(b)**

Figure 3. A batch of cast disk, cube and beam specimens for one mixture (a) molding (b) demolded.

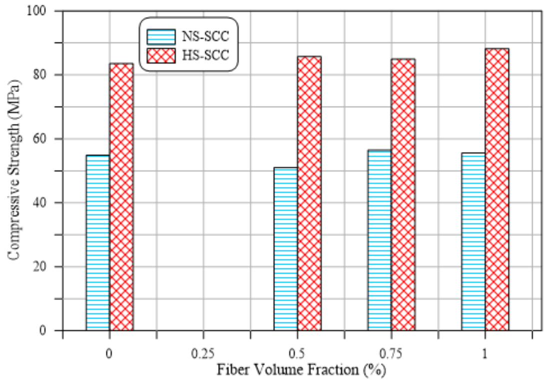
3. *Results and Discussion*

3.1. Fresh properties of SCC

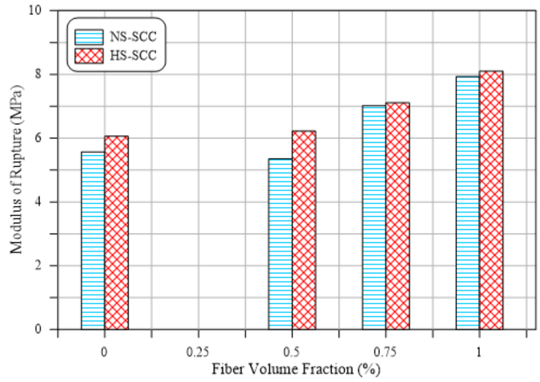
The fresh properties are the slump flow, T_{50} and rapid penetration tests. The test results of all mixtures showed good SCC behavior. The slump flow was within the limitations of EFNARC [2], where the slump flow records of the eight mixtures were in the range of 615 to 755 mm. On the other hand, the T50 records ranged from 2.5 to 4.9 seconds for all mixtures except one mixture, this means that these records are within the limitations of EFNARC [2]. For the HS-SCC with fiber content of 0.5, the T_{50} was 6 seconds, which is quite acceptable as it is quite close to the limitation, especially as the other fresh properties of this mixture were within the limitations. The records of the rapid penetration test of all mixtures were less than 9 mm, which reveals a good resistance to segregation, according to ASTM C1712 [38].

3.2. Compressive and flexural strength

The test results of 70 mm cube compressive strength of the eight mixes at the age of 28 days are shown in Fig. 4a and their corresponding beam flexural strength (modulus of rupture) is shown in Fig. 3b. Fig. 4a shows obviously that the compressive strength of the HS-SCC is higher than that of NS-SCC for all fiber contents. However, it also shows that within each grade of the SCC, the compressive strength was not clearly sensitive to the variation of steel fiber content and this behavior was stated within several previous studies [5, 16, 31, 39]. The compressive strength of NS-SCC was in the range of approximately 51 to 56 MPa, while that of HS-SCC was in the range of 83 to 88 MPa for all fiber contents. Fig. 4b shows that the modulus of rupture increases as the fiber content increases for both concrete grades. The modulus of rupture of NS-SCC increased from 5.57 MPa for plain specimens to 7.93 for 1 % fiber content. Similarly, the modulus of rupture of HS-SCC increased from 6.06 MPa for plain specimens to 8.1 for 1 % fiber content.



a)



b)

Figure 4. (a) Compressive strength and (b) modulus of rupture of NS-SCC and HS-SCC including different fiber contents.

3.3. Effect of fiber content and concrete strength on impact resistance

Fig. 5 shows the retained number of blows at the first crack stage and failure stage for different fiber contents. The results of disk specimens in Fig. 5a shows that the number of retained impact blows increases with the increase of fiber content for both NS-SCC and HS-SCC. This trend is observed for both the first crack stage and the failure stage. This behavior could be due to the important role of the steel fiber to delay the propagation and distribution of micro-cracks though out the hardened concrete matrix while under stresses. The number of impact blows for NS-SCC disk specimens with fiber contents of 0, 0.5, 0.75 and 1.0 % were 42, 106, 177 and 245 blows at the first crack stage, respectively. For HS-SCC disk specimens, the numbers of blows at the first crack stage were 54, 246, 302 and 408 for fiber contents of 0, 0.5, 0.75 and 1.0 %, respectively. The presence of discrete short fibers in the matrix is known to increase the tensile strength, energy absorption of the fibrous concrete and change the failure mode from brittle to more ductile by the potential of crack bridging [40–42], which improves the impact resistance of fibrous specimens showing larger number of impact blows before cracking or failure and more blows after first crack [43–46].

Fig. 5a also shows that for disk specimens, the impact resistance of HS-SCC was superior to that of NS-SCC. This behavior could be attributed to (a) the lower void ratio within the hardened matrix of HS-SCC than one of NS-SCC due to the higher water/cement ratio of NS-SCC, (b) the better aggregate-cement mortar interface of HS-SCC compare to NS-SCC due to the higher cement content of HS-SCC. The number of impact blows at first crack stage (N_1) and at failure stage (N_f) were clearly higher for the HS-SCC than those of NS-SCC for all fiber contents. Comparing the two curves at failure stage, the Nf values for NS-SCC and HS-SCC, respectively, were 43 and 56 for plain SCC, while the N_f values were 120 and 261, 212 and 343 and lastly 293 and 495 for fiber contents of 0.5, 0.75 and 1.0 %, respectively.

Fig. 5b shows N_1 and N_f results of the plain and fibrous NS-SCC and HS-SCC cube specimens. It is clear in the figure that both N_1 and N_f increase with the increase of steel fiber content, which confirms the results obtained from Fig. 5a for disk specimens. However, the differences in N_1 and N_f values between NS-SCC and HS-SCC are not as clear as for disk specimens. The figure shows that N_f records of NS-SCC fibrous cubes are mostly higher than N_1 records of HS-SCC. Such a result was not the case in Fig. 5a where HS-SCC was clearly superior to NS-SCC. Although, N_1 values of HS-SCC still obviously higher than their corresponding NS-SCC N_1 records and similarly N_f records of HS-SCC were higher than those of NS-SCC. N_1 records for NS-SCC were 3, 9 12, and 17 blows for fiber contents of 0, 0.5, 0.75 and 1.0 %, respectively, while their corresponding N_f records were 4, 22, 24 and 39 blows, respectively. On the other hand, N_1 records of HS-SCC were 7, 15, 24 35 blows for fiber contents of 0, 0.5, 0.75 and 1.0 %, respectively, while the corresponding N_f values were 12, 32, 41 and 56, respectively.

The results of the impact beam specimens confirm that regardless of the strength, the inclusion of micro-steel fiber results in higher impact resistance. Fig. 5c shows that the effect of concrete strength was almost negligible at the first crack stage, where poor impact resistance was observed for both NS-SCC and HS-SCC. The recorded N_1 values for NS-SCC beams at the first crack stage were 1, 3, 5 and 6, which are very close to the N_1 values for HS-SCC were 1, 4, 5 and 7 blows for steel fiber contents of 0, 0.5, 0.75 and 1.0 %, respectively. However, significant differences were recorded between NS-SCC and HS-SCC at the failure stage. The recorded N_f values for NS-SCC beams at first crack stage were 13, 15 and 16, while the N_f values for HS-SCC were 20, 24 and 26 blows for steel fiber contents of 0.5, 0.75 and 1.0 %, respectively.

Fig. 6 shows the improvement percentages in retained number of impact blows due the inclusion of micro-steel fiber compared to plain SCC for both NS-SCC and HS-SCC. The improvement or increase in impact resistance due to fiber inclusion was calculated as a percentage ratio, which equals the difference between number of blows of fibrous specimens (each fiber content) and nonfibrous reference specimens (0 % fiber) divided by the number of blows of nonfibrous reference specimens. For disk specimens, Fig. 6a shows an obvious increase behavior of the percentage increase in impact resistance with all steel fiber content. It is obvious that the percentage improvement of N_1 and N_f for both NS-SCC and HS-SCC increases as the fiber content increases.

Another notice is that the percentage increase in N values for HS-SCC was higher than those of NS-SCC at both first crack and failure stages. For example, the percentage increases in impact resistance of 0.75 % steel fiber content were 321, 393, 459 and 512 % for N_1 NS-SCC, Nf NS-SCC, N_1 HS-SCC and N_f HS-SCC, respectively. Similar trend of results was observed for the other fiber contents as shown in Fig. 6a. The percentage improvement in impact resistance for disk specimens ranged from approximately 150 % to approximately 780 % for all tested specimens.

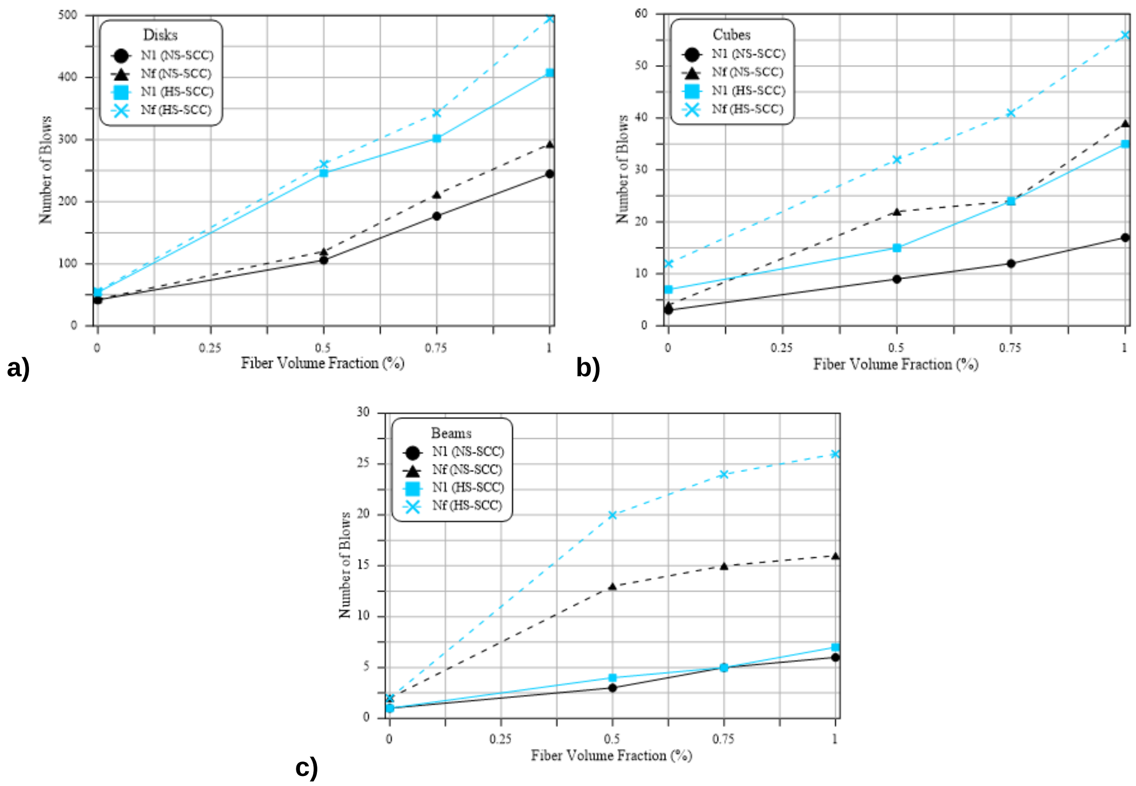


Figure 5 Number of blow at the first crack (N_1) and failure (N_f) stages for (a) disk, (b) cube and (c) beam specimens.

For cube specimens as shown in Fig. 6b, the results trend was different. The cube specimens showed that NS-SCC exhibited higher percentage of developments of impact resistance compared to HS-SCC for all fiber contents. The percentage improvement in N_f values was clearly higher than the N_1 values of NS-SCC, while no noticeable improvement was observed for HS-SCC. For a fiber content of 1.0 % for example, the percentage developments in impact resistance of cube specimens were 467, 875, 400 and 366 % for N_1 NS-SCC, N_f NS-SCC, N_1 HS-SCC and N_f HS-SCC, respectively. In general, the percentage of developments for cube specimens ranged from 114 % to 875 %, which is very close to the development range obtained by disk specimens. The beam specimens showed that the percentage development of N_f values were higher than the N_1 values for both of NS-SCC and HS-SCC. Another notice is that the percentage developments of N_f of HS-SCC were the highest for all fiber contents among the beam specimens and more than those obtained by disk or cube specimens. The percentage of developments in impact resistance of beam specimens were in the range of 200 to 1200 % as shown in Fig. 6c, while the minimum percentage development of Nf for HS-SCC was 900 %.

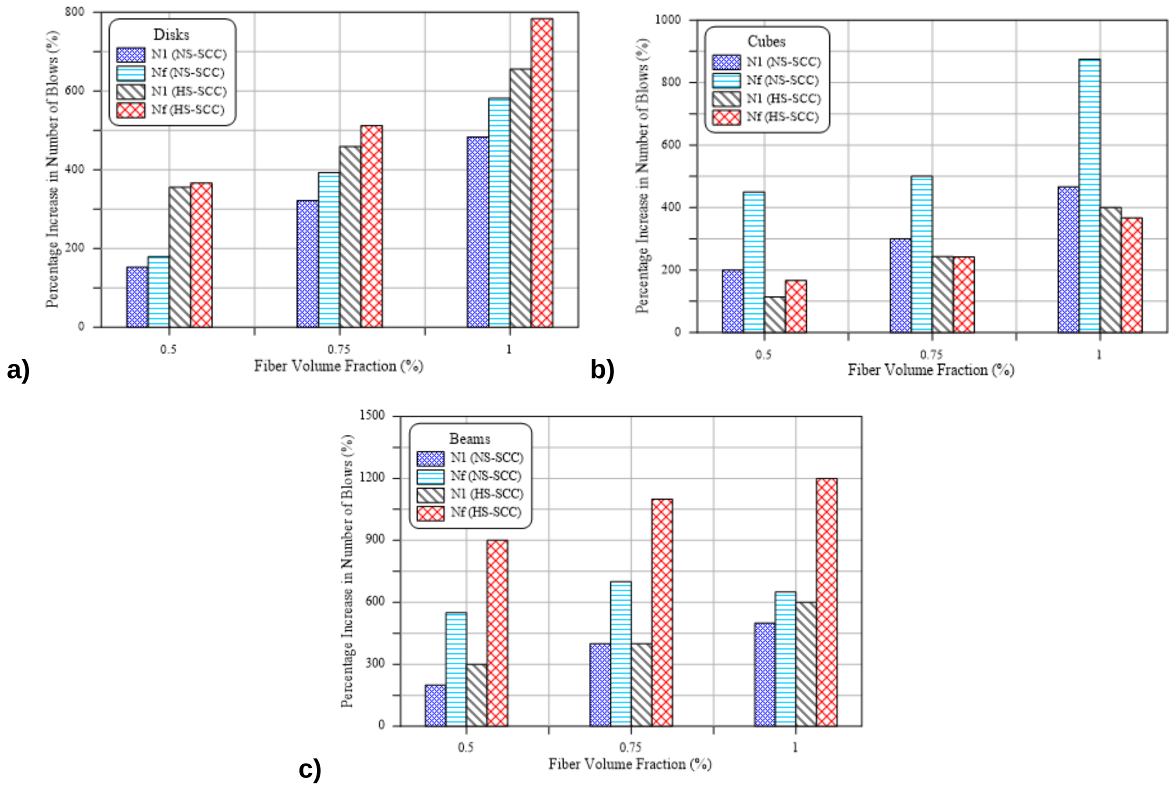


Figure 6. Percentage increase due to fiber addition in number of blows at first crack (N_1) and failure (N_f) stages for (a) disk, (b) cube and (c) beam specimens.

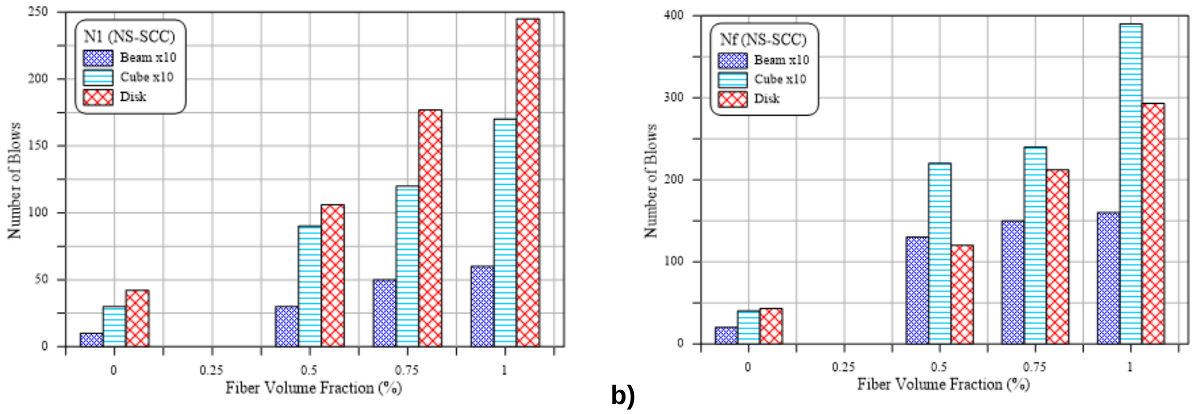
3.4. Effect of specimens shape on the repeated impact test

As mentioned earlier, most of the experimental works on repeated impact tests were either conducted using the ACI 544-2R method, which only uses disc specimens or flexural impact tests on beams. However, few studies used repeated drop-weight impact tests on different configurations of test specimens. Zhu et. al. [39] conducted drop-weight impact tests on U-shaped specimens. Zhu et al. [35] used a drop height of 400 mm and a drop weight of less than 1 kg. Wang and Chouw [40] used cylinder test specimens of 100 mm diameter and 200 mm with a drop weight of 40 kg and drop heights ranging from 500 mm to 2000 mm. The current study and as mentioned above (Section 3), in addition to the ACI 544-2R disc specimens, beams and cubes were tested using the testing procedure of ACI 544-2R. The depth of the beam and cube specimens (70 mm) was chosen to be comparable to the depth of the disc specimens (65 mm).

Fig. 7 and 8 compare the impact resistances of the three tested shapes of specimens (disk, cube and beam) for the two grades of SCC in terms of both N_1 and N_f values. It is disclosed in the previous section that, in general, disk specimens withstand a much higher number of blows compared to cube or beam specimens. This experimental result is shown clearly in Fig. 7 and 8, where N_1 and N_f values of disk specimens are compared with 10 times their corresponding values of cube and beam specimens. The figures show that the N_1 and N_f records of disk specimens with the variation of fiber content were more systematic compared to cube or beam specimens. Fig. 7a shows that in the case of N_1 values for NS-SCC, the disk records were clearly higher than 10 times those of cube and beam specimens for all fiber contents. However, beam specimens showed the lowest recorded values. The N_1 values for disk, cube and beam specimens were 42, 3 and 1, respectively, for plain SCC, while the corresponding N_f values were 43, 4 and 2, respectively, as shown in Fig. 7b. Similarly, the N_1 values were 245, 17 and 6, respectively, for fiber content of 1.0 %, while the corresponding N_f values were 293, 39 and 16, respectively. Fig. 7b shows that the variation of N_f values for NS-SCC between the three shapes of specimens is not as uniform as that of

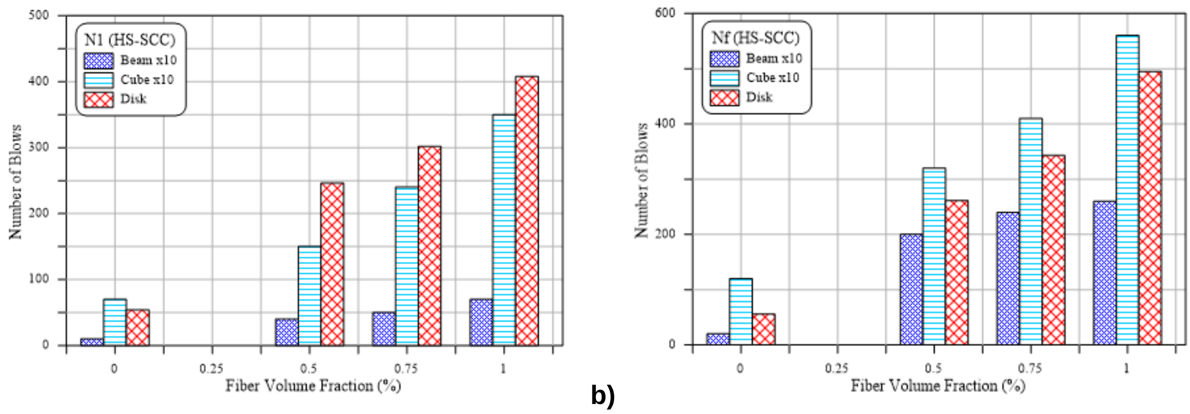
N_1. The cube records multiplied by 10 of fibrous specimens were higher than those of beam specimens and the records of disks, while this was not the case for plain SCC specimens. On the other hand, N_1 results of HS-SCC shown in Fig. 8a shows approximately similar uniform trend as that of Fig. 7a, while Fig. 7b of N_f records of HS-SCC shows similar non uniform variation as that of Fig. 7b. Fig. 9 shows the fiber content effect on the difference between N_f and N_1 of the three shapes of specimens in the case of NS-SCC and HS-SCC. Fig. 9a and Fig. 9b show that the disk specimens absorbed higher number of impact blows after first crack than cube or beam specimens. Disk specimens also show continuous increase in the number of absorbed blows after first crack as fiber content increases. For cube and beam specimens, the inclusion of fiber was effective in terms of increasing the number of absorbed blows, however, no noticeable effect of fiber content increase from 0.5 % to 1.0 % which is represented by the semi-horizontal lines. The results represented in Fig. 9 confirm the superiority of disk specimens over cube and beam specimens to represent the drop-weight impact test.

To check the reliability of the repeated drop-weight impact test results, linear correlations between N_1 and N_f were adopted for each shape of specimens. Fig. 10a, b and c show the linear correlations between N_1 and N_f for both NS-SCC and HS-SCC for the disk specimens, cube specimens and beam specimens, respectively. Fig. 10a shows that the linear correlations between N_1 and N_f have strong coefficient of determination (R2) of more than 0.99 for both NS-SCC and HS-SCC. While, the R-squared values of cube specimens were 0.966 and 0.974 for NS-SCC and HS-SCC, respectively and those ones of beam specimens were 0.846 and 0.901 for NS-SCC and HS-SCC, respectively. Note that the high R-squared value reveals the excellent goodness of the linear fit between N_1 and N_f of disk specimens. Thus, it is clear that the impact tests of disk specimens showed more consistent results compared to those obtained from cube and beam specimens. Considering the uniformity of the variation trend of the number of retained blows with fiber content, the absorbed blows after first crack with fiber content and the goodness of the relation between N_1 and N_f as judgment factors, it is concluded that disk specimen can be considered as a better choice for repeated drop-weigh impact test than beam and cube specimens.



a) b)

Figure 7. Number of blows for different shape NS-SCC specimens (a) at first crack stage (N1) and (b) at ultimate failure stage (Nf).



a) b)

Figure 8. Number of blows for different shape HS-SCC specimens (a) at first crack stage (N1) and (b) at ultimate failure stage (Nf).

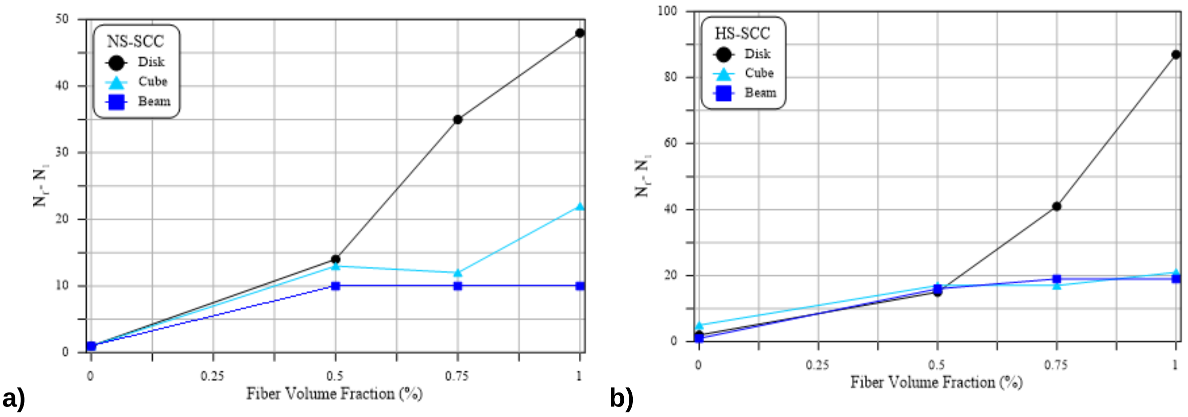


Figure 9. Relation of (Nf – N1) and fiber volume fraction for different specimen shapes for (a) NS-SCC and (b) HS-SCC.

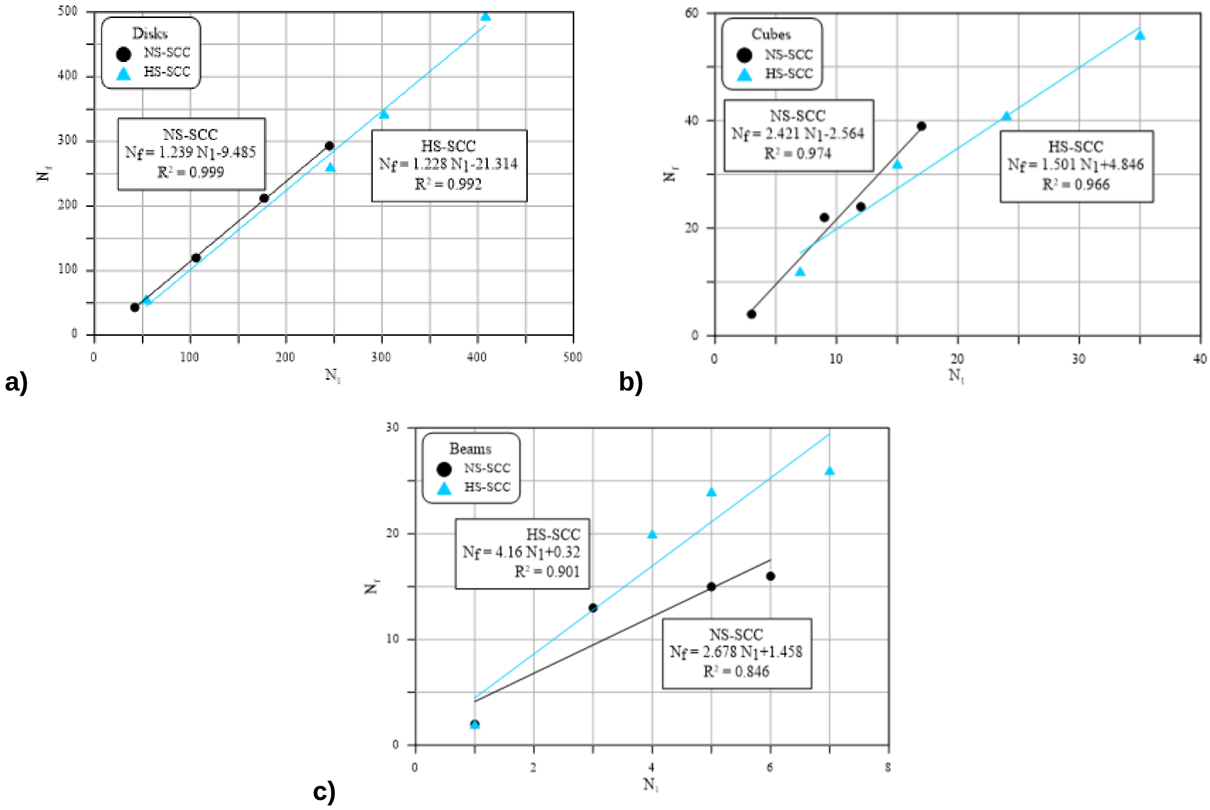


Figure 10. Linear relationships of N_1 and N_f for NS-SCC and HS-SCC for (a) disk, (b) cube and (c) beam specimens.

3.5. Relationship between impact resistance and flexural strength

As presented in section 4.1, the compressive strength was slightly affected by the presence of fibers, while the flexural strength showed a continuous increase with the increase of fiber content. Also, there is no relation can be found in the literature to show the correlation between the impact resistance and the flexural strength. Accordingly, in this study, the flexural strength was chosen to show the relationship between concrete strength and impact absorption capacity of the tested specimens in terms of N_1 and N_f. Such a relation can be used to estimate the impact resistance of fiber-reinforced concrete by conducting a simple test procedure of the flexural test. Due to the limited number of data in this study, test results of other studies were used to create the relationship between the impact resistance and the flexural strength. Most of the available studies in the literature that provide data N_1, N_f and flexural strength were limited to normal strength concrete and disk shape specimens. For this reason, the test results of HS-SCC, cube specimens and beam specimens of the current study were excluded from the correlation. In addition to the test results of the current study, results of Ismail and Hassan [31], AbdelAleem et al. [32] and Mastali et al. [34] were used to create the correlation as shown in Table 3 and Fig. 11. This figure shows that the relationship between impact resistance and flexural strength can be represented by the simple linear correlation. The figure also shows that the goodness of the fit slightly varies from N_1 and N_f. For N_1, the linear relation shows an R-squared value of approximately 0.856, while this value increases to 0.87 for N_f. Equations 1 and 2 below show the linear correlation between the number of blows (impact resistance) and flexural strength for N_1 and N_f, respectively.

$$N_1 = 165.2\, f_r - 789.1 \qquad (R^2 = 0.857) \tag{1}$$

$$N_f = 191.5\, f_r - 920.5 \qquad (R^2 = 0.874) \tag{2}$$

Table 3. Test results used to create relationship between impact resistance and flexural strength.

Resource of Data	Number of Blows at First crack stage, N_1	Number of Blows at First crack stage, N_1	Flexural Strength, f_r (MPa)
Current Study	105	110	5.4
	145	148	5.6
Ismail and Hassan [31]	38	47	4.88
	56	71	5.36
	76	98	5.98
AbdelAleem et al. [32]	141	143	5.7
	185	203	5.7
	275	315	6.2
	243	273	6
	201	234	5.9
	337	391	6.7
Mastali et al. [34]	434	496	7.46

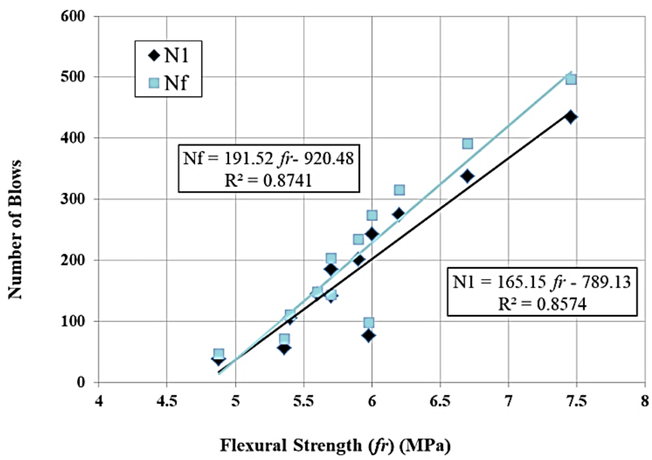


Figure 11. Linear correlations between number of blows and flexural strength for N_1 and N_f.

4. Conclusions

In this study, an experimental work was carried out to evaluate the impact resistance of normal strength and high strength self-compacting concretes incorporating micro-steel fibers. The impact resistance was evaluated using the recorded number of repeated impact blows at first crack and failure stages based on the recommendations of ACI 544-2R, using three shapes of specimen disk, cube and beam. Based on the experimental results of this study, it can be concluded:

1. The addition of steel fibers to the SCC enhances its impact resistance significantly, where the retained number of impact blows increased continuously as the fiber volumetric content increased from 0 to 1.0 %. For example, in the case of disk specimens the number of blows at first crack stage N_1 was recorded 42, 106, 177 and 245 for NS-SCC with steel volume content of 0 %, 0.5 %, 0.75 % and 1.0 %, respectively. Similar sequence of results was obtained for number of blows at failure stage N_f values.

2. The inclusion of micro-steel fibers led to noticeably high percentage improvement in the impact resistance of both NS-SCC and HS-SCC. The percentage improvement in impact resistance ranged from

more than 110 % to 1200 % for all tested specimens. The highest effect of micro-steel fibers on impact resistance was recorded for beam specimens where the minimum percentage improvement was 900 %.

3. HS-SCC retained significantly higher N_f records than NS-SCC for all types of specimens and at all fiber contents. Similarly, N_1 values for HS-SCC were mostly higher than those of NS-SCC. Considering the disk specimen as an example, N_f records for NS-SCC were 43, 120, 212 and 293 blows for fiber volume contents of 0, 0.5, 0.75 and 1.0 %, respectively, while the corresponding values for HS-SCC were 56, 261, 343 and 495 blows, respectively.

4. Disk specimens recommended by ACI 544-2R-2R showed high N_1 and N_f values compared to cube and beam specimens. In general, the N_1 and N_f records of disc specimens were approximately 10 times those of cube specimens, which were approximately twice those of beam specimens.

5. The disk specimens showed more systematic variation in N_1 and N_f values with the variation of fiber content than cube and beam specimens. Similar result were obtained for the relation of the absorbed impact blows after first crack in addition to the correlation between N_1 and N_f. Based on the abovementioned parameters, disk specimens can be considered as a better choice for drop-weight loading impact test than beam and cube specimens.

6. A relationship between the impact resistance and the flexural strength of fiber reinforced concrete was created for the first time. This relation can be used to estimate the number of impact blows of FRC by simple test procedure of flexural strength.

References

1. ACI Committee 237. Self-consolidating concrete. (ACI 237R-07). American Concrete Institute, USA. 2007. Pp. 1–30.
2. EFNARC. Specifications and guidelines for self-compacting concrete. EFNARC, UK. 2002. Pp. 1–32.
3. Sahmaran, M., Yurtseven, A., Yaman, O. Workability of hybrid fiber reinforced self-compacting concrete. Building and Environment. 2005. 40. Pp. 1672–1677.
4. Aslani, F., Nejadi, S. Self-compacting concrete incorporating steel and polypropylene fibers: compressive and tensile strengths, modulus of elasticity and rupture, compressive stress-strain curve, and energy dissipation under compression. Composites: Part B. 2013. 53. Pp. 121–133.
5. Abid, S.R., Hilo, A., Ayoob, N.S., Daek, Y.H. Underwater abrasion of steel fiber-reinforced self-compacting concrete. Case Studies in Construction Materials. 2019. e00299.
6. Travush, V.I., Konin, D.V., Krylov, A.S. Strength of reinforced concrete beams of high-performance concrete and fiber reinforced concrete. Magazine of Civil Engineering. 2018. 77(1). Pp. 90–100.
7. Ayoob, N.S., Abid, S.R, Hilo, A.N., Daek, T.H. Water-Impact Abrasion of Self-Compacting Concrete. Magazine of Civil Engineering. 2020. 4. Pp. 60–69.
8. Nili, M., Afroughsabet, V. Combined effect of silica fume and steel fibers on the impact resistance and mechanical properties of concrete. International Journal of Impact Energy. 2010. 37. Pp. 879–886.
9. Haridharan, M.K., Matheswaran, S., Murali, G., Abid, S.R., Fediuk, R., Amran, Y.H., Abdelgader, H.S. Impact response of two-layered grouted aggregate fibrous concrete composite under falling mass impact. Construction and Building Materials. 2020. 263. 120628.
10. Salaimanimagudam, M.P., Suribabu, C.R., Murali, G., Abid, S.R. Impact response of hammerhead pier fibrous concrete beams designed with topology optimization. Periodica Polytechnica Civil Engineering. 2020. https://doi.org/10.33-11/PPci.16664
11. Abirami, T., Loganaganandan, M., Murali, G. Fediuk, R., Sreekrishna, R.V., Vignesh, T., Januppriya, G., Karthikeyan, K. Experimental research on impact response of novel steel fibrous concretes under falling mass impact. Construction and Building Materials. 2019. 222. Pp. 447–457.
12. ACI 544-2R. Measurement of properties of fiber reinforced concrete. American Concrete Institute. 1999. USA.
13. Yildirim, S.T., Ekinci, C.E., Findik, F. Properties of hybrid fiber reinforced concrete under repeated impact loads. Russian Journal of Nondestructive Testing. 2010. 46. Pp. 82–92.
14. Nili, M., Afroughsabet, V. The effects of silica fume and polypropylene fibers on the impact resistance and mechanical properties of concrete. Construction and Building Materials. 2010. 24. Pp. 927–933.
15. Murali, G., Abid, S.R., Amran, Y.H.M., Abdelgader, H.S., Fediuk, R., Susrutha, R., Poonguzhali, K. Impact performance of novel multi-layered prepacked aggregate fibrous composites under compression and bending. Structures. 2020. 28. Pp. 1502–1515.
16. Nataraja, M.C., Dhang, N., Gupta, A.P. Statistical variations in impact resistance of steel fiber-reinforced concrete subjected to drop weight test. Cement and Concrete Research. 1999. 29. Pp. 989–995.
17. Song, P.S., Wu, J.C., Hwang, S., Sheu, B.C. Assessment of statistical variations in impact resistance of high-strength concrete and high-strength steel fiber-reinforced concrete. Cement and Concrete Research. 2005. 35. Pp. 393–399.
18. Bard, A., Ashour, A.F., Platten, A.K. Statistical variations in impact resistance of polypropylene fiber-reinforced concrete. International Journal of Impact Engineering. 2006. 32. Pp. 1907–1920.
19. Rahmani, T., Kiani, B., Shekarchi, M., Safari, A. Statistical and experimental analysis on the behavior of fiber reinforced concretes subjected to drop weight test. Construction and Building Materials. 2012. 37. Pp. 360–369.
20. Abid, S.R., Abdul-Hussein, M.L., Ayoob, N.S., Ali, S.H., Kadhum, A.A. Repeated drop-weight impact tests on self-compacting concrete reinforced with micro-steel fiber. Heliyon. 2020. 6. Pp. 1–11.

21. Abid, S.R., Abdul-Hussein, M.L., Ali, S.H., Kazem, A.F. Suggested modified testing techniques to the ACI 544-R repeated drop-weight impact test. Construction and Building Materials. 2020. 6. Pp. 1–16.
22. Asrani, N.P., Murali, G., Parthiban, K., Surya, K., Prakash, A., Rathika, K., Chandru, U. A feasibility of enhancing the impact resistance of hybrid fibrous geopolymer composites: Experiments and modelling. Construction and Building Materials. 2019. 203. Pp. 56–68.
23. Jabir, H.A., Abid, S.R., Abdul-Hussein, M.L., Ali, S.H. Repeated drop-weight impact tests on RPC containing hybrid fibers. Applied Mechanics and Materials. 2020. 897. Pp. 49–55.
24. Mohammadi, Y., Carkon-Azad, R., Singh, S.P., Kaushik, S.K. Impact resistance of steel fibrous concrete containing fibers of mixed aspect ratio. Construction and Building Materials. 2009. 23. Pp. 183–189.
25. Rao, M.C., Bhattacharyya, S.K., Barai, S.V. Behaviour of recycled aggregate concrete under drop weight impact load. Construction and Building Materials. 2011. 25. Pp. 69–80.
26. Al-Tayeb, M.M., Abu Bakar, B.H., Ismail, H., Akil, H.M. Impact resistance of concrete with partial replacements of sand and cement by waste rubber. Polymer-Plastics Technology and Engineering. 2012. 51. Pp. 1230–1236.
27. Dey, V., Bonakdar, A., Mobasher, B. Low-velocity flexural impact response of fiber-reinforced aerated concrete. Cement & Concrete Composites. 2014. 49. Pp. 100–110.
28. Zhang, W., Chen, S., Zhang, N., Zhou, Y. Low-velocity flexural impact response of steel fiber reinforced concrete subjected to freeze-thaw cycles in NaCl solution. Construction and Building Materials. 2015. 101. Pp. 522–526.
29. Noaman, A.T., Abu Bakar, B.H., Akil, H.M. The effect of combination between crumb rubber and steel fiber on impact energy of concrete beams. Procedia Engineering. 2015. 125. Pp. 825–831.
30. Kahlil, E., Abd-Elmohsen, M., Anwar, A.M. Impact resistance of rubberized self-compacted concrete. Water Science. 2015. 29. Pp. 45–53.
31. Ismail, M.K., Hassan, A.A. Impact resistance and mechanical properties of self-consolidating rubberized concrete reinforced with steel fibers. ASCE Journal of Materials in Civil Engineering. 2017. 29. Pp. 1–14.
32. AbdelAleem, B.H., Ismail, M.K., Hassan, A.A. The combined effect of crumb rubber and synthetic fibers on impact resistance of self-consolidating concrete. Construction and Building Materials. 2018. 162. Pp. 816–829.
33. Ding, Y., Li, D., Zhang, Y., Azevedo, C. Experimental investigation on the composite effect of steel rebars and macro fibers on the impact behavior of high performance self-compacting concrete. Construction and Building Materials. 2017. 136. Pp. 495–505.
34. Mastali, M., Dalvand, A., Sattarifard, A. The impact resistance and mechanical properties of reinforced self-compacting concrete with recycled glass fiber reinforced polymers. Journal of Clean Production. 2016. 124. Pp. 312–324.
35. Mastali, M., Dalvand, A. The impact resistance and mechanical properties of self-compacting concrete reinforced with recycled CFRP pieces. Composites: Part B, 2016. 92. Pp. 360–376.
36. Mastali, M., Dalvand, A., Sattarifard, A. The impact resistance and mechanical properties of the reinforced self-compacting concrete incorporating recycled CFRP fiber with different lengths and dosages. Composites: Part B. 2017. 112. Pp. 74–92.
37. ASTM C1611. Standard test method for slump flow of self-consolidating concrete. ASTM International, West Conshohocken, USA. 2014.
38. ASTM C1712. Standard test method for rapid assessment of static segregation resistance of self-consolidating concrete using penetration test. ASTM International, West Conshohocken, USA. 2014.
39. Almusallam, T.H., Abadel, A.A., Al-Salloum, Y.A., Siddiqui, N.A., Abbas, H. Effectiveness of hybrid-fibers in improving the impact resistance of RC slabs. International Journal of Impact Engineering. 2015. 81. Pp. 61–73.
40. Abbass, A., Abid, S., Özakça, M. Experimental investigation on the effect of steel fibers on the flexural behavior and ductility of high-strength concrete hollow beams. Advances in Civil Engineering. 2019. 2019. Pp. 1–13.
41. Arna'ot, F.H., Abbass, A.A., Abualtemen, A.A., Abid, S.R., Özakça, M. Residual strength of high strength concentric column-SFRC flat plate exposed to high temperatures. Construction and Building Materials. 2017. 154. Pp. 204–218.
42. Abbass, A.A., Abid, S.R., Arna'ot, F.H., Al-Ameri, R.A., Özakça, M. Flexural response of hollow high strength concrete beams considering different size reductions. Structures. 2019. 23. Pp. 69–86.
43. Wang, S., Le, H.T.N., Poh, L.H., Feng, H., Zhang, M-H. Resistance of high-performance fiber-reinforced cement composites against high-velocity projectile impact. International Journal of Impact Engineering. 2016. 95. Pp. 89–104.
44. Kantar, E., Yuen, T.Y.P., Kobya, V., Kuang, J.S. Impact dynamics and energy dissipation capacity of fibre-reinforced self-compacting concrete plates. Construction and Building Materials. 2017. 138. Pp. 383–397.
45. Luccioni, B., Isla, F., Codina, R., Ambrosini, D., Zerbino, R., Giaccio, G., Torrijos, M.C. Effect of steel fibers on static and blast response of high strength concrete. International Journal of Impact Engineering. 2017. 107. Pp. 23–27.
46. Wang, W., Chouw, N. The behaviour of coconut fiber reinforced concrete (CFRC) under impact loading. Construction and Building Materials. 2017. 134. Pp. 452–461.

Contacts:

Sallal Abid, sallal@uowasit.edu.iq
Sajjad Ali, sajad_alzuhery@yahoo.com
Hussam Goaiz, hussam@uowasit.edu.iq
Thaar Al-Gasham, thaar@uowasit.edu.iq
Ahmed Kadhim, alkadhum.wasit@gmail.com