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Recent Literature on Steel Fiber Improvement of Repeated Impact Strength of Fibrous Concrete

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Abstract

Concrete is a brittle material when subjected to design and accidental impact loads, which are expected along the life span of the structure. To improve the impact performance of concrete, steel fibers are used as short discrete material reinforcing elements. Among the available impact test, the ACI 544-2R repeated impact test is considered as the simplest and cheapest test procedure that needs no sophisticated sensors and costly techniques, which is used as a qualitative tool to evaluate the impact of fibrous concrete. This article introduces a state-of-the-art literature review of the repeated impact performance of steel fiber-reinforced concrete. Rich literature of different steel fiber-reinforced concrete types is reviewed and the effect of steel fibers on the retained cracking and failure impact numbers is highlighted. The sole effects of the geometrical parameters of steel fibers were analyzed in addition to fiber content. Based on the reviewed literature works, it can be summarized that increasing the fiber content increases the impact strength, and using longer fibers affords deeper anchorage lengths inside the cement paste across cracks, which postpones their widening and improves the impact resistance in terms of recorded cracking and failure numbers.

Keywords: Steel fibers; Repeated impact; ACI 544-2R; Fibrous concrete; Cracking; Fiber length

الخلاصة:

الخرسانة تعتبر مادة هشة عند تعرضها الى أحمال الصدمة التصميمية أو الطارئة المتوقع حدوثها خلال عمر المنشأ التشغيلي. لتحسين أداء الخرسانة تحت أحمال الصدمة, تستخدم الألياف الحديدية كناصر تسليح قصيرة متقطعة, و يعتبر فحص الصدمة المتكرر الموصى به من قبل ACI 544-2R من أبسط و أرخص الفحوص للتقييم النوعي لأداء الخرسانة تحت تأثير أحمال الصدمة حيث لا يحتاج الفحص الى المتحسسات المعقدة والمكلفة. يقدم هذا البحث مراجعة حديثة للبحث العلمي المتعلق بأداء الخرسانة المسلحة بأنواع متعددة من ألياف الحديد ويسلط الضوء على تأثير الألياف على مقاومة التشقق والفشل تحت تأثير أحمال الصدمة, كما تم تحليل التأثير المنفرد لشكل و أبعاد الألياف بالإضافة الى كميتها في الخلطة., و بالاعتماد على تحليل البحوث السابقة, يمكن الاستنتاج أن زيادة كمية ألياف الحديد تزيد من مقاومة الخرسانة لأحمال الصدمة, واستعمال ألياف أطول يوفر طول طمر كافي داخل عجينة الاسمنت عبر الشق والذي يؤخر توسع الشق ويؤدي الى زيادة مقاومة الصدمة حيث يزيد عدد الطرقات المسجلة عند التشقق و الفشل.

1. INTRODUCTION

Impact forces can be classified as design and accidental loads, where some structures and structural elements are designed to absorb high impact energies. Examples are the case of landing areas of aircrafts in airports [1-3], protective military and sensitive function structures and bankers where high impact explosive and projectile impact forces are a major design load case [4-6]. Some downstream parts of hydraulic structures are also designed to receive high impact loads from the high velocity water to disturb the energy of the hydraulic jump [7, 8]. In other typical daily used structures, accidental impact forces are probable along their live span. In parking garages for instance, repeated impacts of moving vehicles are expected on columns and walls [9, 10]. The impact strength is evaluated using different tests as detailed in the ACI 544-2R committee [11]. The most famous of these tests is the instrumented drop-weight test, which is usually used to estimate the impact strength of full-scale structural elements [12-15]. Explosive tests [16, 17] and projectile tests [18, 19] are other types of impact tests that are mostly used for the evaluation of the resistance of military or protective structural elements to such kinds of impact loads. All of the previous three types of impact tests are very costly and are not easy to perform, where sophisticated sensors and testing setups are essential. Charpy pendulum is another type of impact test that is used for different industrial and structural purposes [20, 21]. On the other hand, the ACI 544-2R [11] introduced the repeated impact test as a simple and cheap procedure to qualitatively evaluate the impact resistance of fibrous concrete mixtures. Owing to its simplicity and low cost setup, several studies used this test to study the effect of the inclusion of different types of fibers [22-34], recycled rubber [35, 36] and other materials on the impact performance of different concrete types.

Different types of synthetic, metallic and natural fibers were utilized in different concrete types and structural elements to improve the ability of concrete to withstand tensile stresses. However, steel fibers is the most typically used type in concrete structures due to its high tensile strength and bond strength with the surrounding cement paste, which enable it to work as an active micro and macro internal reinforcing element that prevent crack propagation and widening. Rich literature revealed the superior activity of steel fibers as crack arresting elements that improve the materials and structural behavior under the different types of structural loads. Previous studies showed that steel fibers can impressively alter the flexural failure from brittle to ductile, improve the toughness and boost the flexural strength [37-39]. Other researchers reported a proven affectivity of steel fibers at enhancing the tensile strength [40-42] and shear strength [43-47] of concrete, while others reported superior durability and abrasion resistance due to the incorporation of steel fibers [48, 49].

Steel fibers were distinguished by many previous and recent studies as a very effective internal reinforcement that significantly improves the impact resistance and alters the behavior from brittle to ductile under impact loads. Extensive recent research work [50-86], which is detailed in the following sections, was conducted on the impact performance of steel fiber-reinforced concrete using the ACI 544-2R repeated impact test, in which different types and lengths of steel fibers were investigated. However, to the best of the author’s knowledge, no study has tried to collect the literature work on the repeated impact performance of steel fiber-reinforced concrete. Therefore, the current study introduces a state-of-the-art literature review about the previous and recent experimental works where steel fibers were used to improve the repeated impact performance of concrete. The article covers mostly all of the available literature on this topic, which makes it a useful guide for interested researchers to plan their future works by defining the gaps of knowledge on the topic. This article reviews studies on different types of concrete including normal and high strength concrete, high performance concrete, self compacting concrete, rubberized concrete and preplaced aggregate concrete. Furthermore, the effects of the geometrical parameters and the volumetric contents of fibers on the repeated impact performance were also investigated.

2. LITERATURE REVIEW

Several studies were conducted during the last three decades to evaluate the impact performance of steel fiber-reinforced concrete using the ACI 544-2R test recommendations. Nataraja et al. [50] conducted an experimental study to evaluate the statistical variation of the repeated impact test results. One concrete mixture was adopted with a normal nominal compressive strength, which was mixed with or without steel fibers. The steel fibers were crimped with 0.5 mm diameter and 27.5 mm length and were used at a volumetric content of 0.5%. Song et al. [51] prepared steel fiber-reinforced normal strength concrete specimens, which were tested under repeated impact to investigate the scattering of the test results. A 0.5% volume content of 40 mm-length hooked-end steel fibers were used in the study. In another study, Song et al. [52] introduced high-strength plain and steel fiber-reinforced concrete mixtures to study the statistical variation of the repeated impact test records. In the fibrous mixture, 1.0% volume content of hooked-end steel fibers was used, which were 35 mm long. Rahmani et al. [53] attempted to evaluate the statistical variation of the cracking and failure impact results of concrete reinforced with different types of fibers including steel fibers. Hooked-end steel fibers with 35 mm length were used in the study to produce a steel fiber-reinforced concrete mixture with 0.5% volume fraction, while a similar plain mixture was prepared for comparison purposes. Fig. 1 summarizes the obtained result variations in terms of the coefficient of variation (COV) for the cracking (Ncr) and failure (Nf) impact numbers of the four studies. To summarize, the figure shows that for each of the three studies, the scattering of Ncr was generally higher than the scattering of the Nf results. The figure also reveals that as the recorded impact numbers increased, the result variation decreased in most cases.

Nili and Afroughsabet [54] used the ACI 544-2R repeated impact test to investigate the influence of silica fume and steel fibers on the impact response of concrete. They used 60 mm-length hooked-end steel fibers at two dosages of 0.5 and 1.0% by volume with or without partial cement replacement by silica fume. The authors adopted two concrete grades represented by two water-cement ratios and different cement contents, which resulted in concrete compressive strength ranged from approximately 41 to 70 MPa. Ismail and Hassan [55] investigated the repeated impact response of rubberized self-compacting concrete incorporating different volume fractions of steel fibers of 0.35, 0.5, 0.75 and 1.0% in addition to 0%. They used hooked-end steel fibers with two lengths of 35 and 60 mm, while crumb rubber was used as partial replacements of the fine aggregate. Yildirim et al. [56] conducted experimental tests to evaluate the relation between repeated impact strength and ultra-sonic pulse velocity. The authors tested specimens from many fibrous mixtures including three steel fiber-reinforced mixtures, where 60 mm length hooked-end steel fibers were adopted at three volume dosages of 0.5, 0.75 and 1.0%. Mohammadhosseini et al. [57] investigated the repeated impact strength of concrete incorporating waste metalized plastic fibers. The fibers were shredded from waste materials as strip fibers of 2 mm width and 20 mm length and were added to the mixture at different volume contents ranging from 0 to 1.25%. The authors reported continuous improvements in the cracking and failure impact numbers as the fiber content was increased.

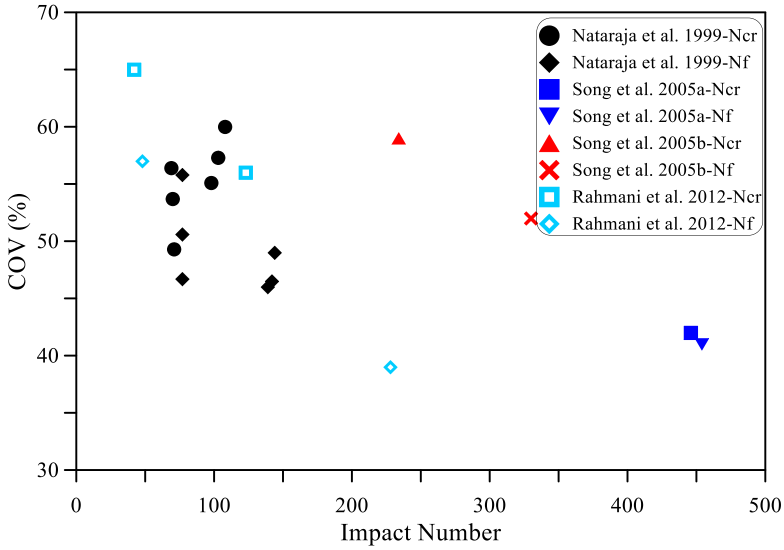
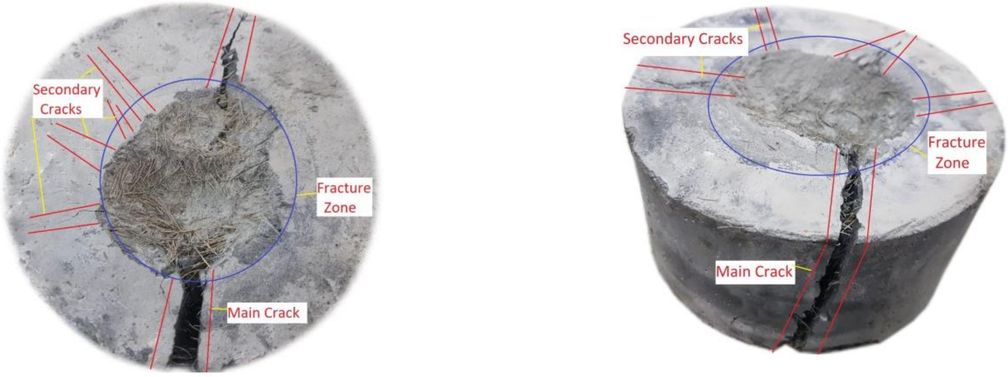


Fig. 1 Impact number-COV relations of statistical literature studies

Abid et al. [58] used the ACI 544-2R test to evaluate the residual repeated impact strength of steel fiber-reinforced concrete after high temperature exposure. Hooked end steel fibers with 35 mm length were used at two dosages of 0.5 and 1.0% and compared with similar plain specimens. The authors revealed that the destructive effect of high temperature exposure on impact strength is significantly higher than on the other mechanical properties. They revealed that the impact strength almost vanished after exposure to 400 °C. Results of tests by Mehdipour et al. [59] confirm the destructive quick deterioration of repeated impact strength under fire temperatures, where 50 mm length steel fibers were used in different mixtures. The same conclusion was also drawn by other researchers [60, 61] for other concrete types.

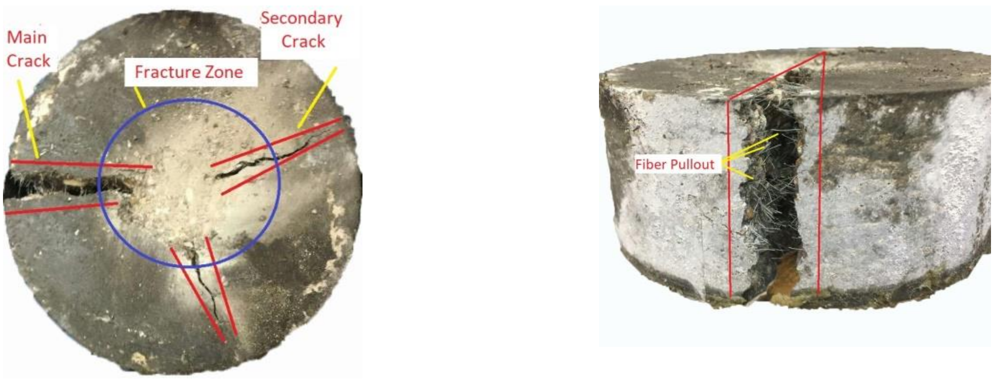
Ding et al. [62] and Chen et al. [63] used the ACI 544-2R repeated impact test with an adjusted drop-height of 600 mm to evaluate the impact performance of high-performance self-compacting concrete. Hooked-end steel fibers with 35 mm length were used with or without steel bar reinforcement. Abid et al. [64] suggested modifications to the ACI 544-2R repeated impact test procedure to reduce the variability of the test results. The authors used a single high-performance concrete mixture with 2.5% of micro-steel fibers, which were straight and 15 mm in length. The authors revealed that due to fiber incorporation, the fracture behavior was more ductile with a central fracture zone and multiple cracking as shown in Fig. 2. Jabir et al. [65, 66] used the repeated impact test procedure with a drop height of 700 mm to evaluate the impact performance of high-performance concrete including different combinations of steel fibers with or without polypropylene fibers. Two micro-steel fibers lengths of 6 and 15 mm were used with straight configuration at a constant volume fraction of 2.5%. The fibers were used in mono and hybrid cases, where 1.25% of each type was used in the latest.

Mahakavi and Chithra [67] used the repeated impact test to evaluate the impact performance of self-compacting concrete reinforced with hooked-end and crimped steel fibers. The two fiber types were utilized at volume contents of 0.25, 0.5 and 0.75% in mono and hybrid combinations. In the hybrid fiber-reinforced mixtures, the total steel fiber volume content reached 1.25%. Kathirvel et al. [68] investigated the repeated impact performance of self-compacting concrete with treated recycled aggregate and hooked-end steel fibers. Abid et al. [69] tested four self-compacting concrete mixtures with four volume contents of steel fibers of 0, 0.5, 0.75 and 1.0% using different combinations of drop-heights and drop-weights. The used fibers were 15 mm length and were straight in shape. The authors also reported that the use of 1.0% steel fibers alters the failure to a ductile failure with a central fracture zone and multi-surface cracking as shown in Fig. 3. In another study, Abid et al. [70] investigated the influence of specimen shape on the impact performance of steel fiber-reinforced self-compacting concrete, where three types of specimens were tested following the ACI 544-2R test procedure with few modifications. The first tested specimen type was the standard disk specimen of the test with a diameter of 150 mm and a thickness of 65 mm, while 70 mm cubes and 70×70×260 mm prisms were the other tested specimen types. In addition to the reference plain mixture, fibrous mixtures with 0.5, 0.75 and 1.0% fiber content were tested. Straight micro-steel fibers with 15mm length were utilized in two sets of normal strength (NC) and high strength (HC) mixtures. The results showed that the standard disks were the more suitable specimen type for the repeated impact test compared to the other specimen configurations and they can sustain noticeably higher impact numbers as shown in Fig. 4. Abid et al. [71] tested the same fibrous self-compacting mixtures under flexural repeated impacts, where the test follows a similar procedure to that of the standard ACI 544-2R, but beam specimens were used instead. The setup of the specimens was a three-point bending with a drop depth of 100 mm as shown in Fig. 5. The authors reported significantly lower impact records compared to the standard test configuration.



(a) (b)

Fig. 2 Central fracturing and multi-cracking of steel fiber-reinforced concrete [64]



(a) (b)

Fig. 3 Ductile fracturing and failure of fibrous self-compacted concrete [69]

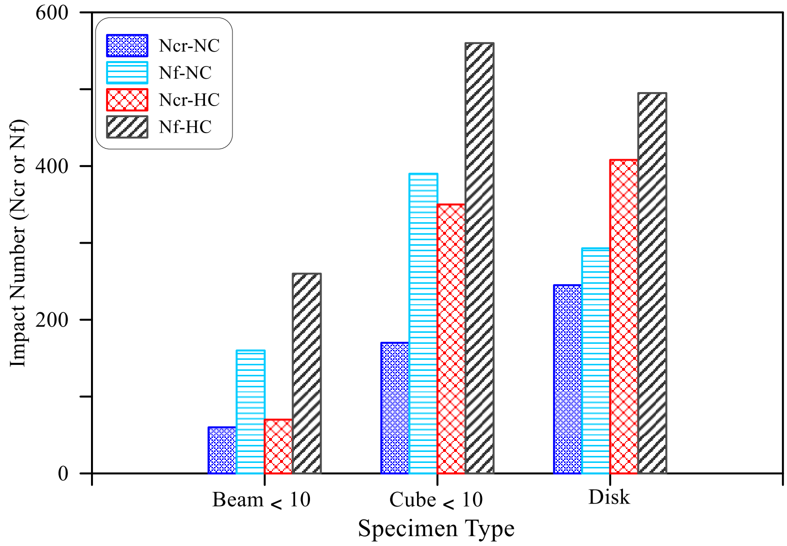
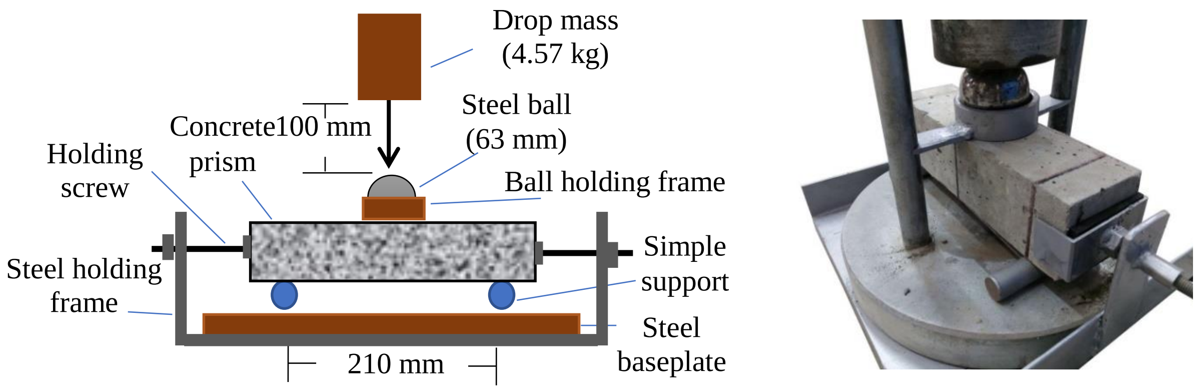


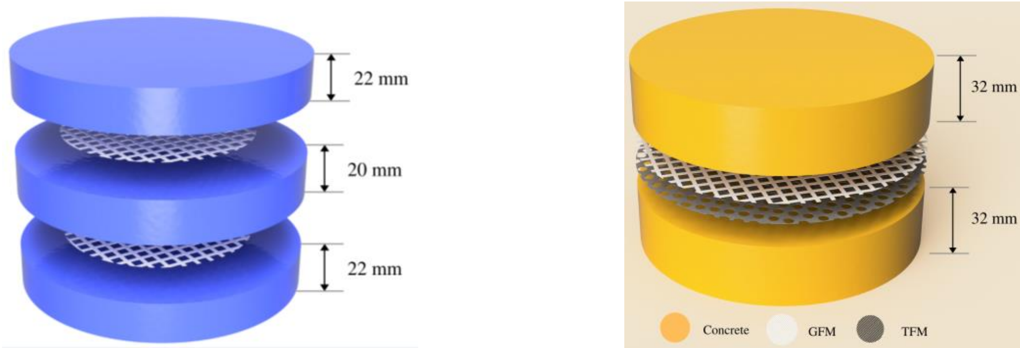
Fig. 4 Effect of specimens shape on the retained cracking number (Ncr) and failure number (Nf) as tested by Abid et al. [70]



(a) Test setup details (b) The holding frame

Fig. 5 Flexural repeated impact test setup of Abid et al. [71]

Murali et al. [72] tested the repeated impact performance of ten preplaced aggregate fibrous concrete mixtures using four types of steel fibers, where crimped steel fibers with 14 and 50 mm length and hooked-end steel fibers with 30 and 60 mm length were utilized. The specimens were made in three subsequent layers with or without two layers of interior glass fiber wire meshes as shown in Fig. 6a. The fiber content at the upper and lower layers was 3.0%, while it was 1.5% at the interior layer. The authors indicated that the intermediate mesh layers provide localized crack arresting zones that enhance the impact performance. However, the positive effect of the intermediate fiber meshes was much lower than that of steel fibers. In another study, Murali et al. [73] tested the repeated impact of preplaced aggregate fibrous concrete specimens made with steel fibers and carbon nanotubes. A new hybrid type of crimped hooked-end steel fibers was utilized with a length of 50 mm and a diameter of 1 mm, while a similar type of steel fibers with 30 mm length and 0.5 mm diameter was utilized in another similar study [74]. The specimens of both studies were made in two layers with intermediate glass fiber mesh layers. A positive effect was reported about the incorporation of carbon nanotubes and glass fiber meshes in enhancing the impact resistance, while the role of steel fibers was dominant. This conclusion was also reported by Haridharan et al. [75], where the repeated impact performance of two-layered grouted aggregate concrete reinforced with hooked-end steel fibers with 63 mm length was investigated. Between the two layers, glass fiber mesh layers with diameters of 50 to 150 mm were added in one or two layers as shown in Fig. 6b. Murali et al. [76, 77] investigated the fiber distribution on the impact performance of three-layered preplaced aggregate fiber-reinforced concrete. Crimped hooked-end steel fibers with 50 mm length were utilized in different mono and hybrid combinations in the subsequent three layers, but the average total volume content of fiber was the same for all mixtures, which was 2.4%. The results showed that adding the steel fibers in the top and bottom layers resulted in the best impact results. Vatin et al. [78] investigated the effect of asphalt coating of aggregate on the repeated impact performance of single-layer fiber-reinforced preplaced aggregate concrete. Crimped hooked-end steel fibers with 50 mm length were utilized at a fiber volumetric content of 3%. Other studies investigated the repeated impact performance of steel fiber-reinforced preplaced aggregate concrete using modified ACI 544-2R impact test procedures [79, 80], repeated projectile impact test [81] and repeated flexural impact test [82].



(a) Three layers [72] (b) Two layers [75]

Fig. 6 Configuration of multi-layered specimens with intermediate wire meshes

3. EFFECT OF STEEL FIBER PARAMETERS IN THE IMPACT RECORDS

3.1 Effect of fiber type

Several types of steel fibers were used to improve the impact performance in the literature as detailed in the previous section. The major types of fibers used were hooked-end steel fibers, crimped steel fibers and straight micro-steel fibers, while 4D and 5D hooked end steel fibers were also utilized in some studies and hybrid crimped hooked-end were used in others. Fig. 7 shows the configurations of the different types of steel fibers. All types of fibers were reported in literature as good impact strength enhancing materials. However, owing to their different configurations, their activity in crack bridging was different. It was reported in previous studies [70] that 1.0% of micro-steel fibers could enhance the repeated impact strength by approximately 480 to 660% at the cracking stage and approximately 580 to 780% at the failure stage compared to plain specimens, while developments up to 860% were reported for the same fiber content in another study [69]. Studies on the impact performance of preplaced aggregate concrete reported percentage developments reaching 3000% due to the incorporation of 3% of hooked-end steel fibers [68], while the incorporation of 1.5% of hooked-end fibers led to percentage developments of approximately 180% at cracking and 480% at failure [83]. Mahakavi and Chithra [67] reported higher cracking and failure impact numbers of specimens incorporating 0.5% of crimped steel fibers compared to others incorporating 0.5% of hooked-end steel fibers, noting that both fibers were equal in length, which was 70 mm. Murali et al. [84] investigated the effect of fiber type on the impact performance of preplaced aggregate concrete, where crimped and hooked-end steel fibers were utilized. The authors reported that hooked-end steel fibers exhibited higher impact performance compared to crimped fibers regardless of the fiber content. However, it should be mentioned that the length of the fibers were different, where the crimped fibers were half the length of the hooked end fibers, which imposes the influence of another effective geometrical parameters rather than only the fiber shape. A similar comparison was also investigated in another study [72], where 50 mm length crimped fibers and 60 mm length hooked-end fibers were utilized in similar preplaced specimens. The authors reported that the specimens with hooked-end fibers exhibited slightly higher impact numbers than the specimens with crimped fibers. The retained cracking impact numbers were 180 and 190, while the failure impact numbers were 345 and 366 for the crimped and hooked-end fibers, respectively. It should also be reminded here that the effect of fiber length was also emerged with the effect of fiber shape in this comparison.

(a) Hooked-end (3D) (b) 4D hooked-end (c) 5D hooked-end

(d) Crimped

(e) Hybrid

(f) Straight micro fibers

Fig. 7 Types of steel fibers

3.2 Effect of fiber content

Ismail and Hassan [55] showed that the recorded cracking impact numbers increased from 550 blows for a steel fiber content of 0.25% to 615, 788 and 922 blows for fiber contents of 0.5, 0.75 and 1.0%, respectively. Similarly, the recorded failure impact numbers were 606, 699, 896 and 1078 blows for fiber contents of 0.25, 0.5, 0.75 and 1.0%, respectively. Abid et al. [69] showed that regardless of the test parameters (drop weight and drop height), increasing the fiber content from 0.5 to 0.75 and 1.0% increases the cracking and failure impact results continuously as shown in Fig. 8. Increasing the fiber content means higher number of fibers would bridge each crack, which of course increases the impact results and leads to higher recorded cracking and failure impact numbers and more ductile failure response. Using hooked-end steel fibers with 30 mm length, Murali et al. [84] reported that the recorded cracking impact numbers were 162, 297 and 429 blows for fiber contents of 1.5, 3.0 and 5.0%, respectively, while the failure impact numbers were 424, 918 and 1378%, respectively. This means that percentage developments of 83 to 165% and 113 to 225% were attained when the fiber content was raised from 1.5 to 3.0 and 5.0%, respectively. To summarize, all of the reviewed literature works confirm this conclusion and agree that increasing the steel fiber content increases the impact resistance.

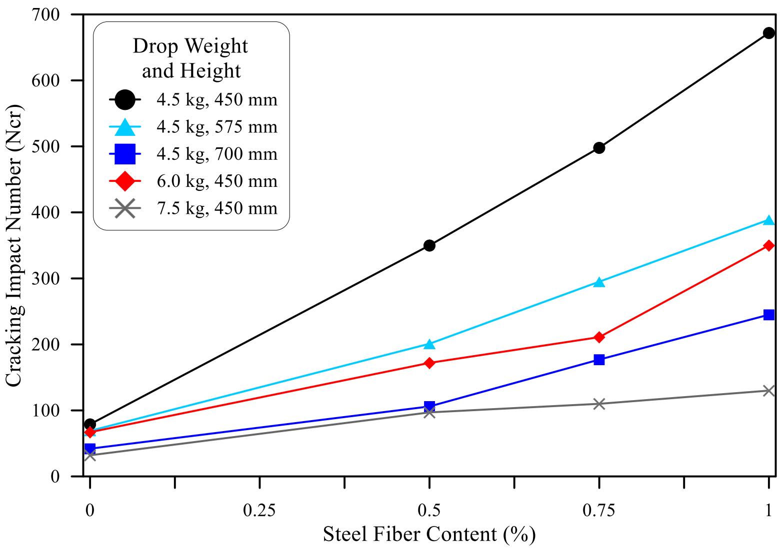


Fig. 8 Effect of fiber length as reported by Abid et al. [69]

3.3 Effect of fiber Length

The effect of fiber length on the retained impact numbers of the repeated impact test was investigated by many previous studies. Jabir et al. [65] tested several high-performance concrete mixtures incorporating mono and hybrid combinations of steel and polypropylene fibers. Two lengths of the same type of straight micro-steel fibers were utilized. The first is 6 mm, while the second is 15 mm. The authors concluded that the longer fibers were superior to short fibers at both impact strength and failure response, where the specimens reinforced with 15 mm length fibers retained higher cracking and failure impact numbers and exhibited more ductile failure compared the specimens with 6 mm fibers. The authors reported that using 2.5% of the 15 mm length fibers resulted in 93% higher impact strength compared to similar specimens with 6 mm fibers. Murali et al. [85] investigated the effect of fiber length on the impact resistance of preplaced aggregate concrete. Hybrid crimped hooked-end steel fibers with two different lengths of 30 and 49 mm were used considering a fixed fiber content of 2.5%. The authors reported high efficiency of both fibers in crack bridging and promoting the impact strength at cracking and failure stages. However, the authors addressed that the longer fibers exhibited higher cracking impact numbers by 11 to 16% and higher failure impact numbers by 31 to 40% compared to the shorter fibers, which was attributed to the deeper anchorage length of the longer fibers that afforded better bond across the cracks. Murali et al. [72] investigated the effect of fiber length on the impact performance of three-layered preplaced aggregate concrete using two types of steel fibers, crimped and hooked-end, where 3% volume content of fibers was incorporated at the top and bottom layers, while 1.5% was incorporated at the middle layer. The crimped fibers were 14 and 50 mm length, while the hooked-end fibers were 30 and 60 mm length. The results of the study confirmed the conclusion that, within the investigated range of fiber lengths, longer fibers better improve the crack arresting activity and hence the retained impact numbers compared to shorted fibers.

5. CONCLUSIONS

Rich literature is available on the repeated impact performance of steel fiber-reinforced concrete, where the ACI 544-2R repeated impact test procedure was adopted with or without modifications. Different types of steel fibers were used in different types of concrete, where crimped, hooked-end and micro steel fibers were the most investigated types. From the review of the literature works, the following points can be summarized as main conclusions.

1- Steel fibers' main function is to arrest crack widening and propagation by extending across the cracks and bearing the tensile stresses that try to open the crack. This bridging activity is attributed to the adequate anchorage of fibers along both sides of the cracks and their high tensile strength. The crack bridging activity improves the impact resistance of the concrete specimens and increases the retained cracking and failure impact numbers.

2- Using the same length of fibers, a previous comparative study showed that, for the same fiber content of 0.5%, crimped steel fibers assured better bond with concrete and thus afforded better crack bridging activity compared to hooked-end steel fibers, which resulted in higher cracking and failure impact numbers. On the other hand, other studies showed comparable or slightly better performance for hooked-end steel fibers compared to crimped fibers. However, the length of fibers was different in these studies, which imposes the influence of another geometrical parameter.

3- Few literature works compared the impact performance of specimens with the same type of fiber but with different lengths. These works agree that increasing the fiber length increases the cracking and failure impact records. This action is attributed to the more adequate bond provided by the additional anchorage length of the longer fibers across the opposite concrete sides of the crack.

4- Within the limits of the reviewed literature works, there is a complete agreement that using higher volume fractions of steel fiber improves the impact performance and increases the recorded cracking and failure impact numbers. This effect was recorded regardless of the test parameters or test modifications adopted to perform the ACI 544-2R repeated impact test. Increasing the fiber content increases the number of fibers crossing each crack, which affords higher crack bridging and arresting activity and postpone crack widening and failure, which increases the recorded number of blows required to crack or fail the specimen.

REFERENCES

1. Zhang, W.; Chen, S.; Liu, Y. Effect of weight and drop height of hammer on the flexural impact performance of fiber-reinforced concrete. *Construction and Building Materials* **2017**, *140*, 31–35.
2. Pan, Y.; Wu, C.; Cheng, X.; Li, V.C.; He, L. Impact fatigue behaviour of GFRP mesh reinforced engineered cementitious composites for runway pavement. *Construction and Building Materials* **2020**, *230*.
3. 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**, *64*, 1244–1258.
4. Liu, J.; Li, J.; Fang, J.; Su, Y.; Wu, C. Ultra-high performance concrete targets against high velocity projectile impact—a-state-of-the-art review. *Int. J. Impact Eng.* **2022**, *160*, 104080.
5. Feng, J.; Gao, X.; Li, J.; Dong, H.; He, Q.; Liang, J.; Sun, W. Penetration resistance of hybrid-fiber-reinforced high-strength concrete under projectile multi-impact. *Constr. Build. Mater.* **2019**, *202*, 341–352.
6. Abid, S.R.; Murali, G.; Ahmad, J.; Al-Ghasham, T.S.; Vatin, N.I. Repeated Drop-Weight Impact Testing of Fibrous Concrete: State-Of-The-Art Literature Review, Analysis of Results Variation and Test Improvement Suggestions. *Materials* **2022**, 15, 3948.
7. Kryžanowski, A.; Mikoš, M.; Šušteršič, J.; Ukrainczyk, V.; Planinc, I. Abrasion resistance of concrete in hydraulic structures. *ACI Mater. J.* **2009**, 106, 349-356.

8. Zarrabi, N.; Moghim, M.N.; Eftekhar, M.R. Effect of hydraulic parameters on abrasion erosion of fiber reinforced concrete in hydraulic structures. *Constr. Build. Mater.* **2021**, 267, 120966.
9. Abid, S.R.; Ali, S.H.; Murai, G.; Al-Gasham, T.S. A simple suggested approach to reduce the testing time of concrete surface abrasion using ASTM C1138. *Case Studies Constr. Mater.* **2021**, 15, e00685.
10. 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*, 522–526.
11. *ACI 544.2R-89*. Measurement of Properties of Fiber Reinforced Concrete. American Concrete Institute: Farmington Hills, MI, USA, 1999.
12. Ashraf, M.R.; Akmal, U.; Khurram, N.; Aslam, F.; Deifalla, A.F. Impact resistance of styrene–butadiene rubber (SBR) latex-modified fiber-reinforced concrete: The role of aggregate size. *Materials* **2022**, *15*, 1283.
13. Batran, T.Z.; Ismail, M.K.; Hassan, A.A.A. Behavior of novel hybrid lightweight concrete composites under drop-weight impact loading. *Structures* **2021**, *34*, 2789–2800.
14. Yılmaz, T.; Anil, Ö.; Tuğrul Erdem, R. Experimental and numerical investigation of impact behavior of RC slab with different opening size and layout. *Structures* **2022**, *35*, 818–832.
15. Huang, Z.; Chen, W.; Tran, T.T.; Pham, T.M.; Hao, H.; Chen, Z.; Elchalakani, M. Experimental and numerical study on concrete beams reinforced with Basalt FRP bars under static and impact loads. *Compos. Struct.* **2021**, *263*, 113648.
16. Yoo, D.Y.; Banthia, N. Mechanical and structural behaviors of ultra-high-performance fiber-reinforced concrete subjected to impact and blast. *Constr. Build. Mater.* **2017**, *149*, 416–431.
17. Ziada, M.; Erdem, S.; Tammam, Y.; Kara, S.; Lezcano, R.A.G. The effect of basalt fiber on mechanical, microstructural, and high-temperature properties of fly ash-based and basalt powder waste-filled sustainable geopolymer mortar. *Sustainability* **2021**, *13*, 12610.
18. Lee, M.; Park, G.K.; Kim, S.W.; Kwak, H.G. Damage characteristics of high performance fiber-reinforced cement composites panels subjected to projectile impact. *Int. J. Mech. Sci.* **2022**, *214*, 106919.
19. Mina, A.L.; Petrou, M.F.; Trezos, K.G. Resistance of an optimized ultra-high performance fiber reinforced concrete to projectile impact. *Buildings* **2021**, *11*, 1–18.
20. Yu, R.; Van Beers, L.; Spiesz, P.; Brouwers, H.J.H. Impact resistance of a sustainable ultra-high performance fibre reinforced concrete (UHPFRC) under pendulum impact loadings. *Constr. Build. Mater.* **2016**, *107*, 203–215.
21. Saleem, M.A.; Saleem, M.M.; Ahmad, Z.; Hayat, S. Predicting compressive strength of concrete using impact modulus of toughness. *Case Stud. Constr. Mater.* **2021**, *14*, e00518.
22. Nili, M.; Afroughsabet, V. The effects of silica fume and polypropylene fibers on the impact resistance and mechanical properties of concrete. *Constr. Build. Mater.* **2010**, *24*, 927–933.
23. Soroushian, P.; Nagi, M.; Alhozaimy, A. Statistical variations in the mechanical properties of carbon fiber reinforced cement composites. *ACI Mater. J.* **1992**, *89*, 131–138.
24. Alavi Nia, A.; Hedayatian, M.; Nili, M.; Sabet, V.A. An experimental and numerical study on how steel and polypropylene fibers affect the impact resistance in fiber-reinforced concrete. *Int. J. Impact Eng.* **2012**, *46*, 62–73.
25. Mastali, M.; Dalvand, A. The impact resistance and mechanical properties of self-compacting concrete reinforced with recycled CFRP pieces. *Compos. Part B Eng.* **2016**, *92*, 360–376.
26. Mastali, M.; Dalvand, A.; Sattarifard, A.R. The impact resistance and mechanical properties of reinforced self-compacting concrete with recycled glass fibre reinforced polymers. *J. Clean. Prod.* **2016**, *124*, 312–324.
27. 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. *Compos. Part B Eng.* **2017**, *112*, 74–92.
28. Wang, W.; Chouw, N. The behaviour of coconut fibre reinforced concrete (CFRC) under impact loading. *Constr. Build. Mater.* **2017**, *134*, 452–461.
29. Ali, M.A.E.M.; Soliman, A.M.; Nehdi, M.L. Hybrid-fiber reinforced engineered cementitious composite under tensile and impact loading. *Mater. Des.* **2017**, *117*, 139–149.
30. Fakharifar, M.; Dalvand, A.; Arezoumandi, M.; Sharbatdar, M.K.; Chen, G.; Kheyroddin, A. Mechanical properties of high performance fiber reinforced cementitious composites. *Comput. Chem. Eng.* **2014**, *71*, 510–520.
31. Ismail, M.K.; Hassan, A.A.A.; Lachemi, M. Performance of Self-Consolidating Engineered cementitious composite under drop-weight impact loading. *J. Mater. Civ. Eng.* **2019**, *31*, 04018400.
32. Al-Ameri, R.A.; Abid, S.R.; Murali, G.; Ali, S.H.; Özakça, M.; Vatin, N.I. Residual impact performance of ECC subjected to sub-high temperatures. *Materials* **2022**, *15*, 454.

33. Al-Ameri, R.A.; Abid, S.R.; Özakça, M. Mechanical and impact properties of engineered cementitious composites reinforced with PP fibers at elevated temperatures. *Fire* **2022**, *5*, 3.
34. Mohammadhosseini, H.; Alrshoudi, F.; Tahir, M.M.; Alyousef, R.; Alghamdi, H.; Alharbi, Y.R.; Alsaif, A. Performance evaluation of novel prepacked aggregate concrete reinforced with waste polypropylene fibers at elevated temperatures. *Constr. Build. Mater.* **2020**, *259*, 120418.
35. AbdelAleem, B.H.; Ismail, M.K.; Hassan, A.A.A. The combined effect of crumb rubber and synthetic fibers on impact resistance of self-consolidating concrete. *Constr. Build. Mater.* **2018**, *162*, 816–829. https://doi.org/10.1016/j.conbuildmat.2017.12.077.
36. Khalil, E.; Abd-Elmohsen, M.; Anwar, A.M. Impact Resistance of Rubberized Self-Compacting Concrete. *Water Sci.* **2015**, *29*, 45–53. https://doi.org/10.1016/j.wsj.2014.12.002.
37. Abbass, A.A.; Abid, S.R; Özakça, M. Experimental investigation on the effect of steel fibers on the flexural behavior and ductility of high-strength concrete hollow beams, Adv. Civ. Eng. **2019**, 2019, Article ID 8390345.
38. Chen, G.; Gao, D.; Zhu, H.; Yuan, J.S.; Xiao, X.; Wang, W. Effects of novel multiple hooked-end steel fibres on flexural tensile behaviour of notched concrete beams with various strength grades. *Structures* **2021**, 33,2021, 3644-3654.
39. Yixin, C.; Jianye, Z.; Jicheng, M.; Shunli, Z.; Yongsheng, L.; Zhixuan, Z. Tensile strength and fracture toughness of steel fiber reinforced concrete measured from small notched beams, *Case Studies Constr. Mater.* **2022**, 17, e01401.
40. Algassem, O.; Li, Y.; Aoude, H. Ability of steel fibers to enhance the shear and flexural behavior of high-strength concrete beams subjected to blast loads. *Eng. Struct.* **2019**, 199, 109611.
41. Larsen, I.L.; Thorstensen, R.T. The influence of steel fibres on compressive and tensile strength of ultra high performance concrete: A review. *Constr. Build. Mater.* **2020**, 256, 119459.
42. Li, X.; Zhang, Y.; Shi, C.; Chen, X. Experimental and numerical study on tensile strength and failure pattern of high performance steel fiber reinforced concrete under dynamic splitting tension. *Constr. Build. Mater.* **2020**,259, 119796.
43. Sabetifar, H.; Nematzadeh, M. An evolutionary approach for formulation of ultimate shear strength of steel fiber-reinforced concrete beams using gene expression programming. *Structures* **2021**, 34, 4965-4976,
44. Yaseen, Z.M.; Tran, M.T.; Kim, S.; Bakhshpoori, T.; Deo, R.C. Shear strength prediction of steel fiber reinforced concrete beam using hybrid intelligence models: A new approach. *Eng. Struct.* **2018**, 177, 244-255.
45. Maya, L.F.; Ruiz, M.F.; Muttoni, A.; Foster, S.J. Punching shear strength of steel fibre reinforced concrete slabs. Eng. Struct. **2012**, 40, 83-94.
46. 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, Constr. Build. Mater. 2017, 154, 204–218.
47. Ju, M.; Ju, J-W. W.; Sim, J. A new formula of punching shear strength for fiber reinforced polymer (FRP) or steel reinforced two-way concrete slabs. *Compos. Struct.* **2021**, 259,113471.
48. Liu,Y-W.; Lin, Y-Y.; Cho, S-W. Abrasion behavior of steel-fiber-reinforced concrete in hydraulic structures. *Appl. Sci.* **2020**, 10, 5562.
49. Ayoob, N.S.; Abid, S.R.; Hilo, A.N. Water-impact abrasion of self-compacting concrete. *Mag. Civ. Eng.* **2020**, 96, 60-69.
50. Nataraja, M.C.; Dhang, N.; Gupta, A.P. Statistical variations in impact resistance of steel fiber-reinforced concrete subjected to drop weight test. *Cem. Concr. Res.* **1999**, *29*, 989–995.
51. Song, P.S.; Wu, J.C.; Hwang, S.; Sheu, B.C. Statistical analysis of impact strength and strength reliability of steel-polypropylene hybrid fiber-reinforced concrete. *Constr. Build. Mater.* **2005**, *19*, 1–9.
52. 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. *Cem. Concr. Res.* **2005**, *35*, 393–399.
53. Rahmani, T.; Kiani, B.; Shekarchi, M.; Safari, A. Statistical and experimental analysis on the behavior of fiber reinforced concretes subjected to drop weight test. *Constr. Build. Mater.* **2012**, *37*, 360–369.
54. 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 Engineering* **2010**, *37*, 879–886.
55. Ismail, M.K.; Hassan, A.A.A. Impact resistance and mechanical properties of self-consolidating rubberized concrete reinforced with steel fibers. *J. Mater. Civ. Eng.* **2017**, *29*, 04016193.
56. Yildirim, S.T.; Ekinci, C.E.; Findik, F. Properties of hybrid fiber reinforced concrete under repeated impact loads. *Russ. J. Nondestruct. Test.* **2010**, *46*, 538–546.
57. Mohammedhosseini, H.; Tahir, M.; Sam, A.R.M. The feasibility of improving impact resistance and strength properties of sustainable concrete composites by adding waste metalized plastic. *Constr. Build. Mater.* **2018**, 169, 223-236.

58. Abid, S.R.; Abbass, A.A.; Murali, G.; Al-Sarray, M.L.J.; Nader, I.A.; Ali, S.H. Post-high-temperature exposure repeated impact response of steel-fiber-reinforced concrete. *Buildings* **2022**, 12, 1364.
59. Mehdipour, S.; Nikbin, I.M.; Dezhampanah, S.; Mohebbi, R.; Moghadam, H.; Charkhtab, S.; Moradi, A. Mechanical properties, durability and environmental evaluation of rubberized concrete incorporating steel fiber and metakaolin at elevated temperatures. *J. Clean Prod.*, **2020**, *254*, 120126.
60. Abid, S.R.; Abbass, A.A.; Murali, G.; Al-Sarray, M.L.J.; Nader, I.A.; Ali, S.H. Repeated Impact Response of Normal- and High-Strength Concrete Subjected to Temperatures up to 600 °C. *Materials* **2022**, 15, 5283.
61. Al-Ameri, R.A.; Abid, S.R.; Murali, G.; Ali, S.H.; Özakça, M. Residual repeated impact strength of concrete exposed to elevated temperatures. *Crystals* **2021**, *11*, 941.
62. 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. *Constr. Build. Mater.*, **2017**, *136*. 495-505.
63. Chen, X.Y.; Ding, Y.N.; Azevedo, C. Combined effect of steel fibres and steel rebars on impact resistance of high performance concrete. *Journal of Central South University of Technology (English Edition)* **2011**, *18*, 1677–1684, doi:10.1007/s11771-011-0888-y.
64. 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. *Constr. Build. Mater.* **2020**, *244*, 118321.
65. Jabir, H.A.; Abid, S.R.; Murali, G.; Ali, S.H.; Klyuev, S.; Fediuk, R.; Vatin, N.; Promakhov, V.; Vasilev, Y. Experimental tests and reliability analysis of the cracking impact resistance of uhpfrc. *Fibers* **2020**, *8*, 1–14. https://doi.org/10.3390/fib8120074.
66. Jabir, H.A.; Abid, S.R.; Hussein, M.L.A.; Ali, S.H. Repeated drop-weight impact tests on RPC containing hybrid fibers. *Appl. Mech. Mater.* **2020**, *897*, 49–55.
67. Mahakavi, P.; Chithra, R. Impact resistance, microstructures and digital image processing on self-compacting concrete with hooked end and crimped steel fiber. Constr. Build. Mater. **2019**, 220, 651–666.
68. Kathirvel, P.; Murali, G.; Vatin, N.I.; Abid, S.R. Experimental study on self compacting fibrous concrete comprising magnesium sulphate solution treated recycled aggregates. *Materials* **2022**, *15*, 340.
69. Abid, S.R.; Abdul-Hussein, M.L.; Ayoob, N.S.; Ali, S.H.; Kadhum, A.L. Repeated drop-weight impact tests on self-compacting concrete reinforced with micro-steel fiber. *Heliyon* **2020**, *6*, e03198.
70. 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. *Mag. Civ. Eng.* **2021**, *105*, 2712–8172.
71. Abid, S.R.; Gunasekaran, M.; Ali, S.H.; Kadhum, A.L.; Al-Gasham, T.S.; Fediuk, R.; Vatin, N.; Karelina, M. Impact performance of steel fiber-reinforced self-compacting concrete against repeated drop weight impact. *Crystals* **2021**, *11*, 1–17.
72. Murali, G.; Abid, S.R.; Mugahed Amran, Y.H.; Abdelgader, H.S.; Fediuk, R.; Susrutha, A.; Poonguzhali, K. Impact performance of novel multi-layered prepacked aggregate fibrous composites under compression and bending. *Structures* **2020**, *28*, 1502–1515.
73. Murali, G.; Abid, S.R.; Karthikeyan, K.; Haridharan, M.K.; Amran, M.; Siva, A. Low-velocity impact response of novel prepacked expanded clay aggregate fibrous concrete produced with carbon nano tube, glass fiber mesh and steel fiber. *Constr. Build. Mater.* **2021**, *284*, 122749.
74. Murali, G.; Abid, S.R.; Amran, M.; Fediuk, R.; Vatin, N.; Karelina, M. Combined effect of multi-walled carbon nanotubes, steel fibre and glass fibre mesh on novel two-stage expanded clay aggregate concrete against impact loading. *Crystals* **2021**, *11*, 720.
75. Haridharan, M.K.; Matheswaran, S.; Murali, G.; Abid, S.R.; Fediuk, R.; Mugahed Amran, Y.H.; Abdelgader, H.S. Impact response of two-layered grouted aggregate fibrous concrete composite under falling mass impact. *Constr. Build. Mater.* **2020**, *263*, 120628.
76. Murali, G.; Prasad, N.; Klyuev, S.; Fediuk, R.; Abid, S.R.; Amran, M.; Vatin, N. Impact resistance of functionally layered two-stage fibrous concrete. *Fibers* **2021**, *9*, 88.
77. Murali, G.; Prasad, N.; Abid, S.R.; Vatin, N.I. Response of functionally graded preplaced aggregate fibrous concrete with superior impact strength. *Buildings* **2022**, *12*, 563.
78. Vatin, N.I.; Murali, G.; Abid, S.R.; de Azevedo, A.R.G.; Tayeh, B.; Dixit, S. Enhancing the impact strength of prepacked aggregate fibrous concrete using asphalt-coated aggregates. *Materials* **2022**, *15*, 2598.
79. Ramakrishnan, K.; Depak, S.R.; Hariharan, K.R.; Abid, S.R.; Murali, G.; Cecchin, D.; Fediuk, R.; Mugahed Amran, Y.H.; Abdelgader, H.S.; Khatib, J.M. Standard and modified falling mass impact tests on preplaced aggregate fibrous concrete and slurry infiltrated fibrous concrete. *Constr. Build. Mater.* **2021**, *298*, 123857.
80. Murali, G.; Abid, S.R.; Amran, M.; Vatin, N.I.; Fediuk, R. Drop-weight impact test on prepacked aggregate fibrous concrete- An experimental study. *Materials* **2022**, *15*, 3096.
81. Murali, G.; Abid, S.R.; Abdelgader, H.S.; Amran, Y.H.M.; Shekarchi, M.; Wilde, K. Repeated projectile impact tests on multi-layered fibrous cementitious composites. *Int. J. Civ. Eng.* **2021**, *19*, 635–651.

82. Murali, G.; Abid, S.R.; Vatin, N.I. Experimental and analytical modeling of flexural impact strength of preplaced aggregate fibrous concrete beams. *Materials* **2022**, *15*, 3857.
83. Swaminathan, P.; Karthikeyan, K.; Subbaram, S.R.; Sudharsan, J.S.; Abid, S.R.; Murali, G.; Vatin, N.I. Experimental and statistical investigation to vvaluate impact strength variability and reliability of preplaced aggregate concrete containing crumped rubber and fibres. *Materials* **2022**, 15, 5156.
84. Murali, G.; Laxminadh Poka.; Parthiban, K.; Haridharan, M.K.; Siva, A. Impact response of novel fibre-reinforced grouted aggregate rubberized concrete. *Arabian. J. Sci. Eng.* **2019**, 44, 8451–8463
85. Murali, G.; Abid, S.R.; Vatin, N.I.; Amran, M.; Fediuk, R. Influence of height and weight of drop hammer on impact strength and fracture toughness of two-stage fibrous concrete comprising nano carbon tubes. *Constr. Build. Mater.* **2022**, 349, 128782.
86. Abbass, A.A.; Abid, S.R.; Abed, A.I.; Ali, S.H. Experimental and statistical study of the effect of steel fibers and design strength on the variability in repeated impact test results. *Fibers* **2023**, *11*, 4.