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Experimental and Statistical Analysis of Repeated Impact Records of Hybrid Fiber-Reinforced High-Performance Concrete

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Abstract: The effect of fiber type and fiber hybridization on the repeated impact strength was investigated experimentally using six high-performance concrete mixtures reinforced with a 2.5% fiber volume fraction. The fiber types considered in this study included short steel fibers (SF) with 6 mm length, long SF with 15 mm length, and polypropylene (PP) fibers. The repeated impact test was conducted using a specially made automatic testing machine following the test setup recommendations of the ACI 544-2R test, where cracking (Ncr) and failure (Nf) impact numbers were recorded and the failure mode and crack pattern were observed. The results were statistically analyzed using the normality test and variations were discussed. The test results showed that specimens with pure long SF (S15) obtained the highest Ncr and Nf values, which were 20% and 327% higher than those of the mixture with pure short SF (S6) owing to the better bond between fibers and the cementitious matrix in S15. Replacing 0.5% of the mixture's SF with PP decreased the cracking resistance by 7% to 15%, while its effect on Nf was dependent on the length of SF. In most cases, the Ncr and Nf records did not exhibit a significant departure from normal distribution, according to the Anderson-darling test.

Keywords: repeated impact; drop-weight; high-performance concrete; steel fiber; polypropylene fiber; hybrid fiber

Citation: Ali, S.H.; Abid, S.R.; Al-Lami, K.; Calabrese, A.S.; Yosri, A.M.; Al-Ghasham, T.S. Experimental and Statistical Analysis of Repeated Impact Records of Hybrid Fiber-Reinforced High-Performance Concrete. *Buildings* **2023**, *13*, 678. https://doi.org/10.3390/buildings13030678

Academic Editor: Jianguang Fang

Received: 21 January 2023
Revised: 10 February 2023
Accepted: 28 February 2023
Published: 3 March 2023

1. Introduction

Concrete is known for its high bearing capacity to compressive stresses, while the weakness of its tensile capacity is also a known fact. Structural members of reinforced concrete (RC) structures are exposed to different types of loads, which often entails for the development of tensile stress in the structural element. Flexural actions are among the most frequent sources of tensile stress in typical RC structures, although other types of loads can also induce other forms of tensile stresses. For instance, coupling beams are exposed to direct normal tension forces [1–4], while diagonal tension is the usual shear failure pattern of deep beams [5–7]. Impact loads impose waves of tensile stresses that have a noticeably higher destructive action than flexural and normal tensile stresses [8–13]. Particular elements in some structures are exposed to repeated impacts from different sources. For instance, columns of parking garages might be exposed to repeated collisions from the moving vehicles [14–16], while land ways of airports are typically impacted by the tires of the landing airplanes [16–18]. The accidental impact of falling building units and objects during construction is another possible source of repeated impact loads [13].

The incorporation of adequate quantities of suitable types of fibers can boost the tensile strength of concrete, increase its stiffness, and alter its brittle failure to ductile cracking [19–22]. Previous studies and reports showed that steel fibers (SF) have the ability to significantly increase the tensile strength, flexural strength, ductility, and shear strength of different concrete types [23–27]. Other studies revealed a considerable capability of synthetic fibers, such as polypropylene fibers (PP), to enhance the tensile, flexural, and shear capacities of fiber-reinforced concrete elements [28–32]. Recent studies revealed that SF [33–36] and PP [37,38] can increase the impact strength of concrete samples subjected to repeated impacts.

The repeated impact test determines the number of impact blows of a defined drop weight and height that cause the first crack (Ncr) and failure (Nf) of test specimens. Song et al. [39] compared two SF-reinforced concrete mixtures with and without PP. Their results revealed slight increases in the number of impact blows that initiated cracking and failure when 0.1% PP was incorporated, with increases of 5.6% and 7.9%, respectively. In another study, Song et al. [40] revealed that adding 0.6 kg/m^3 (0.066%) of PP resulted in 11.9% higher Ncr and 16.9% higher Nf than similar plain concrete specimens. Yildirim et al. [41] reported that 0.1% PP could increase Nf by 100%. Nili and Afroughsabet [42] and Nia et al. [43] showed that 0.2% PP could improve Ncr by 5.3% to 31.4% and Nf by 13.4% to 42.1%, while the incorporation of 0.5% PP led to significant improvements in Ncr and Nf by 29.9% to 476%, respectively. Rahmani et al. [44] reported impact resistance when 0.15% PP was incorporated, with developments of 33.3% at cracking and 47.9% at failure. Myers and Tinsley [45] reported that Ncr increased from 5 (plain concrete) to 18.1 impact blows and Nf increased from 5.6 to 32.4 blows when 0.35% PP was added to the mixture. Fakharifar et al. [46] showed that increasing the PP content in fibrous cementitious composites from 0.5% to 0.75% and 1.0% increased Ncr by 33.1% and 56.9%, respectively, while it increased Nf by 39.2% and 65.6%, respectively. Murali et al. [47] showed that for functionally graded, preplaced fibrous concrete, the use of 2.4% PP led to huge developments in impact behavior, where Ncr increased by more than 200% and Nf increased by more than 400%, which were similar values to those reported by ref. [48]. Using the same PP type and content, Murali et al. [49] reported 350% improvement at cracking and 785% improvement at failure, while Vatin et al. [50] reported percentage increases of 155% and 400% in Ncr and Nf, respectively, by adding 3.0% PP to preplaced aggregate concrete. Ramakrishnan et al. [51] reported that 2.5% PP increased Ncr by 113% and Nf by 1318%. Al-Ameri et al. [52,53] showed that engineered cementitious composites with 0.2% PP could attain 353% higher Nf than normal concrete samples with a similar compressive strength, while no development was recorded at the cracking stage.

Notably, the positive effect of SF was reported to be noticeably higher than that of PP in many previous studies [44,47,49–51]. Nataraja et al. [54] showed that 0.5% SF could increase Ncr and Nf by approximately 46% and 84%, respectively, while Rahmani et al. [44] reported percentage increases in Ncr and Nf of 193% and 375%, respectively, using the same fiber content. With 1.0% SF, developments of 291% and 319% in Ncr and Nf, respectively, were reported by Song et al. [40]. Nili and Afroughsabet [42] showed that 0.5% SF led to developments ranging from 64% to 661% at cracking and 86% to 892% at failure, while 1.0% SF could improve Ncr and Nf by 240% to 883% and 304% to 1108%, respectively. Abid et al. [55] revealed that adding 0.5% micro-steel fibers increased Ncr and Nf by 152% to 356% and increased Nf by 179% to 350%, while adding 1.0% SF led to cracking and failure developments of up to 656% and 784%, respectively. Ding et al. [56] reported that using small amounts of SF (0.26% to 0.45%) led to noticeable developments reaching 107% at the cracking stage and 267% at the failure stage, while Chen et al. [57] showed that using the same amounts resulted in significant cracking resistance improvements. Murali et al. [47–49,58] revealed that using sufficient amounts of SF (2.4% to 3.0%) could significantly improve the impact resistance of preplaced aggregate concrete so that Ncr was increased several times, while Nf could be improved by more than 2000%.

The above reviewed literature shows that extensive research work has been conducted to evaluate the influence of polypropylene and steel fibers on the repeated impact performance of concrete. Similarly, the literature is enriched with studies exploring the mechanical properties of high-performance concrete (HPC) [59–61]. The effect of fiber hybridization on the mechanical properties of concrete was also widely investigated in the literature [62–64]. However, very few articles investigated the effect of fiber hybridization using the ACI 544-2R [65] repeated impact test. Mahakavi and Chithra [66] investigated the hybridization effect of crimped and hooked-end steel fibers, where two SF types were incorporated at different individual fiber contents ranging from 0.25% to 0.75% and composing dual fiber contents ranging from 0.5% to 1.25%. In a more recent study, Jabir et al. [67] investigated the hybridization of both SF and PP. The total fiber content was fixed for all mixtures, while six different mono and hybrid schemes were adopted. However, the tests were limited to the cracking impact number and no results were presented about the failure state, which was attributed to the amount of effort and time required to fail the specimens, thus affecting the test age, where the replicate specimens of each test could not all be tested at the same age.

As addressed in the introduced literature survey, a very limited number of previous studies have investigated the repeated impact performance of high-performance concrete, while only one previous work attempted to investigate the effect of micro steel-polypropylene fiber hybridization on the repeated impact behavior of this material. However, the previous work reported very high impact records and therefore failed to complete the tests until failure. Thus, there is still a need to complete the full picture about the behavior of hybrid fiber-reinforced high-performance concrete under repeated impacts. In this study, HPC mixtures were adopted to cast disk impact specimens with two types of steel fibers and polypropylene fibers. Six different hybridization schemes were tested to compare the impact response of steel fiber-reinforced and hybrid fiber-reinforced HPC. Using a new automatic testing technique, the testing effort and time were significantly reduced so that all specimens were tested to failure. The need for this work arises from the fact that failure impact response of fibrous concrete cannot simply be predicted from cracking impact number as it can for plain concrete. Thus, the results of this study provide a complete picture about the impact performance of HPC with SF or hybrid combinations of SF and PF. Such a material with high capacity to absorb repeated impact energies is required for use in different civil and military applications where impact resistance is the major concern.

2. The Experimental Work

2.1. Materials and Mixtures

In this study, a single high-performance concrete mixture was adopted but with six different fiber combinations, Hence, constant amounts of mixture materials were used in all of the six mixtures with a fiber volume fraction of 2.5%, while the fiber types used in the six mixtures were different, as detailed in Table 1. Three different types of fiber were adopted, including straight micro-steel fibers (SF) with 6 and 15 mm lengths and polypropylene fibers (PP). The physical details of the three fiber types are listed in Table 2, while Figure 1 shows their visual appearance, noting that both SF types had the same appearance but different lengths. The first mixture (S6) included only 6 mm SF, whereas the second mixture (S15) included only 15 mm SF. The third mixture, referred to as HS, incorporated both 6 and 15 mm SF with a 1.25% fiber volume fraction of each. In the acronym HS, the letter H stands for hybrid fiber, while S refers to steel fiber. The fourth and fifth mixtures (PS6 and PS15) included 2.0% fiber volume fractions of 6 mm SF and 15 mm SF, respectively, combined in both cases with a 0.5% PP volume fraction. The sixth mixture (HPS) was a mixture of the three types of adopted fibers, containing 1.0% 6 mm SF, 1% 15 mm SF, and 0.5% PP volume fractions. The letter P in the identification of the last three mixtures refers to the presence of polypropylene fibers.

Table 1. Fiber contents of the six HPC mixtures.

Mixture	SF (6 mm)	SF (15 mm)	PP
S6	2.5	0	0
S15	0	2.5	0
HS	1.25	1.25	0
PS6	2.0	0	0.5
PS15	0	2.0	0.5
HPS	1.0	1.0	0.5

Table 2. Properties of SF and PP fibers.

Fiber Type	Length (mm)	Diameter (mm)	Density (kg/m^3)	Tensile Strength (GPa)
SF6	6	0.12	7800	2.85
SF15	15	0.20	7800	2.60
PP	18	0.50	910	0.35

Figure 1. Visual appearance of the used micro-steel fibers (SF) and polypropylene fibers (PP).

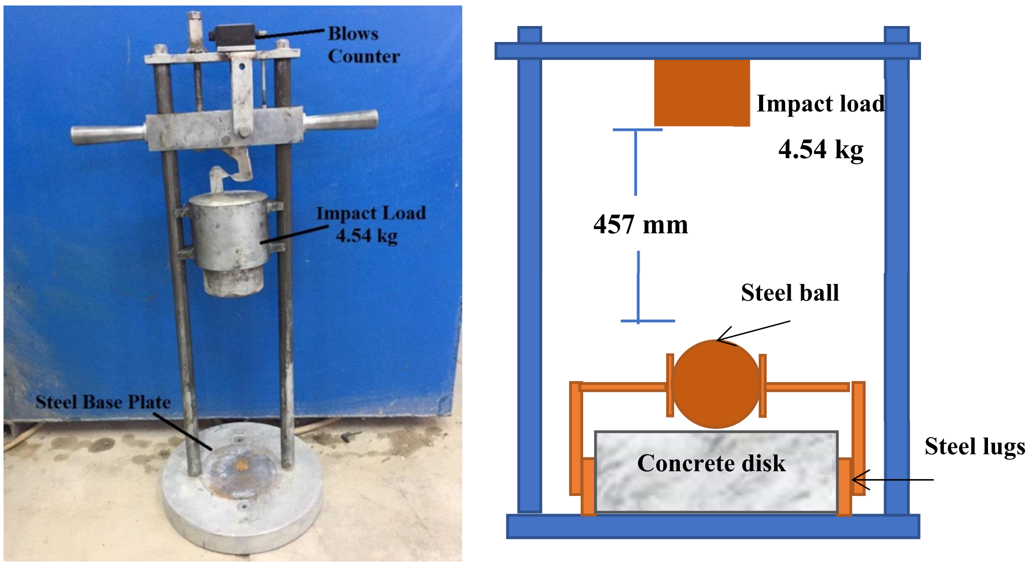
The other quantities of the six mixtures were identical, where 800 kg/m^3 of cement, 240 kg/m^3 of silica fume, and 120 kg/m^3 of fly ash were used as the binder of the mixture, while 960 kg/m^3 of fine silica sand was used as the only filler of the mixture. To assure the required consistency, 232 kg/m^3 of water and 47 kg/m^3 of superplasticizer were used. This study adopted Portland cement type 42.5 (manufactured by Mass cement factory/Sulaimaniya/Iraq) with 3.15 specific gravity and 368 m^2/kg specific surface area. The adopted silica fume was produced by Sika® with a specific gravity and specific surface area of 2.20 and 21,000 m^2/kg, respectively, while the specific gravity of the used fly ash was 2.2. Silica sand with grain sizes ranging from 80 to 200 µm was provided by Sika® with a bulk density of 1500 kg/m^3. The used superplasticizer was ViscoCrete 5930-L, which was also provided by Sika®. All specimens were water cured using temperature controlled water tanks until the date of testing at an age of 28 days. However, due to the high impact records, the time required to complete the impact testing of all specimen replicates increased, resulting in short delays of 1 to 3 days in the testing of some specimens.

2.2. The Repeated Impact Test

The simple repeated impact test was suggested by Schrader [68] and is adopted in the ACI 544-2R method [65]. The results of this test were highly scattered, and therefore it is not introduced as a standard test to quantitatively measure the impact strength of concrete.

Instead, the ACI 544-2R impact test is defined as a qualitative tool to compare the resistance of different concrete mixtures to falling impact loads. The test apparatus comprises a 4.54 kg drop mass that is freely dropped from a height of 457 mm on a cylindrical concrete specimen with approximately 150 mm diameter and 64 mm thickness. The impacts are applied on a 64 mm diameter steel ball that is kept on the center of the specimen's top surface using a steel holding frame, as shown in Figure 1, which also holds the concrete specimen and prevents its rebound. The specimen is also restricted laterally by four steel lugs and elastomer pieces. The impacts are repeated manually until the first cracking of the top surface of the specimen occurs. The number of impacts at this stage is recorded as the cracking impact number (Ncr). Subsequently, the repeated impacts are continued until the specimen fails so that it touches three steel lugs due to fracturing and crack widening. The number of impacts that cause the specimen's failure is defined as the failure impact number (Nf).

In this study, the procedure of the ACI 544-2R impact test was followed to perform repeated impact tests using the automatic testing machine shown in Figure 2, where 10 specimen replicates were used for each test. This machine was designed and manufactured by the research team at Wasit University. Previous works conducted on fibrous concrete [18,22,67] showed that great effort and a long time are required to complete a set of duplicate specimens using the manual apparatus of the ACI 544-2R impact test, thus urging the need for an automated testing machine. Another advantage of this machine is the significant decrease in noise since the machine is placed in a sound-isolation container. The cracking and failure of the specimen are observed using a high-accuracy digital camera and a wide monitoring screen, as shown in Figure 3.



(a) (b)

Figure 2. ACI 544-2R repeated impact testing apparatus. (**a**) ACI 544-2R apparatus. (**b**) Detailed sketch.

Figure 3. The automatic repeated impact testing machine.

3. Results and Discussion

3.1. Compressive Strength

The average of three 100 mm identical cubes was used to obtain the compressive strength of each mixture. The steel fiber-reinforced mixtures S6, S15, and HS obtained 28-day compressive strength records of 88.7, 98.1, and 90.2 MPa, respectively, while the SF-PP hybrid mixtures PS6, PS15, and HPS obtained compressive strengths values of 84.6, 85.4, and 85.6 MPa, respectively. It can be said that, in general, the steel fibrous mixtures could withstand higher compressive stresses than the hybrid fibrous mixtures by approximately 5%, which was obtained by comparing each mixture from the first group with its corresponding mixture from the second group. This trend was attributed to the higher stiffness and strength of SF, which afforded better crack arresting capacity under compressive stresses. On the other hand, the difference in compressive strengths between the three mixtures of each group was minimal. Hence, the difference between the compressive strengths of S6, S15, and HS was generally less than 2%, which was also valid for the hybrid fiber-reinforced mixtures. There is general agreement in the literature that fibers have a smaller effect on compressive strength than on tensile and flexural strengths, where their main role is crack bridging under tensile stress. Nia et al. [43] showed that for similar concrete mixtures, but with 0.5% SF or 0.5% PP, SF-reinforced mixtures obtained slightly higher compressive strengths regardless of the water-cement ratio adopted. They attributed this difference to the higher tensile strength of SF compared to PP. Rahmani et al. [44] showed that the obtained compressive strength of SF-reinforced concrete was approximately 2% higher than that of PP-reinforced concrete. Noting that the adopted fiber content in the previous two studies was not greater than 0.5%, it can be said that these studies support the results obtained in the current study in which replacing 0.5% SF with PP slightly decreased the compressive strength. On the other hand, Murali et al. [47] showed that fully replacing 2.5% SF with 2.5% PP decreased the compressive strength from 50.6 to 37.6 MPa, which was a difference of approximately 26%. This result supports the better superiority of SF over PP in enhancing the compressive strength.

3.2. Cracking Impact Numbers

The obtained cracking impact numbers of the six mixtures are depicted in Figure 4. The ratios of the Ncr records to those of S6 are also depicted in the same figure. Figure 4 shows that the six mixtures exhibited different Ncr results. However, the differences among Ncr values were not huge, with all mixtures obtaining Ncr records in the range of 571 to 930 blows. The S15 mixture with pure 15 mm SF obtained the maximum Ncr, followed by the hybrid mixture PS15 with 2.0% 15 mm SF and 0.5% PP. This indicated that the presence of long steel fibers could better improve the cracking impact strength of the mixture compared to short steel fibers. This could be justified by the higher stiffness and tensile strength of SF with respect to PP, which enable SF to absorb higher impact energies and better arrest concrete cracking under the induced tensile waves generated by repeated impacts [66,69]. The higher capacity of mixtures with long SF can be attributed to the better bond with the surrounding cementitious matrix and a larger shielding area under compressive impact stresses compared to short SF. The higher bond also affords better crack bridging, which delayed the crack appearance of S15 and PS15 compared to the other mixtures. Jabir et al. [67] reported impact results that agreed with this conclusion, where the concrete samples reinforced with longer SF could obtain approximately twice the Ncr records of those reinforced with shorter SF. As shown in Figure 4, S15 could obtain 20% higher Ncr and approximately 7% higher Ncr than S6, while the Ncr records of HS and PS6 were lower by 15% and 7%, respectively. The lowest Ncr was recorded for the hybrid mixture PHS that included PP and both SF types, which was 26% lower than for S6. From the comparisons of S6 with PS6, S15 with PS15, and HS with PHS, it was clear that replacing 0.5% SF with PP decreased Ncr by 7% to 15%, which assured the superiority of SF over PP in crack arresting capacity owing to their higher tensile strength and better crack bridging activity.

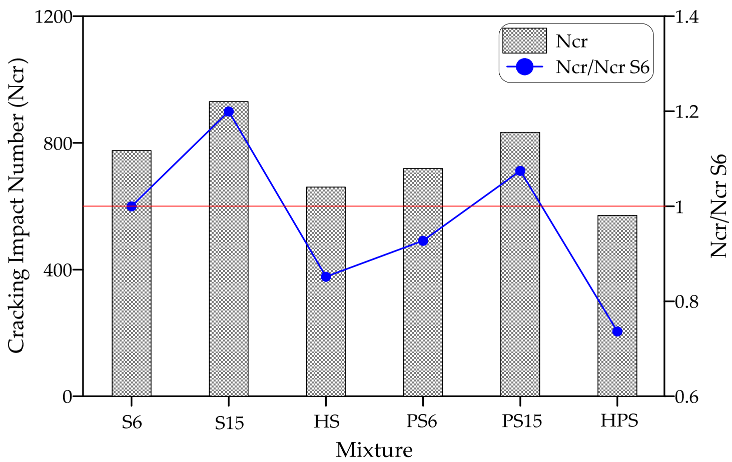


Figure 4. Repeated cracking impact numbers.

Ramakrishnan et al. [51] showed that prepalaced aggregate concrete reinforced with 2.5% SF obtained 44% higher Ncr than an identical mixture but with 2.5% macro PP, which was similar to the results of Vatin et al. [50] who reported 54% higher Ncr for 3.0% SF-reinforced specimens. Meanwhile, using the same fiber types and 2.4% fiber content, Murali et al. [49] showed that the Ncr records of SF-reinforced samples were approximately twice those of PP-reinforced samples. These results showed that the full replacement of PP by SF in mixtures with high fiber content can improve the cracking resistance by approximately 50% to 100%, which supported the results of this study in which SF showed better crack bridging and impact energy development capacities compared to PP. The percentage differences in improvement were attributed to the partial replacement (only 0.5% out of 2.5%) of SF with PP in this study. A study that included short and long crimped and hooked-end SF [58] revealed that the Ncr records of samples with longer SF were 46%

to 51% higher than those of samples with shorter similar fibers. This result confirmed the outcomes of the present study, where 15 mm steel fiber-reinforced samples attained higher Ncr than 6 mm steel fiber-reinforced samples. Hence, longer fibers can extend to longer distances across the concrete of both sides of the crack, which increases the bond with the surrounding concrete and delays the propagation of internal cracks to the sample surface.

3.3. Failure Impact Numbers

The differences among the impact records of the six mixtures were much higher at the failure stage than at the cracking stage. As shown in Figure 5, wide differences were recorded between Nf values attained by the six mixtures considered. The failure of S6 specimens occurred a few impact blows after cracking, which was associated with fracturing and extensive widening of cracks. In particular, an average of approximately 12 additional impact blows was enough to split the cracked S6 specimens. On the other, several hundreds of additional impact blows were required to fail the cracked S15 specimens. As shown in Figure 5, 3353 blows was the Nf record for S15, while the obtained Nf record for S6 was 786 blows, keeping in mind the corresponding Ncr records were 931 and 776 blows, respectively. These results reflected that shorter SF (6 mm) had trivial effect on controlling crack widening and formation, while longer SF (15 mm) had a distinguished role in boosting the failure resistance under impact loads.

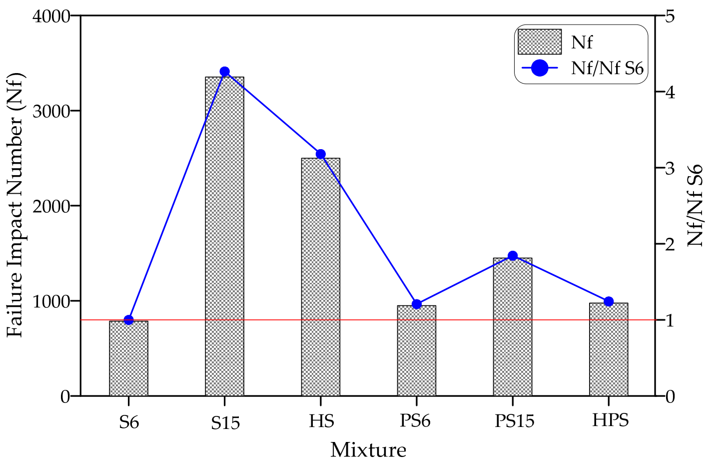
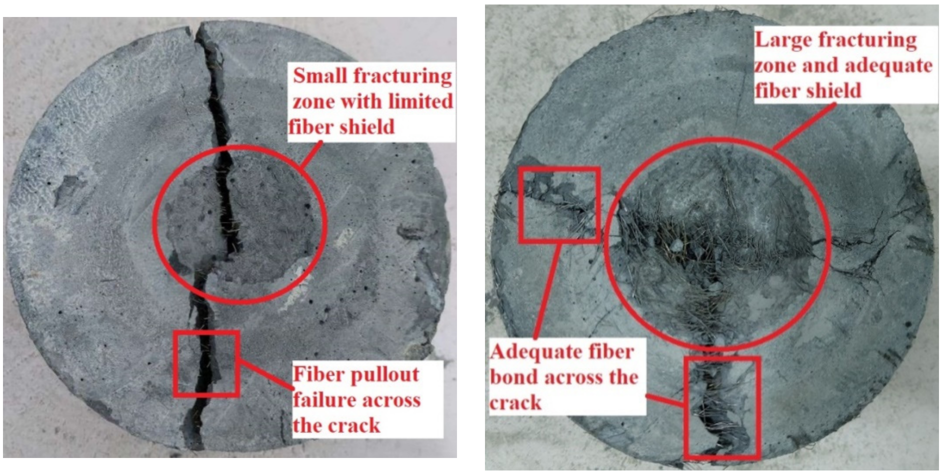


Figure 5. Repeated failure impact numbers.

Figure 6a,b show the failure patterns of 6 mm and 15 mm SF-reinforced specimens, respectively. As inferred by Figure 6a, due the reduced length of steel fibers (6 mm) in S6 specimens, the fibers' effectiveness in controlling crack widening by bridging across its edges was limited and fiber pull-out occurred at low crack amplitude, resulting in the specimen splitting after a small number of impact blows beyond Ncr. Conversely, the longer fibers (15 mm) in S15 delayed failure to several hundreds of extra impact blows due to a wider anchorage length on both sides of the crack (see Figure 6b), which guaranteed a more effective and prolonged bridging capacity. Another observation from Figure 6a is that the short fibers in S6 samples could not compose an effective shielding zone under the steel-ball central impact area, which resulted in quicker failure with a small central fracturing zone. In contrast, the longer steel fibers composed an effective shielding zone under the central impact point that effectively resisted the concentrated impact forces and delayed the fracture of the specimens by sustaining higher local fracturing, as shown in Figure 6b.



(a) (b)

Figure 6. Failure patterns of SF-reinforced specimens. (**a**) S6; (**b**) S15.

The combination of both fibers in HS specimens led to a similar behavior as that of S15, but with a lower Nf record. Replacing 50% of shorter SF with longer SF significantly improved the response of HS specimens to additional post-cracking impacts, which raised Nf to 2499 blows, resulting in a 218% increase compared to S6, while it was lower than that of S15 containing 100% longer fibers. These results were in agreement with those in the previous section in which replacing 0.5% SF with a similar volumetric content of PP in the hybrid mixtures PS6, PS15, and HPS reduced the cracking resistance of these mixtures compared to the corresponding pure SF mixtures. However, the contribution of PP at the failure stage depended on the replaced SF type. Replacing 0.5% short steel fibers in S6 with PP increased obtained Nf, meaning that PP enhanced the crack bridging activity, where Nf of PS6 was 949 blows, which was 21% higher than that of S6. As discussed above, short SF were not able to afford any noticeable post-cracking resistance to impact forces and crack widening. This meant that in PS6, 0.5% PP could be considered as the main effective fibers in the post-cracking stage, which improved the failure impact blow number compared to S6 samples. The obtained Nf record of PS15 was 1450 blows, while that of HPS was 977 blows. These values were respectively 84% and 24% higher than those of S6, but were lower than the corresponding values of S15 and HS by 57% and 61%, respectively.

3.4. Impact Ductility

In flexure, ductility is an index that reflects the ability of a member to sustain plastic deformations and is calculated as the ratio of the ultimate deformation to that measured at the yield of tension steel bars [70,71]. Using the ACI 544-2R repeated impact test, the impact ductility index (DI) is defined as the ratio between Nf and Ncr, which measures the ability of the specimen to resist a higher number of impact blows after cracking, before the occurrence of failure [51,58]. Figure 7 shows that the mixtures S15 and HS with higher 15 mm SF content exhibited the highest ductility index values of 3.60 and 3.78, which was attributed to their higher Nf records, while S6 obtained the lowest DI (1.01) due to its weakness in resisting post-cracking impacts. On the other hand, the SF-PP hybrid mixtures were less ductile with DI values of 1.32, 1.74, and 1.71 for PS6, PS15, and HPS, respectively. These results reflected that PP had a smaller effect on enhancing the post-cracking resistance.

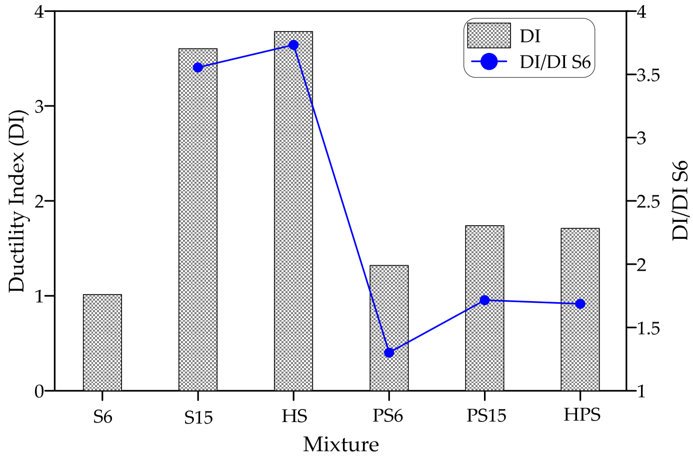


Figure 7. Impact ductility of all mixtures.

4. Statistical Analysis of Repeated Impact Results

4.1. Variation of Impact Numbers

As disclosed in Section 2.1, the ACI 544-2R repeated impact test is simple and low-cost. However, the test results are often characterized by wide scatter, which is attributed to the randomly distributed position and orientation of fibers and the brittle nature of concrete. In the literature [18,72], it was reported that wide ranges of coefficient of variations (COV) were recorded for Ncr and Nf. COV values that range from 30% to 55% were reported in ref. [38,46,73–75], whereas Rahmani et al. [44] reported COV values ranging from 39% to 65% and Chen et al. [57] showed that the COV values for the results of the ACI 544-2R impact test could reach up to 75%.

The coefficients of variation of specimens tested in this study are reported in Figure 8, which fell in the range of 12.3–25.0% for all the considered mixtures. As shown in Figure 8, the COV values of the mixtures with 15 mm SF were generally lower than those of the specimens with 6 mm SF, whereas the COV values of S6 and PS6 samples were in the range 16.9–18.5% for both Ncr and Nf, while the COV values of the S15 and PS15 mixtures ranged from 12.3% to 13.9%. These results may have reflected the more uniform distribution of longer fibers in the matrix, leading to closer results. On the other hand, the hybrid mixture HPS exhibited the highest variations among the six mixtures, with COV values of 23.4 for Ncr and 25.0 for Nf, which reflected that mixing the three fiber types resulted in less uniform fiber distribution in the mixture.

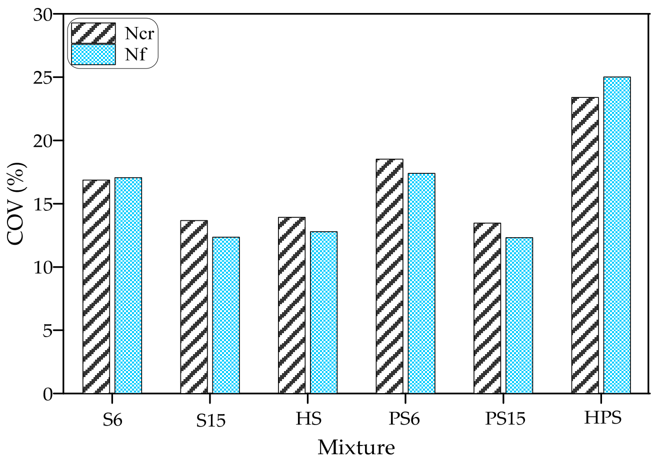
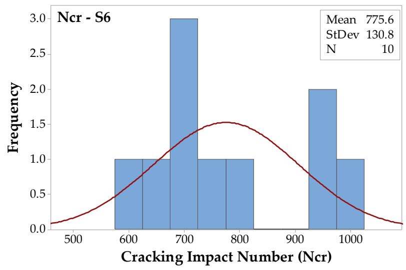


Figure 8. COV values of the repeated impact test records.

4.2. Normal Probability of Impact Numbers

Normal probability was used by many previous studies [18,37–40,44,46,73–75] to evaluate the distribution of the cracking and failure impact results. Many of these studies showed that Ncr and Nf results do not follow normal distributions, while others showed that these results can be evaluated using normal probability. The normal probability test was also used in this study to evaluate the distribution of the impact results. The distribution histograms shown in Figure 9 revealed that the Ncr results of the six mixtures did not show a distribution trend that followed normal distribution. However, the Anderson-Darling test presented in the probability plots shown in Figure 10 revealed a different behavior. It should be mentioned that the Anderson-Darling test was adopted because it was designed to evaluate small sample sizes, which makes it suitable for the current repeated impact test in which 10 replicates were used for each test. Figure 10 shows that except HPS (Figure 10a), the probability was generally greater than 0.05, which accepted the null hypothesis and reflected no significant departure from normal distribution, while the *p*-value of HPS was 0.033, which rejected the null hypothesis of normality and reflected that within the limit of the 95% degree of confidence, the Ncr records of HPS did not follow normal distribution. Noting the distribution of data around the linear fit, it can be seen that the records were not in good agreement with the fit, but they did not significantly depart from it. Thus, it can be concluded that the Ncr results of HPC mixtures were not perfectly normally distributed, but they did not significantly depart from this distribution.



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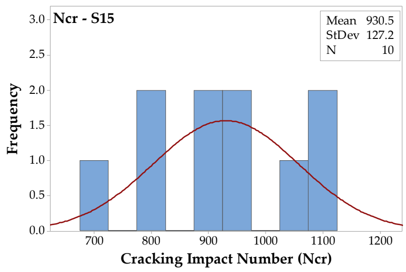

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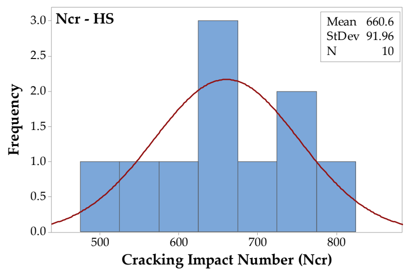

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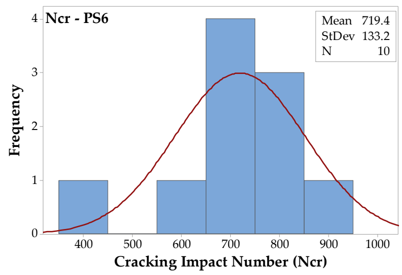
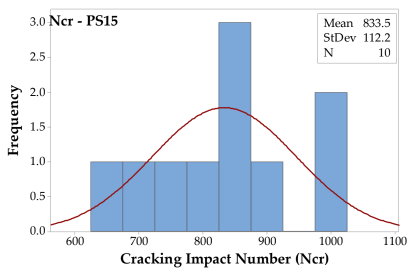
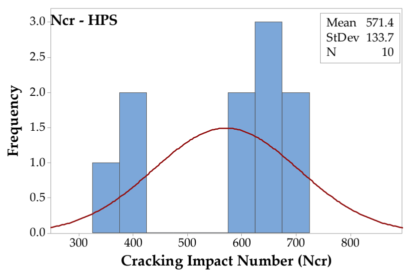


(**d**)



(**e**)



(**f**)

Figure 9. Normal distribution histograms of the cracking impact number Ncr. (**a**) S6; (**b**) S15; (**c**) HS; (**d**) PS6; (**e**) PS15; (**f**) HPS.

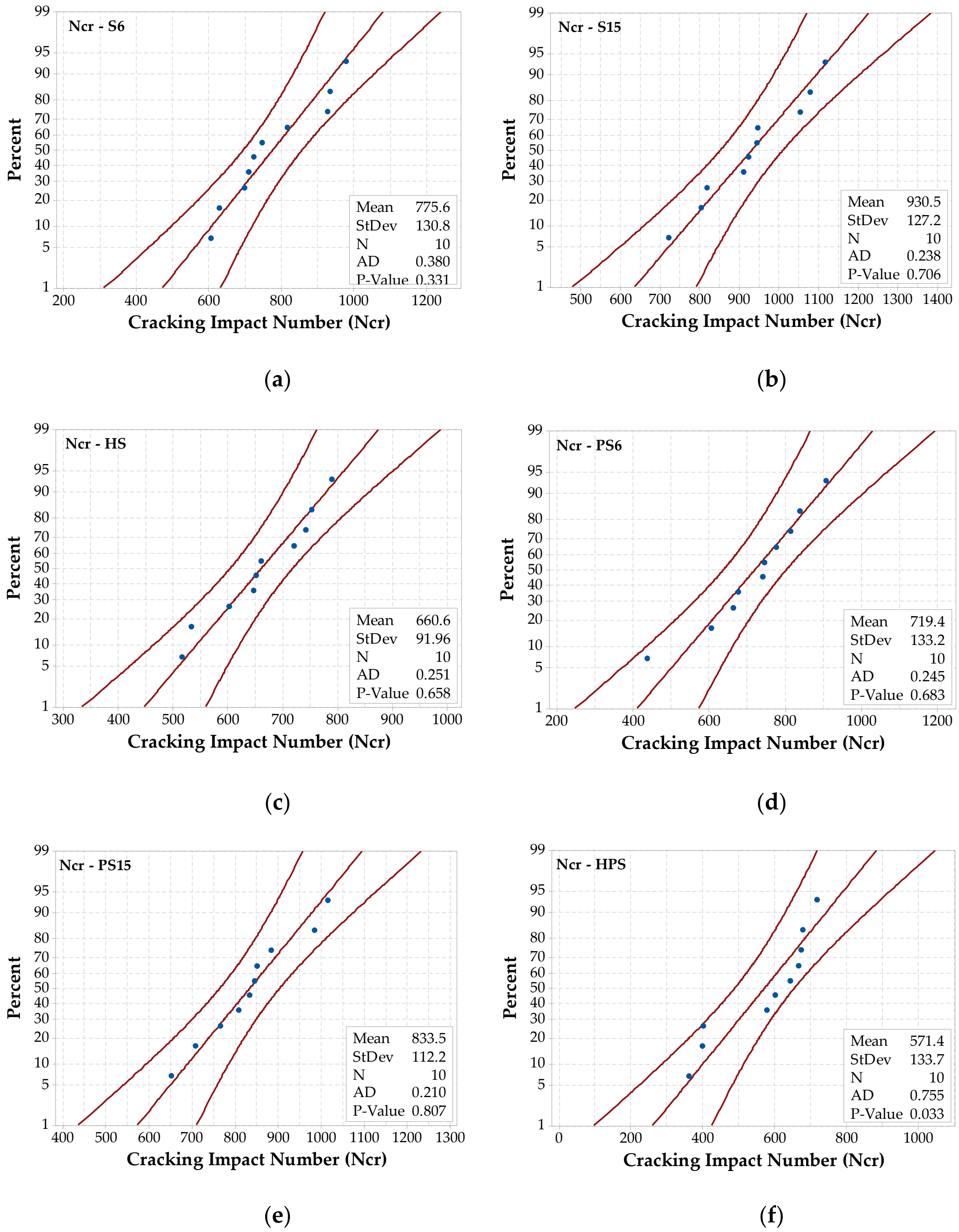


Figure 10. Normal probability plots of the cracking impact number Ncr. (**a**) S6; (**b**) S15; (**c**) HS; (**d**) PS6; (**e**) PS15; (**f**) HPS.

The histogram distributions of the Nf results of the six mixtures are shown in Figure 11 and their normal probability plots are given in Figure 12. As shown in Figure 11c, it can be seen that the distribution of Nf records of the HS mixture reflected good agreement with normal distribution. This agreement was also confirmed in Figure 12c, where the data agreement with the linear fit was more evident and the *p*-value was much higher than 0.05, reflecting a very small departure from normal distribution. Conversely, S15 failure impact numbers exhibited a disturbed histogram (Figure 11b) and large scattering from a linear fit (Figure 12b), associated with a *p*-value of 0.053, which reflected a disagreement with normal distribution. The other mixtures followed a similar trend to the general behavior discussed for Ncr, with *p*-values larger than 0.05 but with noticeable variation around the linear fit. Hence, it can be said that the Ncr and Nf values did not perfectly follow normal distribution, but neither did they exhibit a significant departure from it.

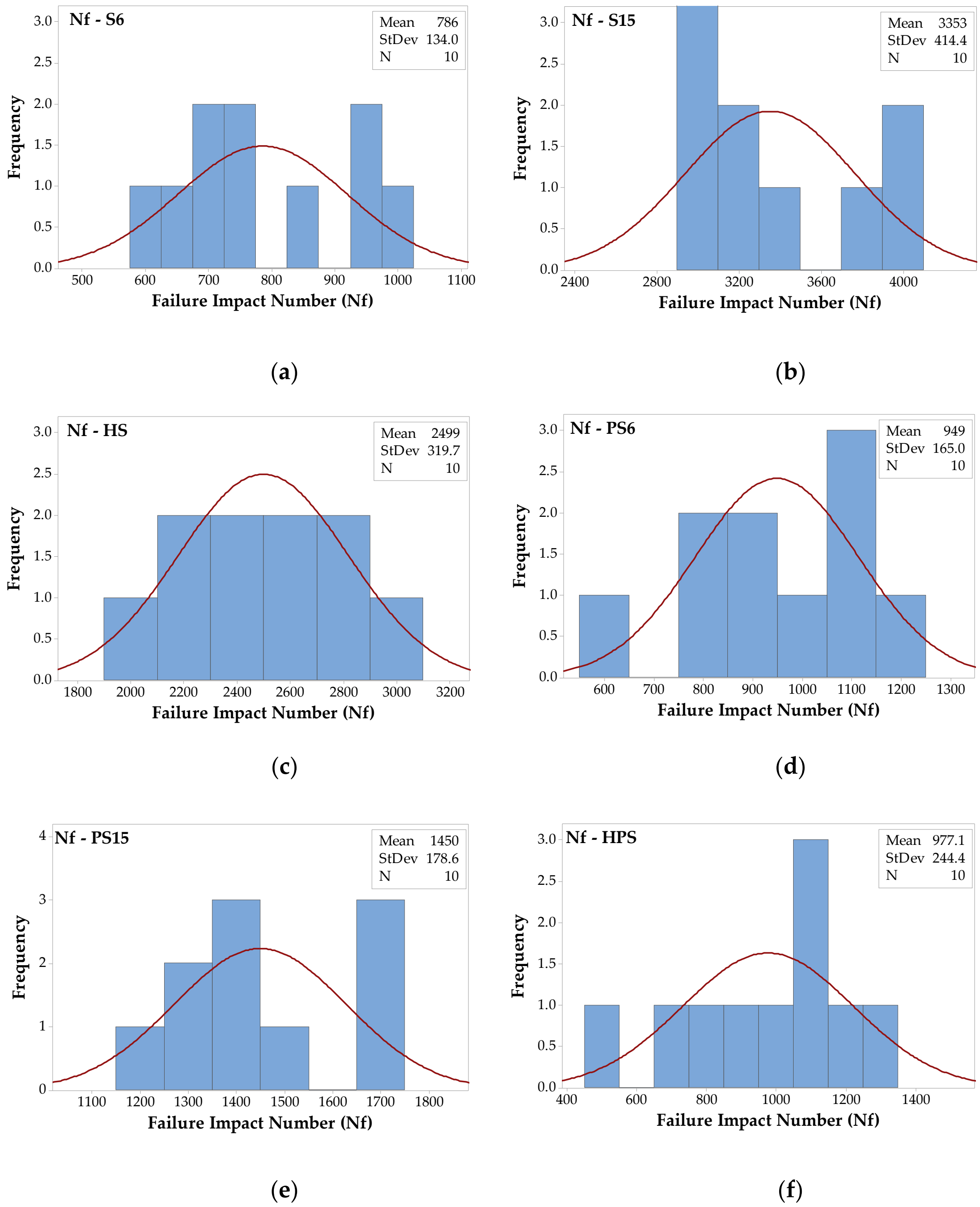


Figure 11. Normal distribution histogram of the cracking impact number Ncr. (**a**) S6; (**b**) S15; (**c**) HS; (**d**) PS6; (**e**) PS15; (**f**) HPS.

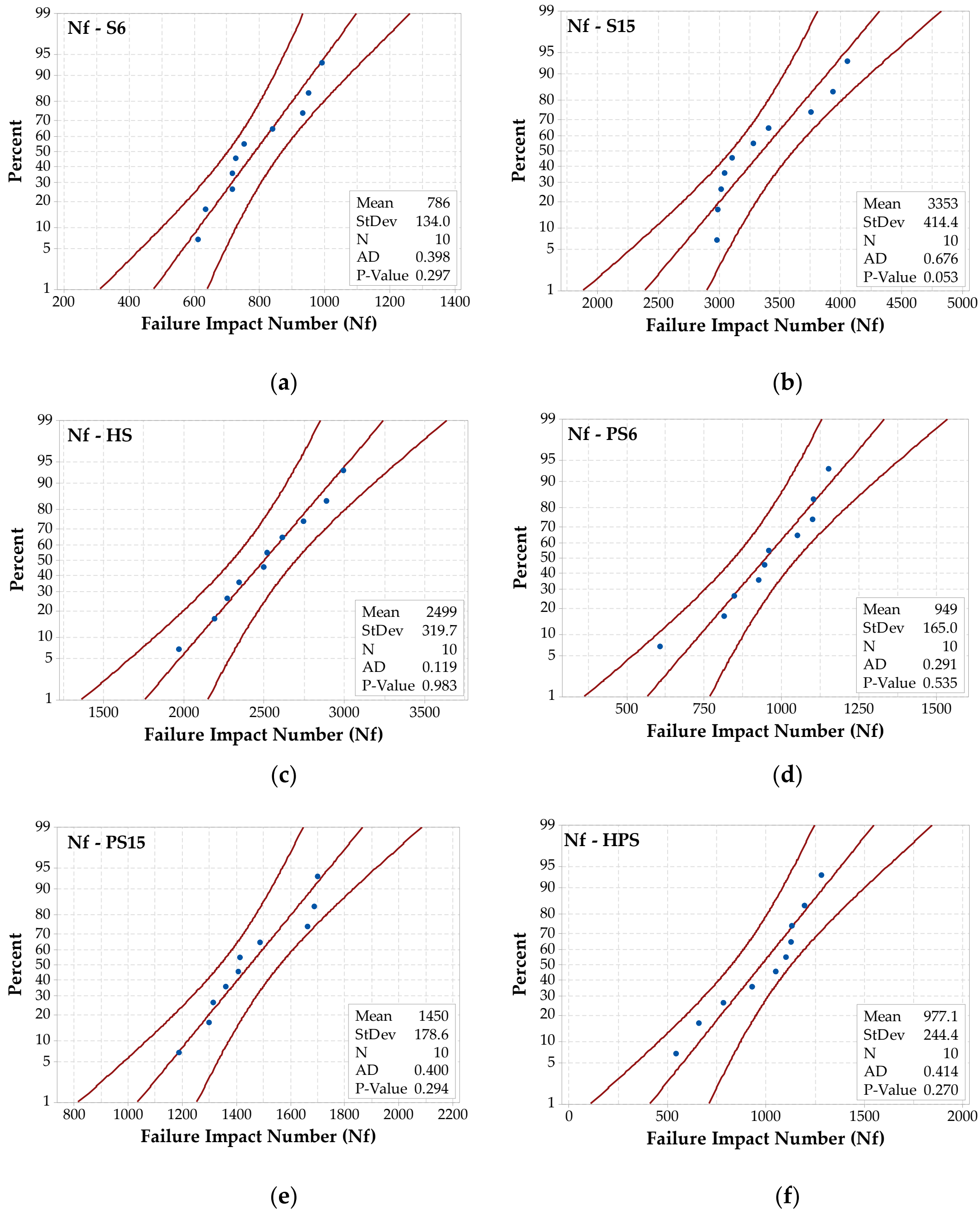


Figure 12. Normal probability plots of the cracking impact number Nf. (**a**) S6; (**b**) S15; (**c**) HS; (**d**) PS6; (**e**) PS15; (**f**) HPS.

5. Comparison of Impact Results with Those of the Study by Jabir et al.

As previously mentioned in the introduction, Jabir et al. [67] tried to evaluate the repeated impact performance of SF-reinforced and PP-SF-reinforced HPC mixtures. However, they could not complete the tests until failure, so only Ncr results were introduced. Because Ncr cannot express the full response of HPC under impact loads, the same mixtures were adopted in this study and tested until failure using the automatic impact testing machine shown in Figure 2. Therefore, it is important to compare the results of this study with those obtained by Jabir et al. Before discussing differences in the results, it should be mentioned that Jabir et al. did not restrict the ACI 544-2R impact test requirements; the drop weight and height were increased to 10 kg and 700 mm and the specimen diameter was reduced to

125 mm. Conversely, in this study, the standard drop weight and height were 4.54 kg and 457 mm, respectively, and the specimen diameter was 150 mm.

5.1. Repeated Impact Numbers

Since Jabir et al. [67] tested the specimens only until cracking, all comparisons in this section are limited to the Ncr results. Figure 13 shows that Ncr values recorded in this study were clearly higher than those of Jabir et al. For the six mixtures, the obtained Ncr records were in the range of 571 to 931 blows, while those of Jabir et al. were in the range of 102 to 245 blows. The ratio of Ncr values in this study to those of Jabir et al. ranged between 3.8 and 6.1 for the six mixtures, as shown in Figure 13. The significant differences between the results of the two studies can be justified by the use of different test parameters. Accordingly, the higher drop weight and height adopted by Jabir et al. increased the impact energy of each blow, which accelerated the cracking of the specimens. The impact energy of each impact blow due to the drop weight and height of 10 kg and 700 mm equaled 68.7 J, while that of the standard test equaled 20.4 J. Hence, each impact blow in the Jabir et al. study imposed an impact energy that was more than three times that of the standard test used in the present study.

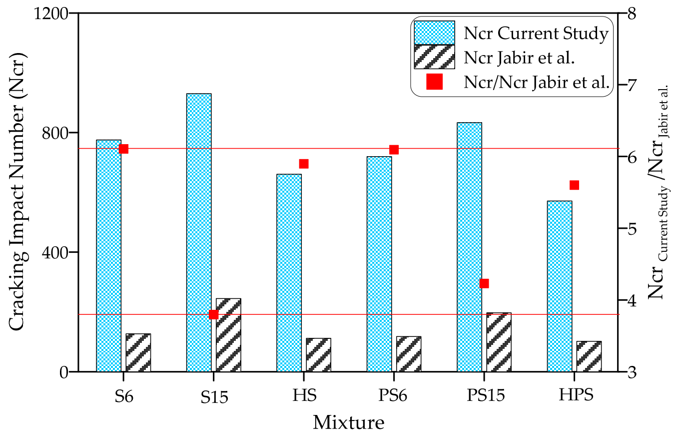


Figure 13. Comparison of Ncr records in the study by Jabir et al. [67] with the Ncr records of the current study.

To provide a fairer comparison, the cracking impact energy (Ecr) can be used as a comparison element between the results of both studies. Accordingly, Figure 14 compares the cracking results of both studies in terms of Ecr, which obviously shows that the differences between the recorded cracking results in the two studies became narrower. The ratios of Ecr values in this study to those of Jabir et al. were in the range of 1.13 to 1.81. This indicated that, although the differences between the two studies were not huge, the results obtained in this study were still higher than those of Jabir et al., which could be attributed to the smaller size specimens used by Jabir et al. (diameter 125 mm). Therefore, to account for the effect of specimen size, a simple normalization technique was used by multiplying the Ecr results of Jabir et al. by the ratio of the cross-sectional area of the standard specimen to that of the 125 mm specimens. This normalization was adopted because as impact loads are concentrated on the center of the top surface and spread diagonally in all directions, it is believed that stresses are resisted by the whole area of the specimen. It should be noted that the thicknesses of specimens in both studies were approximately equal. Figure 15 compares the Ecr values of this study with the corrected (normalized) Ecr values of Jabir et al. The figure shows that by using the normalized Ecr values, the differences between the two studies became smaller, where the ratios of Ecr values in this study to the normalized Ecr values of Jabir et al. were in the range of 0.78 to 1.26. These results can be justified considering that the specimens of the two studies were from different batches and a certain scattering is typical for the ACI 544-2R impact test.

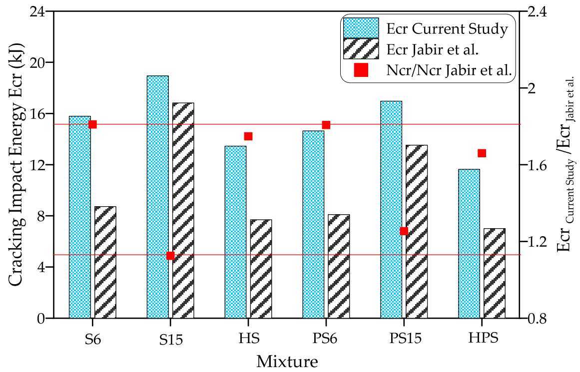


Figure 14. Comparison of cracking impact energy Ecr values of Jabir et al. [67] with those of the current study.

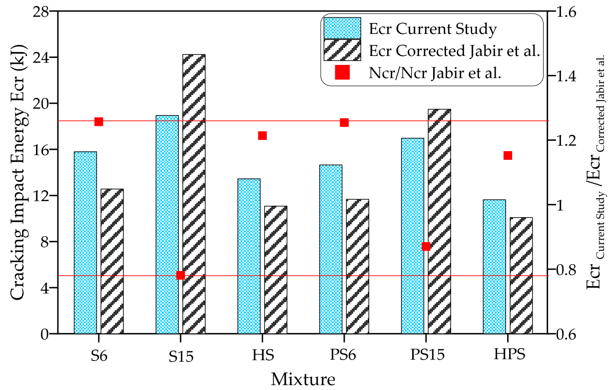


Figure 15. Comparison of corrected cracking impact energy Ecr values of Jabir et al. [67] with those of the current study.

5.2. Variation of Impact Numbers

Figure 16 compares the COV values of the Ncr results of the current study with those reported by Jabir et al. As inferred by Figure 16, the COV values of this study were significantly smaller than those of Jabir et al., which reflected less result scattering in this study. Jabir et al. used a manual testing apparatus that may have induced an additional source of scattering due to the lower control of the testing parameters, whereas better control may have been provided by using the automatic testing machine employed in this study. Moreover, the crack observation technique adopted in this study, based on the use of a high-accuracy digital camera and large screen monitor, was another source of scattering control, which enabled the tester to more accurately define the cracking number compared to visual inspection of the manual testing apparatus.

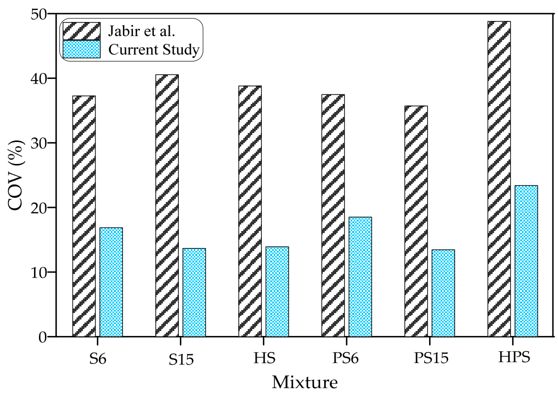


Figure 16. Comparison of cracking COV values of Jabir et al. [67] with those of the current study.

6. Conclusions

The impact performance of six mono and hybrid fiber-reinforced HPC mixtures was examined in this study using the ACI 544-2R repeated impact test, where the cracking (Ncr) and failure (Nf) impact numbers were the main experimental records. From the experimental results and the statistical analysis conducted in this study, the following conclusions can be drawn:

1. Comparing each SF-reinforced mixture with its corresponding hybrid fiber-reinforced mixture, it was found that replacing 0.5% SF with PP reduced the compressive strength by approximately 5.0%, which was attributed to the higher stiffness and tensile strength of steel fibers compared to polypropylene fibers. On the other hand, the difference between the compressive strengths of mixtures of each of the two groups (SF-reinforced and hybrid fiber-reinforced mixtures) was in general less than 2.0%.
2. The Ncr results showed that the differences among the six mixtures were not large, while it was clear that specimens with longer SF could better resist cracking under impact loads than those with shorter SF by approximately 20%. This action was attributed to the better ability of longer fibers to afford adequate anchorage lengths inside the matrix across both sides of the crack, which delayed the propagation of cracks.
3. S15 specimens with pure 15 mm SF obtained the highest Nf record (3353 impact blows), while S6 specimens with pure 6 mm SF obtained the lowest Nf record (786 impact blows). Thus, Nf of S15 was more than 4 times that of S6, revealing the weakness of short SF and adequacy of long SF to afford the required bond that arrests cracking and prevents crack widening and propagation. The hybridization of both fibers led to an Nf record of 2499 blows, which was higher than the Nf record of S6 and lower than that of S15.
4. The long SF could compose a shielding zone under the central impact area of the specimen's top surface, thereby resisting a wide central fracturing area and increasing crack bridging effectiveness, which enhanced the failure capacity and altered the brittle fracturing behavior of concrete to adopt a more ductile characteristic. In addition, the ductility index values of specimens with high 15 mm SF content were in the range of 3.60 to 3.78. On the other hand, the short SF failed to compose a central shielding zone and the failure of S6 specimens was characterized by a very low ductility index (DI = 1.01).
5. The effect of hybridization of HPC with SF and PP was found to be dependent on the test stage and length of SF fibers. The results revealed that replacing 0.5% SF with 0.5% PP reduced the crack resistance capacity (Ncr) of the three SF-reinforced mixtures by 7% to 15%. On the other hand, it was found that PP had minor post-cracking crack arresting activity compared to 15 mm SF, but they exhibited better activity than 6 mm SF. The ductility index values of SF-PP hybrid mixtures ranged from 1.32 to 1.74, meaning that PP had a much smaller effect on enhancing post-cracking resistance than long SF, but a better effect than short SF.
6. The specimens with long SF exhibited lower Ncr and Nf variations than those with short SF, where the COV values of mixtures with long and short SF were in the ranges of 12.3% to 13.9% and 16.9% to 18.5%, respectively. On the other hand, mixing the three fiber types resulted in the highest result scattering, with the highest COV value of 25.0 recorded for the HPS hybrid mixture. The Anderson-Darling normal probability test indicated that most of the Ncr and Nf records did not perfectly follow normal distribution, but they also did not exhibit significant departures from this distribution.

Author Contributions: Conceptualization, S.R.A. and T.S.A.-G.; methodology, S.H.A., K.A.-L., T.S.A.-G. and S.R.A.; software, S.R.A., K.A.-L. and T.S.A.-G.; validation, S.R.A. and A.M.Y.; formal analysis, S.H.A. and A.M.Y. investigation, T.S.A.-G. and S.H.A.; resources, T.S.A.-G., S.H.A. and A.M.Y.; writing—original draft preparation, S.R.A.; writing—review and editing, A.S.C., A.M.Y. and T.S.A.-G.; visualization, S.R.A. and A.S.C.; supervision, S.R.A.; project administration, S.R.A.; funding

acquisition, S.R.A., K.A.-L. and A.S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors gratefully acknowledge the support of the material construction laboratory at Wasit University and the Al-Sharq laboratory.

Conflicts of Interest: The authors declare no conflict of interest.

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