Effect of macro polypropylene fiber and basalt fiber on impact resistance of basalt fiber - reinforced polymer - reinforced concrete

Qingxuan Wang[1], Yining Ding[1,*], Yulin Zhang[2], Cecilia Castro[2]

[1]State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China

[2]University of Minho, Centre of Mathematics, Braga 4700-052, Portugal

***Correspondence** Tel: +86 411 84709756; Email: ynding@hotmail.com

Abstract

In this paper, the effect of macro non-metallic fibers (i.e. polypropylene fibers and basalt fibers) on the impact response of basalt FRP-reinforced concrete discs is experimentally investigated using a self-developed drop-weight impact test device. The plain concrete and conventional steel reinforced concrete samples are explored as references. The impact resistance and failure behaviors are analyzed. Statistical analyses for first-crack strength and failure strength are performed. The composite effect of basalt FRP bars and macro non-metallic fibers on the impact energy at failure is also compared. The results indicate that the behaviors under impact load, i.e. failure strength, crack number, the indent diameter and penetration depth of the shriveled area, are greatly improved by adding of macro non-metallic fibers, in particular macro polypropylene fibers. Additionally, the incorporation of these fibers into the basalt FRP-reinforced concrete transforms the brittle failure mode into a well ductile failure mode. Two-parameter Weibull models are fitted by graphical methods and used to characterize the first crack strength and failure strength distributions. Reliability functions for first crack strength and for failure strength are estimated and failure strength can be predicted from first-crack strength by using a linear regress model. The hybrid use of basalt FRP bars and macro non-metallic fibers demonstrates a positive synergetic effect on the impact energy at failure.

KEYWORDS

basalt FRP bars, macro non-metallic fibers, impact resistance, synergetic effect, two-parameter Weibull distribution

Nomenclature

MPF:	macro polypropylene fiber;
MBF:	macro basalt fiber;
PC:	plain concrete;
FRP:	fiber-reinforced polymer;
BFRP:	basalt fiber-reinforced polymer;
Steel-RC:	steel reinforced concrete;
BFRP-RC:	basalt FRP-reinforced concrete;
MPFx:	macro polypropylene fiber reinforced concrete with fiber content of x kg/m^3, for example, MPF5: macro polypropylene fiber reinforced concrete with fiber content of 5 kg/m^3;
MBFy:	macro basalt fiber reinforced concrete with fiber content of y kg/m^3, for example, MBF20: macro basalt fiber reinforced concrete with fiber content of 20 kg/m^3;
B-MPFx:	basalt FRP-reinforced concrete in combination with x kg/m^3 macro polypropylene fiber, for example, B-MPF5: basalt FRP-reinforced concrete in combination with 5 kg/m^3 macro polypropylene fiber;
B-MBFy:	basalt FRP-reinforced concrete in combination with x kg/m^3 macro basalt fiber, for example, B-MBF20: basalt FRP-reinforced concrete in combination with 20 kg/m^3 macro basalt fiber;
IE	impact energy;
δ	standard deviation;
CV	coefficient of variation;

1 INTRODUCTION

Plain concrete (PC) is a brittle material with low tensile capacity and poor impact resistance. However, concrete elements for applications in civil engineering may be subjected to impact loads during their service life, and typical examples of such loads are caused by surface irregularities for bridge decks, driving process for precast concrete piles, aircraft landing for airport pavements and pounding by waves for hydraulic structures.[1,2] Steel reinforced concrete (Steel-RC) has been used extensively for many decades in civil engineering structures to resist impact loads.[3] Some problems (e.g., low shatter resistance[3]) exist in this method, though the impact resistance of the concrete is remarkably improved. In particular, the corrosion of steel reinforcement is one of the causes that influences the structural capacity of concrete elements especially for the structures in marine and salt environments.[4] According to the data reported by Banthia et al.[5], the maintenance costs caused by the corrosion of steel reinforcement, both of financial and environmental, are very high, and the annual cost amounts to billions of dollars. In this case, non-corrosive fiber-reinforced polymer (FRP) bar is regarded as a preferred strengthening material over conventional steel reinforcement for civil engineering structures. The advantages of FRP bars also include low density (only 1/3 times of the density of steel), high tensile strength (2-3 times of the tensile strength of steel), non-magnetic characteristics apart from the non-corrosive property.[6]

In spite of these advantages, the tensile behavior of BFRP bar is characterized by a linearly elastic stress-strain relationship until failure. unlike the behavior of steel rebar. As a result, the failure of FRP-reinforced concrete (FRP-RC) member is sudden and catastrophic.[5,7] In addition, because of the lower elastic modulus of FRP bars in comparison with that of the steel reinforcement, FRP-reinforced concrete (FRP-RC) flexural member displays lower post-cracking bending stiffness than conventional Steel-RC flexural member.[8] In order to remedy the drawbacks of FRP bars, e.g., brittleness, several improved approaches are proposed such as using FRP bars as a reinforcement in nonstructural components, adopting both FRP bars and steel reinforcement as reinforcements in structural components, employing FRP bars in combination with high-performance cementitious composites and stipulating higher margin of safety for FRP-RC members than that used in traditional Steel-RC design.[5,9-11] Moreover, the addition of short randomly distributed fibers into the concrete matrix has also been shown to be effective for FRP-RC members.[12]

The impact resistance is regarded as one of the significant properties of concrete for structural applications in civil engineering, and quite a few investigations have been previously carried out to study the influence of various reinforcements (e.g., FRP composites and fibers) on the response of the concrete under impact load in Refs.[13-21]. For instance, Goldston et al.[13] studied the effects of glass FRP (GFRP) bar as reinforcement on the behavior of concrete beams under impact loading. The results showed that the over-reinforced beams experienced minor inclined shearing cracking and crushing of concrete cover around the impact zone at approximately 45° angles, resulting in a shear plug type of failure. Branston et al.[17] observed that the addition of minibars had a meaningful effect on the post-cracking behavior of concrete, and fiber dosages of 6 kg/m^3 and 20 kg/m^3 of minibar resulted in a comparable post-cracking performance to the steel fiber at a dosage of 40 kg/m^3 under flexural and impact loading, respectively. However, these studies are mainly focused on the impact properties of the concrete specimens with mono use of FRP composites or fibers, and the literature addressing the performance of BFRP-RC under impact load, especially that incorporated with macro non-metallic fibers, remains very limited.

Macro polypropylene fiber (MPF, length $\geq$3 cm) has been widely used in civil engineering, and considerable improvements can be obtained regarding the post-cracking residual strength, toughness, cracking control of the concrete.[22-24] Additionally, the MPF has better features in density and corrosion resistance compared with steel fibers. Macro basalt fiber (MBF), a novel type of epoxy resin based composite (length ≥3 cm) reinforced with basalt filaments, has generated considerable research interest in recent years due to the excellent mechanical properties of basalt fiber and its environmentally friendly manufacturing process.[17,25] Moreover, there is a lack of knowledge about MBF and its effect on the impact resistance of the concrete. In addition, compared to other types of non-metallic fibers such as PE and PVA fibers, the MPF and MBF fibers are more cost efficient and easily available in the domestic market. Therefore, MPF and MBF are selected as the reinforcements for the concrete in conjunction with BFRP bars, which is anticipated to provide structures with substantial energy absorption ability and ductility when subjected to impact loads.

In this paper, the impact behaviors of BFRP-RC specimens with or without non-metallic fibers (i.e. MPF and MBF) using a self-developed drop-weight test device are experimentally investigated. The impact resistance and failure behaviors (i.e. failure mode, cracking behaviors and the indent diameter and penetration depth of the shriveled area of the disc specimens) are analyzed, the variations in the experimental results are statistically evaluated, and the hybrid effect of BFRP bars and MPF/MBF on the impact energy at failure are compared. The results reveal that the incorporation of macro non-metallic fibers notably improves the impact performance of BFRP-RC. BFRP bars in combination with macro non-metallic fibers could be considered as an alternative strengthening system to conventional steel reinforcement in concrete for the structures in marine and salt environments.

2 EXPERIMENTAL PROGRAM

2.1 Materials

The PC is made out of ordinary Portland cement, fly ash, regular drinking water, superplasticizer, quartz sand as the fine aggregate and natural crushed gravel as the coarse aggregate. The mixture proportion of PC concrete is as follows: CEM I 42.5 390 kg/m^3, fly ash 155 kg/m^3, quartz sand with particle size of 0-5 mm 822 kg/m^3, the coarse aggregate natural crashed gravels with particle size between 5-10 mm 848 kg/m^3, water 272.5 kg/m^3 and superplasticizer 7.6 kg/m^3.

In the present study, the sand-coating BFRP bar with a diameter of 12 mm is adopted as the internal reinforcement of the concrete to study the impact resistance of BFRP-RC. The deformed steel rebar with a diameter of 12 mm is used as reference. For investigating the influence of hybrid use of BFRP bars and macro-nonmetal fibers on the impact performance of the concrete, MPF and MBF (Figure 1) are incorporated into the concrete matrix, and their properties are given as follows. The MPF has a length of 30 mm, an equivalent diameter of 0.67 mm and a tensile strength of 490 N/mm^2. The MBF has a length of 36 mm, an equivalent diameter of 0.7 mm and a tensile strength of about 1000 N/mm^2.

2.2 Specimen preparation

In this work, two fiber contents for each fiber are selected for investigating the effect of macro non-metallic fibers on the impact behaviors of BFRP-RC specimens under impact load. For MPF, the designed fiber contents are 5 and 7 kg/m^3, and for MBF, the designed fiber contents are 20 and 30 kg/m^3. The reinforcement ratio of the Steel-RC specimens is 1.9%, and this reinforcement ratio is often used for the applications in civil engineering, e.g., bridge decks and precast piles.

Each type of fresh concrete is cast into cubic (100 mm) and cylindrical (152×75 mm) discs to be used in the compressive and impact tests, respectively. The cast specimens are demolded at a concrete age of 24 hours and then placed in a curing room, subsequently, the specimens are cured at 20 °C with 95% relative humidity up to the age of 28 days.

2.3 Testing methods

A versatile and economical drop-weight test device based on the recommendation of ACI Committee 544[26] is fabricated, as shown in Figure 2. The boundary conditions in the impact test, i.e. the height and the loading point of the drop hammer for each blow, can be guaranteed by adjustable cantilever bracket and positioning slot, which contributes to minimizing the scatter of the test results. In the test, the cylindrical disc is set on a baseplate within four positioning lugs and impacted by repeated blows. The blows are introduced through a 4.54 kg hammer falling repeatedly from an initial height of 457 mm onto a steel ball with a diameter of 64 mm located at the centre of the top surface of the disc. The number of blows to cause the first visible crack, recorded as N_1, is defined as first-crack strength, and the number of blows resulting in that the disc touches three of the lugs, recorded as N_2, is defined as failure strength.[27,28]

The impact resistance of the specimens is determined in terms of first-crack strength and failure strength, and correspondingly the impact energy for each specimen can be calculated using the following equation (Eq. (1)) in accordance with ASTM standard D5628[29]:

$$IE = N_i \cdot h \cdot w \cdot f \qquad (1)$$

where IE is the impact energy, J; N_i is the number of blows (i=1 or 2); h is the initial height of the drop hammer, mm; w is the mass of the drop hammer, kg; f is a constant with a value of 9.806×10^{-3}, m/s^2.

3 RESULTS AND DISCUSSION

3.1 Compressive strength

Table 1 shows the compressive strength of the specimens with or without fiber reinforcement after 28 days.

From Table 1, it can be observed that the compressive strength of the concrete is somewhat increased by adding MPF compared to that of PC specimen. However, the addition of MBF results in a drastic reduction in compressive strength, e.g., for MBF30 specimen, the compressive strength is decreased by about 31% compared to that of PC specimen.

It should be pointed out that although the adverse effect of MBF on the compressive strength, the addition of the fibers aids in converting the brittle properties of concrete into a ductile material.[30,31] Furthermore, it is evident that the addition of basalt fibers is not an effective method of increasing compressive strength. Rather, it is more important to ensure their addition does not hinder compressive strength.[17,32,33]

3.2 Impact resistance

3.2.1 Impact resistance

The results of the impact test performed on different disc specimens at the age of 42 days are listed in Table 2.

From Table 2, it can be observed that a relatively small number of blows are required to cause failure in the PC specimen. However, the incorporation of MPF gives rise to a substancial increase in failure strength, which varies from 113% to 153% for MPF5 and MPF7 specimens, respectively. Similarly, the addition of MBF leads to a remarkable increase in failure strength by 77% and 87% for MBF20 and MBF30 specimens, respecitively, compared to that of PC specimen. The significant improvement in the failure strength is mainly attributed to the energy-absorbing mechanisms and load transfer mechanisms of MPF and MBF throughout the concrete matrix. These fibers, acting as miniature energy-absorbing mechanisms, can support a certain percentage of the load during each blow before cracking and dissipate the impact energy by the process of debonding, slipping and pulling out from the concrete matrix after cracking, thus reinforcing the discs against more impact blows.[27] In addition, the fibers, also acting as load transfer mechanisms in the post-cracking stage, can ease the crack-tip stress intensity, transfer stresses by bridging the fractured crack surfaces and defend the cracked discs against the tendency to fail into pieces.[27,34,35]

The failure strength of MPF7 specimen is increased by about 43% compared to that of MBF20 specimen; this would indicate that MPF can improve much more failure strength than MBF at the same fiber volume fraction. In addition, it can be found that the use of mono MPF or MBF appears to have no significant effect on the first-crack strength.

The failure strength of BFRP-RC specimen is 87 blows. Compared to failure strength of BFRP-RC specimen, the increments for failure strength of the BFRP-RC specimens with 5 and 7 kg/m^3 MPF achieve about 125% and 210%, respectiely. Similarly, the addition of 20 and 30 kg/m^3 MBF enhances the failure strength of the BFRP-RC specimens by about 67% and 67%, respectively. It means that the hybrid use of BFRP bars and macro non-metallic fibers, in particular MPF, significantly improves the failure strength of the BFRP-RC specimens. The reason for the great enhancement of the failure strength could be traced back to both the strengthening mechanism of the fibers (i.e. energy-absorbing mechanisms and load transfer mechanisms) and the improvement in the bond strength of the BFRP bar to the concrete due to the addition of these fibers.[1,27,36,37]

Among all the tested specimens, the B-MPF7 specimen exhibits the highest failure strength of 270 blows, and the corresponding impact energy at failure is 5493 J. The impact energy at failure for B-MPF7 specimen is increased by about 7% compared to that of Steel-RC specimen.

The coefficient of variation (CV) is considered as a more meaningful index of variability than the standard deviation because it accounts for the mean value as well as the standard deviation. It can be observed from Table 2 that the CVs of the failure strengths for all the remaining specimens except the Steel-RC specimen range from 16% to 43%. These values are close to those reported by previous studies[38,39] on the modified ACI drop-weight impact test. It indicates that the test results is reliable, and a reasonable scope for the CV can be obtained by using this self-developed drop-weight test device.

3.2.2 Failure behaviors

The comparison of failure patterns of disc specimens with different reinforcements (i.e. PC, RC, BFRP, MPF7, MBF30, B-MPF7 and B-MBF30 specimens) under impact load is shown in Figure 3. Table 3 summarizes the number of cracks (n), the indent diameter (d_s) and the penetration depth (h_s) of the shriveled area for all the tested specimens, wherein the number of cracks is determined by the accounting the visible cracks of the concrete samples, the indent diameter and the penetration depth of the shriveled area are measured manually.

From Figure 3 and Table 3, the following statements can be concluded.

For the specimens of PC, the failure demonstrates clearly brittle behavior with only one main crack throughout the specimen as shown in Figure 3a. The specimens are broken down abruptly after cracking and shattered into two fragments. The values of d_s and h_s of the shriveled area are about 25 mm and 3 mm, respecitively.

For the Steel-RC specimens (Figure 3b), the number of cracks induced by the impact load is 5 for most tests, and the values of d_s and h_s of the shriveled area are about 57 mm and 17 mm, respecitively. It indicates that the behaviors under impact load (e.g., failure strength, crack number and penetration resistance) are significantly improved compared to PC specimens without any reinforcements. This can be attributed to the perfect bond behavior between concrete and reinforcement which is mainly governed by the mechanical action due to the bearing of the ribs of the rebars against the concrete. On the one hand, the rebars can improve stress redistribution and arrest crack propagation. On the other hand, the slipping between the concrete and rebars can significantly diffuse the energy.[1] Therefore, the impact behaviors can be greatly improved, and the final failure is mainly caused by the longitudinal and cumferential cracks.

For the BFRP-RC specimens (Figure 3c), the crack number at failure is 4 in most cases, and the values of d_s and h_s of the shriveled area are about 38 mm and 6 mm, respectivily. Moreover, when the failure occurs, some fragments are isolated from the specimen, which demonstrates the brittle behavior like that of PC specimen. Compared to PC specimen, the values of d_s and h_s of the shriveled area of the BFRP-RC specimens are enhanced by about 52% and 100%, respectively. Compared to Steel-RC specimen, the values of d_s and h_s of the shriveled area of the BFRP-RC specimens are decreased by about 33% and 65%, respecitivily. The beneficial effect of the BFRP bar which performs worse than that of the steel reinforcement on failure behaviors is well anticipated given weak bond of BFRP bar to the concrete and the linear-elastic nature until failure in BFRP bar.[5,13,36]

For the specimens reinforced with only macro non-metallic fibers (e.g., Figure 3d and e), they are capable to sustain additional blows after cracking because of the incoporation of the randomly distributed fibers. The fibers continue to transfer tensile stresses across the crack in the concrete and prevent the further spread of the cracks and this leads to an improvement in tensile strength and ductility of concrete. As a result, a more even stress redistribution in these specimens is achieved compared to that of PC specimen. The final failure is mainly caused by the partial breaking down and partial pull-out of MPF or the overall pull-out of MBF. The number of cracks at failure is 3 in most cases for MPF and MBF specimens. Compared to PC speimen, the values of d_s of the shriveled area of MPF5, MPF7, MBF20 and MBF30 specimens are increased by about 80%, 88%, 68% and 80%, respectively; the values of h_s of the shriveled area of MPF5, MPF7, MBF20 and MBF30 specimens are increased by about 200%, 267%, 133% and 200%, respectively. However, these values (i.e. n, d_s and h_s) are much smaller than those of Steel-RC specimen.

For BFRP-RC specimens incorporating non-metallic fibers (e.g., Figure 3f and g), similar multi-crack pattern as Steel-RC specimens has been developed, i.e. the crack pattern is changed from one main crack in the case of PC specimen into multiple fine cracks (i.e. 5 or 6). Meanwhile, compared to the specimens with only BFRP bars or macro-nonmetallic fibers, the values of n, d_s and h_s is obviously increased. These indicate that the brittleness is greatly improved and the stress redistribution in these specimens is achieved more evenly than that of the specimens with mono reinforcement due to the composite effect of BFRP bars and macro-nonmetallic fibers in the concrete. Compared to PC specimen, the values of d_s of B-MPF5, B-MPF7, B-MBF20 and B-MBF30 specimens are increased by about 112%, 124%, 100% and 112%, respectively; the values of h_s of B-MPF5, B-MPF7, B-MBF20 and B-MBF30 specimens are increased by about 367%, 467%, 300% and 367%, respectively.

3.2.3 Statistical analysis of first-crack strength and failure strength

Statistical models like log-normal and Weibull have been widely used to analyze the fatigue and impact test data of concrete over last few decades.[1,27,28,40-43] In particular, the two-parameter Weibull distribution has been suggested by some investigations to evaluate the fatigue life of the concrete.[40-42] Due to the similar mechanism between impact test and fatigue test, the two-parameter Weibull distribution is employed to analyze the impact test data. The probability density function of the two-parameter Weibull distribution can be expressed by:

$$f(N_\varepsilon) = \frac{\alpha}{u}\left(\frac{N_\varepsilon}{u}\right)^{\alpha-1} exp\left[-\left(\frac{N_\varepsilon}{u}\right)^{\alpha}\right] \tag{2}$$

where α is the shape parameter; u is the scale parameter; N_ε is the specific value of the random variable N (N_1 or N_2).

The cumulative distribution function is:

$$F_N(N_\varepsilon) = 1 - exp\left[-\left(\frac{N_\varepsilon}{u}\right)^{\alpha}\right] \tag{3}$$

Leading to the following expression for the survivorship function

$$L_N = 1 - F_N\left(N_\varepsilon\right) = exp\left[-\left(\frac{N_\varepsilon}{u}\right)^{\alpha}\right] \tag{4}$$

Taking logarithms twice in both sides of Eq. (4) gives

$$\ln\left[\ln\left(\frac{1}{L_N}\right)\right] = \alpha \ln N_\varepsilon - \alpha \ln u \tag{5}$$

Eq. (5) can be rearranged to

$$\ln N_\varepsilon = \frac{1}{\alpha}\ln\left[\ln\left(\frac{1}{L_N}\right)\right] + \ln u \tag{6}$$

Eq. (6) is the equation of a straight line in the variables ($\ln[\ln(1/L_N)]$, $\ln N_\varepsilon$), whose intercept is $\ln u$ and whose slope is $1/\alpha$. In order to estimate L_N, order statistics and probability plots can be used.[44,45] Setting

$$L_N = 1 - \frac{i}{k+1} \tag{7}$$

where i is the failure order number; and k is the total number of the samples of each group, a linear regression analysis with the least squares can be applied to ($\ln[\ln(1/L_N)]$, $\ln N_1$ (or $\ln N_2$)) as shown in Figures 4 and 5. The slope of the regressed line in Figures 4 and 5 provides an estimate of the shape parameter (α), and the scale parameter (u) can be obtained by calculating the value at which the line intersects the $\ln[\ln(1/L_N)]$ axis. The shape parameter (α), scale parameter (u) and the coefficient of determination (R^2) for all the tested specimens are demonstrated in Table 4.

As shown in Figures 4 and 5, the sample values calculated from first-crack strength and failure strength are distributed uniformly on both sides of the regressed line. From Table 4, it can be observed that the values of R^2 for all the tested specimens are equal to or higher than 0.844. According to the investigation conducted by Rahmani et al.[43], a coefficient of determination within the range of 0.7-1.0 is sufficient for a reasonable reliability model. Therefore, it can be concluded that the two-parameter Weibull distribution can be used to characterize the statistical features of first-crack strength and failure strength in the impact test. In addition, the value of the shape parameter α for failure strength is much greater than that for first-crack strength apart from the specimens of PC. This indicates that the relative difference between the sample values and their mean value of failure strength is smaller than that of first-crack strength for each group of specimens, i.e. the scatter of the values of failure strength is remarkably improved. This can be attributed to that the reinforcements (i.e. BFRP bars, MPF and MBF) show beneficial effect on improving the stress redistribution and the ductility of the concrete in the post-cracking stage, while they have little effect on the properties of the concrete during the elastic stage.

Based on the defined parameters tabulated in Table 4, i.e. α and u, the failure strength corresponding to different failure probabilities can be given in equation as follows:

$$N_2 = exp(\frac{\ln[\ln(1/L_N)]}{\alpha} + \ln u) \tag{8}$$

This reliability equation can be considered as a useful tool to quickly estimate the failure strength without conducting costly and time-consuming additional impact test.

Some investigations[27,36] indicate that a linear correlation exists between failure strength and first-crack strength. In this work, a linear regression model is considered to predict failure strength by means of first crack strength.

$$N_2 = a \times N_1 + b \tag{9}$$

where a and b are unknown parameters.

Table 5 shows the values of a, b and R^2 experimentally obtained for the first-crack strengths and failure strengths in each group of specimens. It can be observed that the values of R^2 are all equal to or higher than 0.75, which exceeds the low limit of 0.7 suggested by Rahmani et al.[43]. Therefore, these equations can be used with reasonable accuracy to predict the failure strength by means of first-crack strength.

3.2.4 Hybrid effect of BFRP bars and macro non-metallic fibers on the impact energy at failure

It is very crucial for the various hybrid mixes to evaluate if the hybridization is successful. In this work, the synergetic effect of BFRP bars and non-metallic fibers (i.e. MPF and MBF) on the impact energy at failure is evaluated based on the following theory.[46]

The impact energy at failure for the concrete reinforced with A, the concrete reinforced with B and the concrete reinforced A and B are IE_{A}, IE_{B} and $IE_{\mathrm{A+B}}$, respectively. The impact energy at failure for PC without any reinforcements is IE_0. The increased impact energy at failure (ΔIE_i) is introduced by the following expression:

$$\Delta IE_i = IE_i - IE_0 \tag{10}$$

where IE_i is the impact energy at failure for the concrete with different reinforcements.

A positive synergetic effect is realized if it conforms to the following inequality (Eq. (11)), and otherwise the hybrid performs poorer than the sum of its parts.

$$\Delta IE_{\mathrm{A+B}} > \Delta IE_{\mathrm{A}} + \Delta IE_{\mathrm{B}} \tag{11}$$

In order to study the hybrid effect of BFRP bars and MPF on the impact energy at failure, the results of the increased impact energy at failure ($\Delta IE_{\mathrm{B\text{-}MPF}}$, $\Delta IE_{\mathrm{BFRP}}$ and ΔIE_{MPF}) is calculated and plotted in Figure 6. It can be noted that compared to the sum of BFRP-RC specimen and MPF5 specimen, the mean value of $\Delta IE_{\mathrm{B\text{-}MPF}}$ of B-MPF5 specimen is increased by about 82%. Compared to the sum of BFRP-RC specimen and MPF7 specimen, the mean value of $\Delta IE_{\mathrm{B\text{-}MPF}}$ of B-MPF7 specimen is increased by about 133%.

In order to study the hybrid effect of BFRP bars and MBF on the impact energy at failure, the results of the increased impact energy at failure ($\Delta IE_{\mathrm{B\text{-}MBF}}$, $\Delta IE_{\mathrm{BFRP}}$ and ΔIE_{MBF}) is calculated and plotted in Figure 7. It can be noted that compared to the sum of BFRP-RC specimen and MBF-20 specimen, the mean value of $\Delta IE_{\mathrm{B\text{-}MBF}}$ of B-MBF20 specimen is increased by about 44%. Compared to the sum of BFRP-RC specimen and MBF-30 specimen, the mean value of $\Delta IE_{\mathrm{B\text{-}MBF}}$ of B-MBF30 specimen is increased by about 39%.

Based on above analysis, it can be concluded that the hybrid use of BFRP bars and macro non-metallic fibers, in particular MPF, shows much greater effect on the improvement of the impact energy at failure than the sum of BFRP bars and macro non-metallic fibers. This indicates a very positive synergetic effect of combining BFRP bars and macro non-metallic fibers on the impact energy at failure. The positive synergetic effect can be explained as follows: i) The addition of mono BFRP bars and mono fibers can restrict crack propagation after cracking of concrete, and meanwhile improve the stress redistribution in the concrete matrix; ii) Furthermore, there is positive interaction between BFRP bars and non-metallic fibers. The fibers may not delay the formation of the first crack, they can keep crack width small, resist additional tensile forces and prevent the occurrence of circumferential cracks in case of mono use of BFRP bars, thereby preserving the bond strength between the bar and the surrounding concrete matrix. As a result, the discs can bear increased impact blows, indicating the improvement of the impact energy at failure. Additionally, the higher the fiber content is, the higher the increased value of impact energy at failure for B-MPF specimen. However, the enhancement effect is weakened for B-MBF specimen, which can be attributed to that the increment of the interfaces between the matrix and fibers decreases the compactness of the concrete, thus giving rise to excessive reduction in the strength of the concrete.

4 CONCLUSIONS

- The coefficients of variation for the failure strength range from 16% to 43% among all the tested specimens apart from steel reinforced concrete specimen of which is 57%; this indicates the stability and reliability of the impact test can be realized by using the self-developed drop-weight test device.
- The behaviors under impact load (i.e. failure strength, crack number, the indent diameter and penetration depth of the shrived area) can be improved by the incorporation of macro nonmetallic fibers, especially macro polypropylene fibers, into the concrete, while the first-crack strength is basically unaffected.
- The basalt FRP-reinforced concrete specimen under impact load demonstrates the brittle failure behavior like that of the plain concrete specimen. The addition of macro polypropylene fibers or macro basalt fibers into the concrete transforms the brittle failure mode into a well ductile failure mode.
- Two-parameter Weibull models can be fitted to characterize the statistical features of first-crack strength and failure strength of the concrete specimens with or without reinforcements in the impact test. Moreover, the value of the shape parameter α for failure strength is much greater than that for first-crack strength for reinforced concrete specimens (e.g., fiber reinforced concrete, steel reinforced concrete and basalt FRP-reinforced concrete).

- The failure strength of the concrete specimens under impact load can be estimated by a reliability equation. Also, failure strength can be predicted by a linear model with reasonable accuracy from first-crack strength.
- The combination of basalt FRP bars and macro non-metallic fibers, especially macro polypropylene fibers, demonstrates a positive synergetic effect on the impact energy at failure. The best composite design throughout the proposed ones in this study is basalt FRP-reinforced concrete specimen with 7 kg/m^3 macro polypropylene fibers which achieves the highest impact energy at failure.
- The hybrid use of basalt FRP bars and macro non-metallic fibers (i.e. polypropylene fibers and basalt fibers) can be one of the most efficient ways for enhancing of the impact performance of basalt FRP-reinforced concrete. This offers a promising alternative substitute to conventional steel reinforcement for the structures in marine and salt environments.

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TABLE 1 Comparison of compressive strength after 28 days

Mixtures	PC	MPF5	MPF7	MBF20	MBF30
Compressive strength (MPa)	35	37.9	38.5	28.5	24.2

TABLE 2 Drop-weight test results

Specimen	First-crack strength			First-crack impact energy (J)	Failure strength			Impact energy at failure (J)
	First-crack strength (blows)	δ	CV (%)		Failure strength (blows)	δ	CV (%)	
PC	30	12	39	610	30	12	39	610
Steel-RC	51	31	62	1038	252	144	57	5127
BFRP-RC	25	18	70	509	87	18	20	1770
MPF5	31	16	52	631	64	15	23	1302
MPF7	36	11	31	732	76	12	16	1546
MBF20	26	24	89	529	53	23	43	1078
MBF30	20	8	38	407	56	22	39	1139
B-MPF5	39	30	76	793	196	41	21	3988
B-MPF7	43	24	57	875	270	64	24	5493
B-MBF20	34	26	77	692	145	58	40	2950
B-MBF30	27	15	54	549	145	48	33	2950

TABLE 3 Comparison of the number of the cracks (n), the diameter (d_s) and the penetration depth (h_s) of the shriveled area for all the tested specimens.

Specimen	n	d_s (mm)	h_s (mm)
PC	1	25	3
Steel-RC	5	57	17
BFRP-RC	4	38	6
MPF5	3	45	9
MPF7	3	47	11
MBF20	3	42	7
MBF30	3	45	9
B-MPF5	5	53	14
B-MPF7	6	56	17
B-MBF20	5	50	12
B-MBF30	6	53	14

TABLE 4 Shape parameter, scale parameter and coefficient of determination for the tested specimens

Specimen	N_1			N_2		
	α	u	R^2	α	u	R^2
PC	3.133	32.858	0.938	3.133	32.858	0.938
Steel-RC	2.140	61.507	0.938	2.453	282.622	0.844
BFRP-RC	2.289	29.245	0.959	5.961	89.633	0.943
MPF5	2.821	33.821	0.958	5.413	66.433	0.940
MPF7	3.751	38.473	0.930	7.539	77.277	0.902
MBF20	1.966	32.498	0.989	2.96	58.731	0.962
MBF30	3.164	21.951	0.953	3.351	60.754	0.959
B-MPF5	1.813	50.513	0.889	5.733	201.884	0.884
B-MPF7	2.275	50.801	0.943	5.673	276.705	0.995
B-MBF20	2.049	42.216	0.979	3.439	154.715	0.966
B-MBF30	2.400	31.724	0.959	5.024	151.965	0.960

TABLE 5 Estimated parameters a, b and coefficient of determination R^2 for the tested specimens

Specimen	a	b	R^2
PC	1	0	1
Steel-RC	4.338	32.205	0.881
BFRP-RC	0.908	64.307	0.750
MPF5	0.925	36.112	0.943
MPF7	0.985	40.521	0.830
MBF20	0.919	28.794	0.830
MBF30	2.748	1.661	0.884
B-MPF5	1.280	145.955	0.864
B-MPF7	2.571	160.286	0.932
B-MBF20	2.159	70.558	0.947
B-MBF30	3.282	56.046	0.964

Figure captions

FIGURE 1 Macro non-metallic fibers: (a) MPF; and (b) MBF

FIGURE 2 Schematic diagram of the self-developed drop-weight test device

FIGURE 3 Comparison of failure patterns of disc specimens with different reinforcements: (a) PC; (b) Steel-RC; (c) BFRP-RC; (d) MPF7; (e) MBF30; (f) B-MPF7; and (g) B-MBF30

FIGURE 4 Weibull distribution of first-crack strength: (a) Reference specimens; (b) Specimens reinforced with only BFRP bars or macro non-metallic fibers; and (c) Specimens reinforced with BFRP bars and macro non-metallic fibers

FIGURE 5 Weibull distribution of failure strength: (a) Reference specimens; (b) Specimens reinforced with only BFRP bars or macro non-metallic fibers; and (c) Specimens reinforced with BFRP bars and macro non-metallic fibers

FIGURE 6 Comparison of synergetic effect between specimens of B-MPF and the sum of BFRP-RC and MPF on impact energy at failure

FIGURE 7 Comparison of synergetic effect between specimens of B-MBF and the sum of BFRP-RC and MBF on impact energy at failure