

Research Article

Flexural Toughness of High-Performance Concrete with Basalt and Polypropylene Short Fibres

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In this work, an investigation is made to evaluate the flexural toughness of hybrid fibre-reinforced high-performance concrete (HPC) containing different combinations of basalt (B) and polypropylene (P) fibres. The experimental studies consisted of the three-point flexural tests on notched beam specimens. The specimens incorporated basalt/polypropylene (BP) fibres in 11 mixtures with proportions of 0/0, 100/0, 75/25, 50/50, 25/75, and 0/100% by volume at total volume fractions of 1 and 2%. The evaluation of the experimental results was done according to the CECS 13:2009 and PCS (postcrack strength) methods. The results indicate that high-performance concrete containing basalt/polypropylene fibre mixtures of 50/50% and with only polypropylene fibre content of 0/100% can be pronounced as the most appropriate combinations to be used in high-performance concrete for flexural toughness.

1. Introduction

High-performance concrete is a brittle material; hence, the addition of randomly distributed fibres improves its mechanical properties, especially tensile strength, flexural strength, flexural toughness, and ductility. The effectiveness of improving these parameters depends, among other things, on the type of fibre, size, aspect ratio, and volume fraction of fibres. In the last decades, there has been considerable interest not only in fibre hybridization, mostly in combinations of long and short steel fibres [1, 2] but also in concrete with hybrid synthetic fibres [3, 4], or mishmashes of various types of steel and synthetic fibres [5–9] in order to obtain the optimal performance of hybrid fibre-reinforced concrete. Mechanical properties such as compressive strength, flexural strength, and flexural toughness of concrete reinforced with different types of hybrid fibres have been examined by various researchers [3, 4, 10–12], and the results clearly indicate that fibre hybridization is a promising idea. However, it is necessary to conduct further testing of hybrid fibre concrete, as there are many types of fibres available on the market produced from different materials having changed lengths and geometry.

The polypropylene fibres used in high-performance concrete can increase its tensile strength, toughness parameters, and fire and impact resistance and decrease long-term shrinkage [13–17]. On the other hand, the basalt fibres are not yet widely used in civil engineering, although they show a good compatibility with concrete. Li and Xu [18] indicated that the addition of basalt fibre can significantly improve the deformation and energy absorption capacity of geopolymeric concrete, but there is no significant improvement in dynamic compressive strength. Jiang et al. [19] showed that the basalt fibres significantly improve tensile strength, flexural strength, and toughness index of the concrete, but the compressive strength shows no obvious increase. They also found that the fibre length has a significant effect on the tested parameters. Kabay [20] revealed that basalt fibres can also be very useful in improving flexural strength, fracture energy, and abrasion resistance even at low contents. On the contrary, inclusion of basalt fibre in concrete resulted in a decrease in the compressive strength. Furthermore, basalt fibre is not an expensive material and can be an effective approach to increase toughness, plastic shrinkage, and shock resistance of high-performance

concrete. The important reasons for the simultaneous application of basalt and polypropylene fibres in concrete can be replaced cracks control, improved flexural toughness resistance, and improved fire resistance.

The main advantage of fibre reinforcement in concrete is toughness improvement. The most frequently used procedures for evaluating toughness test results are specified in the Japanese standard [21] and the United States standard [22]. According to these standards, toughness tests are performed on concrete beams of size $150 \times 150 \times 600$ mm or of size $100 \times 100 \times 400$ mm. Flexural load is applied at one-third of the beam specimen span under constant rate of displacement.

In this study, the flexural toughness parameters are obtained for notched hybrid basalt-polypropylene high-performance concrete beams of size $80 \times 150 \times 700$ mm using the procedures given in the Chinese standard [23] and the postcrack strength (PCS) method [24]. In hybrid composites, there is a synergic effect between the fibres and the resulting performance can exceed the sum of single fibre efficiencies [25]. Basalt fibre is stronger and ensures sensible first-crack strength and ultimate strength. This fibre is also ecologically safe and cheaper to produce. On the other hand, polypropylene fibre is comparatively flexible and leads to improved strain capacity in the postcrack zone and toughness. The three-point flexural toughness tests with notched beams are performed because they are not dependent on the first-crack deflection value compared with the JCI SF-4 and ASTM C 1609 methods and thus reduce the error induced by the difficulties in judging first-crack deflection.

2. Materials and Methods

2.1. Materials and Concrete Mixtures. The straight basalt and polypropylene fibres are used in the tests, and the main characteristics of fibres are given in Table 1. In previous investigations, the concrete components used in this experimental test had been found appropriate for the production of fibre-reinforced high-performance concrete [7, 8, 26]. The ordinary Portland cement CEM I 52.5R was used in all mixtures. The aggregates contained basalt rock ranging in size from 2 to 5 mm with a continual size distribution and quartz sand with a maximum particle size of 2 mm. The high efficient water-reducing agent based on polycarboxylate ether was also used. The mixture compositions with the experimental design of 11 groups of fibre combinations are shown in Table 2.

2.2. Specimens' Specifications and Production Process. All tests were conducted on a set of 3 specimens for each mixture. The compressive and splitting tensile strength tests were performed on 66 cubes ($100 \times 100 \times 100$ mm). For flexural toughness tests, 33 notched beam specimens ($80 \text{ mm} \times 150 \text{ mm} \times 700 \text{ mm}$) were used. A notch with a depth of 50 mm and a thickness of 3 mm was made at each beam midspan. For this purpose, a thin steel sheet with a sharpened tip was fixed at the middle of the beam before concreting. The concrete mixtures were prepared in a 100 L mixer in about 12 min. Firstly, the aggregates were mixed for

3 min before the addition of part of the water. Secondly, after 2 min, cement, silica fume, the rest of the water, and the superplasticizer were added. In order to make fibres evenly dispersed in the concrete, after 3 min, basalt and polypropylene fibres were applied manually. The mixing was finished after a homogeneous mixture was obtained. The molds with the fresh concrete mixture were vibrated at a rate of 150 Hz on a vibrating table. All specimens were cured 28 days in water in standard conditions.

2.3. Test Equipment and Solutions. Based on the RILEM recommendations [27, 28], the notched beam flexural toughness test was performed. Before the test, 2 steel sheets were glued on the edges of the beam notch. The tests were performed using the MTS 319.25 servohydraulic testing machine with a flexural capacity of 250 kN. The notched beams were loaded in a three-point loading configuration with two rolling supports spaced at a distance of 600 mm and using the single-point loading at midspan. The crack mouth opening displacement (CMOD) was measured through a clip-gagger fixed between 2 rigid steel sheets at the bottom of the beam. The test setup is shown in Figure 1(a). The toughness test used deflection as the control signal at a rate of 0.05 mm/min.

In accordance with the EN 12390-3 [29] and EN 12390-6 [30] standards, compressive (Figure 1(b)) and splitting tensile (Figure 1(c)) strengths were determined using an Advantest 9 servohydraulic press of 3 MN capacity.

3. Results and Discussion

3.1. Slump. High workability is necessary for high-performance concrete beam-column joints, while low workability is requested in pavements or large sections. In this study, a highly effective superplasticizer was used to get good slump test results. The components are mixed till full homogeneous mixture is formed, and then the fibres were fed gradually. Addition of fibres provided more friction force between the components of the mixtures. However, there was no aggregate segregation and no clustering of fibres but fully homogeneous mixtures were observed. The slump results are presented in Table 3. It can be seen that the slump dropped due to fibre addition. It can be concluded that the workability of high-performance concrete decreased with the increase of basalt and polypropylene fibres. The reason for this phenomenon is that the network structure can be formed in the concrete from the dispersed fibres and restrain the fresh mixture before segregation and flow. Due to the high content and large surface area of fibres, they may absorb more cement paste, and the increase of the mixture viscosity leads to decrease in the slump [31].

Furthermore, it can be noticed that the addition of 12 mm basalt fibre in concrete shows a lower slump than that of 12 mm polypropylene fibre with the same volume fraction. The reason may be that the distribution density of polypropylene fibres is larger and more fibres are present per unit volume. Therefore, the fibres are more difficult to distribute in concrete matrix due to the larger friction force, which may result in slump reduction.

TABLE 1: Properties of fibres.

Type	Shape	Length (mm)	Nominal diameter (mm)	Aspect ratio (-)	Density (g/cm ³)	Modulus of elasticity (GPa)	Tensile strength (MPa)	Strain at failure (%)
Basalt fibre	Straight	12	0.013	923	2.7	70	1700	2.5
Polypropylene fibre	Straight	12	0.025	480	0.9	3.5	350	7

TABLE 2: High-performance concrete mixture proportions.

Material	C0	B1	B0.75P0.25	B0.5P0.5	B0.25P0.75	P1	B2	B1.5P0.5	B1P1	B0.5P1.5	P2
Cement (kg/m ³)	670.5	670.5	670.5	670.5	670.5	670.5	670.5	670.5	670.5	670.5	670.5
Silica fume (kg/m ³)	74.5	74.5	74.5	74.5	74.5	74.5	74.5	74.5	74.5	74.5	74.5
Basalt (kg/m ³)	990	990	990	990	990	990	990	990	990	990	990
Quartz sand (kg/m ³)	500	473	477.5	482	486.5	491	446	455	464	473	482
Superplasticizer (l/m ³)	20	20	20	20	20	20	20	20	20	20	20
Water (l/m ³)	210	210	210	210	210	210	210	210	210	210	210
Basalt fibre (kg/m ³) (%)	—	27	20.25	13.5	6.75	—	54	40.5	27	13.5	—
	—	1	0.75	0.5	0.25	—	2	1.5	1	0.5	—
Polypropylene fibre (kg/m ³) (%)	—	—	2.25	4.5	6.75	9	—	4.5	9	13.5	18
	—	—	0.25	0.5	0.75	1	—	0.5	1	1.5	2
Water/binder ratio	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28

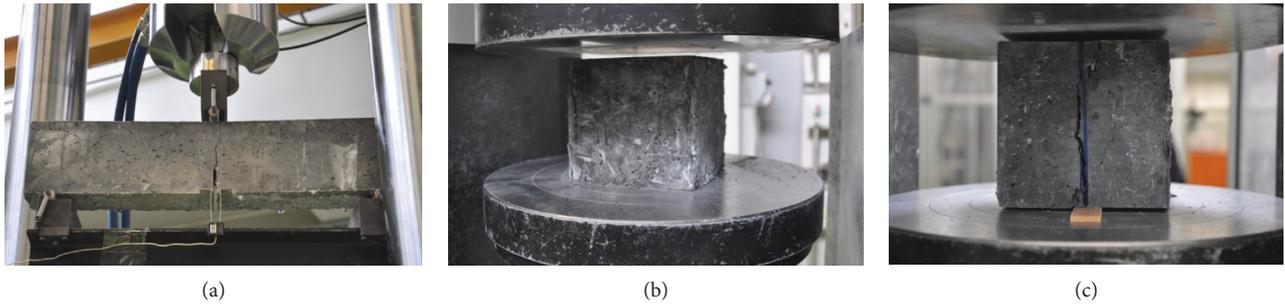


FIGURE 1: Test setup: (a) three-point flexural toughness, (b) compressive strength, and (c) tensile splitting strength.

TABLE 3: Compressive strength and splitting tensile strength of high-performance concrete.

Type	Slump (mm)	Reduction in slump (%)	Compressive strength f_c (MPa)	Coefficient of f_c weakness	Splitting tensile strength $f_{ct,sp}$ (MPa)	Coefficient of $f_{ct,sp}$ enhancement
C0	121	0.00	131.2	1.00	5.7	1.00
B1	102	15.70	112.1	0.85	5.8	1.02
B0.75P0.25	101	16.53	114.0	0.87	6.8	1.19
B0.5P0.5	99	18.18	115.7	0.88	8.1	1.42
B0.25P0.75	95	21.49	116.9	0.89	8.2	1.44
P1	93	23.14	119.8	0.91	8.6	1.51
B2	87	28.10	104.6	0.80	7.6	1.33
B1.5P0.5	83	31.40	107.5	0.82	7.8	1.37
B1P1	80	33.88	108.6	0.83	8.3	1.46
B0.5P1.5	78	35.54	111.6	0.85	8.7	1.53
P2	74	38.84	117.0	0.89	10.4	1.79

3.2. *Compressive Strength and Splitting Tensile Strength.* Table 3 provides the results of hybrid fibre high-performance concrete compressive strength and splitting tensile strength. It can be found that the addition of 12 mm fibres affect the plain high-performance concrete compressive strength

slightly. Compared with the plain concrete, it only decreased by 9% (P1) to 20% (B2). The highest decrease in the compressive strength of fibre concrete was observed with the addition of 2% basalt fibres. Banthia and Soleimani [1] reported a 13% reduction in the compressive strength of

concrete containing only polypropylene fibres as compared to that of fibre-free concrete. Moreover, the results described by Kabay [20] and Jiang et al. [19] showed that the compressive strength of HPC decreased with an increase in the basalt fibre content. There were some reasons which might have led to these results. Firstly, the basalt fibres may create poor void regions in HPC and failure may occur due to them. In addition, the basalt fibres during mixing had absorbed too much of water and the cement may lack sufficient water for hydration.

In contrast, the fibres can improve splitting tensile strength significantly. Compared with the plain concrete, it increased by 2% to 79%. Splitting tensile strength of polypropylene fibre concrete at a fibre volume of 2% (P2) increased significantly. The influence of the volume fraction of basalt fibres and polypropylene fibres on the splitting tensile strength was analyzed in the same way by Jiang et al. [19]. With the increase in the fibre fraction, the splitting tensile strength of fibre-reinforced concrete increased by about 14–26%. Yurtseven et al. [32] stated that the addition of polypropylene fibre at 0.5% volume fraction can improve splitting tensile strength of concrete by 19.5% at 28 days. It is mainly due to the bridging action of the fibres across cracks, which effectively restrains the propagation of microcracks in the early stages of curing. After the formation of the first crack, the stress is transferred to the bridging fibres and the development of cracks is delayed, thus improving the splitting tensile strength.

3.3. Load-Deflection Curves. The typical load-deflection and load-CMOD curves from the toughness tests of basalt fibre-reinforced concrete beams, basalt-polypropylene fibre-reinforced concrete beams, and polypropylene fibre-reinforced concrete beams, with 1% and 2% of fibre volume contents, are shown in Figure 2, and the relationship between the deflection and CMOD is displayed in Figure 3 and Table 4.

Figures 2 and 3 and Table 4 show that the first cracks are very close, and the concrete with basalt fibres is characterized by plastic damage. When the notched beam specimen cracks, it will collapse suddenly. It is noteworthy that the load-CMOD and load-deflection curves of type B0.5P1.5 and B0.25P0.75 and type B1.5P0.5 and B0.5P0.5 are similar, respectively. At the beginning of stress, load and deflection show linear dependence. As the load increases, cracks form in the concrete. Due to the fibre bridging effect, the fibres will carry the load; so, the load-deflection curve gradually bends to the right up to the peak point. After reaching the ultimate load, the crack width increases and propagates upwards and the flexural efficiency decreases. High modulus basalt fibres are pulled out from the concrete matrix. On the other hand, low elastic modulus polypropylene fibres are broken, and this process needs to absorb more energy. So, in the latter case, the rate of decline of the flexural capacity is delayed. The curve of P2 type falls slowly and covers an area meaningfully greater than the other types, due to a 2.8-fold larger strain at failure of the polypropylene fibre compared to such strain of the basalt fibre. It also means that the

polypropylene fibres with lower modulus of elasticity and lower aspect ratio can provide higher capacity of deformation and better flexural toughness than basalt fibres with higher elastic modulus and higher aspect ratio.

Figure 3 illustrates that there is a linear relationship between the deflection and CMOD in which the slope corresponds to the crack control ability of concrete. CMOD of type P2 < CMOD of types B1P1, B2, P1, B1, B0.5P1.5, B0.25P0.75 < CMOD of types BP (B0.75P0.25, B0.5P0.5, and B1.5P0.5) when the deflection is determined; so, crack control ability of concrete revealed an inverse correlation. Because the fibre contents and types are different, crack control abilities of the hybrid fibre concrete which is compared with single fibre concrete has different levels of increase, the anticrack performance enhance and perform good flexural toughness. Referring to the data shown in Figures 2 and 3, it is interesting to note that the applied combination of fibres is far more significant than the fibre volume. Furthermore, it can be observed that polypropylene fibres bridged cracks better than basalt fibres with a higher volume content in mixtures with hybrid fibres.

3.4. Energy Absorption and Flexural Toughness. According to the CECS 13:2009 [23], energy absorption value and equivalent flexural strength can be used to evaluate the fibre effect on concrete toughness improvement (Figure 4(a)). Energy absorption value of the concrete cracking, D_{cr} , corresponding to the deflection, $\delta_L + 0.3$ mm, on the numerical value is equal to the area ABC. Fibre on concrete contributions of energy absorption values $D_{1f} = D_1 - D_{cr}$ and $D_{2f} = D_2 - D_{cr}$ when midspan deflections are $\delta_1 = \delta_L + 0.65$ mm and $\delta_2 = \delta_L + 2.65$ mm, respectively, on the numerical values are equal to the areas BDEC and BFGC. Equivalent flexural toughness is calculated by the following formula:

$$f_{eq1} = \frac{D_{1f}l}{0.5b(h-a_0)}, \quad (1)$$

$$f_{eq2} = \frac{D_{2f}l}{2.5b(h-a_0)},$$

where l is the distance between the supports, b and h are the width and height of the beam, and a_0 is the height of the notch. The results are summarized in Table 5.

As can be seen from Table 5, energy absorption value of fibre-reinforced concrete is the highest for concrete with polypropylene fibres and is not dependent on the fibres volume content. Slightly lower energy values were obtained for the concrete with the addition of equal proportions of polypropylene and basalt hybrid fibres to the volume. The flexural toughness indexes of hybrid fibre-reinforced concrete are lower than those of polypropylene fibre-reinforced concrete, but higher than those of concrete with basalt fibres. D_{cr} , D_{1f} and f_{eq1} , and D_{2f} and f_{eq2} of polypropylene-reinforced fibres concrete were mostly increased by 1.36–1.67 times, 1.18–1.25 times, and 0.99–1.85 times than those of hybrid fibre-reinforced concrete at 1% of fibre volume content and were increased by 1.07–1.88 times, 1.01–1.64 times, and 1.58–1.88 times at 2% vol. fibres. On the other

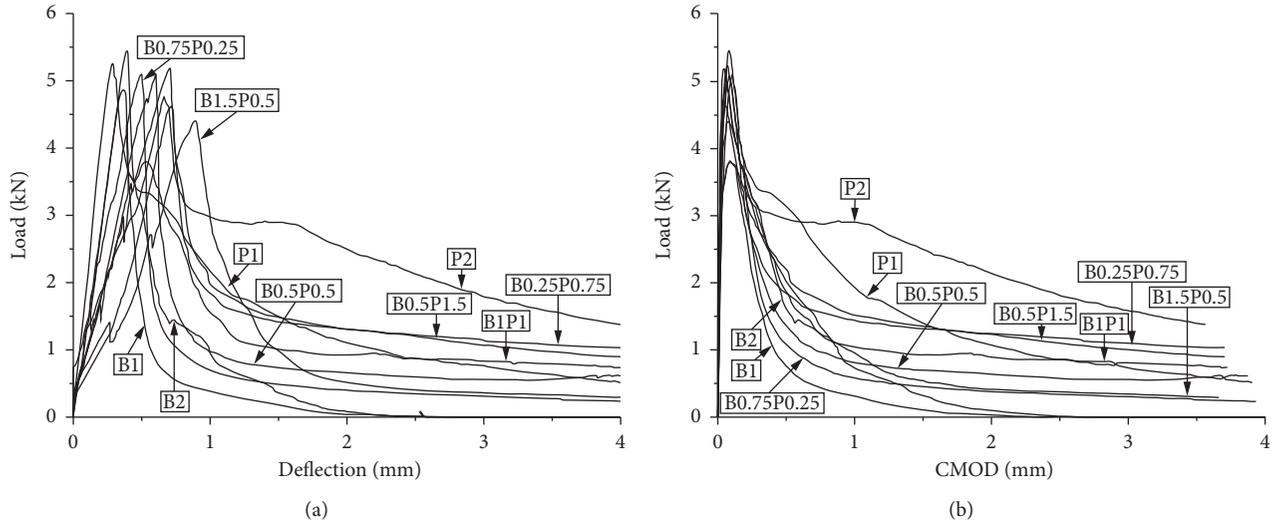


FIGURE 2: Typical (a) load-deflection and (b) load-CMOD curves of FRC beams.

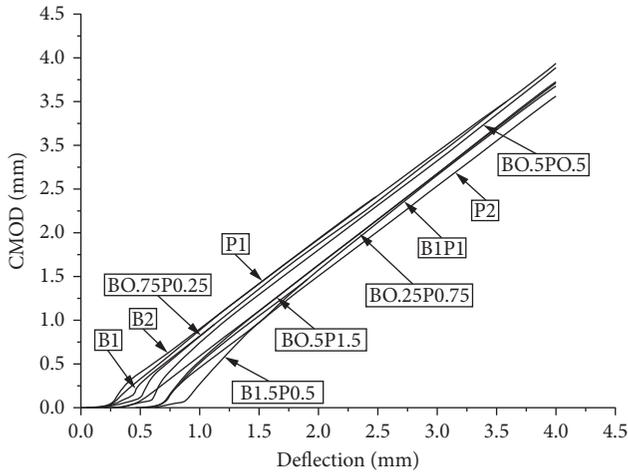


FIGURE 3: Deflection-CMOD relationship of FRC beams.

TABLE 4: Deflection-CMOD fitted curves.

Type	Fitted curves	R ²
B1	$y = 1.0214x - 0.1566$	0.9995
B0.75P0.25	$y = 1.0405x - 0.2315$	0.9992
B0.5P0.5	$y = 1.0412x - 0.2910$	0.9984
B0.25P0.75	$y = 1.0218x - 0.4079$	0.9933
P1	$y = 1.0212x - 0.1392$	0.9997
B2	$y = 1.0210x - 0.1042$	0.9998
B1.5P0.5	$y = 1.0453x - 0.5195$	0.9855
B1P1	$y = 1.0200x - 0.4342$	0.9962
B0.5P1.5	$y = 1.0218x - 0.4079$	0.9966
P2	$y = 0.9820x - 0.4271$	0.9920

hand, the above parameters of basalt fibre-reinforced concrete were almost always decreased by 0–0.18 times, 0.04–0.09 times, and 0.15–0.54 times than those of hybrid fibre-reinforced concrete at 1% fibre content and were decreased by 0.12–0.93 times, 0.36–0.99 times, and 0.12–0.42 times at 2% vol. fibres. This shows that the impact of polypropylene fibres

on the flexural toughness is better than that of basalt fibres at the same fibres length, but almost two times lower with aspect ratio. Polypropylene fibre can effectively improve the flexural toughness of concrete. On the contrary, polypropylene and basalt fibres have a good synergic effect when the fibre content of at least half of the polypropylene fibres is present. It is interesting to note that the same flexural toughness values, f_{eq1} , given in Table 5 are higher than the equivalent flexural toughness, f_{eq2} . The dependence of $f_{eq2} < f_{eq1}$ displays that load-deflection curves gradually decrease with increasing beam deflection. In ASTM C 1609 [22], along with the increase in beam deflection, the toughness index I increases. Thus, compared with this evaluation method, the equivalent flexural strength method is more advantageous and more convenient, and by determining the peak load with a rate of 0.05 mm/min, deflections can be faultlessly determined at the first-crack deflection. This method of assessing the flexural toughness of fibre-reinforced concrete can also be used for different types and contents of fibre.

The load-deflection curves of fibre-reinforced concrete were also analyzed by the postcrack strength (PCS) method, described by various scientists [1, 24]. It is a method of converting the deflection-load curve into an equivalent curve of flexural strength and then locating the peak load and dividing the curve into two regions: prepeak load and postpeak load (Figure 4(b)). The points in the postpeak region are located according to the deflections coinciding with various span fractions. For a notched beam, the postcrack strength (PCS) at a deflection of l/m (for $m = 600, 400, 300,$ and 200) is given by the following expression:

$$PCS = \frac{E_{post}l}{((l/m) - \delta_{peak})b(h - a_0)^2} \quad (2)$$

Toughness indexes calculated according to the PCS method are listed in Table 6.

Table 6 shows that concrete containing 100% polypropylene fibres showed the highest PCS values. These values

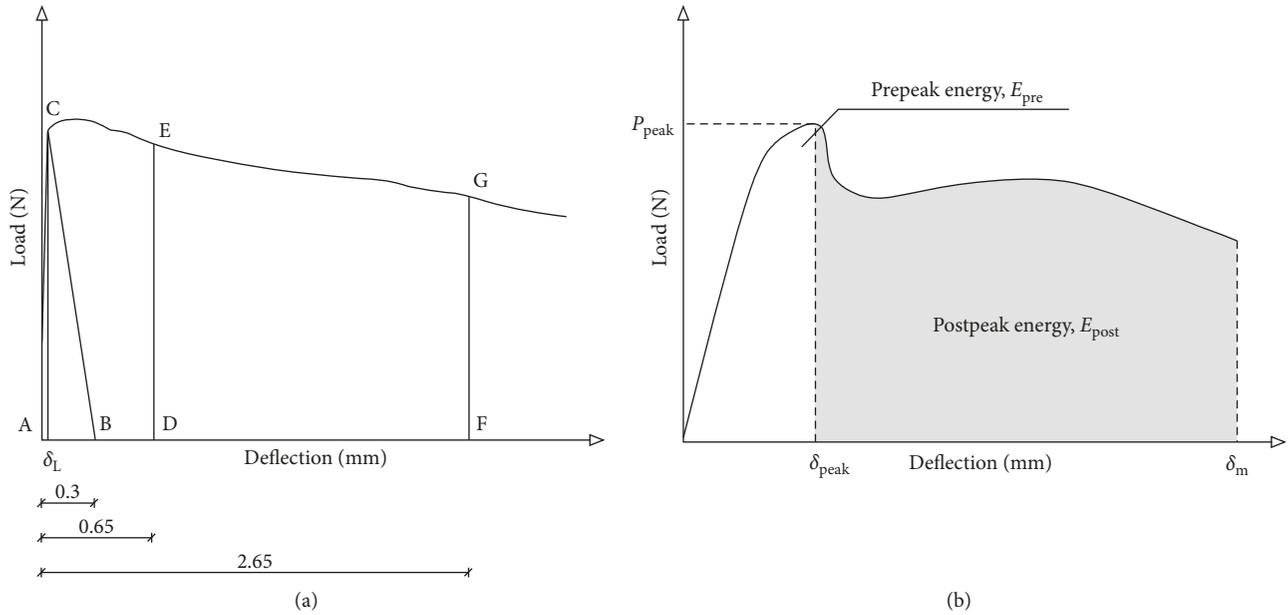


FIGURE 4: Methodology for calculating toughness indexes according to (a) CECS 13:2009[23] and (b) PCS.

TABLE 5: Energy absorption and equivalent flexural toughness based on CECS 13:2009.

Type	D_{cr} (kN × mm)	D_{1f} (kN × mm)	D_{2f} (kN × mm)	f_{eq1} (MPa)	f_{eq2} (MPa)
B1	0.09	1.53	2.33	2.29	0.70
B0.75P0.25	0.09	1.66	2.73	2.49	0.82
B0.5P0.5	0.11	1.68	3.35	2.52	1.01
B0.25P0.75	0.09	1.59	5.10	2.38	1.53
P1	0.15	1.98	5.06	2.97	1.52
B2	0.11	1.69	2.58	2.54	0.77
B1.5P0.5	0.09	0.88	3.71	1.32	1.11
B1P1	0.14	1.43	3.90	2.15	1.17
B0.5P1.5	0.08	1.10	4.40	1.65	1.32
P2	0.15	1.44	6.95	2.16	2.09

were also high at 25% replacement of polypropylene fibres by basalt fibres. The flexural toughness of basalt-polypropylene fibre-reinforced concrete is little lower than the toughness of polypropylene fibre-reinforced concrete and gradually decreases with higher volume contents of basalt fibres. As shown in Table 6, it can be concluded that when the beam deflection reaches $l/600$, $l/400$, $l/300$, and $l/200$, the toughness index ratio of the basalt-polypropylene fibre-reinforced concrete B0.25P0.75 and B0.5P1.5 and the polypropylene fibre-reinforced concrete P1 and P2 is 0.95, 0.84, 0.85, and 0.92 at 1% fibre volume content, respectively, and 0.75, 0.62, 0.55, and 0.57 at 2% fibre volume content, respectively. In addition, the PCS method is not dependent on the first-crack deflection value compared with, e.g., ASTM-C1018 [33], which reduces the possibility of making the error caused by the difficulty in evaluating first-crack deflection. The toughness analysis is carried out using the variable l/m for the toughness index after the peak load, which makes the toughness measurement more precise.

4. Conclusions

Compressive strength, splitting tensile strength, and flexural toughness of hybrid fibre-reinforced concrete containing different combinations of basalt and polypropylene fibres have been investigated. Flexural toughness indexes were obtained from the load-deflection curves, in accordance with the procedure set out in CECS 13:2009 [23] and with the PCS technique [24]. The conclusions based on the results and discussion presented in this study are as follows:

- (1) Compressive strength of all fibre-reinforced high-performance concrete mixtures decreased by 9% (P1) to 20% (B2) compared with the plain high-performance concrete. In contrast, splitting tensile strength increased significantly in all fibre mixtures, up to 79% for polypropylene fibre-reinforced concrete at the content of 2%.
- (2) The results obtained in static flexural toughness tests show that in terms of flexural toughness, concrete with 100% of polypropylene fibres provides the best

TABLE 6: Mean toughness index of PCS method.

Type of concrete	PCS600 (MPa)	PCS400 (MPa)	PCS300 (MPa)	PCS200 (MPa)
B1	0.896	0.597	0.443	—
B0.75P0.25	1.052	0.738	0.602	0.467
B0.5P0.5	1.301	0.921	0.778	0.642
B0.25P0.75	2.263	1.637	1.411	1.197
P1	2.386	1.949	1.660	1.297
B2	1.506	1.037	0.761	0.475
B1.5P0.5	2.802	1.572	1.093	0.723
B1P1	1.965	1.404	1.169	0.964
B0.5P1.5	1.937	1.447	1.280	1.112
P2	2.579	2.340	2.231	1.962

performance. Concrete with a fibre combination of 50% basalt fibres + 50% polypropylene fibres offers slightly lower parameters and display positive hybrid effect. Increasing the high-density basalt fibre portion in the hybrid fibre system in combination with low-density polypropylene fibres may lead to reduced flexural toughness of hybrid fibre-reinforced HPC mixtures.

- (3) The test method of the notched beams loaded at midspan can simplify the testing device. The energy absorption values D_{cr} and the equivalent flexural tensile strength f_{eq1} and f_{eq2} are indexes that evaluate the flexural toughness of hybrid fibre concrete. This assessment method is very comprehensive and practicality. Also, the PCS method reduces the possibility of making an error, because it is not dependent on the first-crack deflection, and the analysis allows to accurately determine the flexural toughness.

Data Availability

The data underlying this article are not available to protect their commercial confidentiality.

Conflicts of Interest

The author declares no conflicts of interest.

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