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EXPERIMENTAL AND EMPIRICAL STUDY OF BASALT FIBER REINFORCED CONCRETE

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Abstract: Basalt fiber reinforced concrete (BFRC) can be used for structural applications like buildings and bridges. The BFRC can be developed with the addition of $CaCO_3$ whisker due to their improved mechanical properties. The experimental investigation on BFRC is going on but at the same time the empirical formulation is also of great concern. Therefore, the experimental and empirical formulation needs to be studied at the same time. In this work, the impact of different basalt fiber lengths on flexural energy absorption of basalt fiber reinforced concrete (BFRC) will be investigated. In addition to this, the empirical equation modeling for the calculation of flexural strength will also be discussed. The mix design ratio of HFRC is 1:2:1.5 (cement: sand: aggregate) with a water-cement ratio of 0.50. The basalt fiber and $CaCO_3$ whisker content of 5%, by cement mass, are added. To prepare BFRC1, BFRC2 and BFRC3, different basalt fiber length of 12 mm, 25 mm and 37 mm, respectively, are added. For determination of flexural strength, pre-crack/post-crack energy absorption and toughness indices, beam of size 100 mm width, 100 mm depth and 400 mm length are cast and will be tested under flexural load as per ASTM standard. Increase in flexural energy absorption of BFRC is observed with increasing length of basalt fiber. Further study on optimization of basalt fiber length and content for mechanical properties is suggested.

1 INTRODUCTION

The engineering properties of concrete can be improved by addition of fibers. These properties are load bearing capacity after cracking, toughness, deformation capability, abrasion, fatigue, impact, flexural and tensile strength (Yazıcı et al. 2007 and Mohammadi et al. 2008). Fiber reinforced concrete (FRC) is widely used due to sufficient durability, high ductility and high resistance against corrosion (Jiang et al. 2014). $CaCO_3$ whisker is a new type of inorganic micro-fiber which is used in cement mortar to improve its mechanical properties (Cao et al. 2013). $CaCO_3$ whisker can be used as reinforcement in concrete due to the outstanding mechanical properties i.e diameter (0.5-2 μm), aspect ratio (20-60), tensile strength (410-710 GPa) and elastic modulus (3-6 GPa). Also, the $CaCO_3$ whisker has the low production cost of about $236 per ton which may be helpful in producing low cost cement based composites (Cao et al. 2014). Recently, basalt fiber has gained the popularity due to its environmental friendly manufacturing process and excellent mechanical properties in concrete (Branston et al. 2016). The tensile strength of basalt fiber is greater than that of E-glass fiber and steel fiber (Branston et al. 2016). Basalt fiber is extruded from melted basalt rock and is a new kind of inorganic fiber available commercially (Jiang et al. 2014). The manufacturing process of basalt fiber is same as that of glass fiber, but with the consumption of less energy and without additives which make it economical than carbon and glass fiber (Deák and Czigány 2009, Lopresto et al. 2011, Borhan 2012). The currently commercial availability, excellent interfacial shear strength, good resistance to chemical attack, heat resistance and high modulus are the other benefits which make it a good alternative in concrete matrix as compared to carbon and glass fiber (Jiang et al. 2010). Jiang et al. (2014) studied the mechanical properties of basalt fiber reinforced concrete (BFRC). The mix design ratio for cement: sand: aggregate: fly-ash was 1: 1.4: 2.3: 0.3 with water-cement (w-c) ratio of 0.60. The length of basalt fiber was 12 mm with content of 0.28%, 0.56%, 1.66% and 2.77%, by cement mass. The flexural strength (fs) was improved by 6.30-9.58%. Kizilkanat et al. (2015) performed experimental study on mechanical properties of BFRC. The mix design ratio was 1: 1.4: 1.2: 2.6 for cement, crushed sand, river sand and coarse aggregate. The w-c ratio was 0.5, with different super plasticizer content of 0.8-2.2%, by cement mass. The basalt fiber with 1.9%, 3.8%, 5.6% and 7.5%, by cement mass, was added. The fs was increased by 13% with addition of 3.8% basalt fiber content. The experimental investigation had been done on BFRC but the empirical relation is also necessary to be established at the same time.

In this study, a new kind of fiber hybridization with the micro-fibers ($CaCO_3$ whisker) and meso-fibers (basalt fibers) is considered. The flexural properties of basalt fiber reinforced concrete (BFRC) with different basalt fiber length i.e. 12 mm, 25 mm and 37 mm are investigated. The basalt fiber and $CaCO_3$ whisker both content are added 5%, by cement mass. The load-deflection curves are recorded. Also, the strengths, pre/post and total energy absorbed and toughness under flexural load are determined. In addition to this, an empirical relation between basalt fiber length and flexural strength is also developed.

2 EXPERIMENTAL PROCEDURE

2.1 Raw materials

The $CaCO_3$ whisker, basalt fiber, coarse aggregate, sand, cement, water and super plasticizer were the raw materials. The properties of $CaCO_3$ whisker and basalt fiber provided by manufacturer are shown in Table 1.The maximum size of aggregates was 18 mm. The $CaCO_3$ whisker and basalt fiber (BF) with different lengths are shown in Figure 1.

Table 1: Properties of $CaCO_3$ whisker and Basalt fiber

Material	Density ($g \cdot cm^{-3}$)	Size	Mechanical properties (GPa)
$CaCO_3$ whisker	2.86	Length 20-30μm Diameter 0.5~2μm	Tensile strength 3-6 Elastic modulus 410-710
Basalt fiber	2.63~2.65	Length 12, 25, 37 mm Diameter 7~15 μm	Tensile strength 3-4.8 Elastic modulus 91-110

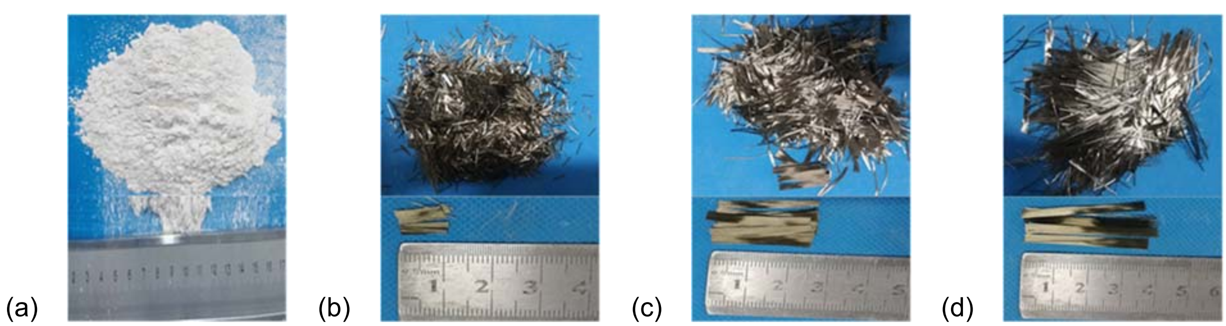

Figure 1: Fibers used in this study; (a) $CaCO_3$ whisker (b) BF 12 mm (c) BF 25 mm (d) BF 37 mm

2.2 Mix design ratio, casting and curing of specimens

For PC, the mix design ratio was 1:2:1.5:0.5 (cement: sand: aggregate: water). The same mix design ratio was used for BFRC. The BFRC batches were prepared with combination of $CaCO_3$ whisker and basalt fiber. Different basalt fiber lengths i.e. 12 mm, 25 mm and 37 mm are considered. The $CaCO_3$ whisker and basalt fiber both contents are added 5%, by cement mass. The super plasticizer content of 1%, by cement mass, is added to BFRC1, BFRC2 and BFRC3. The quantity of sand in the concrete is kept higher because there should be more mortar available to grasp basalt fibers (Khan and Ali 2018). The content of basalt fiber and whisker is selected based on literature review (Kizilkanat et al. 2015 and Cao et al. 2014). The superplasticizer is added to improve the workability.

The whole material was added into the mixer for PC and mixer was rotated for four minutes. For production of BFRC mix, the whole material was added into the mixer in layers as adopted by Ali et al. (2012) to avoid balling effect. A layer one-third aggregate was added first, followed by layers of one-third sand, cement, $CaCO_3$ whisker and basalt fibers. The other layers were also added using the same sequence until all the material was finished. The mixer was rotated for 30 seconds with dry material for uniform distribution of fiber. After that, the half of water was poured into the mixer and was rotated for two minutes. More water was then added and mixer was again rotated for four minutes. The super plasticizer was mixed into the water before pouring into the mixer.

For preparing BFRC samples, the moulds were filled and were put on mechanical vibrator for compaction. After 24 hours, the specimens of BFRC were de-moulded and placed into the curing room for 28 days. The size of beam was 100 mm depth, 100 mm width and 400 mm length for flexural tests. Three specimens are cast from each batch of PC, BFRC1, BFRC2 and BFRC3. The BFRC denotes basalt fiber reinforced concrete containing $CaCO_3$ whisker and numbers 1, 2 and 3 denotes the basalt fiber length of 12 mm, 25 mm and 37 mm, respectively. The ASTM C192 is followed for making and curing concrete specimens.

2.3 Testing procedure

2.3.1 Workability of fresh concrete

The slump test was performed for all mixes before pouring into moulds following ASTM C143/143M-15a for workability of PC. To the best knowledge of author's, no ASTM standard is available to determine workability of BFRC. Thus, the same procedure was used to determine the workability of BFRC.

2.3.2 Flexural strength test

ASTM C1609/C1609M-12 was followed for flexural strength test, to study flexural behaviour, to calculate flexural strength (fs), and to determine pre-crack energy absorbed in flexural (EFPr), post-crack energy absorbed in flexural (CFpo), total energy absorbed in flexural (EFt) and toughness index in flexural (TIF). The load-deflection curves are recorded for all concrete mixes. Average of three reading is taken. The schematic diagram of four point loading is shown in Figure 2.

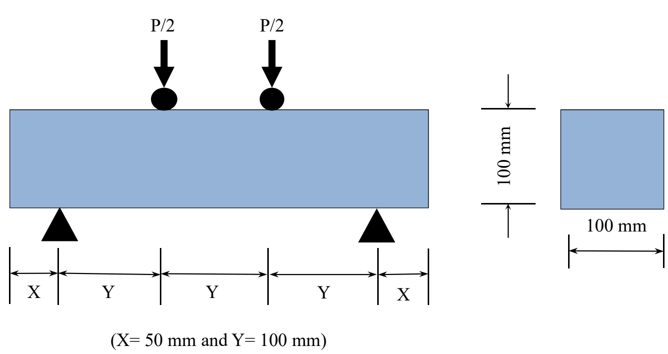

Figure 2. Schematic diagram of four point loading

3 TEST RESULTS

3.1 Workability of fresh concrete

The slump values of PC and BFRC are shown in Table 2. The slump of PC, BFRC1, BFRC2 and BFRC3 are reduced by 33%, 44%, and 67%, respectively, as compared to that of PC. The reduction in slump with addition of basalt fibers is also reported by Jiang et al. (2014). The slump is less due to the addition of $CaCO_3$ whisker and different basalt fiber length. Even with the addition of super plasticizer in BFRC, the slump was further decreased due to the addition of longer length of basalt fiber. The large surface area of fibers results in slump loss because the more cement-paste is absorbed by fibers to wrap around which leads to viscosity of the mix (Chen and Liu 2005). Also, the distributed fiber forms a network structure which restrains the flow and segregation of concrete mix.

Table 2: Slump of PC and BFRC

Concrete mixes	PC	BFRC1	BFRC2	BFRC3
Slump values (cm)	18	12	10	6

Note: The slump of BFRC is with super plasticizer content of 1%, by cement mass.

3.2 Flexural properties

3.2.1 Flexural behaviour

Load-deflection curves for PC and all BFRC are shown in Figure 3. As expected all, BFRC curves show more deflection than PC. The BFRC shows better deflection capacity at ultimate load and shows higher load capacity in load-deflection curve after the peak load as compared to that of PC. The deflection capacity at ultimate load of BFRC is up to 1.98 mm which is approximately 4 times of PC. The BFRC3 shows higher load absorption capacity at peak while BFRC1 shows higher load absorption capacity after peak deflection to ultimate deflection which shows the synergy of fibers. At first crack load, the PC specimens were broken in to two pieces; while in all BFRC, the specimens were not broken in to two pieces (refer Figure 4). Similar trend is observed in all specimens with different maximum and ultimate load. The reason is the presence of hybrid fibers which provided the bridging effect across the cracks in all BFRC. Also, it was visually observed that crack width and length at maximum load is greater than that of first crack load in all BFRC. Similar behaviour is also observed at ultimate load as compared to that of first crack and maximum load. The resistance against crack propagation after peak load is more in BFRC1. This behaviour may be due to the higher quantity of shorter fibers as compared to that of longer fibers. The BFRC3 shows sudden drop after peak load and also demonstrates flatter load-deflection curve after peak load as compared to that of BFRC1. The bridging effect offer by basalt fibers results in eliminating the sudden brittle failure after maximum load than that of PC. Also, the cross-section of intentionally broken beam shows the uniform distribution of basalt fibers in the matrix. It was also visually observed over the surface area of specimen that the shorter basalt fibers showed the fiber pull-out failure and the longer basalt fibers showed the fiber fracture failure. The basalt fibers pull-out and fracture may be attributed towards the shorter and longer embedment length of fiber, respectively. Also, the length of the fibres plays a role in the post-peak response. The pull-out mode of fiber in BFRC1 and BFRC2 results in a softening response in the post peak. Conversely, the fracture mode of fiber in BFRC3 results in a sudden loss of load capacity. All of BFRC specimens exhibit single crack behaviour.

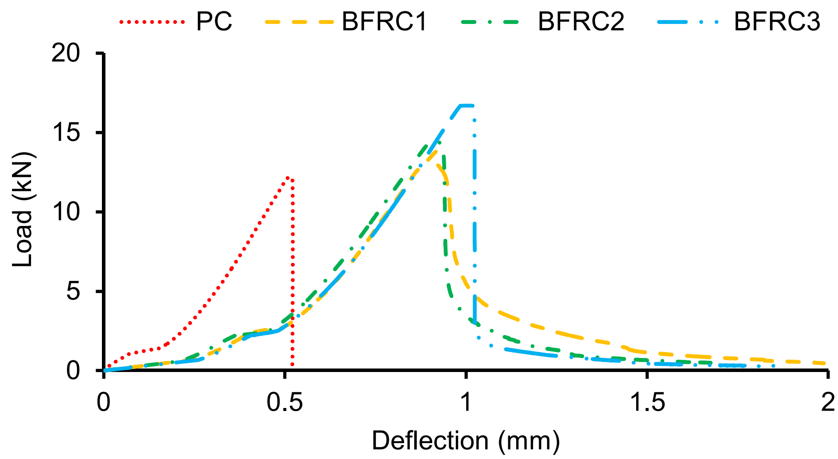

Figure 3: Typical load-deflection curves of PC and BFRC

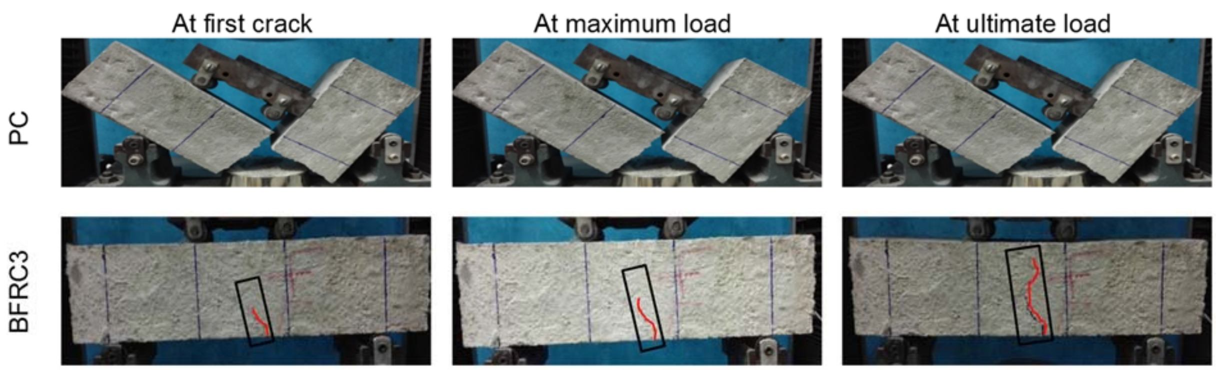

Figure 4: Behaviour of PC and BFRC3 under flexural load

3.2.2 Flexural strength (ƒs), energy absorbed in flexural and toughness index

Flexural strength (ƒs) is calculated from the peak load of the load-deflection curve. Pre-crack energy absorbed in flexural (EFpr) is calculated as the area under the load-deflection curve up to the maximum load. The area under the load-deflection curve from maximum load to the ultimate load is taken as the post-crack energy absorbed in flexural (EFpo). Total energy absorbed in flexural (EFt) is calculated as the area under the load-deflection curve from zero to ultimate load. The ultimate load is load at the maximum deflection. Toughness index in flexural (TIF) is the ratio of total energy absorbed in flexural to the pre-crack energy absorbed in flexural (i.e. EFt / EFpr). Table 3 shows the ƒs, EFpr, EFpo, EFt and TIF of all concrete mixes. The ƒs of BFRC is increased up to 6.67 ±0.31 MPa. The percentage of standard deviation error (SDE) in ƒs is up to 10%. The increasing trend is observed in ƒs with increase in basalt fiber length. The BFRC3 with 37 mm basalt fiber length shows the enhanced ƒs as compared to that of PC, BFRC1 and BFRC2. The ƒs is increased due to the crack arresting mechanism of $CaCO_3$ and basalt fibers. However, the ƒs of all BFRC is higher than that of PC. The longer basalt fiber provides more resistance against cracking as compared to that of shorter fiber due to its more embedment length. Jiang et al. (2014) and Kizilkanat et al (2015) also reported the increment in flexural strength with addition of basalt fiber in concrete.

Table 3. ƒs, EFpr, EFpo, EFt and TIF of PC and BFRC

Parameters	Concrete mix			
	PC	BFRC1	BFRC2	BFRC3
FS (MPa)	4.84 ±0.53	5.52 ±0.31	5.75 ±0.12	6.67 ±0.31
EFpr (kN.mm)	3.85 ±0.23	8.85 ±0.72	8.99 ±0.89	11.60 ±0.77
EFpo (kN.mm)	0.00 ±0.00	14.21 ±1.20	15.80 ±1.76	17.52 ±2.13
EFt (kN.mm)	3.85 ±0.23	23.06 ±1.89	24.79 ±2.61	29.12 ±2.95
TIF (-)	1.00 ±0.00	2.61 ±0.19	2.76 ±0.14	2.51 ±0.32

The EFpr range is from 8.85 ±0.72 kN.mm to 11.60 ±0.77 kN.mm for BFRC which is more than that of PC. The EFpr shows the concave upward increasing trend. The improved EFpr may be due to the addition of micro fiber ($CaCO_3$ whisker) which offers resistance at early stage. In BFRC, the EFpo is higher than PC, ranging from a minimum of 14.21 ±1.20 kN.mm to a maximum of 17.52 ±2.13 kN.mm. The addition of hybrid fiber in BFRC results in increased deflection capacity after peak load which results in enhanced EFpo. The EFt of BFRC is greater than that of PC i.e. up to 29.12 ±2.95 kN.mm. The EFt of all BFRC is enhanced than that of PC due to the incorporation of hybrid fiber which provides resistance against stresses. The TIF of PC is 1 ±0 because there is no EFpo. A maximum of 10% SDE is observed for EEt. A convex upward trend is observed in TIF for BFRC. As anticipated, the TIF of BFRC is higher than that of PC because of improved post-cracking behaviour and energy absorption. The TIF of BFRC3 is reduced than that of BFRC1 and BFRC2 because the EFpr is increased which results in less TIF. For TIF, the SDE is up to 12%. The enhanced toughness index with addition of basalt fiber is also reported by Jiang et al. (2015). The constrainment effect and crack arresting mechanism of $CaCO_3$ whisker and basalt fiber result in improved EFt and TIF due to the hybridization of fibers.

Figure 5 demonstrates the comparisons of flexural properties of PC and BFRC. The comparison of all flexural properties is w.r.t that of PC. It may be noted that the small caps on the bars shows the SDE percentage. There is an increase of 14%, 18% and 37% in ƒs of BFRC1, BFRC2, and BFRC3, respectively. The increment in EFpr is up to 201%. The EFt of PC, BFRC1, BFRC2, and BFRC3 is improved by 498%, 543%, and 655%, respectively. The improvement in TIF is observed up to 175%. The reason for enhanced flexural properties is the strong bridging effect and pull-out resistance offered by hybrid fibers. However, a growing trend is observed for ƒs, EFpr, EFpo and EFt while a concave trend is observed for TIF.

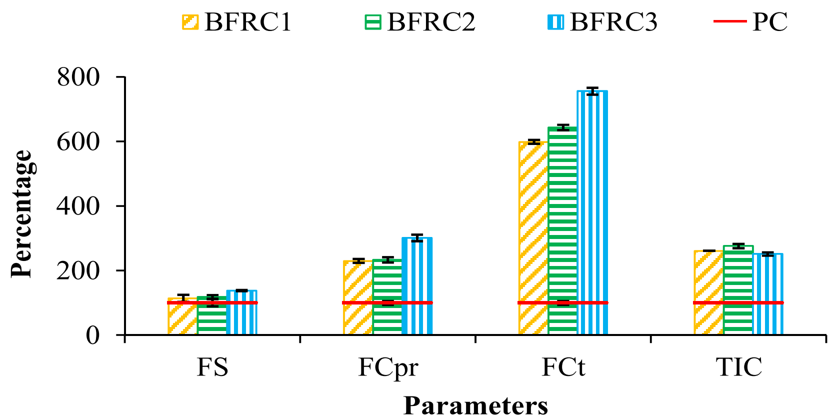

Figure 5: Comparison of flexural properties of PC and BFRC

4 DISCUSSION

4.1 Flexural properties and structural application

In this study, the mix design ratio for all mixes is 1:2:1.5:0.5 (cement: sand: aggregate: water). The basalt fiber and $CaCO_3$ whisker is added 5%, by cement mass, with different lengths of basalt fiber i.e. 12 mm, 25 mm, and 37 mm. The length of $CaCO_3$ whisker is 20–30 µm. The super plasticizer content of 1%, by cement mass, is added to BFRC1, BFRC2, and BFRC3. The addition of hybrid fiber shows enhanced flexural properties of concrete. The fs, EFpr, EFt and TIF of BFRC are increased up to 37%, 201%, 655% and 175%, respectively. The improved properties may be due to the addition of micro fiber ($CaCO_3$ whisker) which offers resistance to micro-cracks at early stage. In addition to this, whisker affects the shear resistance and increases the bond strength. The further increment in flexural properties may be because of the bridging effect due to the addition of basalt fibers. Jiang et al. (2014) and Kizilkanat et al. (2015) observed the increment in flexural strength with addition of basalt fibers in concrete up to 9.5% and 34%, respectively. The enhanced toughness index with addition of basalt fibers is also reported by Jiang et al. (2014). Khan and Ali (2016) stated that improved tensile strength and better post-cracking behaviour might be helpful for controlling the early age micro cracking, ultimately resulting in enhanced durability. A more crack-resistant concrete can be greatly increased the lateral load carrying capacity and structural durability (Nguyen et al. 2014). The flexural properties of BFRC are increased due to crack-arresting mechanism of $CaCO_3$ whisker and basalt fibers at micro- and meso-level. Burgueno at al. (2010) reported that the performance of bridge structures is greatly dependent on the energy dissipating capacity and tough behaviour of piers. The better energy absorption capacity of BFRC will result in more energy dissipation in concrete and will improve the capacity/tough behaviour, ultimately enhancing the performance of structural members. Thus, the crack arresting power of hybrid fibers at micro-and meso-level does not allow the moisture to penetrate in to the concrete which will ultimately reduce the deterioration of concrete and will improve the durability of concrete. Also, the addition of hybrid fibers results in improved energy dissipation capacity and toughness which favours its utility to be used for the structural application like buildings and bridges.

4.2 Empirical relation between fs and fiber length

The empirical equation has been developed by average experimental results with best fit curve ($R^2 = 0.95$). The relation after simplifying the coefficient is shown as below (refer equation 1).

[1] $fs = 4.87e^{0.008L}$

Whereas; fs is flexural strength in MPa and L in the power denotes the basalt fiber length in mm.

The average value from experimental and empirical equation is shown in Table 4. The correlation of experimental results with empirical results is closer to each other which show good relation between them. The maximum error is observed up to 0.22 MPa. The comparison of experimental and empirical data is shown in Figure 6. It may be noted that the highest error was observed up to 8% for PC while for BFRC the error was up to 4.48%. This shows the fit relation between experimental and empirical data. The equation 1 is purely empirical and it limited to current study only. Also, the basalt fiber length can be changed for this particular type of concrete mix; but the content of $CaCO_3$ whisker and basalt fiber is constant. The short fibers (i.e. less than 25 mm in length) results in pull-out failure, whereas the longer fibers (greater than 25 mm length) will result in fiber fracture failure as discussed earlier in section 3.2.

Table 4. Experimental and empirical fs of PC and BFRC

	fs (MPa)			
	PC	BFRC1	BFRC2	BFRC3
Experimental	4.84	5.52	5.75	6.67
Empirical	4.87	5.37	5.96	6.57

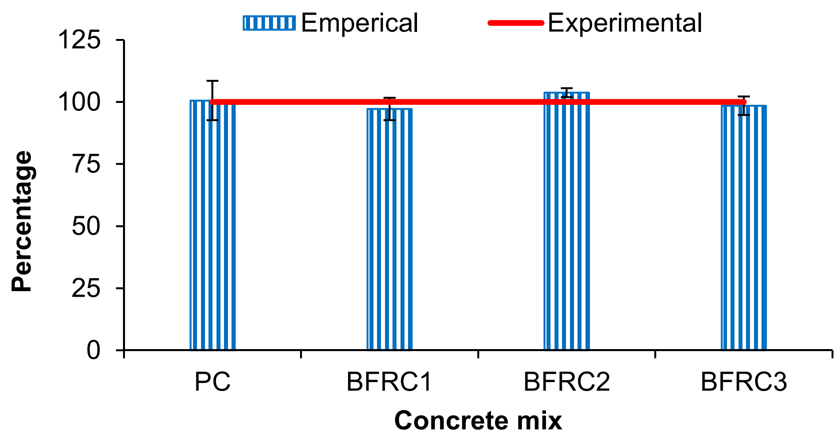

Figure 6: Comparison of experimental and empirical data

5 CONCLUSIONS

In this research, basalt fiber reinforced concrete (BFRC) with addition of $CaCO_3$ whisker is investigated for the structural application. The BFRC with different basalt fiber lengths (12 mm, 25 mm, and 37 mm) are studied. The super plasticizer content is 1% for BFRC. The mix design ratio of BFRC is 1:2:1.5 (cement: sand: aggregate) with water to cement ratio of 0.50. Following conclusions are made:

- The workability of different BFRC mixes is reduced up to 67% as compared to that of plain concrete (PC) mixes even with increased super plasticizer content.
- The increment in BFRC is observed up to 37%, 201%, 655% and 175%, for flexural strength, pre-crack energy absorbed, total energy absorbed and toughness index, respectively, as compared to that of PC.
- The improved flexural properties may be due to the bridging effect of $CaCO_3$ whisker and basalt fiber which results in high energy dissipation ultimately improves the durability of structural applications.
- The BFRC3 with 37 mm basalt fiber length, 5% basalt fiber and $CaCO_3$ whisker content and 1% super plasticizer content, by cement mass, is suggested to be the optimum.
- The empirical equation is established with the help of experimental data with a maximum percentage error of up to 8%.

Hence, based on above outcomes, the enhanced properties of BFRC with combination of $CaCO_3$ whisker show positive sign for its usefulness in structural application. Further study on optimization and development of empirical equation for basalt fiber length and content for mechanical properties of concrete is suggested.

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