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Effect of hybrid fibers on tension stiffening of reinforced geopolymer concrete

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Abstract. An experimental work was carried out to study the effect of hybrid fiber on the tension stiffening and cracking characteristics of geopolymer concrete (GPC). A total of 24 concentrically reinforced concrete specimens were cast and tested under uniaxial tension. The grade of concrete considered was M40. The variables mainly consist of the volume fraction of crimped steel fibers (0.5 and 1.0%) and basalt fibers (0.1, 0.2 and 0.3%). The load deformation response was recorded using LVDT's. At all the stages of loading after the first cracking, crack width and crack spacing were measured. The addition of fibers in hybrid form significantly improved the tension stiffening effect. In this study, the combination of 0.5% steel fiber and 0.2% basalt fiber gave a better comparison than the other combinations.

Keywords: fiber reinforced concrete; fly ash; ground granulated blast furnace slag (GGBS); steel fibers; basalt fibers; tension stiffening; cracking

1. Introduction

The utilization of hybrid fibers in structural members is intended to improve the performance of reinforced concrete structures with regard to cracking, ductility, energy absorption capacity etc.,. The characteristics of fiber-reinforced concrete (FRC) depend on many factors such as size, type, elastic properties, aspect ratio, and volume fraction of fibers, and each type of fiber can be effective in some specific function Bentur and Mindess (1990). In the past many attempts have been made to study the effect of fibers on tension stiffening (Ahmed *et al*. 2007, Qian *et al*. 2000). The hybrid fibers follows the concepts of controlling the propogation of microcracks by non metallic fibers which are small and soft and the macro cracks by metallic fibers which are strong and have high aspects ratio (Ganesan *et al*. 2013, Sivakumar and Santhanam 2007). Such hybrid fiber reinforcement offers more attractive engineering properties because the presence of one type of fiber effectively uses the properties of other fiber Mobasher and Li (1996). Some researcher conducted uniaxial tension tests on steel fiber reinforced concrete (SFRC) members containing conventional reinforcement and studied the behaviour of cracking. The presence of conventional

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reinforcement significantly altered the behaviour of SFRC Deluce and Vecchio (2013). Tension stiffening is the ability of concrete to carry tension between cracks, which provides additional stiffness for a reinforced concrete member in tension Bischoff (2003). The studies of Fields and Bischoff (2004) revealed that under service loads the tension stiffening can significantly affect member stiffness, deflection and width of cracks. In the case of high strength concrete specimens enhanced tension stiffening effect was observed and infact at higher ratios of reinforcement tension stiffening effect was found to be decreased. The presence of steel fibers is effective in controlling splitting cracks and increases the tension stiffening effect significantly because the fiber concrete is able to carry tensile stress through the crack opening Abrishami and Mitchell (1997).

An investigation was carried out by Vilanova (2014) to study the effect of tension stiffening on glass fiber reinforced polymer RC (reinforced concrete) tensile elements under sustained loading and the results showed an increase in reinforcement strain and degradation in the tension stiffening effect. The parametric study on hybrid steel bar and glass fiber reinforced polymer fiber reinforced concrete elements revealed, the fracture increase of energy and reduction in the tension stiffening effect Mazaheripour *et al*. (2016). An equation was proposed from Desayi and Ganesan (1985) for predicting the maximum width and spacing of cracks in flexural members. The equation was further modified by Ganesan and Shivananda (1997) by introducing a correction factor to account for the tension stiffening effect of SFRC. An analytical model that adopted a cohesive interface approach to predict the crack spacing observed in very ductile specimens in tension by Fantilli *et al*. (2009).

Portland cement is an important ingredient of normal strength concrete. The process of cement production is highly energy intensive and results in the emission of greenhouse gases such as carbon dioxide (McCaffrey 2002, Mehta 2001). The major issue from the sustainability point of view is to Control of these gases. And furthermore, under certain environmental conditions, concrete structures made with ordinary Portland cement are less durable Neville (1995). In this respect, to provide an alternative binder to ordinary Portland cement, Geopolymer technology was introduced by Davidovits (1991).

Geopolymer concretes (GPCs), which are inorganic polymer composites with the potential to form a substantial element of an environmentally sustainable construction by replacing or supplementing conventional concretes Davidovits (1994). In geopolymer concrete, the industrial by products materials such as fly ash and GGBS can play a vital role, in the context of sustainability and environmental issue Duxson (2007). Islam *et al*. (2014) and Pradip *et al.* (2014) observed that the inclusion of different proportion of GGBS with class F flyash, increases the strength significantly and the workability with a lower sodium silicate to sodium hydroxide ratio in mixture.

Ng *et al*. (2013) studied the behaviour of steel-fibre-reinforced geopolymer concrete (SFRGPC) beams under shear. The test results showed that the shear strength increased significantly with an increase in fibre content and that an improvement in cracking behaviour was achieved through the addition of fibres. Recently Basalt fiber, made of crude lava (containing basalt), possesses excellent physical and mechanical properties, and thus, has been used as reinforcing material for concrete. Dias *et al*. (2005) investigated the influence of the volume fraction of fiber on the fracture toughness of basalt fiber reinforced geopolymeric concrete (BFRGC). The experiment results show that BFRGC has better fracture properties than basalt fiber reinforced OPC concrete. Hence attempts have been made in the past to improve the tension stiffening effect of conventional concrete by the addition of short discrete fibers in the matrix. In this study, the combined effect of

Table 1 Physical and chemical properties of fly ash and GGBS

Materials	Specific Gravity	Fineness m^2/kg	Insoluble residue	Loss of Ignition	Chemical Composition in percentage							
					Al_2O_3	Fe_2O_3	SiO_2	MgO	K_2O	MnO	TiO_2	CaO
Fly ash	2.40	1134.10	0.00	0.90	27.74	9.74	55.36	0.00	2.55	0.00	1.07	3.55
GGBS	2.90	370.00	0.05	0.30	15.74	0.65	37.21	8.65	0.00	0.33	0.00	37.23

Table 2 Properties of fibers

Type of Fiber	Crimped steel	Basalt
Length of fiber (mm)	30	18
Diameter of fiber (mm)	0.45	0.013
Aspect ratio	66	1384
Ultimate tensile strength (MPa)	800	4.10 to 4.87

(a) Crimped steel fibers

(b) Basalt fiber

Fig. 1 Fibers used

metallic and non metallic fibers are tried to investigate the tension stiffening characteristics and cracking resistance of GPC and HFRGPC.

2. Experimental programme

The experimental programme included casting and testing on 24 reinforced concrete prismatic tension members having cross sectional dimensions of 60×60×600 mm axially loaded in tension to investigate the post cracking response of reinforced GPC. The grade of concrete used was M40 and the steel reinforcement consisted of 10 mm diameter high yield strength deformed (HYSD) bars. The variables include the volume fraction (V_f) of crimped steel fibers (0.50% and 1%) and volume fraction of basalt fibers (0.10%, 0.20% and 0.30%).

2.1 Material and mix proportion

As GPC's are a new class of construction material, standard mix designs are not available. Based on the guidelines given by Rangan (2008), GPC mix proportion for M40 grade concrete was obtained by trial and error. Low calcium (ASTM Class F) fly ash obtained from Mettur Thermal

Table 3 Mix proportion

Materials	Quantity kg/m^3
Coarse aggregates	975
Fine aggregates	285
Fly ash	447.3
GGBS	191.7
Sodium silicate solution	180
Sodium hydroxide soultion	72
Water	57
Super plasticizer	8

Fig. 2 Reinforcement bar in the steel mould

Power Plant, Tamil Nadu and GGBS brought from Quality Polytech (a chemical firm), Mangalore was used as source materials. The chemical composition of fly ash and GGBS was examined using both Scanning Electron Microscope (SEM) and Energy dispersive X-ray (EDX) methods. Table 1 shows the physical and chemical properties of fly ash and GGBS. Locally available river sand passing through 4.75 mm IS sieve conforming to grading zone II of IS: 383-1970 (reaffirmed 2002), having a fine modulus of 2.83 and specific gravity of 2.55 was used . The maximum size of coarse aggregate was 20 mm with a fineness modulus of 7.69 and specific gravity of 2.70. Sodium silicate and sodium hydroxide were as alkaline activators to prepare alkaline solution (Fernandez *et al*. 2006, Hardjito *et al*. 2004, Rashad *et al*. 2013). A naphthalene based super plasticizer (Conplast SP 430) was employed during mixing operations in order to improve the workability of concrete. Properties of crimped steel fibers and basalt fibers are given Table 2 and shown in Fig. 1.

The objectives for performing the trial-and-error procedure were to obtain the desired compressive strength at the end of 28 days and to obtain a good cohesive mix with satisfactory workability (slump of 75-125 mm). Sodium silicate to sodium hydroxide ratio by mass was kept at 2.5 (Mustafa *et al*. 2012) and the ratio of activator solution to Fly-ash was selected as 0.36. Details of the mix proportions are given in Table 3.

2.2 Casting of specimen

To prepare the test specimens Fly ash, GGBS, river sand, coarse aggregate, sodium silicate and sodium hydroxide were used. To form the alkaline solution, Sodium hydroxide was used in pellet form, mixed with water to form a 14 M solution **(**Hardjito *et al*. 2004, Vanchai *et al*. 2013), and then mixed with sodium silicate, 24 hours prior to casting. All the aggregates were prepared in saturated surface dry condition. Mixing of the dry materials was carried out first in a drum-type mixer. Super plasticiser was mixed with the alkaline solution and was then added to the dry materials.

The required quantities of steel fibers and basalt fibers were taken according to the volume

Fig. 3 Specimen in steam curing chamber

Fig. 4 Experimental set up

fraction and these were then added while mixing. Reinforcement consisted of a single 10 mm diameter high yield strength deformed bar of Fe 415 grade and which is placed concentrically in the steel mould. The bar had a total length of 1100 mm, allowing an additional length of 250 mm on both ends of the specimen for gripping purposes. Fig. 2 shows the typical arrangement of the reinforcement in the steel mould. The freshly mixed GPC was then poured into the mould layer by layer so that the total number of layers was three and each layer was vibrated for 15 seconds for proper compaction. The top surface was leveled to a smooth finish and the moulds were covered with plastic sheet to prevent loss of moisture. The covered specimens were allowed to rest for 3 days. They were then transferred to a steam curing chamber Fig. 3 where they were cured for 24 hours at a constant temperature of 60℃. Details of tested specimens and variables are given in Table 4.

2.3 Specimen testing

A universal testing machine (UTM) of capacity 1000 kN was used to test all the specimens under uniaxial tension. Axial elongation of the specimens was monitored using a linear variable differential transducer (LVDT) fixed on one side of the concrete prism. Crack widths were measured using a crack width measuring microscope having a least count of 0.05 mm, at each load increment of 0.5 kN. Crack spacing was also measured. A data acquisition system was used to

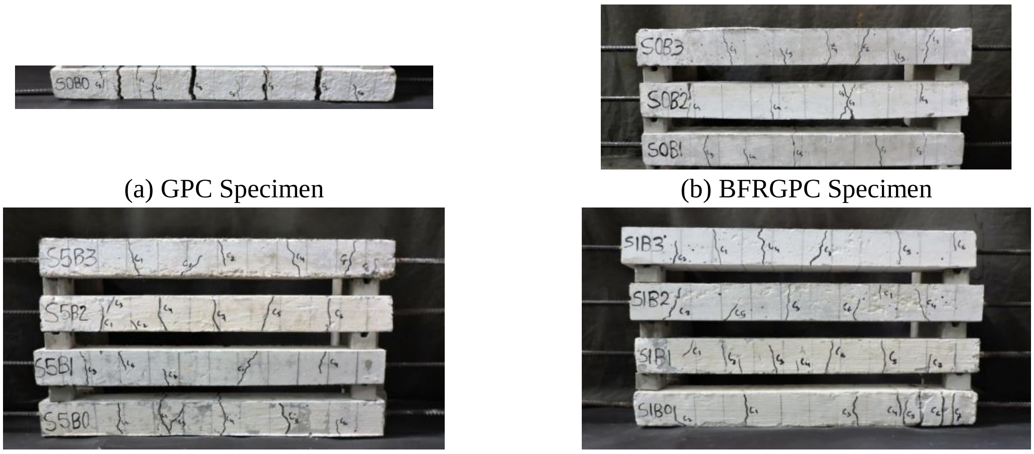
Table 4 Details of specimen and variables

Serial No.	Specimen designation	Volume fraction of fiber %		No. of Specimen
		Steel	Basalt	
1	GPC	0	0.0	2
2	BFRGPC1		0.1	2
3	BFRGPC2		0.2	2
4	BFRGPC3		0.3	2
5	SFRGPC1	0.5	0.0	2
6	HFRGPC1		0.1	2
7	HFRGPC2		0.2	2
8	HFRGPC3		0.3	2
9	SFRGPC2	1	0.0	2
10	HFRGPC4		0.1	2
11	HFRGPC5		0.2	2
12	HFRGPC6		0.3	2

Table 5 Test results

Specimen designation	First crack load, kN	Yield load, kN	No. of transverse cracks	Average crack spacing, mm
GPC	12.7	41	8	73
BFRGPC1	13.2	40	5	74
BFRGPC2	14.1	44	5	76
BFRGPC3	15.2	46	6	73
SFRGPC1	13.9	43	6	70
HFRGPC1	16.1	49	5	69
HFRGPC2	16.8	51	7	71
HFRGPC3	17.9	50	6	74
SFRGPC2	18.5	47	7	65
HFRGPC4	17.6	54	6	66
HFRGPC5	17.3	52	7	63
HFRGPC6	16.4	51	7	62

record displacement signals from the LVDT having a range of ±20 mm and 0.01 mm resolution. A grid with a spacing of 100 mm was drawn on the front face of the specimen before testing to identify the crack locations continuously during the test. The location of each crack was marked on the specimen immediately after its appearance during the test. The crack spacing was measured along the centreline of the front face of the specimen. Crack widths were measured along the specimen at regular intervals using a crack detection microscope with 25× magnification. The test set-up is shown in Fig. 4. The testing was done under a load-control condition and continued until yielding occurred. One longitudinal reinforcement bar was also tested under the same loading condition to obtain the response of the bare bar. For each mixture, two specimens were cast and



(a) GPC Specimen

(b) BFRGPC Specimen

(c) HFRGPC specimens with 0.5% steel fibers and varying values of basalt fibers

(d) HFRGPC specimens with 1% steel fibers and varying values of basalt fibers

Fig. 5 Crack pattern of specimens tested

tested. The average values of two results are presented in Table 5.

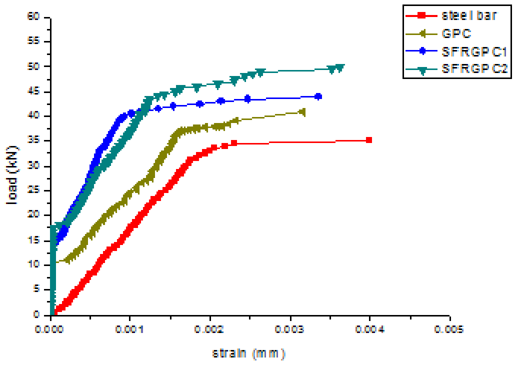
3. Test results and discussion

3.1 Behaviour of crack pattern

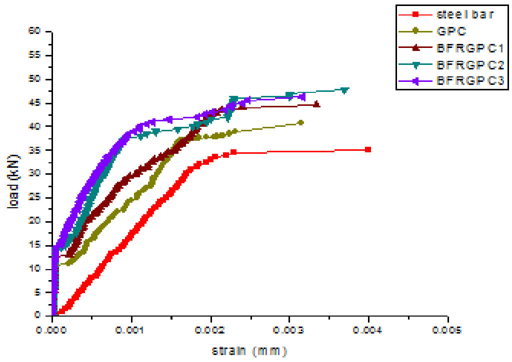
The crack patterns of tested specimen are as shown in Fig. 5. The first transverse crack appeared near the middle portion of the specimen in GPC specimens. As the load increased, the first crack widened and additional cracks appeared. The crack development was not uniform on all sides of the specimen. Longitudinal splitting cracks also formed. In steel fiber-reinforced, geopolymer concrete (SFRGPC) specimens, a large number of finer cracks developed. Basalt fiber-reinforced, geopolymer concrete (BFRGPC) specimens exhibited less cracks with reduced width as the volume fraction increased. The cracks were finer in HFRGPC specimens. This can be seen from Table 5 that, in general the average crack spacing is less for HFRGPC specimens which indicates more number of finer cracks on these specimens than a fewer number of wider cracks in other specimens. This could be attributed to the ability of basalt fibers in arresting the micro cracks, which delays the formation of macro cracks (Sivakumar and Santhanam 2007). The fibers bridging at the cracks was noted in all specimens containing steel and basalt fibers.

3.2 Load deformation behaviour

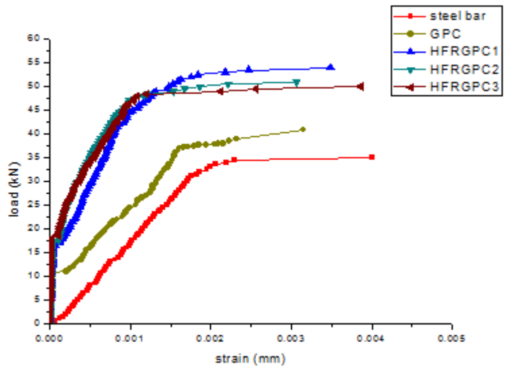
The load-deformation response of the specimen can be obtained by plotting axial load with member strain. The response of all the specimens compared with GPC and bare bar is shown in Fig. 6. For all the specimens, the behaviour was linear up to first crack and the initial stiffness of specimens was higher than the stiffness of bare bar. It can be noted from Fig. 6(a) that, after the formation of first crack, the specimen containing steel fibers exhibited increased stiffness compared to GPC without fibers. Also, as the fiber content increased from 0.5% to 1%, the



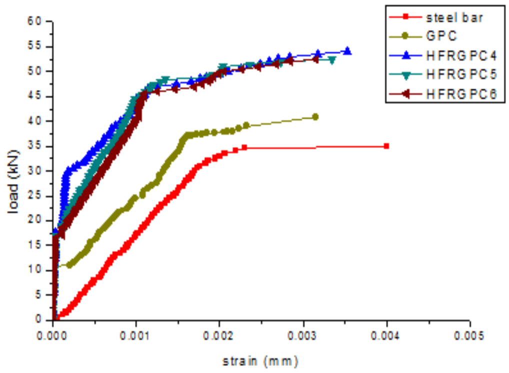
(a) SFRGPC Specimen



(b) BFRGPC Specimen



(c) HFRGPC specimen with 0.5% steel fiber and varying values with basalt fiber



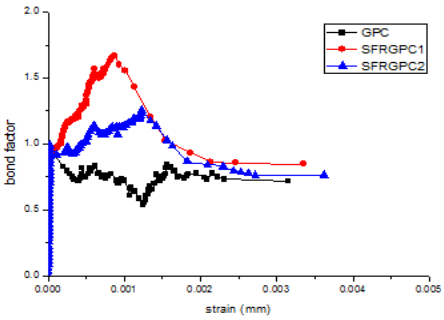
(d) HFRGPC specimen with 1% steel fiber and varying values with basalt fiber

Fig. 6 Axial load- strain response of all specimen

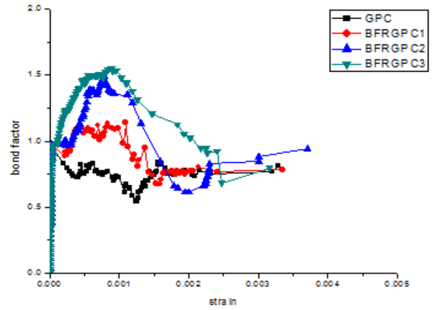
stiffening effect increased markedly. BFRGPC specimens (Fig. 6(b)) also exhibited an increased tension stiffening effect compared to the GPC specimen. Figs. 6(c)-(d) show the behavior of HFRGPC specimens. For all the hybrid fiber-reinforced geopolymer concrete specimens, the strains are much lower than that of the bare bar tested.

Even after cracking, for all the hybrid fiber-reinforced concrete specimens, the strains are much lower than that of the bare bar tested, which shows the tension stiffening effect of the matrix at the uncracked sections and the contribution of fibers to the axial-load carrying capacity. This may be attributed to the ability of basalt fibers in delaying the formation and propagation of microcracks and that of steel fibers in carrying stresses across the macrocracks. Among HFRGPC, specimens those with 0.1% basalt fibers showed a higher tension stiffening effect than those with 0.2% and 0.3%. In HFRGPC specimens with 1% steel fiber, it can be seen that HFRGPC4 and HFRGPC5 have an almost identical response, while HFRGPC6 showed a slight decrease in tension stiffening effect.

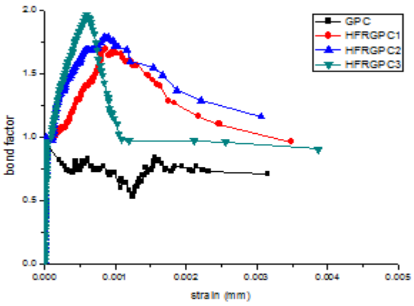
This may be due to reduced workability of concrete at higher fiber contents due to the balling effect of fibers. The results obtained from the tests are shown in Table 6. It can be observed that the hybrid fiber-reinforced composites exhibit high values of first crack load compared to mono-fiber composites. Load at yielding was approximately the same for the GPC specimen and bare reinforcement, whereas it is approximately 20% higher in SFRGPC and 30% higher in HFRGPC



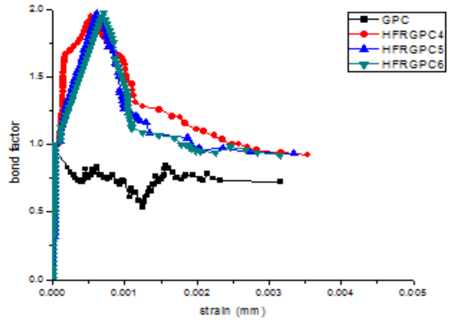
(a) SFRGPC specimens



(b) BFRGPC specimens



(c) HFRGPC specimen with 0.5% steel fiber and varying values with basalt fiber



(d) HFRGPC specimen with 1% steel fiber and varying values with basalt fiber

Fig. 7 Tension stiffening bond factor

containing 0.10% basalt fibers. Specimens with fibers exhibit tension stiffening even after yielding of the reinforcing steel because of the ability of fibers to carry tensile stresses across the cracks. The number of transverse cracks presented in Column 4 of Table 5 is the number obtained at the final stage of loading; the average crack spacing given in Column 5 corresponds to the final stage of loading beyond which no further cracks appear. Also, it can be seen that the average crack spacing decreases as the fiber content increases.

3.3 Tension stiffening bond factor

The tension stiffening contribution of each mixture is represented by the tension stiffening bond factor, which is calculated by dividing $P_{c,m}$ with P_{cr} (Bischoff 2003), where $P_{c,m}$ is average load carried by cracked concrete and is obtained by subtracting the bare steel response from the specimen responses, and P_{cr} is the load carried by concrete at first cracking. Tension stiffening bond factor 'β' is calculated for all mixtures, and Fig. 7 compares the bond factors of mono-fiber and hybrid fiber concrete with that of GPC without fibers.

For all FRC mixtures, it can be noted from Fig. 7 that the ratio of $P_{c,m}/P_{cr}$ is found to be more than unity for all which contradicts earlier findings, in which the bond factor is less than 1. Because geopolymer fiber-reinforced cementitious composite behaves similarly to engineered

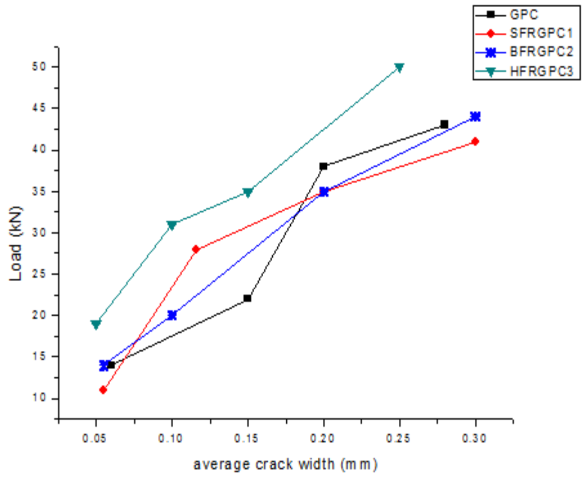


Fig. 8 Comparison of crack widths

cementitious composites (ECCs), which exhibit strain hardening with relatively high strain capacity, the average tensile strength in concrete increases even after the first crack, which leads to enhanced values of bond factor. An increase in the β-value indicates an increase in the stiffness of the member. It can be observed from Fig. 7 that all FRC specimens show considerable tension stiffening effect compared to GPC. From referring Figs. 7(a)-(b), it can be seen that as the volume fraction of fibers increases, the bond factor also increases significantly. It may be noted from Figs. 7(c)-(d) that the specimens containing hybrid fibers exhibit higher values of β compared to mono-fiber composites. This can be attributed to the confinement and bridging effects imparted by steel and basalt fibers in HFRGPC composites after cracking, which reduces the crack width and leads to enhanced bond resistance of reinforcing bars embedded in such composites.

As cracking is an important limit state of serviceability, an attempt is made to obtain the variation of average width of crack as the load increases. Fig. 8 shows the variation of average crack width with load. It may be seen from Fig. 8, that after cracking, for a given stage of loading, the width of cracks exhibited by BFRGPC (basalt fibers) and SFRGPC (Steel fibers) specimens are less than those values given by GPC specimens. The width of cracks of HFRGPC (Basalt and Steel fiber) specimen shows further reduction in the width of cracks compared to GPC, BFRGPC and SFRGPC. This indicates that the effect of hybrid fibers in reducing the width of crack is much more significant than other individual fiber effect.

4. Conclusions

The following conclusions are made based on the results of this study:

1. The tension stiffening effect was considerably improved by the addition of steel and basalt fibers.

2. Load at yielding was 20% higher in SFRGPC than GPC specimen also and approximately 30% higher in HFRGPC containing 0.2% basalt fibers than GPC specimens.

3. With a combination of 1% steel fibers and 0.1% basalt fibers, HFRGPC specimen significantly improved the tension stiffening effect when compared to other combinations

considered in this study.

4. Incorporation of steel and basalt fiber in hybrid form improve the cracking characteristics of the composite significantly by reducing the width of cracks, which in turn enhances the performance from serviceability criteria.

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