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Mechanical and fracture properties of glass fiber reinforced geopolymer concrete

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Abstract. This paper investigates the effect of inclusion of glass fibers on mechanical and fracture properties of binary blend geopolymer concrete produced by using fly ash and ground granulated blast furnace slag. To study the effect of glass fibers, the mix design parameters like binder content, alkaline solution/binder ratio, sodium hydroxide concentration and aggregate grading were kept constant. Four different volume fractions (0.1%, 0.2%, 0.3% and 0.4%) and two different lengths (6 mm, 13 mm) of glass fibers were considered in the present study. Three different notch-depth ratios (0.1, 0.2, and 0.3) were considered for determining the fracture properties. The test results indicated that the addition of glass fibers improved the flexural strength, split tensile strength, fracture energy, critical stress intensity factor and critical crack mouth opening displacement of geopolymer concrete. 13 mm fibers are found to be more effective than 6 mm fibers and the optimum dosage of glass fibers was found to be 0.3% (by volume of concrete). The study shows the enormous potential of glass fiber reinforced geopolymer concrete in structural applications.

Keywords: geopolymer concrete; glass fiber; fracture properties; flexural strength

1. Introduction

Concrete is the most widely used building material around the world and its usage is second only to water. Ordinary Portland cement (OPC) is conventionally used as the primary binder to produce concrete. CO_2 emission from concrete industry is an environmental issue, with the cement manufacturing contributing about 95% of the total CO_2 emission from the concrete industry (Bakri *et al*. 2011). Since the cement industry uses raw materials and energy that are non-renewable, it does not fit the contemporary picture of a sustainable industry.

Various efforts were made to find an alternative cement-less binder material and the development of geopolymer concrete (GPC) is a promising solution. Geopolymer concrete is a result of reaction of materials containing alumina and silica with alkaline solution to produce an inorganic polymer binder (Davidovits 1994, Hardjito and Rangan 2005) Industrial waste product materials like fly ash (FA) and ground granulated blast furnace slag (GGBFS) or materials of

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geological origin such as rice husk, metakaolin, pumice etc. can be used as the source material for alumina and silica (Palomo *et al*. 1999, Puertas *et al*. 2000, Hardjito *et al*. 2004). Compared to Ordinary Portland Cement concrete, geopolymer concrete has high early strength gain, higher fire resistance and is durable against chemical attack (Bakharev 2005, Zhao *et al*. 2007, Rao and Rao 2015, Rao and Rao 2017). However geopolymer concrete has got some inherent disadvantages which limits its use in several applications. GPC, owing to its brittle and ceramic-like nature exhibit poor tensile and bending strength (Natali *et al*. 2011, Venu and Rao 2017). In order to improve tensile strength of concrete, ferro mesh, fibers and polymer sheets can be used of which, use of fibers is most economical and effective in improving the fracture parameters and tensile strength of concrete (Giancaspro *et al*. 2010, Silva and Thaunmaturgo 2003, Bernal *et al*. 2010, Li and Xu 2009).

Fracture mechanics is a failure theory that determines material failure by energy criteria and considers failure to be propagating throughout the structure. Fracture is related to propagation of cracks in the material. Fracture energy (G_F), critical stress intensity factor (K_{Ic}) and critical crack mouth opening displacement (CMOD) are some of the fracture parameters used to quantify the fracture behaviour of concrete. Fracture energy is an important parameter in determining the resistance of a material to crack propagation while stress intensity factor is defined to quantify the stresses at the crack tip. A material fails by fracture when the stress intensity factor reaches a critical value K_{Ic}, called critical stress intensity factor.

From the past researches, it is clear that the addition of fibers to the concrete mix improves the hardened properties of the mix as fibers hold the concrete mix and arrest crack propagation. Choia and Yuan (2005) studied the effect of inclusion of glass and polypropylene fibers on mechanical properties of cement concrete. Compressive strength and split tensile strength of the fiber reinforced concrete at 7, 28, 90 days were determined. The results showed that the inclusion of fibers improved the split tensile strength by 20-50%. Nematollahi *et al*. (2014) investigated the effect of addition of glass fibers on fresh and hardened properties of fly ash based geopolymer concrete and the result indicated that with increase in fiber content, compressive strength, flexural strength and density of geopolymer concrete increases, while a decrease in workability is reported with increase in fiber content. Vijai *et al*. (2012) studied the properties of glass fiber reinforced geopolymer concrete composites containing 90% fly ash and 10% OPC. Three different volume fractions (0.01%, 0.02%, and 0.03%) of glass fibers were used in the study and the results showed an increase in compressive, split tensile and flexural strength of geopolymer concrete composite with increase in fiber content. Alomayri (2017) conducted studies on microstructural and mechanical properties of geopolymer composites containing glass microfibers and found that the addition of fibers improved compressive strength, fracture toughness, Young's modulus and hardness of GPC composite. Yan *et al*. (2012) studied the fatigue performances of glass fiber reinforced concrete in flexure and concluded that the fatigue performance of glass fiber reinforced concrete is better than plain concrete.

The effect of glass fibers on workability, density, compressive strength, flexural strength and split tensile strength of geopolymer concrete was investigated by several researchers but the effect of inclusion of glass fibers on fracture properties of GPC has received less attention. However, numerous research works are available in literature on the role of basalt (Dias and Thaumaturgo 2005), PVC and carbon fibers (Natali *et al*. 2011) in improving fracture parameters of GPC. The present study aims to evaluate the effect of volume fraction and length of glass fibers on the fracture parameters and indirect tensile strength of binary blend geopolymer concrete.

Table 1 Mineralogical composition of FA and GGBFS

Material	SiO_2	CaO	Al_2O_3	MgO	Fe_2O_3	SO_3	Na_2O	LOI
FA (% by mass)	60.23	3.98	27.52	1.75	4.31	0.41	0.19	0.88
GGBFS (% by mass)	33.86	33.67	21.4	7.76	0.79	0.92	0.12	0.36

2. Experimental program

2.1 Materials

2.1.1 Binder material

A combination of low calcium fly ash (ASTM class F) and ground granulated blast furnace slag was used as the binder material. Fly ash used was having a specific gravity of 2.17 and fineness of 350 m^2/kg, while GGBFS was having a specific gravity of 2.9 and fineness of 385 m^2/kg. The mineralogical composition of the binder material used is given in Table 1.

2.1.2 Alkaline activator solution

Alkaline activator solution used was a mix of sodium hydroxide solution (NaOH) of 8 mol/lit and sodium silicate solution (Na_2SiO_3). The sodium silicate solution (SiO_2=26.5%, Na_2O=8%, and water=65.5%, by mass) was purchased from a local supplier. The alkaline ratio i.e., mass ratio of Na_2SiO_3 to NaOH was taken as 2.5 and kept constant for all the mixes (Mustafa *et al*. 2012).

Alkaline activator solution was prepared one day prior to the casting. 320 grams of NaOH pellets was dissolved in distilled water to obtain 1 litre of 8M NaOH solution. Dissolution of NaOH in water is an exothermic reaction which liberates a lot of heat. After the NaOH solution gets cooled, sodium silicate solution was added to NaOH solution and mixed properly.

2.1.3 Aggregates

Crushed granite was used as natural coarse aggregate while locally available river sand was used as fine aggregate which conforms to Zone-3 as per to IS 383-1970. Mono sized aggregates were obtained by sieving aggregates in consecutive sieves. The bulk density and specific gravity of coarse and fine aggregates used were 1.624 g/cc, 2.68 and 1.789 g/cc, 2.61 respectively.

Fig. 1 Alkali resistant glass fibers

2.1.4 Glass fibers

Alkali resistant glass fibers containing zirconium dioxide (ZrO_2) was added to the GPC mix as fiber reinforcement. (see Fig. 1)

2.1.5 Superplasticiser

Water-reducing admixture, CONPLAST SP-430, purchased from Fosroc Chemicals, India was used to obtain desired workability for all the mixes.

2.2 Mix design and preparation

2.2.1 Mix design

To study the effect of glass fibers on flexural and fracture parameters, the mix design parameters like binder content, alkaline solution/binder ratio, sodium hydroxide concentration and aggregate grading were kept constant. A total of 9 mixes were cast, each mix includes 12 prisms of 100×100×500 mm dimension, 3 cubes of 100 mm dimension and 3 cylinders of 100 mm diameter and 200 mm height. Four different volume fractions (0.1%. 0.2%, 0.3%, 0.4% of total volume of concrete) and two different lengths of glass fibers (6 mm, 13 mm) were considered in the study. Three different notch depth ratios (0.1, 0.2, and 0.3) were used to study the fracture parameters under single point loading test. The mix design of

Table 2 Mix proportions of geopolymer concrete

Grade of concrete	30 MPa
Fly ash/GGBFS ratio	70:30
Aggregate/binder ratio	3.85
Solution/binder ratio	0.50
Coarse aggregate/Total aggregate ratio	0.562
Molarity of NaOH	8M
Alkaline ratio (Na_2SiO_3/NaOH	2.5
Binder content (kg/m^3)	450
Coarse aggregates (kg/m^3)	973.67
Fine aggregates (kg/m^3)	758.84
Alkaline solution (kg/m^3)	225

Table 3 Mix details with fiber length and volume

Grade of concrete mix	Mix Designation	Fiber content (%)	Fiber Length (mm)	Fiber diameter (μm)
M30	M0	0	-	-
	M1	0.1	6	13.5
	M2	0.2	6	13.5
	M3	0.3	6	13.5
	M4	0.4	6	13.5
	M5	0.1	13	13.5
	M6	0.2	13	13.5
	M7	0.3	13	13.5
	M8	0.4	13	13.5

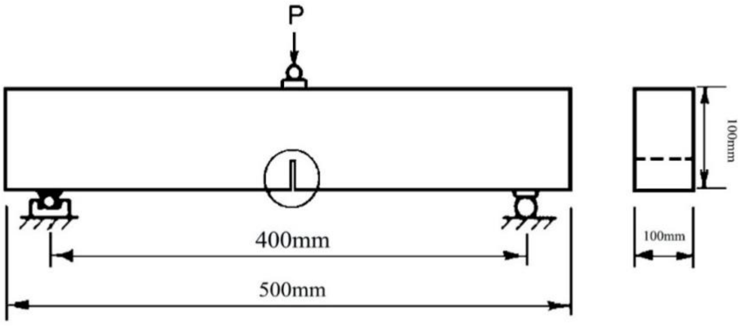

Fig. 2 Schematic diagram for single point loading test

GPC was adopted based on the procedure suggested by Rao *et al*. (2016) and is given in Table 2.

The mix details with fiber volume and length of fiber is shown in Table 3. The Mix 'M0' is a control mix without fibers.

2.2.2 Preparation of test specimens

Alkali resistant glass fibers were scattered in the binder (FA+GGBFS) and is mixed thoroughly to avoid formation of any lumps of fibers in the mix. Coarse aggregates and fine aggregates were mixed thoroughly for 2 minutes in a concrete mixer. Then binder, pre-mixed with fibers, was added to the aggregate mixture and continued to mix for another 3 minutes. Alkaline activator solution along with super plasticiser was added to this dry mixture, and mixed for about 5 minutes until homogeneity is achieved. After mixing, the concrete was filled in standard moulds in three layers, each layer was tamped 15 times with a tamping rod along with vibration to expel air voids. The moulds were demoulded after one day and cured under sunlight until day of testing. Notches of desired depth were cut in beam specimens by using a concrete cutter, one day before testing.

2.3 Test methods

Non-destructive testing viz. rebound hammer test and ultra-sonic pulse velocity (UPV) test were carried out on cube specimens before they were tested for compressive strength. In order to determine fracture parameters of glass fiber reinforced geopolymer concrete (GFRGPC) specimens, single point loading test on notched beam specimens was carried out on dynamic compression testing machine of 1000 kN capacity. The test was conducted under displacement control with the rate of loading kept constant at 0.2 mm/minute. During testing, CMOD was recorded using LVDT. Fracture energy was calculated as per RILEM recommendations. Schematic diagram for single point loading test on notched beams is shown in Fig. 2 and actual test setup is shown in Fig. 3. In addition to fracture parameters, compression strength test was carried out on 100×100×100 mm cube specimens, flexural strength test (two point loading test) was performed on 100×100×500 mm beam specimens as per IS 516:1959 and split tensile strength test was carried out on 100×200 mm cylindrical specimens as per IS 5816:1999.

The total fracture energy (GF) of the specimen is calculated as per RILEM TC50-FMC as

$$G_F = \frac{W_F}{b(d - a_0)} \tag{1}$$

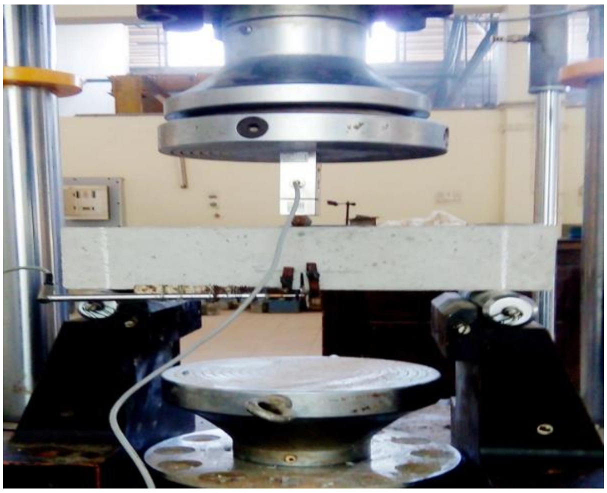

Fig. 3 Actual test setup for single point loading test

Where,
W_F=area under load-central displacement graph
b=beam width
d=beam depth
a_0=notch depth
Critical stress intensity factor (K_{Ic}) is calculated as

$$K_{Ic} = \frac{PS}{bd^{3/2}} \times f(\alpha) \tag{2}$$

$f(\alpha)$ is given by Eq. (3)

$$f(\alpha) = \frac{3\alpha^{1/2}[(1.99-\alpha)(1-\alpha)(2.15-3.93\alpha+2.7\alpha^2)]}{2(1+2\alpha)(1-\alpha)^{3/2}} \tag{3}$$

Where,
$\alpha=a_0/d$ (notch depth ratio)
P=peak load
S=distance between support points
b=beam width
d=beam depth

3. Results and discussions

3.1 Non-destructive test results

Rebound hammer test and ultra-sonic pulse velocity test were carried out on cube specimens and the results are tabulated in Table 4. The results reported are the average of 6 readings. GPC shows relatively lower rebound hammer values than cement concrete mix due to the presence of

Table 4 Non-destructive test results

Mix ID	Length of fibers (mm)	Volume fraction of fibers (%)	Rebound hammer value	UPV value (km/sec)
M0	-	-	25.5	2.412
M1	6	0.1	25.2	2.908
M2	6	0.2	22.6	3.141
M3	6	0.3	24.4	2.933
M4	6	0.4	23.8	2.653
M5	13	0.1	25.3	2.793
M6	13	0.2	24.7	3.125
M7	13	0.3	23.2	2.947
M8	13	0.4	24.1	2.596

Table 5 Compression test on cube specimens

Mix ID	Fiber length (mm)	Fiber volume fraction (%)	SP dosage (%)	Compressive strength (MPa)	Slump value (mm)
M0	-	-	4	30.7	185
M1	6	0.1	5.5	31.1	155
M2	6	0.2	6	30.9	135
M3	6	0.3	7	31.7	110
M4	6	0.4	9	31.5	95
M5	13	0.1	5.5	30.9	155
M6	13	0.2	6	31.1	110
M7	13	0.3	7	31.0	95
M8	13	0.4	9	28.7	80

more surface pores. Rebound hammer values are almost similar irrespective of length and volume fraction of fibers. UPV values increased with increase in volume of fibers up to a fiber volume of 0.2% and thereafter it decreased. UPV values indicate that the presence of fibers increased the homogeneity of GFRGPC mix.

3.2 Compressive strength

The cube specimens were tested under uniaxial compression and the results are shown in Table 5. The dosage of super plasticizer indicated in the table is with respect to the weight of the binder. The mix “M0” is the control mix (without fibers) and has a compressive strength of 30 MPa. The addition of fibers to control mix in different volume fractions doesn’t have any significant effect on the compressive strength. The addition of fibers reduced the workability and superplasticizer was added to obtain a workable GPC mix. With increase in volume fraction of fibers, super plasticizer dosage was increased to obtain medium workability (>75 mm slump). However the dosage of super plasticizer was kept constant for same volume fraction of fibers of 6 mm and 13 mm length and the slump values were compared. The result shows that the mix with 13 mm glass fibers was less workable than that with 6 mm fibers. Due to its high aspect ratio, 13 mm fibers offer greater resistance to the flow of concrete.

Table 6 Indirect tensile strength test results

Mix ID	Flexural strength (MPa)	Split tensile strength (MPa)	% increase in flexural strength	% increase in split tensile strength
M0	2.154	2.046	-	-
M1	2.170	2.186	0.74	6.84
M2	2.848	2.274	32.22	11.14
M3	3.282	2.692	52.37	31.57
M4	3.003	2.550	39.42	24.63
M5	2.816	2.797	30.73	36.71
M6	3.024	2.879	40.39	40.71
M7	3.383	3.018	57.06	47.51
M8	3.132	2.872	45.40	40.37

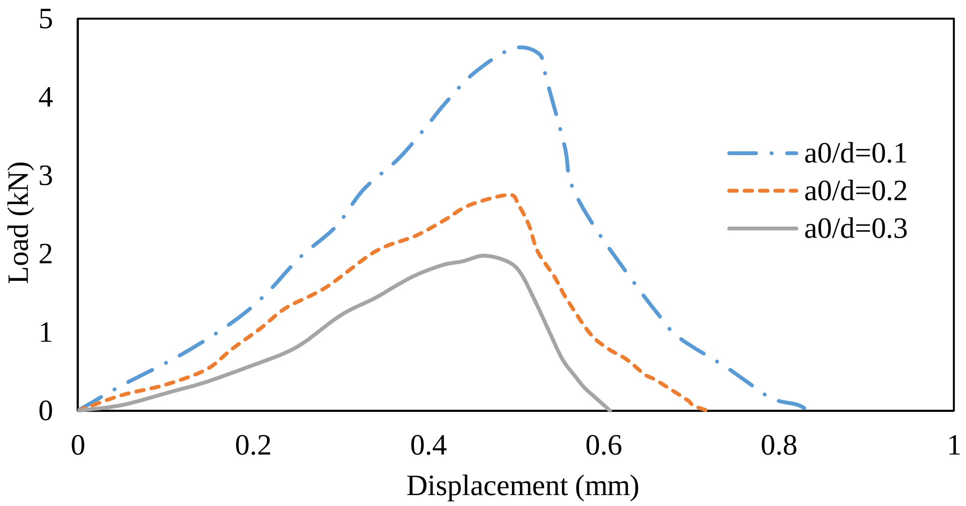

Fig. 4 Load-displacement graph for M0 mix (control mix)

3.3 Indirect tensile strength

Flexural strength and split tensile strength results are tabulated in Table 6 along with the percentage increase in strength with respect to control mix. Flexural strength and split tensile strength is seen to increase with increase in volume fraction of fibers and is maximum at 0.3%. At 0.3% addition of glass fibers, split tensile strength increased by 31.6% and 47.5%, while increase in flexural strength was 52.4% and 57% for 6 mm fibers and 13 mm fibers respectively. Further increase in volume fraction of fibers in the mix tends to reduce these properties. This is due to the reduction in homogeneity of concrete mix at higher volume fraction of fibers. Balling of fibers will occur at very high volume fraction of fibers, resulting in the formation of voids in concrete. The result shows that GFRGPC mix with 13 mm fibers have higher flexural strength and split tensile strength than that with 6 mm fibers irrespective of fiber volume fraction. 13 mm fibers holds/binds the concrete more effectively than 6 mm fibers due to its larger length and is better in crack arresting.

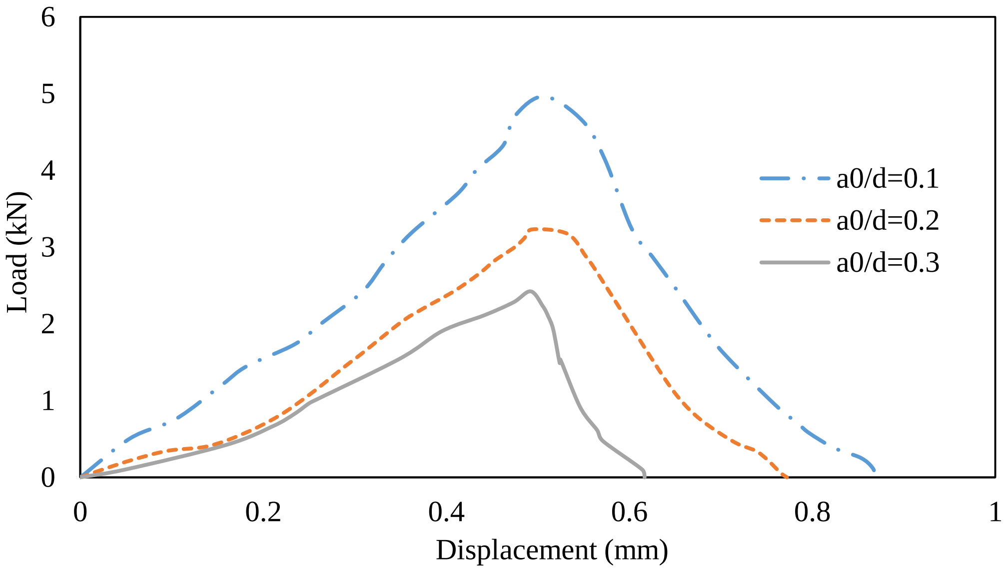

Fig. 5 Load-displacement graph for M1 mix (6 mm-0.1% vf)

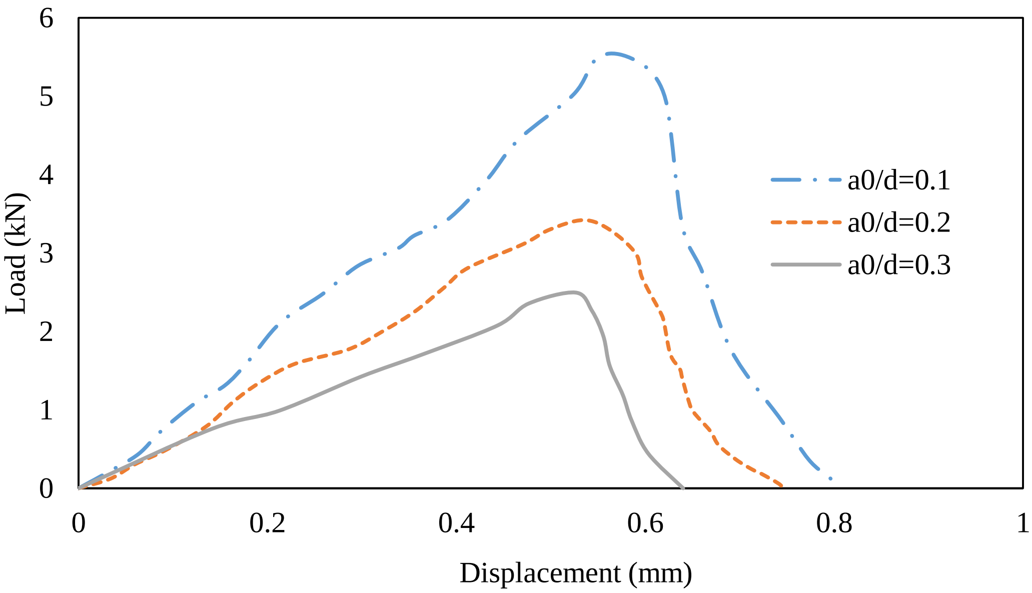

Fig. 6 Load-displacement graph for M2 mix (6 mm-0.2% vf)

3.4 Fracture properties

3.4.1 Fracture energy and critical stress intensity factor

Fracture energy for all the mixes were calculated as per RILEM recommendations and the stress intensity factor was calculated from peak loads obtained from single point loading test on

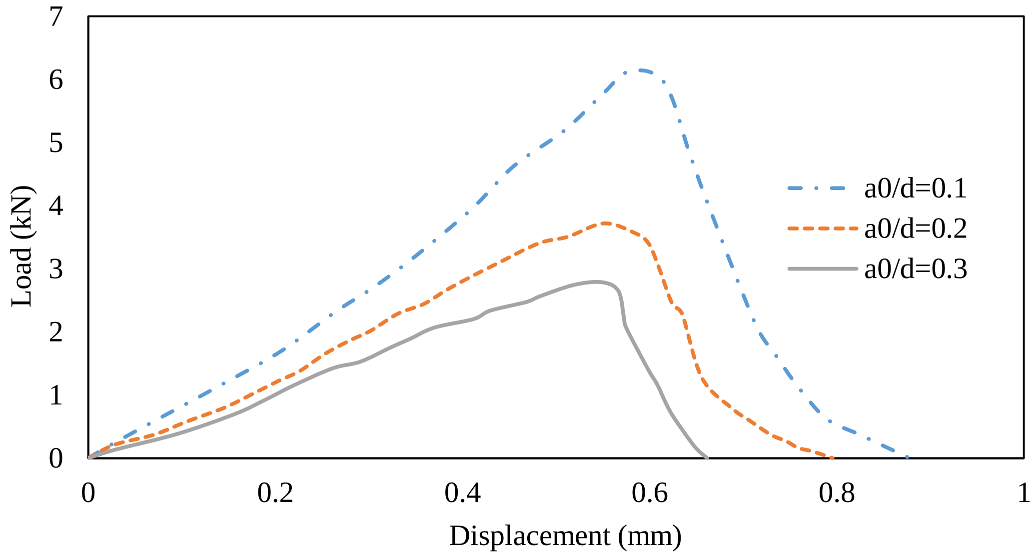

Fig. 7 Load-displacement graph for M3 mix (6 mm-0.3% vf)

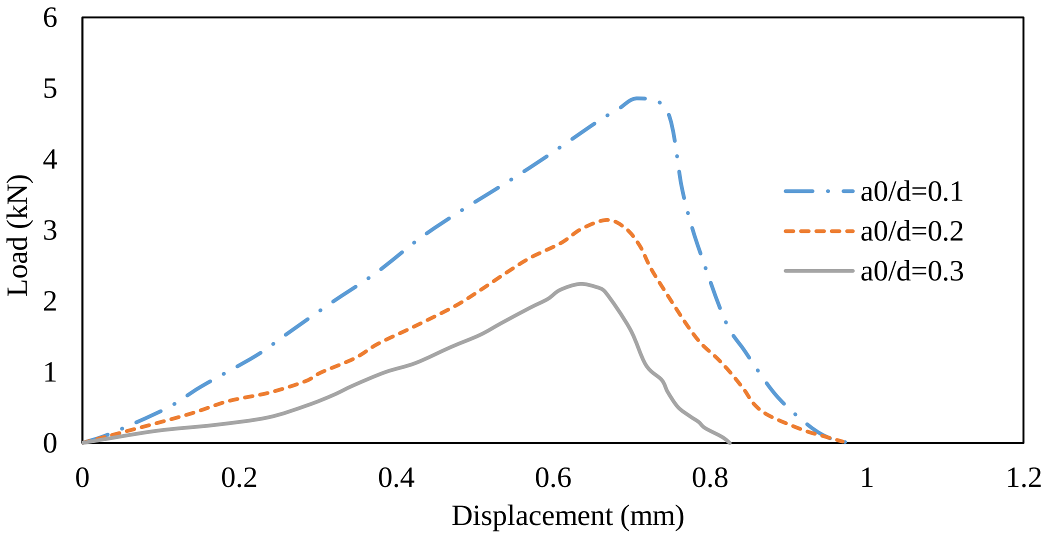

Fig. 8 Load-displacement graph for M4 mix (6 mm-0.4% vf)

notched beam specimens. Figs. 4-12 shows the ‘load’ versus ‘displacement’ graphs obtained from single point loading test conducted on GFRGPC beam specimens of different notch depth ratios.

From Figs. 4-12, it is evident that by increasing the volume fraction of fibers, the displacement corresponding to maximum load increases, which indicates that the addition of fibers impart ductility to the concrete. This effect is observed for all notch-depth ratios. By increasing the notch-depth ratio, the peak load carried by the beams decreases due to the decrease in effective depth at notch.

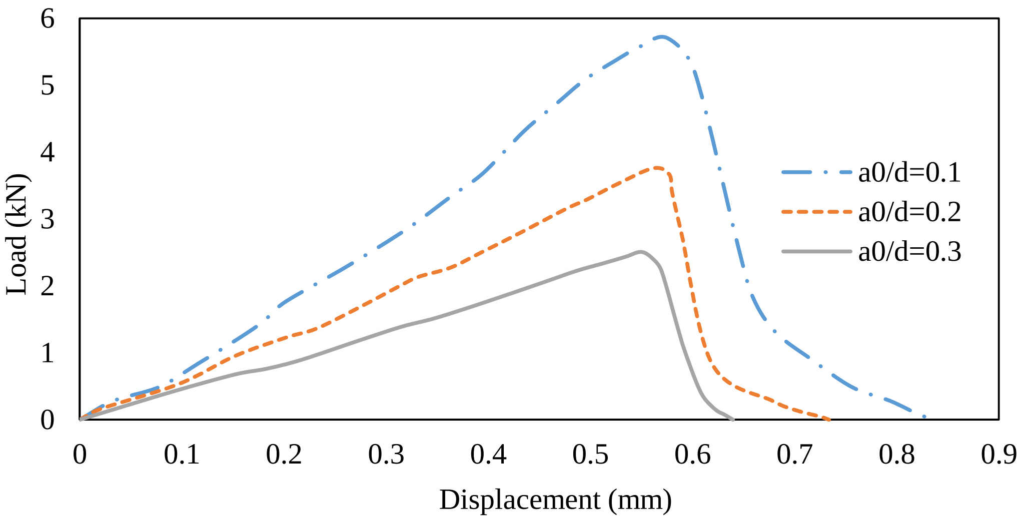

Fig. 9 Load-displacement graph for M5 mix (13 mm-0.1% vf)

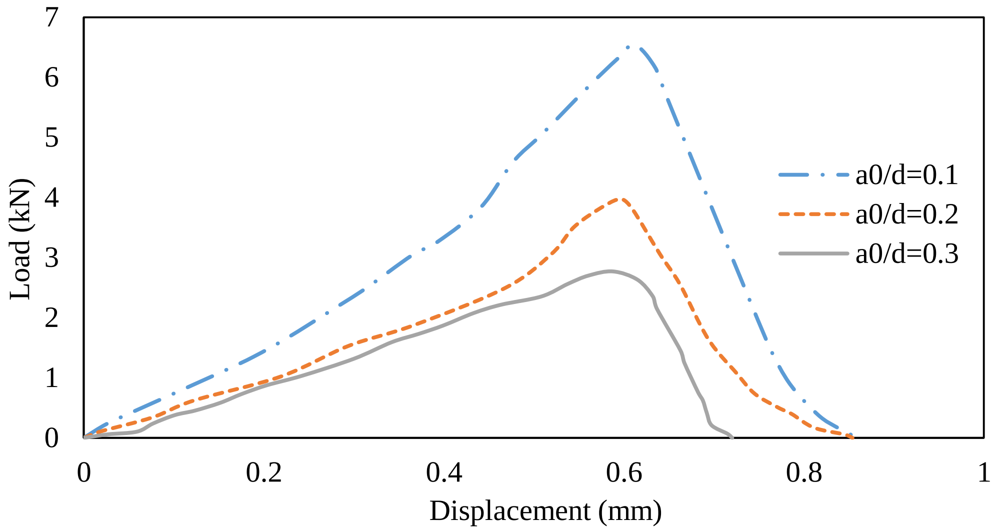

Fig. 10 Load-displacement graph for M6 mix (13 mm-0.2% vf)

The fracture energy required for the propagation of crack of unit length is more for a mix with 13 mm fibers than for a mix with 6 mm fibers, for all notch-depth ratios. Owing to its length, 13 mm fibers are better in crack arresting than 6 mm fibers, which resulted in this trend.

The variation of fracture energy and critical stress intensity factor with fiber volume fraction is shown in Figs. 13-16. G_F and K_{Ic} increases with increase in fiber volume fraction up to 0.3% addition of fibers, irrespective of length of the fibers and notch depth ratios. For a volume fraction of 0.3%, fracture energy has increased by 46.7%. 56.6%, 67.6% for notch depth ratios of 0.1, 0.2, and 0.3 respectively for GPC mix with 6 mm fibers, while the percentage increase in G_F for GPC mix with 13 mm fibers were 63.7%, 64.9%, 97.8% respectively. Similarly, for a volume fraction

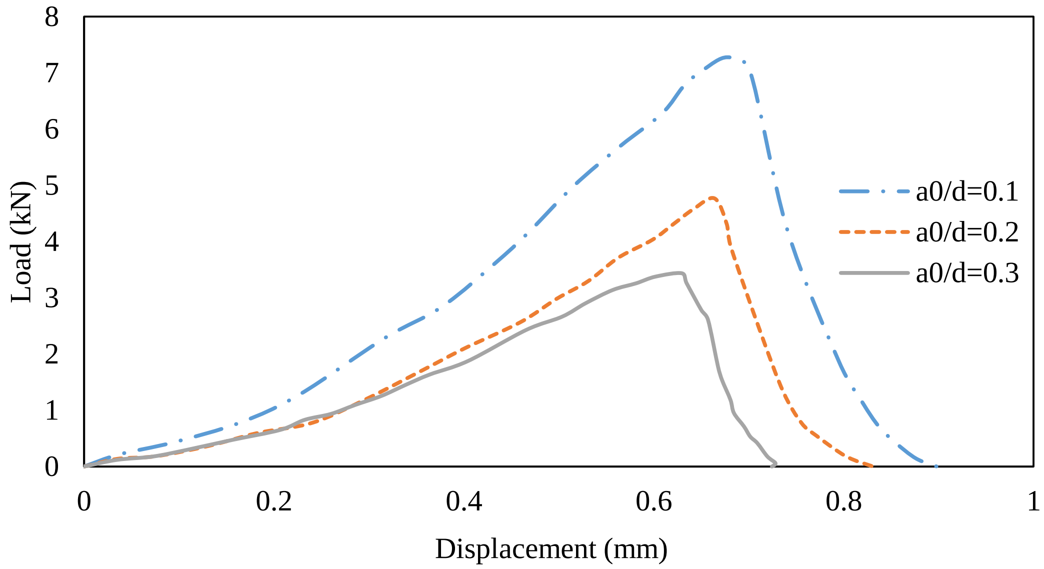

Fig. 11 Load-displacement graph for M7 mix (13 mm-0.3% vf)

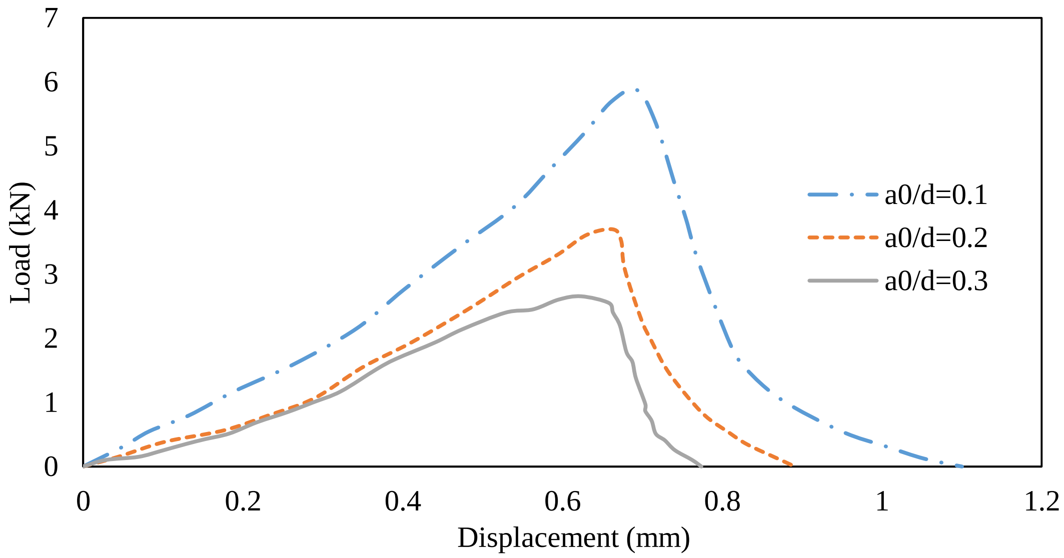

Fig. 12 Load-displacement graph for M8 mix (13 mm-0.4% vf)

of 0.3%, critical stress intensity factor has increased by 32.6%, 35%, 41% for GPC mix with 6 mm fibers and 57.4%, 73.1%, 73.8% for GPC mix with 13 mm fibers for notch depth ratios of 0.1, 0.2, and 0.3 respectively. GPC mix with 13 mm fibers have shown higher fracture energy and stress intensity factor than that with 6 mm fibers for all volume fraction of fibers and notch depths. The result shows that G_F and K_{Ic} decreases with increase in notch depth ratio irrespective of fiber volume fraction.

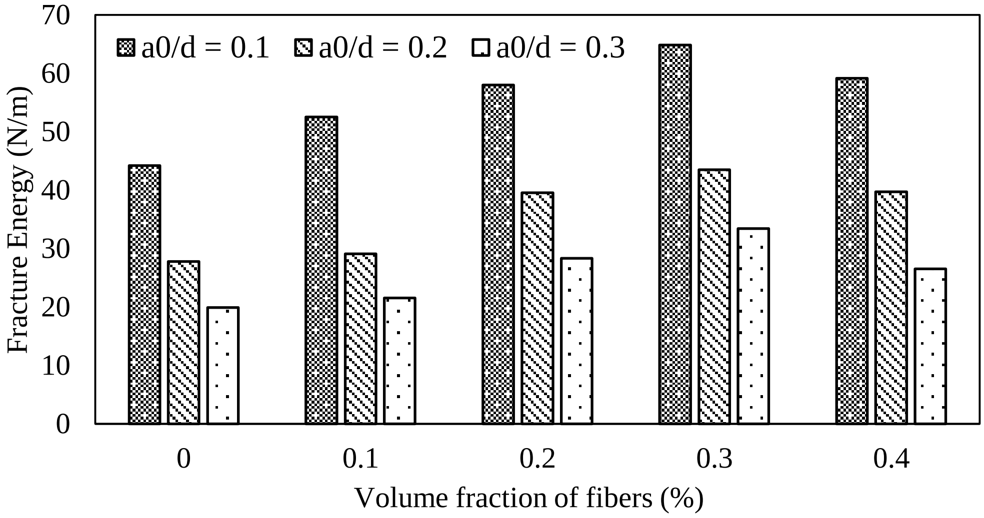

Fig. 13 Variation of G_F for different notch depth ratios for 6 mm fibers

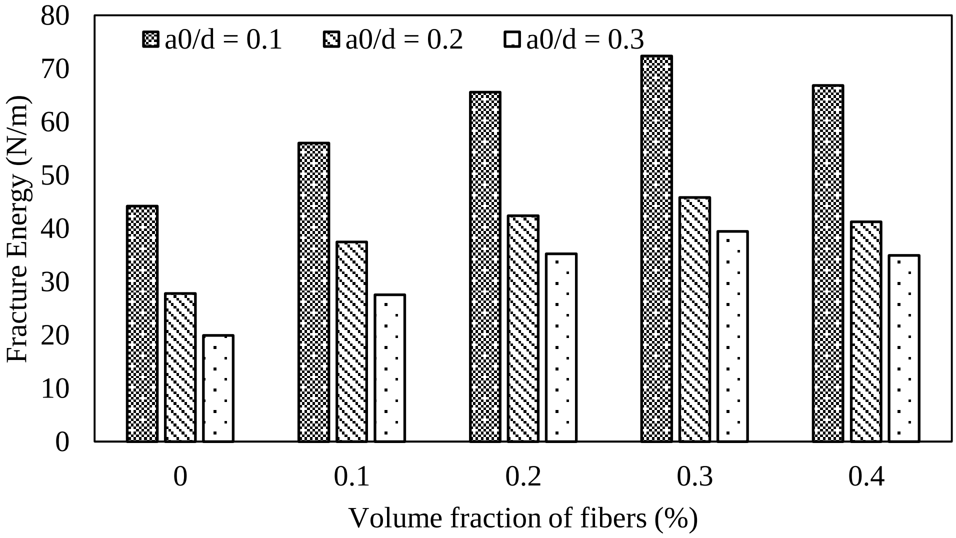

Fig. 14 Variation of G_F for different notch depth ratios for 13 mm fibers

3.4.2 Critical CMOD

During single point loading test on notched GFRGPC beam specimens, crack mouth opening displacement was measured by using LVDT. Critical CMOD at peak load for all the mixes were compared as shown in Figs. 17-18.

The results clearly show that critical CMOD increases with increase in fiber content, irrespective of notch depth ratio. Also, critical CMOD increases with increase in notch depth ratio for all volume fractions of fibers. The increase in critical CMOD for GPC mix with 6 mm fibers with volume fraction 0.4% were 109.48%, 88.53%, 69.63% respectively for a_0/d ratios of 0.1, 0.2, 0.3. In the same way, the increase in critical CMOD for GPC mix with 13 mm fibers with volume

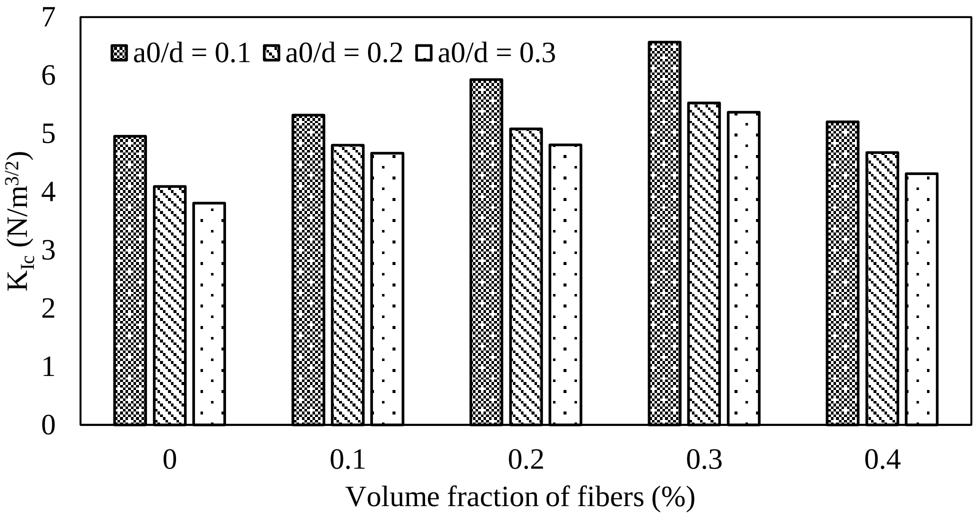

Fig. 15 Variation of critical stress intensity factor with fiber volume for 6 mm fibers

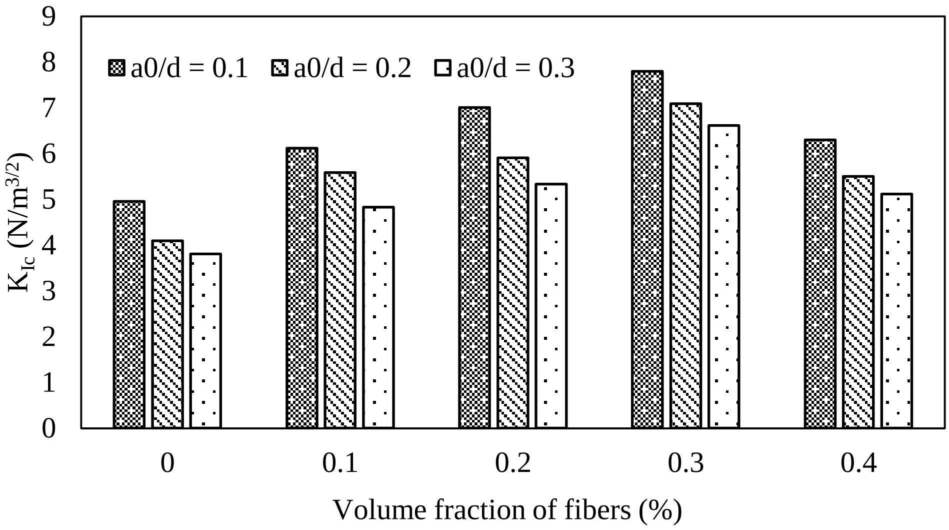

Fig. 16 Variation of critical stress intensity factor with fiber volume for 13 mm fibers

fraction 0.4% were 116.81%, 96.93%, 80.31% respectively for a_0/d ratios of 0.1, 0.2, 0.3. The result shows that GPC mix with 13 mm fibers have higher critical CMOD than that with 6 mm fibers which indicates that 13 mm fibers are more effective in improving the ductile behaviour of GFRGPC.

5. Conclusions

Based on the experimental study conducted on GFRGPC specimens, the following conclusions

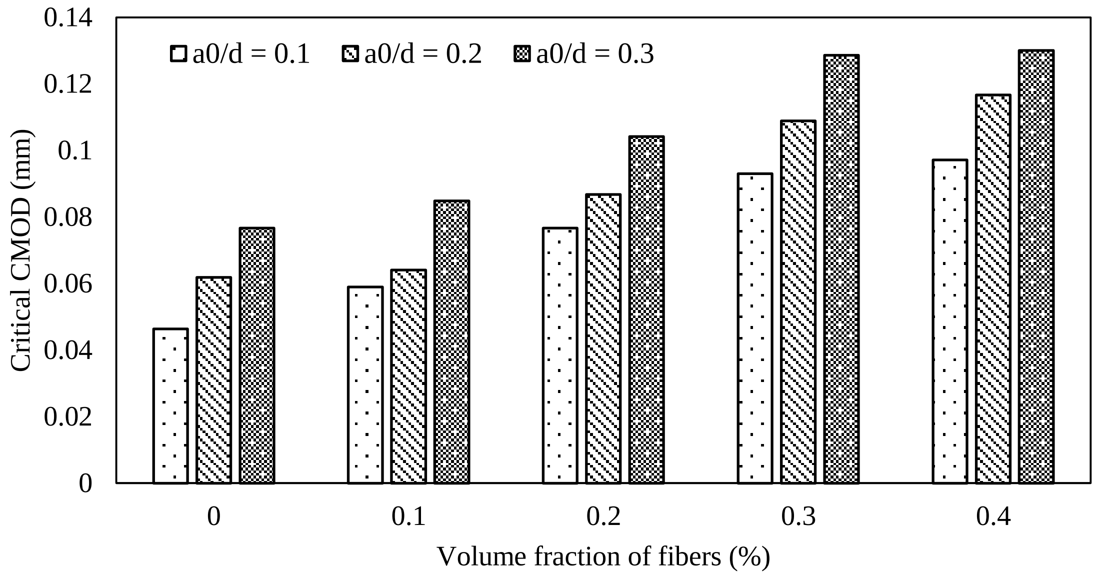

Fig. 17 Variation of critical CMOD with volume fraction of fibers for 6 mm fibers

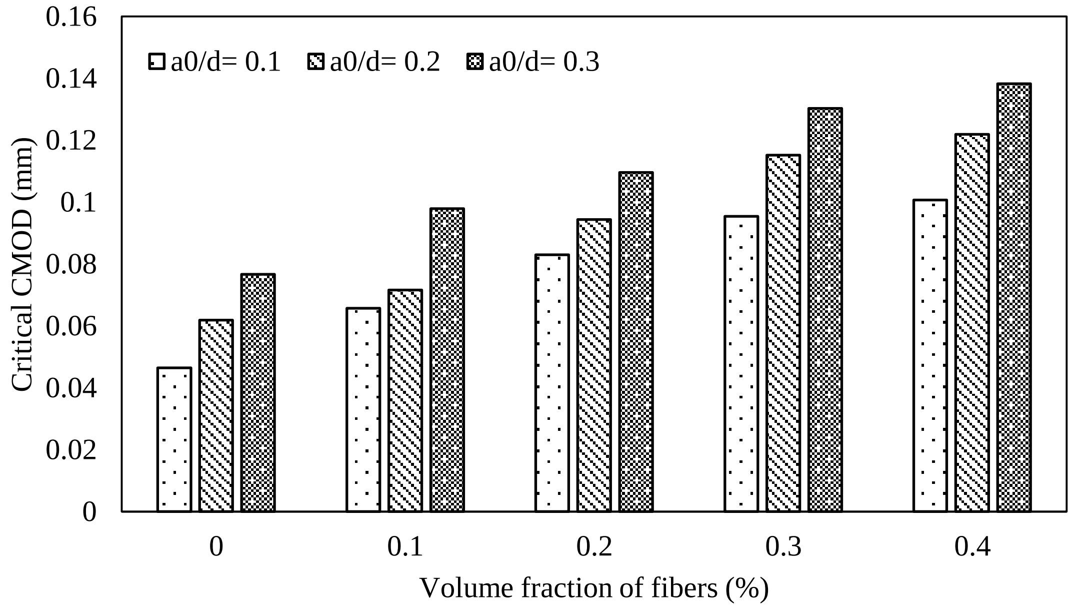

Fig. 18 Variation of critical CMOD with volume fraction of fibers for 13 mm fibers

were drawn:

- Addition of glass fibers to geopolymer concrete improved the fracture parameters viz. fracture energy, critical stress intensity factor and critical CMOD.
- The presence of glass fibers improved the flexural and split tensile strength of geopolymer concrete.

- Optimum dosage of glass fibers was found to be 0.3% (by volume of concrete) in improving fracture and flexural properties.
- 13 mm fibers are more effective in improving flexural strength, split tensile strength and fracture properties of geopolymer concrete than 6mm fibers.
- Geopolymer concrete reinforced with glass fibers exhibit better mechanical performance than control mix which shows that GFRGPC is an optimal alternative for applications in conditions where higher flexural strength and crack resistance is required.

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