Hindawi Publishing Corporation
Indian Journal of Materials Science
Volume 2013, Article ID 357563, 8 pages
http://dx.doi.org/10.1155/2013/357563

Research Article

Effect of Steel Fibres and Low Calcium Fly Ash on Mechanical and Elastic Properties of Geopolymer Concrete Composites

Atteshamuddin S. Sayyad and Subhash V. Patankar

Department of Civil Engineering, SRES's College of Engineering, Kopargaon, Maharashtra 423601, India

Correspondence should be addressed to Atteshamuddin S. Sayyad; attu_sayyad@yahoo.co.in

Received 17 August 2013; Accepted 7 November 2013

Academic Editors: D. Gomez-Garcia, F. M. Morales, A. Simar, and S. Thomas

Effect of steel fibres and low calcium fly ash on mechanical and elastic properties of geopolymer concrete composites (GPCC) has been presented. The study analyses the impact of steel fibres and low calcium fly ash on the compressive, flexural, split-tensile, and bond strengths of hardened GPCC. Geopolymer concrete mixes were prepared using low calcium fly ash and activated by alkaline solutions (NaOH and Na_2SiO_3) with solution to fly ash ratio of 0.35. Crimped steel fibres having aspect ratio of 50 with volume fraction of 0.0% to 0.5% at an interval of 0.1% by mass of normal geopolymer concrete are used. The entire tests were carried out according to test procedures given by the Indian standards wherever applicable. The inclusion of steel fibre showed the excellent improvement in the mechanical properties of fly ash based geopolymer concrete. Elastic properties of geopolymer concrete composites are also determined by various methods available in the literature and compared with each other.

1. Introduction

Plain cement concrete suffers from numerous drawbacks such as low tensile strength, brittleness, unstable crack propagation, and low fracture resistance. Addition of steel fibres in plain cement concrete improves its mechanical and elastic properties. Hence, steel fibre reinforced concrete has been proved as a reliable and promising composite construction material having superior performance characteristics compared to conventional concrete.

The rate of production of carbon dioxide released to the atmosphere is increasing due to the increased use of Portland cement in the construction. Each ton of Portland cement releases a ton of carbon dioxide into the atmosphere. The greenhouse gas emission from the production of Portland cement is about 1.35 billion tons annually, which is about 7% of the total greenhouse gas emissions. On the other side, fly ash is the waste material of coal based thermal power plant available abundantly but this poses disposal problem. Several hectares of valuable land are acquired by thermal power plants for the disposal of fly ash. With silicon and aluminium as the main constituents, fly ash has great potential as a cement replacing material in concrete. The concrete made with such industrial wastes is eco-friendly. Although the use of Portland cement is still unavoidable, many efforts are being made in order to reduce the use of Portland cement in concrete. Davidovits [2] have invented a new technology called geopolymer, in which cement is totally replaced by fly ash (Pozzolanic material) and activated by alkaline solution. It is found that geopolymerisation can make a profitable contribution towards recycling and utilization of waste materials such as fly ash. This technology is, however, still fairly unknown and predictably viewed with skepticism by most workers in the field of traditional waste processing techniques [2–4].

Chindaprasirt et al. [5] studied the workability and strength of coarse high calcium fly ash geopolymer concrete. Rangan [6] have proposed the mix design procedure for production of fly ash based geopolymer concrete, whereas Anuradha et al. [7] have presented modified guidelines for mix design of geopolymer concrete using Indian standard. Patankar et al. [8] studied the effect of sodium hydroxide on flow and strength of fly ash based geopolymer mortar. Theory and applications about the potential use of geopolymeric

Table 1: Chemical composition of fly ash.

Chemical composition	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	CaO	Total chlorides	Loss of ignition
Percentage (%)	77.10	17.71	1.21	0.90	2.20	0.80	0.62	0.03	0.87

materials to immoblise toxic metals have been presented by Van Jaarsveld et al. [9]. Effect of recycled concrete aggregate on various strengths of geopolymer concrete has been studied by Anuar et al. [10]. Alonso and Palomo [11] have used metakolin as a substitute for the fly ash to study the effect of temperature and activator concentration on geopolymer concrete. Sumajouw et al. [12] have carried out a study on slender reinforced columns using fly ash-based geopolymer concrete. Bakharev [13] studied the resistance of geopolymer material to acid attack, whereas Pernica et al. [14] studied the effect of test condition on the bending strength of a geopolymer reinforced composite. Vijai et al. [15–17] has studied effect of glass fibres and steel fibres on various strengths of geopolymer concrete. Sathish Kumar et al. [18] also studied the properties of glass fibre reinforced geopolymer concrete. Bhowmick and Ghosh [19] studied the effect of synthesizing parameters on workability and compressive strength of fly ash based geopolymer mortar. Ghugal and Bhalchandra [20] studied the effect of steel fibre on mechanical and elastic properties of high strength silica fume concrete.

In the present study, an experimental investigation on mechanical and elastic properties of low calcium fly ash based GPCC has been carried out. Geopolymer concrete mixes were prepared with solution to fly ash ratio of 0.35. Crimped steel fibres having aspect ratio of 50 are used.

2. Experimental Programme

Experimental work is designed to study the effect of steel fibres on mechanical and elastic properties on geopolymer concrete. The materials used for making fly ash geopolymer concrete composite specimens are low-calcium fly ash, course and fine aggregates, steel fibres, alkaline solution, and water.

2.1. Fly Ash. Fly ash is the residue from the combustion of pulverized coal collected by mechanical or electrostatic separators from the flue gases of thermal power plants. One of the important characteristics of fly ash is the spherical form of the particles. This shape of particle improves the flow ability and reduces the water demand. In this experimental work, the fly ash used is obtained from the silos of Eklahare Thermal Power Station, Nasik, Maharashtra, India, which is of low calcium, Class F (American Society for Testing and Materials). The fly ash which contains less than 10% calcium oxide is called Class F or low calcium fly ash. It is mainly pozzolanic and reacts with calcium hydroxide formed during the hydration process in moist condition to produce cementitious compounds when used with cement. Low calcium fly ash makes substantial contributions to the workability, chemical resistance, and reduction in thermal cracking. Table 1 shows the chemical composition of fly ash used for the experimental investigation.

Table 2: Chemical composition of sodium hydroxide and sodium silicate.

Chemical composition			
Sodium hydroxide	Percentage (%)	Sodium silicate	Percentage (%)
Sodium hydroxide (min. assay)	97	Na_2O	16.37
Carbonate	2	SiO_2	34.31
Chloride	0.01	Total solid	50.68
Sulphate	0.05	Water content	49.32
Potassium	0.1	—	
Silicate	0.05	—	
Zinc	0.02	—	

Table 3: Properties of aggregates.

Physical properties	Coarse aggregate (CA)		Fine aggregate (FA)
	CA-I	CA-II	
Type	Crushed	Crushed	River sand
Maximum size	20 mm	12.5 mm	4.75 mm
Specific gravity	2.641	2.639	2.563
Water absorption	0.59%	0.82%	1.56%
Moisture content	Nil	Nil	Nil

2.2. Alkaline Solution. The laboratory grade sodium hydroxide (NaOH) in flake form and sodium silicate (Na_2SiO_3) solution were used as alkaline activators. The chemical compositions of both activators are given in Table 2. Concentration of NaOH is fixed at 13 M as per a previous research [8].

2.3. Aggregates. Locally available river sand is used as a fine aggregate (FA) and crushed basalt stones of nominal maximum size of 20 mm and 12.5 mm are used as coarse aggregates (CA). The physical properties of CA and FA are shown in Table 3 whereas Table 4 shows grading of CA.

2.4. Steel Fibres. Crimped steel fibres with aspect ratio (L_f/h_f) 50 is used with modulus of elasticity (E) of 210 GPa.

2.5. Mix Proportion of Geopolymer Concrete. Fly ash, coarse aggregates, fine aggregate, and steel fibres are initially mixed together in dry state and then the liquid component of the mixture is added to prepare wet mix until it gives homogeneous mix. Mix proportion and fibre quantity of geopolymer concrete per cubic meter are given in Tables 5 and 6 respectively.

Table 4: Grading of course aggregates.

Serial number	IS Sieve size (mm)	CA-I 20 mm	CA-II 12.5 mm	CA-I : CA-II 65 : 35	Required grading as per IS 383-1970
1	40	100	100	100	100
2	25	100	100	100	—
3	20	90.60	100	93.89	90–100
4	16	6.80	100	39.42	—
5	12.5	0.40	96.5	34.04	—
6	10	0.00	76.4	26.74	25–35
7	4.75	0.00	0.90	0.32	0–10
8	2.36	0.00	0.00	0.00	—

Table 5: Mix proportion of geopolymer concrete per cubic meter.

Fly ash	NaOH	Na_2SiO_3	FA	CA	Extra water
300	52.5	52.5	722.24	1341.30	61.46
1	0.175	0.175	2.40	4.4771	0.20

Table 6: Quantity of fibres for various mixes.

Steel fibre (%)	0.0	0.1	0.2	0.3	0.4	0.5
Fibre quantity (kg/m^3)	0.0	2.53	5.06	7.59	10.12	12.65

3. Test Results

The workability of fresh geopolymer concrete is measured by flow table apparatus as per IS: 1199–1959. After making the homogeneous mix, concrete was placed in two layers; each layer should be compacted 20 times with the tamping rod and then level the top surface. Lift the mould away from the concrete one minute after completing the mixing operation. Then apply fifteen jolting and measure the average diameter of subside concrete at minimum six equal intervals expressed as a percentage of the original base diameter. Examination of Table 7 indicates that the workability of geopolymer concrete including steel fibre reduces with increases in fibre content. It might be due to viscous nature of geopolymer concrete and uneven distribution of fibres in the mix. The maximum decrease in flow is 22.72% at 0.5% of fibre content. Wet and dry densities were recorded throughout the experimental program and the average values for densities are listed for various volume fractions of fibres. Table 7 shows that inclusion of fibres increases the density of concrete due to good particle packing and reduction in air content. The maximum increase in wet density is 2.98%, whereas it is 3.13% in case of dry density.

3.1. Discussion on Mechanical Properties. The tests on hardened geopolymer concrete composites are carried out according to the relevant standards wherever applicable. New expressions for mechanical properties of GPCC are proposed in this investigation. Comparison of various strengths obtained using experimental work is presented in Table 8. Compressive strength is determined by carrying out compressive strength test on cubes of sizes 150 mm × 150 mm × 150 mm. The compressive strength of specimen is calculated by

$$f_{\text{cu}} = \frac{P_c}{A}. \quad (1)$$

The compressive strength of concrete increases with respect to fibre content up to 0.2% and then it decreases because higher percentage of fibre content reduces the workability of GPCC. The maximum increase in compressive strength of GPCC is 29.98% over that of normal geopolymer concrete. Expression for compressive strength in the third degree polynomial in terms of V_f is given by the following equation:

$$f_{\text{cu}} = 371.48V_f^3 - 361.58V_f^2 + 96.695V_f + 28.593. \quad (2)$$

Flexural test is carried out on beams of size 100 mm × 100 mm × 500 mm with two-point loads applied at the middle third of the span. The flexural strength is obtained by using

$$f_{\text{cr}} = \frac{PL}{bd^2}. \quad (3)$$

From Table 8, it is observed that the maximum increase in flexural strength is 30.0% with 0.2% of fibre content over that of normal geopolymer concrete. Expression for flexural strength in the third degree polynomial in terms of V_f is given by the following equation:

$$f_{\text{cr}} = 26.204V_f^3 - 31.742V_f^2 + 9.5717V_f + 3.1575. \quad (4)$$

Cylinders of size 100 mm diameter and 300 mm length are used to obtain split-tensile strength. The split-tensile strength is obtained by using

$$f_{\text{cr}} = \frac{2P}{\pi dL}. \quad (5)$$

The maximum increase in split-tensile strength is 30.05% with 0.2% of fibre content over that of normal geopolymer concrete. Expression for split-tensile strength in the third degree polynomial in terms of V_f is given by the following equation:

$$f_{\text{cys}} = 28.056V_f^3 - 33.702V_f^2 + 10.1117V_f + 3.316. \quad (6)$$

Table 7: Workability, wet density, and dry density of GPCC Mixes.

V_f (%)	Flow (mm)	Decrease in flow (%)	Degree of workability	Density (kg/m^3)		Increase in density (%)	
				Wet	Dry	Wet	Dry
0.0	62.93	0.00	High	2583	2453	0.0	0.0
0.1	60.40	4.02	High	2592	2460	0.34	0.28
0.2	57.33	8.89	High	2616	2479	1.27	1.05
0.3	54.13	13.98	High	2634	2505	1.97	2.11
0.4	51.73	17.79	High	2641	2515	2.24	2.52
0.5	48.40	22.72	Medium	2660	2530	2.98	3.13

Table 8: Comparison of compressive strength (f_{cu}), flexural strength (f_{cr}), split-tensile strength (f_{cys}), and bond strength (f_{bd}) for various percentages of steel fibres (V_f).

V_f	Strengths (MPa)				Percentage increase in strength			
	f_{cu}	f_{cr}	f_{cys}	f_{bd}	f_{cu}	f_{cr}	f_{cys}	f_{bd}
0.0	28.89	3.20	3.36	12.10	0.00	0.00	0.00	0.00
0.1	33.55	3.68	3.87	12.82	16.13	15.00	15.17	5.95
0.2	37.55	4.16	4.37	14.05	29.98	30.00	30.05	16.11
0.3	33.11	3.87	4.06	13.59	14.61	20.90	20.83	12.31
0.4	32.22	3.52	3.70	13.33	11.53	10.00	10.11	10.16
0.5	31.5	3.31	3.48	12.94	9.03	3.43	3.57	6.94

The bond strength test was carried out according to IS 2770 [21]. A 16 mm diameter deformed steel reinforcing bar was embedded into the concrete cube at centre up to depth of 150 mm. The total length of bar is 600 mm. All specimens are tested up to failure of bar matrix interfacial bond. The peak load at failure of bond and maximum slip is observed. All specimens failed with vertical crack along the embedded length of bar with cracking sound. The maximum increase in strength is 16.11% with 0.2% of fibre content over that of normal geopolymer concrete. The bond strength has been computed from the following expression:

$$f_{bd} = \frac{P}{\pi DL}. \tag{7}$$

Expression for bond strength in the third degree polynomial in terms of V_f is given by the following equation:

$$f_{bd} = 22.87V_f^3 - 37.706V_f^2 + 14.91V_f + 12.008. \tag{8}$$

Optimum fibre content for various strengths of geopolymer concrete is presented in Table 9. Figures 1, 2, 3, and 4 show the variation of various strengths of geopolymer concrete composites with the percentage of steel fibres. The comparison of various strengths of geopolymer concrete composites obtained using proposed empirical formulas is presented in Table 10.

3.2. Elastic Properties. Elastic properties such as modulus of elasticity, modulus of rigidity, and Poisson's ratio are the important parameters in the analysis of structures. These properties are obtained by various methods available in the literature.

Table 9: Optimum fibre content and maximum percentage increase in various strengths.

Strength	V_f	Maximum strength (MPa)	Percentage increase in strength (%)
f_{cu}	0.2	37.55	29.98
f_{cr}	0.2	4.16	30.00
f_{cys}	0.2	4.37	30.35
f_{bd}	0.2	14.05	16.11

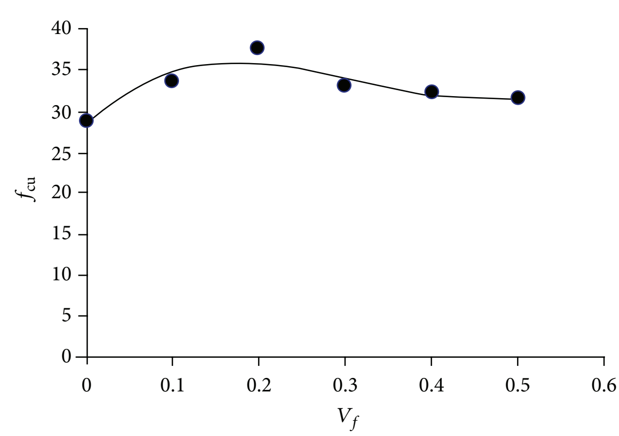

Figure 1: Variation of compressive strength (f_{cu}) with respect to percentage of steel fibres (V_f).

3.2.1. Modulus of Elasticity. The modulus of elasticity is obtained by various methods available in the literature as given below.

Table 10: Compressive strength (f_{cu}), flexural strength (f_{cr}), split-tensile strength (f_{cys}), and bond strength (f_{bd}) for various percentage of steel fibre (V_f) obtained using proposed equations.

V_f	Strength (MPa)				Percentage increase			
	f_{cu} Equation (2)	f_{cr} Equation (4)	f_{cys} Equation (6)	f_{bd} Equation (8)	f_{cu}	f_{cr}	f_{cys}	f_{bd}
0.0	28.59	3.15	3.32	12.00	0.00	0.00	0.00	0.00
0.1	34.71	3.82	4.01	13.14	20.35	21.26	20.78	9.50
0.2	35.83	4.01	4.21	13.66	25.32	27.30	26.80	13.83
0.3	34.18	3.87	4.07	13.70	19.55	22.85	22.59	14.16
0.4	31.98	3.58	3.76	13.40	11.85	13.65	13.25	11.66
0.5	31.47	3.32	3.45	12.98	10.07	5.39	3.91	8.16

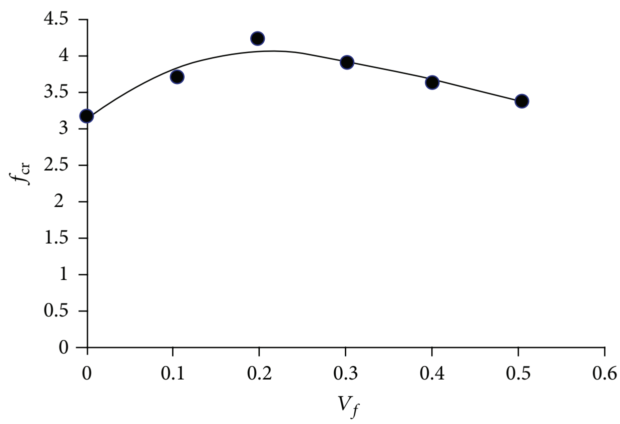

Figure 2: Variation of flexural strength (f_{cr}) with respect to percentage of steel fibres (V_f).

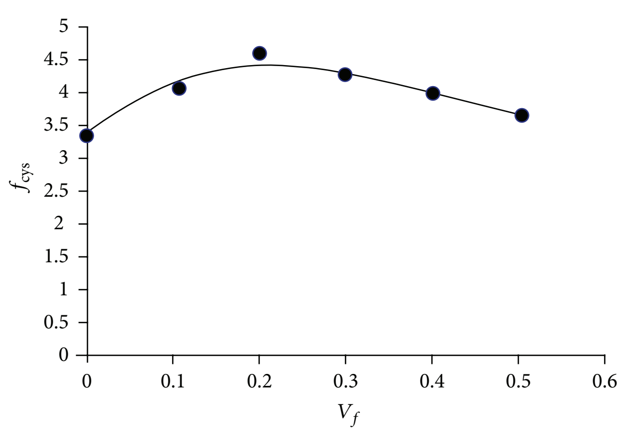

Figure 3: Variation of split-tensile strength (f_{cys}) with respect to percentage of steel fibres (V_f).

As per IS: 456 [22], the modulus of elasticity is calculated as

$$E_{fc} = 5\sqrt{f_{cu}}. \tag{9}$$

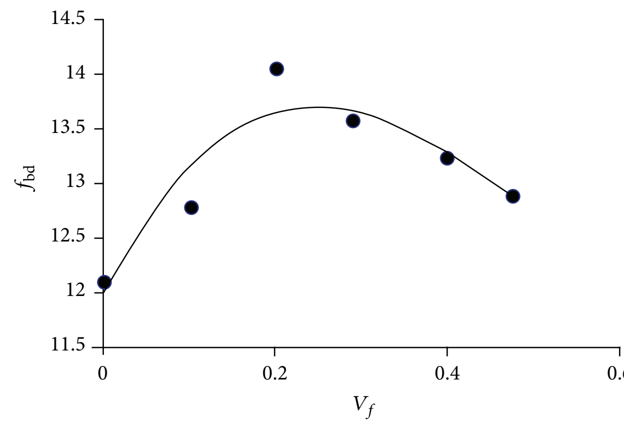

Figure 4: Variation of bond strength (f_{bd}) with respect to percentage of steel fibres (V_f).

Modulus of elasticity of fibre reinforced composites can be calculated using law of mixtures as suggested by Hannant [23] and Tan et al. [24] as

$$E_{fc} = \left(1 - \eta_1\eta_2V_f\right)E_m + \eta_1\eta_2V_fE_f, \tag{10}$$

where

η_1 = fibre orientation factor (1/6),

η_2 = efficiency factors (1/3),

V_f = fibre content (%),

E_m = modulus of elasticity of matrix (GPa) = $5\sqrt{f_{cu}}$,

E_f = modulus of elasticity of fibre (GPa) = 210.

The equation of modulus of elasticity in terms of compressive strength (f_{cu}) and specific gravity (γ) is also given by Kakizaki et al. [25] as

$$E_{fc} = 0.8\times10^5\left(\frac{\gamma}{2.3}\right)^{1.5}\sqrt{\frac{f_{cu}}{350}}, \tag{11}$$

where γ = specific gravity of concrete (dry density of composite/1000).

Table 11: Elastic properties of geopolymer concrete composites (GPCC).

V_f	Modulus of elasticity (E_{fc})				Poisson's ratio (μ)
	Equation (9)	Equation (10)	Equation (11)	Equation (12)	Equation (20)
0.0	26.874	36.931	26.516	26.046	0.1107
0.1	28.96	27.881	28.455	28.069	0.1096
0.2	30.63	32.603	29.300	29.690	0.1107
0.3	28.77	31.76	30.46	27.884	0.1168
0.4	28.38	32.37	27.986	30.050	0.1092
0.5	28.06	31.90	29.713	27.198	0.1050

Table 12: Modulus of elasticity and shear modulus using Halpin Tsai equations [1].

V_f	η_L Equation (15)	η_T Equation (16)	E_L (GPa) Equation (13)	E_T (GPa) Equation (14)	E_R (GPa) Equation (17)	G_R (GPa) Equation (18)	E_{fc} (GPa) Equation (19)
0.0	0.063	0.694	26.87	26.87	26.87	10.07	26.874
0.1	0.058	0.675	46.02	35.24	93.28	14.56	35.353
0.2	0.054	0.661	64.40	44.63	52.04	19.21	41.632
0.3	0.058	0.678	80.22	50.81	61.84	22.73	43.286
0.4	0.059	0.681	97.66	60.25	74.28	27.27	44.568
0.5	0.060	0.683	115.71	71.70	88.21	32.39	44.106

For average value of specific gravity, (11) leads to the following form:

$$E_{fc} = 4846\sqrt{f_{cu}}. \quad (12)$$

The modulus of elasticity obtained by using (9) through (12) is shown in Table 11. Halpin Tsai equations [1] based on micromechanics analysis can also be used to predict the elastic constants of fibre composites. The longitudinal (E_L) and transverse moduli (E_T) can be evaluated using following equations:

$$E_L = E_m \frac{1 + \left(2\lambda\eta_L V_f\right)}{1 - \eta_L V_f}, \quad (13)$$

$$E_T = E_m \frac{1 + \left(2\eta_T V_f\right)}{1 - \eta_T V_f}, \quad (14)$$

where

$$\eta_L = \frac{\left(E_f/E_m\right) - 1}{\left(E_f/E_m\right) + 2\lambda}, \quad (15)$$

$$\eta_T = \frac{\left(E_f/E_m\right) - 1}{\left(E_f/E_m\right) + 2}, \quad (16)$$

where λ is the aspect ratio of fibre (L_f/h_f) where L_f is the length of fibre and h_f is the thickness of fibre. Modulus of elasticity and shear modulus of randomly oriented fibre reinforced concrete can be predicted using the following relations:

$$E_R = \frac{1}{8}\left(3E_L + 5E_T\right), \quad (17)$$

$$G_R = \frac{1}{8}\left(E_L + 2E_T\right), \quad (18)$$

where E_L and E_T are, respectively, the longitudinal and transverse moduli of fibre composite having the same fibre aspect ratio and fibre volume fraction. The results obtained using (17) are modified according to (19) to have the similar trend with the other results and are presented in Table 12:

$$E_{fc} = \left(1 - V_f\right) E_R. \quad (19)$$

The behavior of geopolymer concrete is very complex. So, the modulus of elasticity calculated by various methods does not match with each other. But it is observed that the modulus of elasticity increases with incorporation of steel fibres up to 0.2% by volume and then decreases with increase in fibre content but higher than plain geopolymer concrete. This means that fibre improves the elastic behavior of geopolymer concrete which is more brittle than cement concrete.

3.2.2. Poisson's Ratio. The Poisson's ratio (μ) is determined according to Ghugal [26] using strength of material theory based on flexural strength and compressive strength and is given by the following relation:

$$\mu = \frac{f_{cr}}{f_{cu}}. \quad (20)$$

Table 11 shows the effect of steel fibers on Poisson's ratio of GPCC.

4. Conclusions

Geopolymer concrete is a new invention in the world of concrete in which cement is totally replaced by industrial waste which contributes towards the global worming by reducing use of cement and utilisation of byproducts like fly ash. Since geopolymer concrete is more brittle than conventional concrete, steel fibres are used to make it an elastic one.

This paper presents the effect of steel fibres on mechanical and elastic properties of geopolymer concrete. From the experimental results it is concluded that the wet and dry densities of geopolymer concrete composites increased continuously with increase in fibre content, whereas the workability of geopolymer concrete composites reduced with increase in fibre content. Optimum fibre content for the maximum value of various strengths of geopolymer concrete composites is 0.2%. The maximum percentage increase in compressive strength, flexural strength, split tensile strength, and bond strength is 29.98%, 30%, 30.05%, and 16.11%, respectively. The proposed equation for modulus of elasticity yield excellent result and Poisson's ratio varies between specified limit.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The support from Saurabh Shah, Sanket Sakalkar, Amol Gite, Ritesh Gajare and Chetan Shahare, Graduate students, Department of Civil Engineering, SRES's College of Engineering, Kopargaon, Maharashtra, India, for this study is gratefully acknowledged.

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