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Effect of GGBFS on Workability and Strength of Alkali-activated Geopolymer Concrete

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Abstract

This paper focuses on the development of a concrete material by utilizing fly ash and blast furnace slag in conjunction with coarse and fine aggregates with an aim to reduce pollution and eliminate the use of energy extensive binding material like cement. Alternative binding materials have been tried with an aim to get rather an improved concrete material. Alkali-Activated Solution (AAS) made of the hydroxide and silicate solutions of sodium was adopted as the liquid binder whereas, Class F" fly ash and Ground Granulated Blast Furnace Slag (GGBFS) mixed in dry state were used as the Geopolymer Solid Binder (GSB). The liquid binder was used to synthesize the solid binder by thermal curing. The paper investigates the use, influence and relative quantities of the liquid and solid binders in the development of the alkali-activated GGBFS based Geopolymer Concrete (GPC). Varying ratios of AAS to GSB were taken to assess their optimum content. Further, different percentages of GGBFS were used as a partial replacement of Class F fly ash to determine the optimum replacement of GGBFS in the GPC. In order to assess their effects on various properties test samples of cubes, cylinders and beams were cast and tested at 3, 7, and 28 days. Thermal curing of GPC has also resorted for favorable results. It was found that AAS to GSB ratio of 0.5 and GGBFS content of 80% yielded the maximum strength with a little unfavorable effect on workability. The overall results indicated that AAS and GGBFS offer good geopolymer concrete which will find its applicability in water scarce areas.

Keywords: Fly Ash; GGBFS; Geopolymer Solid Binder; Alkali-Activated Solution; Geopolymer Concrete; Workability; Mechanical Properties.

1. Introduction

The most widely used material to bind the constituents of conventional concrete has been Portland cement. The gain in strength and durability properties of Portland cement concrete is also considerable. Cement production, on one hand consumes a significant amount of energy and natural raw materials and, on the other hand it liberates solid wastes and carbon dioxide (CO_2) gas which cause environmental pollution. The cement industries contribute as much as 5-7% to global CO_2 emissions [1, 2]. Massive heaps of wastes of fly ash from coal-based power plants and slag from primary units of iron industries have come up. Disposal of industrial wastes is a big challenge. The process of disposal of industrial and constructional wastes might be uneconomical but increasing demand and price of raw materials coupled with uncompensable damage to the environment have increased the importance of the utilization of these by-product wastes [3]. However, with the use of modern green engineering technologies, environment friendly

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and more energy-saving binding materials are possible. "Class F" fly ash which is a low calcium by-product with pozzolanic property [4], is formed from anthracite or bituminous coal. At an elevated temperature low calcium fly ash reacts with alkali-activated solution (AAS) which is a mixture of the hydroxide and silicate of sodium solution (NaOH & Na_2SiO_3). The reaction product is an inorganic alumino-silicate polymer known as geopolymer [5, 6]. Fly ash (Class F) and slag act as a geopolymer solid binder (GSB) whereas AAS acts as a geopolymer liquid binder in the GGBFS-alkali activated geopolymer concrete. Fly ash (Class F) contains more quantity of alumina and silica compounds as compared to other classes of fly ash [7]. Slag is reach in calcium oxide, silica, and alumina. The geopolymerisation process is slow at ambient temperature because of the low reactivity of the solid binder with the liquid binder [8]. The rise in the curing temperature accelerates the reactivity of the solid binder with the liquid binder. The solid binders when react with an alkali-activated solution result in sodium aluminosilicate and calcium aluminosilicate gels, respectively at thermal curing conditions. With the higher percentage of GGBFS/slag content, the sodium aluminosilicate gel transforms into calcium aluminosilicate gel. The matrix of the transformed product, because of its higher density, is advantageous in improving durability and strength properties [9, 10].

In the coming years, Class F fly ash might be used as a solid binder in geopolymer to gain higher early strength and better acid and temperature resistance [7, 11]. Most of the parameters such as the concentration of sodium hydroxide solution, the ratio of silicate to hydroxide of sodium solution, the ratio of AAS to GSB, the quantity of fly ash and the curing technique affect the strength properties of the geopolymer concrete. The concentration of sodium hydroxide increases the strength of the geopolymer concrete. Many researchers [10, 12-16] have obtained the optimum ratio of the silicate to hydroxide of sodium between 1.5 to 2.5 keeping a higher molarity of sodium hydroxide (10 to 16 M) to obtain higher compressive strength. Fly ash based geopolymer concrete gains strength very slowly at an ambient temperature. However, a reasonable gain in strength has been found by resorting to oven curing in the temperature range of 40-90°C [17]. Vijai et al. (2010) and Noushini et al. (2020) [18, 19] have found that fly ash based geopolymer concrete gained maximum strength when cured in the range of 60-75 °C for 24 hrs. Additives like GGBS and slag have also been used to improve the mechanical and durability properties of geopolymer concrete [1, 7, 8, 10, 20]. It has also been reported that with the use of 75% fly ash, 25% slag and 14 M concentration of NaOH in preparation of geopolymer concrete yielded a compressive strength value of 35 MPa even at 28 days of ambient curing [7]. The compressive strength of geopolymer concrete increased with the increase of slag content and concentration of NaOH solution [10, 20]. Bellum (2019) found that geopolymer concrete containing 30% fly ash and 70% GGBS yielded compressive strength of 34.15 MPa at a ratio of AAS to GSB of 0.35 and 70°C oven curing for 24Hr followed by 28 days of ambient curing [21]. Ma et al. (2019) reported a maximum compressive strength with 30% slag in geopolymer concrete. However, it also reported that the concentration of NaOH made little difference on 28 days compressive strength [22].

It is seen that most of the researchers emphasize broadly that the geopolymer concrete mixed with fly ash and alkali-activated solution (AAS) can yield the maximum compressive strength at a concentration of NaOH between 15.5 -16 M and at a ratio of silicate to hydroxide of sodium solution between 1.5-2.5. Very few investigations have reported about the mechanical properties of geopolymer concrete (GPC) containing fly ash and ground granulated blast furnace slag (GGBFS) and about the ratio of AAS to GSB.

Therefore, this research work strives to develop a concrete material composed of fly ash and blast furnace slag together with coarse and fine aggregates with an aim to reduce the environmental pollution by utilizing fly ash and blast furnace slag and also to eliminate the use of energy extensive binding material like cement. Alternative binding materials containing the hydroxide and silicate of sodium (known as the liquid binder AAS) have been tried with an aim to get an improved concrete material. Apart from the liquid binder, Class F" fly ash and ground granulated blast furnace slag (GGBFS) mixed in dry state have also been used as the solid binder. This research paper focuses on the determination of the optimum quantity of GGBFS relative to fly ash to get the maximum strength and workability. Experimental, investigations to determine the effect of the ratio of AAS to GSB on the compressive strength of alkali-activated GPC have been conducted. Thermal curing at 60°C for 24hours was also adopted to watch for its favourable effect. Further, the mechanical properties of GPC containing various percentages of GGBFS as a partial replacement of fly ash, in order to achieve improvement in properties, have been investigated by conducting various experiments like compressive strength, flexural strength, modulus of rigidity and split tensile strength tests.

2. Experimental Investigation

2.1. Materials

The geopolymerisation reaction between the solid binder ("Class F" fly ash and GGBFS) and liquid binder (AAS) forms the geopolymer binding material which is the counter-part of aluminosilicate in Portland cement. Tables 1 and 2 present physical properties and compositions of Class F fly ash and GGBFS. The main components of liquid binder are sodium hydroxide and sodium silicate solutions. Fine and graded coarse aggregates for use in geopolymer concrete were obtained from the local source. The physical properties and grading curve of coarse and fine aggregates (FA) of Zone III as per IS: 383 [23] are specified in Table 3 and Figure 1, respectively.

Table 1. Physical properties of "Class F" fly ash and GGBFS

Sr. No.	Physical Properties	"Class F" fly ash	GGBFS
1	Color	Light brown	Off white
2	Residue retained on 45 µm, (%)	1.2	2.3
3	Specific surface area (Blaine), (m^2/kg)	392	378
4	Specific gravity	2.23	2.81
5	Moisture content, (%)	0.09	0.11
6	Autoclave expansion, (%)	0.04	0.38

Table 2. Chemical composition by mass % of "Class F" fly ash and GGBFS

Sr. No.	Chemical compounds	"Class F" fly Ash (%)	GGBFS (%)
1	SiO_2	60.4	31.6
2	Al_2O_3	25.8	14.2
3	Fe_2O_3	4.1	1.7
4	CaO	2.8	39.5
5	MgO	0.8	5.9
6	SO_3	0.65	1.68
7	K_2O	1.8	0.38
8	Na_2O	0.76	0.5
9	Loss of ignition	2.08	3.7

Table 3. Physical properties of coarse and fine aggregates

Sr. No.	Physical properties	Coarse aggregate (CA)		Fine aggregate (FA)
		CA-I (fraction I)	CA-II (fraction II)	
1	Shape	Angular	Angular	Rounded
2	Maximum size	16 mm	12.5 mm	4.75 mm
3	Water absorption	0.58%	0.71%	1.43%
4	Surface moisture content	Nil	Nil	Nil
5	Specific gravity	2.71	2.69	2.65
6	Fineness modulus	------	------	2.437
7	Aggregate Crushing value	21.4%	22.1%	------
8	Aggregate Impact value	23.7%	24.2%	------

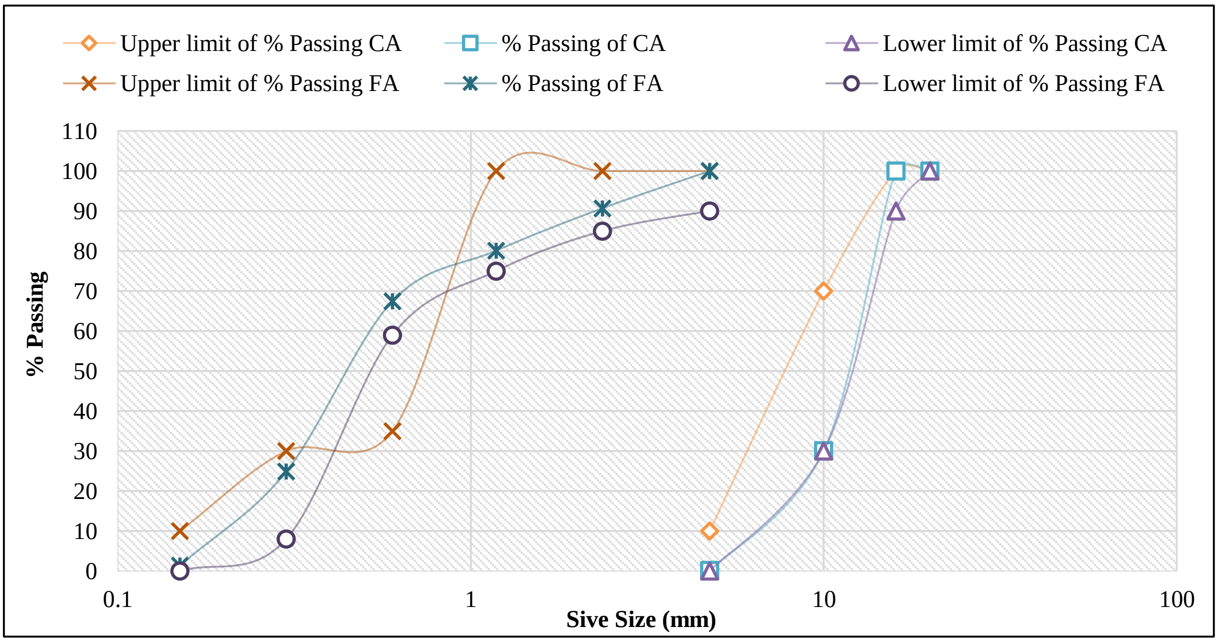

Figure 1. Grading curves of aggregates

2.2. Preparation of the Binder

One day before the casting of the GPC, sodium hydroxide solution was prepared. Sodium hydroxide pellets were kept in plastic vessel of tap water having 97% purity and pH value 7.12-7.20. A magnetic stirrer was used to stir thoroughly until they dissolved. Safety measures were exercised as significant quantity of heat evolved due to exothermic chemical reactions. The alkaline solution was then capped and allowed to cool. The concentration of sodium hydroxide as well as the optimum ratio of sodium silicate to sodium hydroxide was kept 16 M and 1.8 respectively, based on the results of previous studies.

The pH value and specific gravity of 16 M NaOH solution were 12.4 and 1.44, respectively. The sodium silicate solution in gel form was collected from the market. The sodium silicate solution composed of silicon dioxide (SiO_2)-30.4%, disodium oxide (Na_2O)-11.6%, water-56.9% and the remaining were filler materials. The specific gravity of sodium silicate was 1.38. The sodium silicate gel was mixed with the sodium hydroxide solution. This solution was stirred thoroughly for 5 minutes which resulted in an alkaline-activator solution (liquid binder) through an exothermic reaction [24]. This solution was kept in a tightly capped container.

2.3. Mix Proportion, Mixing, and Preparation of Sample

The mixing process of geopolymer concrete can be either through the dry mix process or wet-mix process. In this study, the dry mix process was adopted. “Class F” Fly ash, GGBFS, alkaline-activator solution (AAS) of NaOH and Na_2SiO_3 solutions, fine aggregate, coarse aggregate, and water were proportioned. To study the effectiveness of the ratio of AAS to GSB on the strength properties of fly ash based GPC, various ratios (0.40, 0.45, 0.50, and 0.55) were adopted. Further, to study the effectiveness of GGBFS in geopolymer concrete, varying proportions of GGBFS by replacing fly ash from the mix were used.

The fly ash was partially replaced by GGBFS in 20, 40, 60, 80, and 100% by the weight of fly ash in the mix. The concrete constituents were proportioned on the trial and error method because of the unavailability of the exact design procedure [15]. The mix design criterion in this study is based on the specific gravity of ingredients. The quantities and proportions of the ingredients of the GPC mix are given in Table 4. The total weight of the solid binder was kept fixed which is 460 kg/m^3. The absolute volume, grading curve of aggregates and specific gravity of materials have been used to determine the quantity of aggregates. The mix design methodology is presented in the form of a flowchart as shown in Figure 2.

The surface dried coarse and fine aggregates, fly ash and GGBFS were mixed in a dried state in a rotating mixer machine for 120 seconds. The AAS and water (pH=7.12-7.20) were gradually mixed together for 60 seconds and then mixed with the mixture of coarse and fine aggregates, fly ash and GGBFS continuously for further 180 seconds to achieve a uniform concrete mixture. This freshly mixed geopolymer concrete was cast in 150 mm cube moulds, 150×300 mm cylinder moulds, and 100×100×500 mm beam moulds. Compaction of concrete moulds was done on a vibration table. The concrete-filled moulds were enclosed with a plastic wrapping sheet to stop the evaporation of free water from the green concrete.

Table 4. Mix proportion of fly ash and slag based geopolymer concrete

Mix No.	W/GSB	AAS/GSB	Molarity of SH_{sol}	SS_{sol}/SH_{sol}	% of GGBFS by weight of GSB (Fly ash + GGBFS)	CA by weight of GSB	FA by weight of GSB
$M_{0.40}$	0.23	0.40	16	1.8	0	2.47	1.07
$M_{0.45}$	0.23	0.45	16	1.8	0	2.44	1.06
$M_{0.50}$	0.23	0.50	16	1.8	0	2.41	1.05
$M_{0.55}$	0.23	0.55	16	1.8	0	2.35	1.04
$M_{20.50}$	0.23	0.50	16	1.8	20	2.46	1.07
$M_{40.50}$	0.23	0.50	16	1.8	40	2.51	1.09
$M_{60.50}$	0.23	0.50	16	1.8	60	2.55	1.11
$M_{80.50}$	0.23	0.50	16	1.8	80	2.60	1.13
$M_{100.50}$	0.23	0.50	16	1.8	100	2.65	1.15

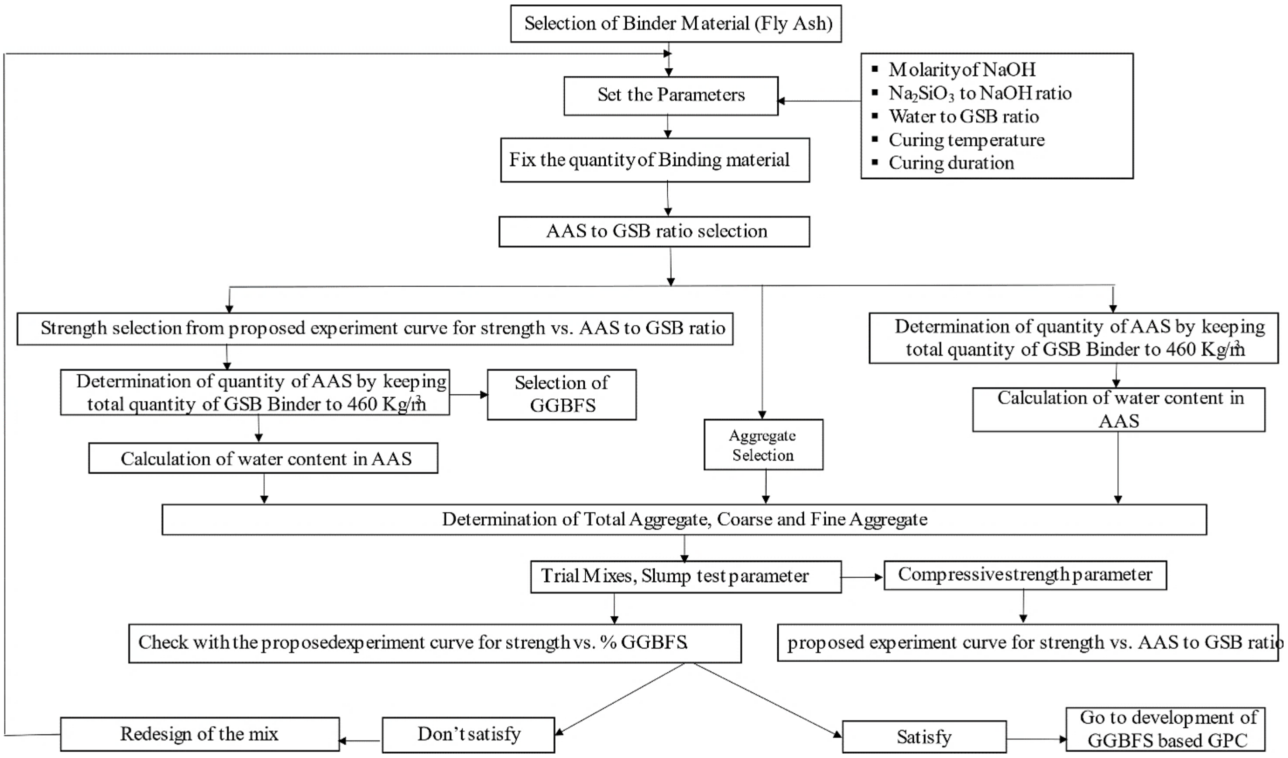

Figure 2. Flowchart of design methodology

2.4. Slump Test

Workability of freshly mixed geopolymer concrete was determined by Slump test apparatus. The apparatus essentially consisted of a steel mould in the shape of a frustum of a cone along with a tampering steel rod. The inner diameters of the frustum at the bottom and top are 200 mm and 100 mm respectively. The height of the frustum is 300 mm. Workability was determined as per the Indian Standard (IS: 7320).

2.5. Curing of Samples

The concrete-filled moulds wrapped with plastic sheet were left at ambient temperature for 60 minutes. After 60 minutes of ambient curing, the moulds [21, 25] were kept in an oven for heat curing at a controlled temperature of 60°C for 24 hours. The oven-cured specimen moulds shown in Figure 3 were kept at an ambient temperature of 24-26°C and relative humidity of 60 ± 5% until testing.

Figure 3. Sample moulds of cube, beam and cylinder

3. Test Instruments and Experiments

3.1. Compressive Strength Test

The compressive strengths of GPC cubes were determined at 3, 7, and 28 days using a hydraulic digital compression testing machine (Figure 4.a) having a capacity of 2000 kN and the least count of 0.1 kN as per Indian Standard IS: 516 [26]. The test was conducted keeping a displacement rate of 1.4-1.6 Kg/min. Three cubes of each mix were tested and an average compressive strength value was obtained.

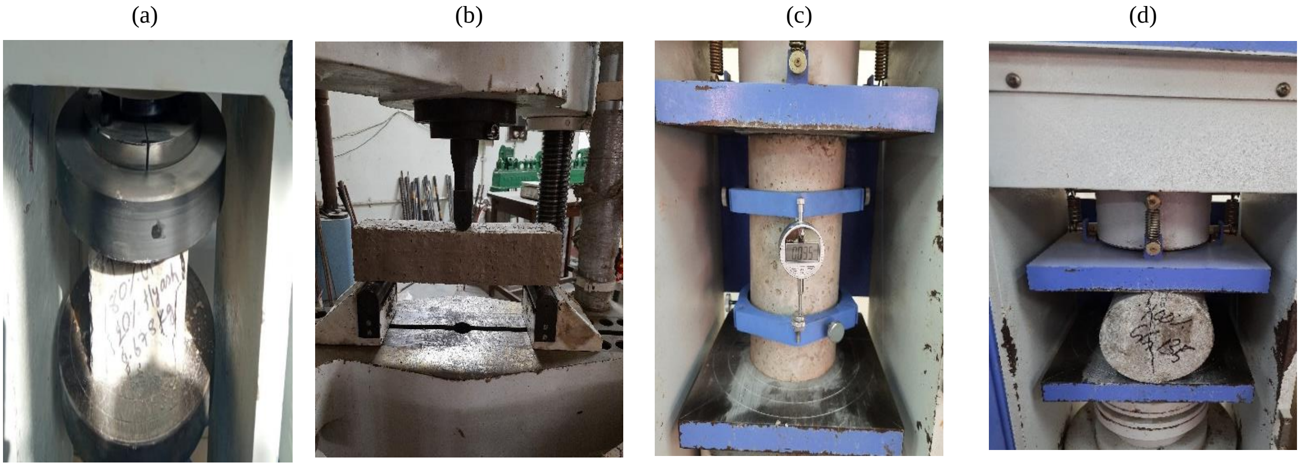

Figure 4. a) Compressive test of the cube specimen. b) Flexural test of the beam specimen. c) Extensometer used to measure deflection with applied uniaxial compression load. d) Split tensile test of the cylinder specimen

3.2. Flexure Test

The flexural strength test was done on a digital flexure testing machine (Figure 4.b) having a capacity of 100 kN and the least count of 0.1 kN. The flexural strength of a beam of dimensions 100×100×500 mm was determined by subjecting the beam to center point loading as per ASTM Standards ASTM C-293-02, 2002 [27]. Three beams of each mix were tested, and an average flexural strength value was obtained.

3.3. Modulus of Elasticity

An extensometer equipped with a dial gauge was mounted in the middle portion of the cylindrical specimen (Figure 4.c) to measure the deformation of the cylindrical sample [28, 29]. Cylindrical specimens were tested under uniaxial compression load at a displacement rate of 1.4-1.6 Kg/min.

3.4. Split Tensile Test

The split tensile test was done on the same compressive testing machine as per Indian standard IS:5816 [30]. Split strength was measured on 150×300 mm cylinders subjected to compression load transverse to the longitudinal axis of the cylinder (Figure 4.d). The same displacement rate of 1.4-1.6 kg/min was maintained. Three cylinders of each mix were tested at 28 days, and average values were obtained.

4. Results and Discussion

Nine different mix proportions of GGBFS and alkali based geopolymer concrete were tested. The workability and various strengths such as compressive, split, flexure strengths, as well as elastic modulus, were determined.

4.1. Effect of GGBFS and AAS/GSB on Workability

The geopolymer concrete mixes were designed with the solid binder (GGBFS and fly ash), liquid binder (Alkaline activated solution), aggregates, and water. In present research obtained quantity of water has fixed for all design mix. Obtained quantity of water has divided in two part. One part used in the preparation of AAS solution and other part used for slump. Higher AAS to GSB ratio have used more quantity of water for preparation of AAS and remaining water used for slump. This concrete mix was found to be cohesive and highly plastic for lower ratio of AAS to GSB content, because less water consumed in preparation of AAS and remaining more water used to make more workable GPC. The slump values have been obtained to optimised ratio of AAS to GSB in without GGBS design mixed as shown in Figure 5. The inclusion of GGBFS in the geopolymer concrete mix also reduced the slump values at optimized ratio of AAS to GSB. A comparative plot of the slump test result with the quantity of alkali-activated solution and inclusion of GGBFS into geopolymer concrete is shown graphically in Figure 5. The increasing percentage content of GGBFS increases the stiffness of the geopolymer concrete mix. It has been also observed that the geopolymer concrete and Portland cement concrete are rheologically different. Reactive and excess water has participated in the hydration process and slump of Portland cement concrete respectively while water is used in GPC only for preparation of AAS and gaining workability. As observed from previous studies, workability of GPC mix was decreased by adding slag [24, 31]. Superplasticizer can be added to improve workability at higher content of GGBFS in geopolymer mix. The mechanical and physical properties of the hardened concrete may be affected by workability.

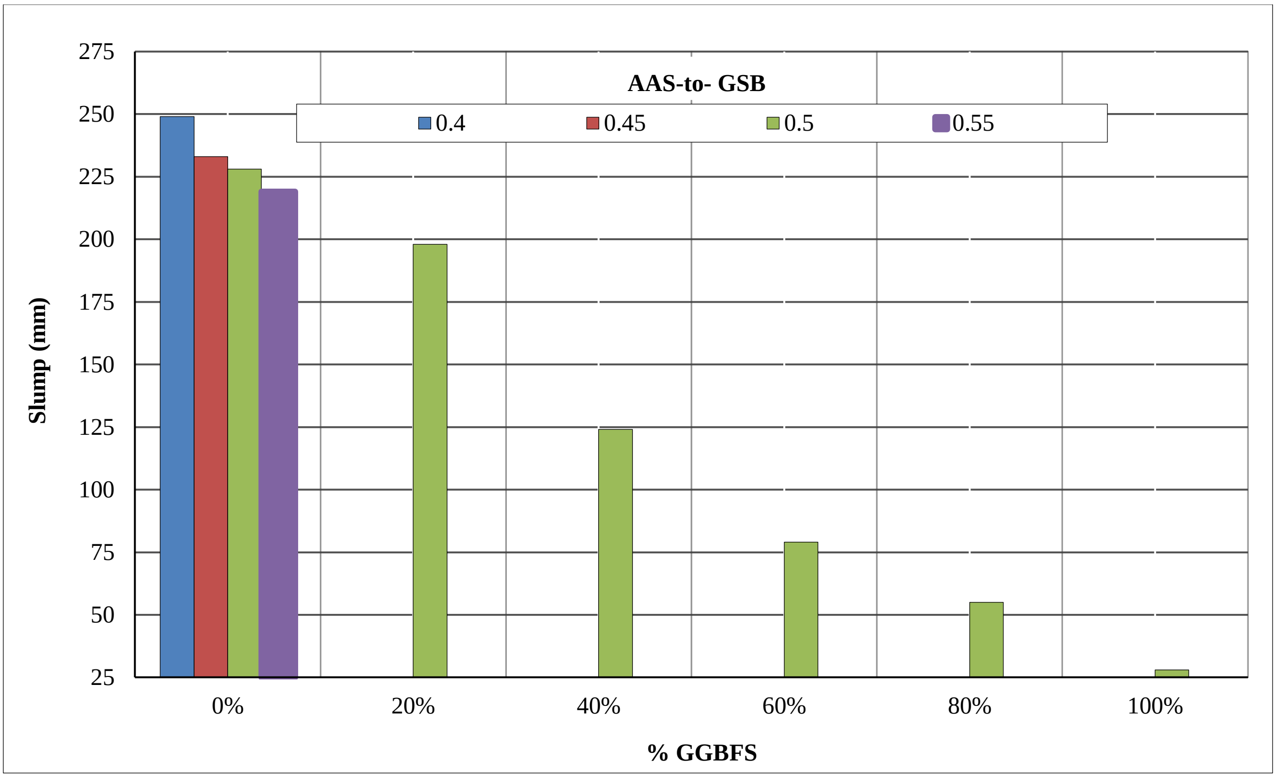

Figure 5. Slump value of geopolymer concrete of different AAS-to-GSB ratios with % GGBFS

4.2. Compressive Strength of GPC

In the present investigation, two broad modifications in the GPC were considered. In the first, four different alkali-activated solutions (AAS) to geopolymer solid binder (GSB) ratios were applied. These ratios were 0.40, 0.45, 0.50 and 0.55. In the second, five different replacements of fly ash by GGBFS were applied. These replacements were 20%, 40%, 60%, 80%, and 100% by weight of total fly ash. Samples of GPC with these modifications were tested. The results of compressive strengths at 3, 7, and 28 days are presented in Figures 6 and 7.

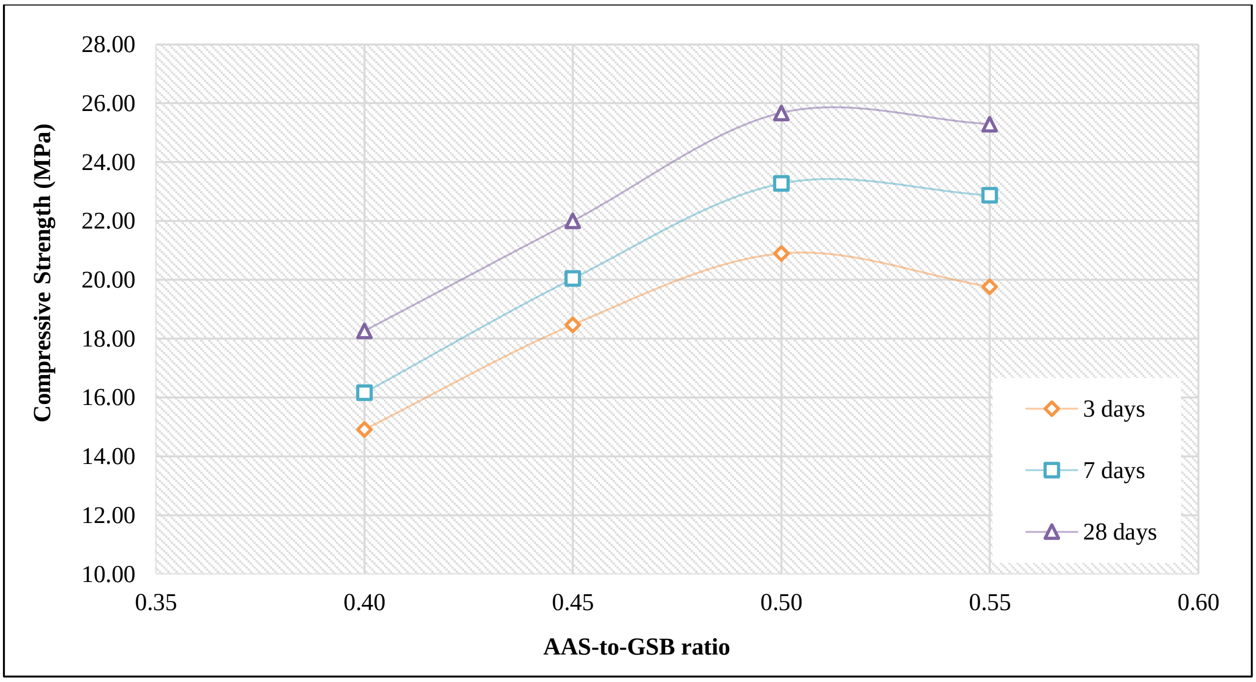

Figure 6. Compressive strength value of geopolymer concrete with varying AAS-to-GSB ratio

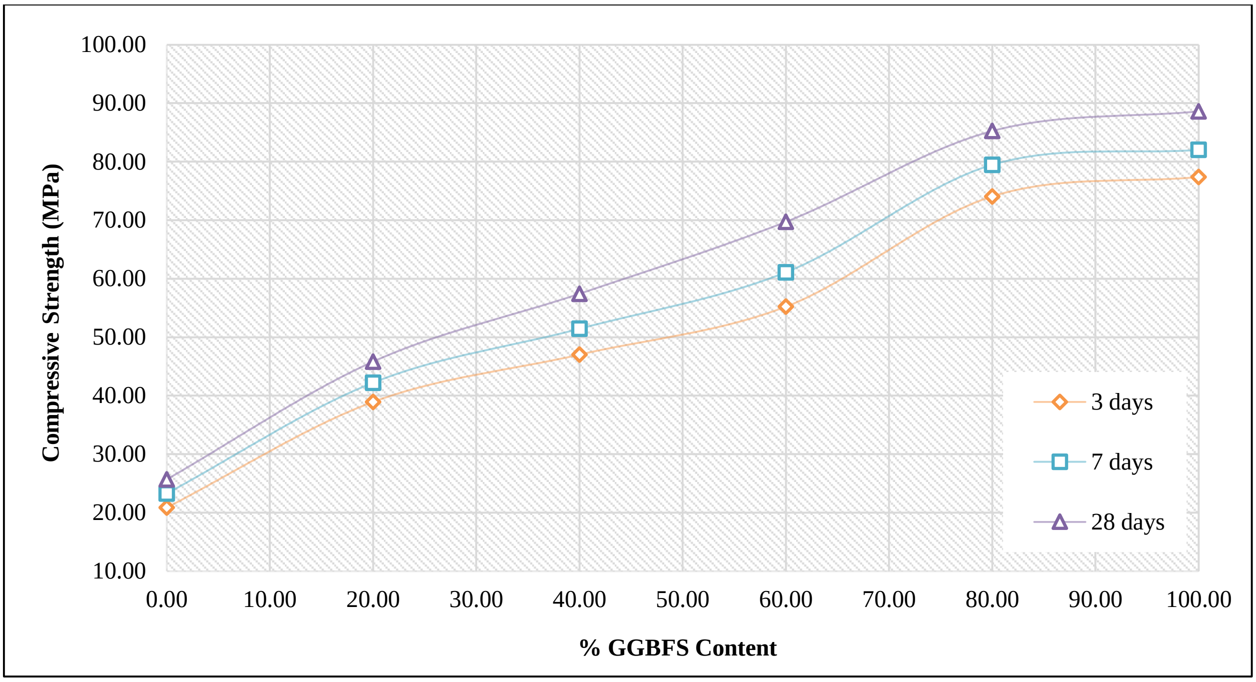

Figure 7. Compressive strength value of geopolymer concrete with varying % GGBFS at an AAS-to-GGBFS ratio 0.50

4.3. Impact of the Ratio of AAS-to-GSB on the Compressive Strength of GPC

A chart of compressive strengths of GPC at 3, 7, and 28 days for four AAS-to-GSB ratios is presented in Figure 6. It is seen that the maximum increase in the value of compressive strength is obtained at an AAS-to-GSB ratio of 0.5. Fly ash based GPC gives moderate strength.

4.3.1. Effect of GGBFS on Compressive Strength of GPC

To study the effect of GGBFS content in the GPC, different proportions of GGBFS were applied keeping AAS to GSB ratio fixed at 0.50. Figure 7 shows the influence of varying GGBFS on compressive strengths at 3, 7, and 28 days of curing. The compressive strength values at 28 days were found to increase by 232% and 245% respectively, over the ordinary (fly ash based) geopolymer concrete when 80% and 100% fly ash were replaced by GGBFS. Figure 7 shows that a 60% replacement of fly ash by GGBFS has increased the compressive strength moderately. The same rate of gain in strength is almost valid for 40% replacement of fly ash by GGBFS in GPC. However, a sharp rise in strength has been observed for 80% fly ash replacement by GGBFS. A very marginal rise in strength is observed at 100% GGBFS content in GPC. The optimum compressive strength was found at 80% GGBFS content in the GPC.

Fly ash based GPC with zero GGBFS content has yielded a 3 days compressive strength upto to 88% of 28 days compressive strength. Addition of GGBFS influences the early strength as compared to the fly ash based GPC as shown in Figure 7. However, as compared to OPC or PPC based concrete, GGBFS-fly ash-based GPC has also yielded a high early strength upto 77-86% of the 28 days strength. No surface cracks were visible after oven curing at 60°C. However, surface cracks caused by the shrinkage of the alkali-activated slag concrete have been reported by some investigators [10]. Moderate compressive strength with the participation of slag in GPC at ambient curing has been reported by some investigators [21, 25, 32-34]. Accelerated polymerization process among fly ash, GGBFS, and AAS are predominant at 60°C [25, 35]. The higher gain in compressive strength is credited to the greater content of calcium in GGBFS [35]. The GGBFS mainly contributes to the interaction of hydrates of calcium silicate, calcium aluminosilicate, and sodium aluminosilicate gels which are accountable for the increase in compressive strength.

4.4. Flexural Strength of GPC

Flexural strength represents the ability of beams to resist failure in bending. The flexural strengths of the specimens at the end of 28 days are listed in Table 5. The flexural strength was found to be influenced by the AAS-to-GSB ratio in GPC. The flexural strength value of geopolymer concrete without GGBFS was obtained maximum at an AAS-to-GSB ratio of 0.5. It is seen from Figure 8 that the optimum value of the flexural strength is obtained at 80% of GGBFS content. Normally, the compressive and flexural strengths have a strong relationship with each other. The predicted flexural strength of Portland cement concrete can be obtained by the ACI 318 Building Code [36], an expression for which can be given as:.

$$f_{rs} = 0.62 \times \sqrt[2]{f_c} \quad \text{MPa.} \tag{1}$$

Where f_c and f_{rs} are the flexural and compressive strengths (MPa) respectively, of GPC at 28 days. The flexural strength of most of the specimens were found to be 2-20% more than the predicted flexural strength from Equation 2. Based on experimental results, the authors present a formula for the estimation of flexural strength of alkali- activated-GGBFS based geopolymer concrete as:

$$f_{rs} = 0.3377 \times f_c^{0.674} \quad \text{MPa.} \tag{2}$$

A comparison of the flexural strengths obtained by Diaz-Loya et al. (2011), ACI M318-05 (2005) and Nath & Sarker (2016) [29, 36, 37] vis. a vis. authors' is presented in Figure 8. The expressions for estimating flexural strength are in terms of compressive strength. It is seen that the predicted value of flexural strength by Diaz-Loya et al. (2011) [29] is given as $f_{rs} = 0.69 \times \sqrt[2]{f_c}$ which gives higher values of flexural strength than the authors' values for GGBFS content upto 60% whereas, the same gives lower values of flexural strengths for GGBFS content more than 60% . However, the expression $f_{rs} = 0.93 \times \sqrt[2]{f_c}$ obtained from [37] yields higher flexural strength than the authors' predicted value (Equation 2). However, it is obvious that the flexural strength of alkali-activated-GGBFS based GPC is more as compared to OPC based concrete [38].

Table 5. Mechanical properties of GGBFS- alkali-activated geopolymer concrete at 28 days.

Mix No.	Flexural Strength (MPa)	Elastic Modulus (MPa)	Split Tensile Strength (MPa)	Unit Weight (Kg/m^3)
$M_{0.40}$	2.70	10260.00	1.69	2375.70
$M_{0.45}$	2.88	12890.00	1.81	2390.81
$M_{0.50}$	2.97	13950.00	1.90	2404.44
$M_{0.55}$	2.94	13790.00	2.10	2398.52
$M_{20.50}$	4.04	20200.00	20.20	2411.56
$M_{40.50}$	5.10	24500.00	22.50	2467.56
$M_{60.50}$	5.75	26980.00	23.98	2489.19
$M_{80.50}$	6.98	31280.00	26.72	2593.78
$M_{100.50}$	7.02	30750.00	26.75	2546.37

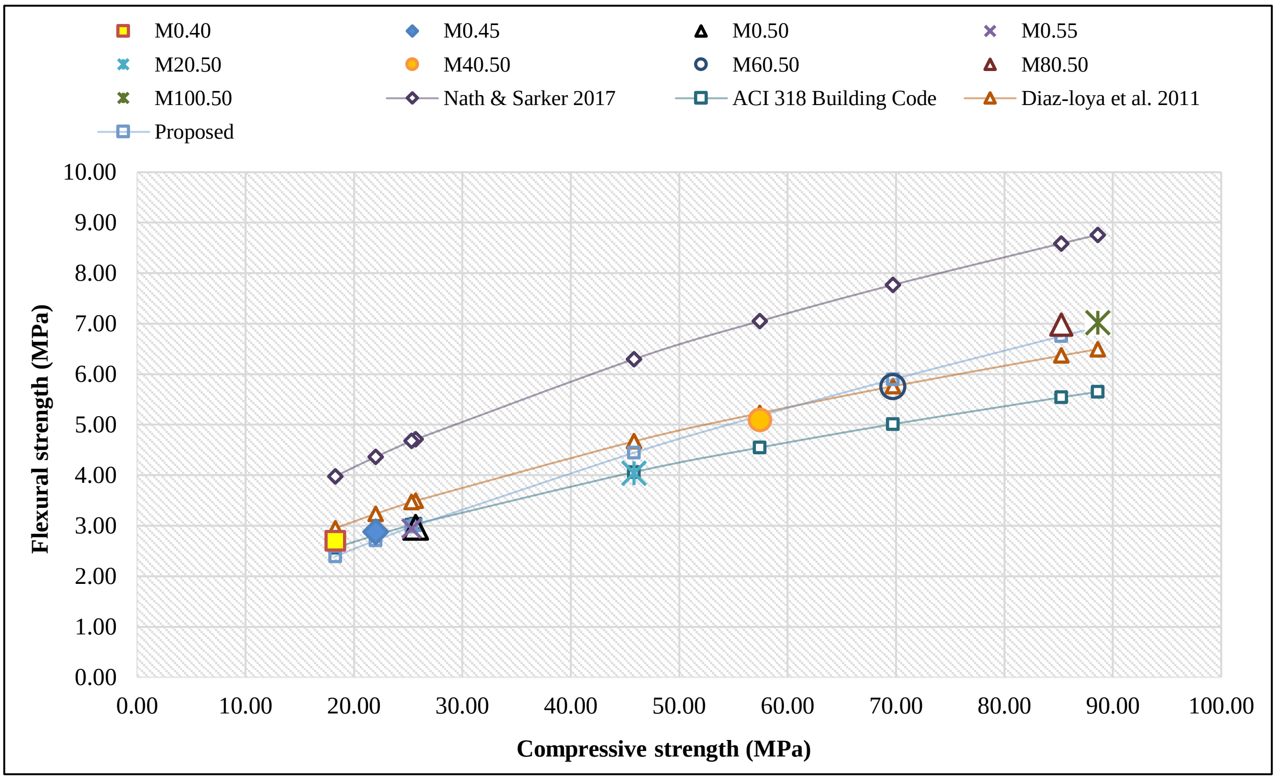

Figure 8. Comparison of measured flexural strengths of fly ash/GGBFS-alkali-activated geopolymer concrete with published research and Codal values

4.5. Modulus of Elasticity of GPC (MOE)

A comparison of the elastic modulus of "class F" fly ash and GGBFS based geopolymer concrete is presented in Figure 9. The elastic modulus values show a rising trend when the AAS-to-GSB ratio was increased up to 0.50. The modulus of elasticity values are compared with the predicted elastic moduli of Portland cement concrete by ACI Building Code [36] and "FIP Model Code" [39]. The elastic modulus of Portland cement concrete as per [39] can be estimated as:

$$E_c = 8482.50(f_c)^{1/3} \quad \text{MPa.} \tag{3}$$

Where, E_c is the static elastic modulus (MPa) of Portland cement concrete at 28 days. As per ACI Building Code [36], the expression for estimating static elastic modulus of Portland cement concrete (bulk density between 2375 to 2593 Kg/m^3) can be given as:

$$E_c = 0.043\, w_c^{1.5} \times f_c^{0.5} \quad \text{MPa.} \tag{4}$$

Where w_c is the bulk density (kg/m^3). As shown in Figure 9, the authors' experimentally obtained modulus of elasticity value is lower as compared to the modulus of elasticity estimated by Equations 3 and 4.

The experimentally determined values of elastic modulus were also compared with those obtained from Lee and Lee (2013) [10], where the expression for elastic modulus is given as $E_c = 5300(f_c)^{\frac{1}{3}}$. Elastic modulus values as per Lee and Lee (2013) [10] were found to be higher than the authors' experimental values for GGBFS content upto 40%, whereas, for GGBFS content more than 50% in GPC, lower than the experimental values of elastic modulus are shown (Figure 9). The elastic modulus values obtained by Lee et al. (2013), Hu et al. (2019) and Sofi et al. (2013) [10, 28, 40]. They were also found to be lower than the values obtained from ACI M318-05 and CEB-FIP Model [36, 39]. It is understood that the elastic modulus of GPC with high GGBFS content is more as compared to the GPC without GGBFS content. The reason for higher modulus of elasticity can be attributed to the increased production of the hydrates of calcium silicate and calcium aluminosilicate gels. These calcium compounds are produced in abundance as compared to the hydrate of sodium aluminosilicate gel in a highly GGBFS content GPC which causes higher elastic modulus. Some more researchers have also observed that the increased quantity of GGBFS increases the elastic modulus value of GPC [25, 28, 41].

Based on experimental results, a formula for the estimation of static elastic modulus of alkali activated-GGBFS based GPC is proposed as:

$$E_c = 1610 \times f_c^{0.664} \quad \text{MPa.} \tag{5}$$

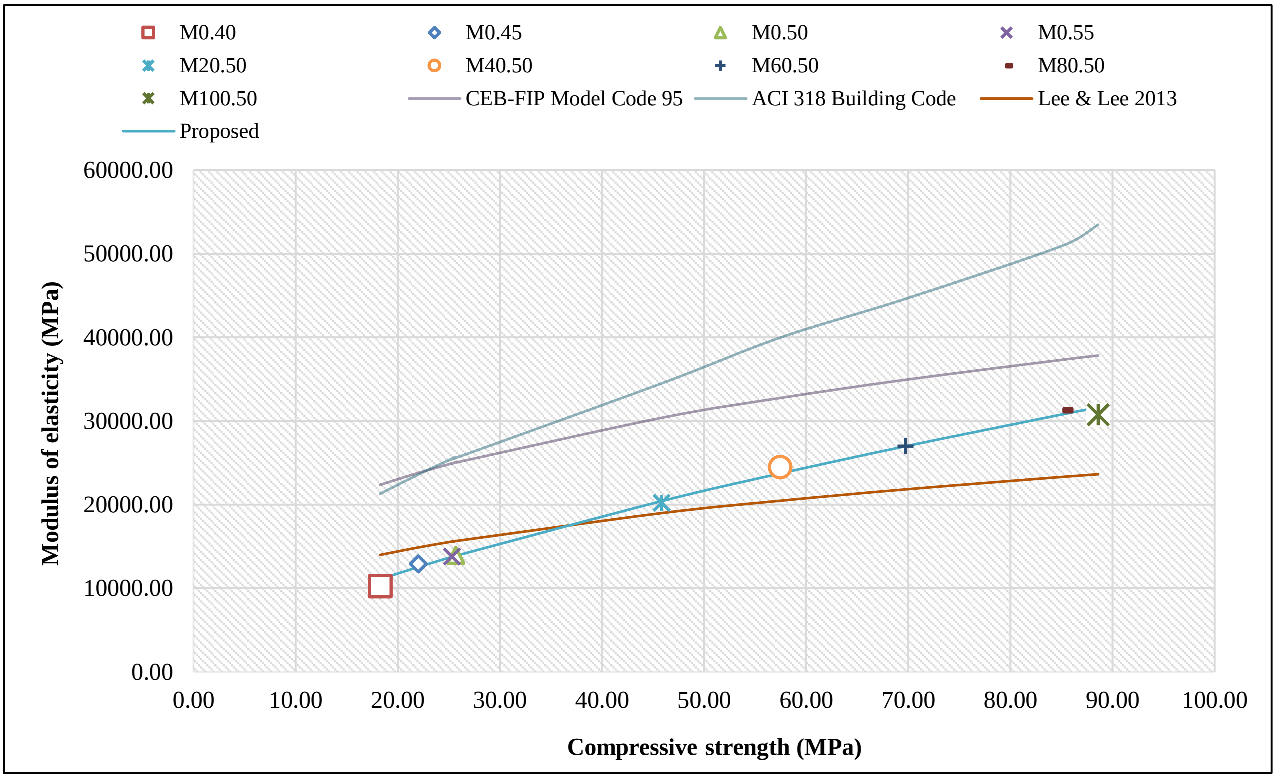

Figure 9. Comparison of measured modulus of elasticity of fly ash/GGBFS based geopolymer concrete with other published research and Codal values

4.6. Split Tensile Strength Test

The split tensile strength of GPC is known to have related to some aspects of crack initiation and propagation in the concrete structure. The split tensile strength shows a rising trend when the content of GGBFS was increased keeping a constant AAS/GSB ratio of 0.50 in alkali-activated-GGBFS based geopolymer concrete. Predicted splitting tensile strength (f_{ctm}) of Portland cement concrete as per CEB-FIP Model Code 95 [39] and ACI 318 Building Code [36] respectively, are given by:

$$f_{ctm} = 0.335(f_c)^{2/3} \text{ MPa.} \tag{6}$$

$$f_{ct} = 0.56(f_c)^{0.50} \text{ MPa.} \tag{7}$$

where f_{ctm} and f_{ct} are the mean tensile strength value and tensile strength value of concrete at 28 days, respectively. Another study by Lee and Lee (2013) [10] showed that the splitting tensile strength value of alkali-activated-GGBFS based geopolymer concrete was 0.45 times the square root of its compressive strength. Based on experimental results (Figure 10), a formula for estimating the splitting tensile strength of alkali-activated-GGBFS based geopolymer concrete is proposed as:

$$f_{ct} = 0.108(f_c)^{0.868} \text{ MPa.} \tag{8}$$

As shown in Figure 10, the experimentally obtained splitting tensile strength value is lower than the value predicted by ACI M318-05 and CEB-FIP Model [36, 39] for Ordinary Portland cement concrete. But for the sample mix $M_{80.50}$ and $M_{100.50}$ the obtained splitting tensile value are more than the values obtained from [36]. The split tensile strength values found by Lee et al. (2013), Hu et al. (2019) and Sofi et al. (2013) [10, 28, 40]. They were also lower than the ACI M318-05 and CEB-FIP Model [36, 39] predicted values obtained from Equations 6 and 7. However, the split tensile strength values calculated according to Lee and Lee (2013) [10] were higher than the presented experimental values up to 50% GGBFS content, but those were lower than the present experimental values for more than 50% GGBFS content in GPC as shown in Figure 10.

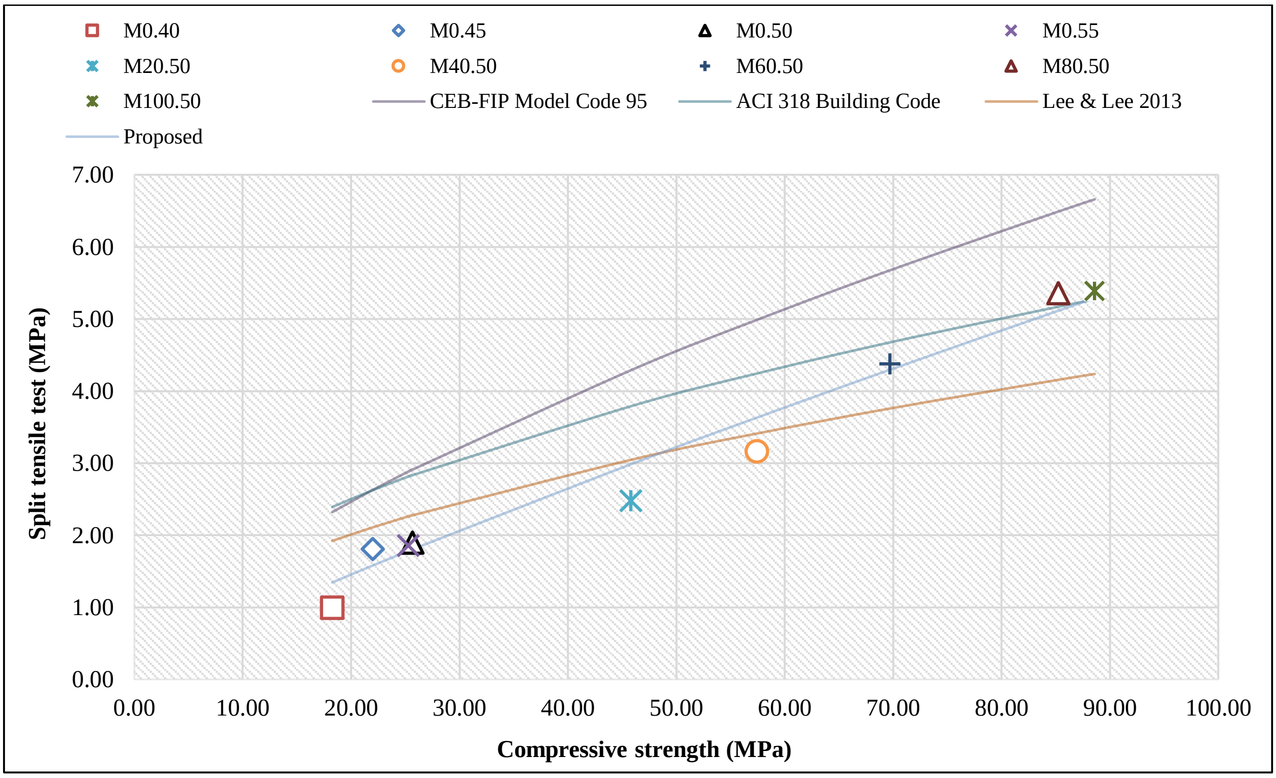

Figure 10. Comparison of present measured splitting tensile strength of "class F" fly ash/GGBFS geopolymer concrete with other published results and Codal values

5. Conclusions

In this study, an attempt has been made to develop alkali-activated ground granulated blast furnace slag (GGBFS) based geopolymer concrete of considerable high strength. The achievement of this strength is attributed to the alkali-activated solution (AAS) containing hydroxide and silicate solutions of sodium and GGBFS. Investigation of strength and workability revealed the following facts.

- Increased quantity of GGBFS reduces the workability but increased AAS-to-GSB ratio increases the workability of the geopolymer concrete.
- Increased AAS-to-GSB ratio in fly ash based GPC contributes to the increased strength. However, an increase in the ratio beyond 0.5 does not bring any appreciable change in strength. AAS-to-GSB ratio of 0.50 yields maximum compressive strength value in the fly ash based GPC.
- Substantial improvement in the mechanical properties of GPC is attained with the increased content of GGBFS. It is seen that 80% GGBFS content in GPC has produced maximum strength. The rise in strength in GPC having more than 80% GGBFS content is negligible.
- GPC when cured at 60° C for 24 hours attains high early strength upto 77-86% of the 28 days compressive strength.
- Empirical formulae have been proposed to estimate the flexural strength, elastic modulus and split tensile strength in terms of compressive strength of GPC cured at 60°C for 24hrs. It is expected that these formulae will be helpful for the concrete technologists.

The present paper has strived to bring out a somewhat novel concrete material, based on ground granulated blast furnace slag and alkali-activated solution that possesses substantial mechanical properties while utilizing the industrial wastes. It is expected that this concrete material will find its wide applicability as structural concrete. It would be useful much more in areas where mixing water is not available.

6. Abbreviations and Nomenclature

AAS: alkali-activated solution

CA: Coarse aggregate

FA: Fine Aggregate

GGBFS: Ground granulated blast furnace slag

GLB: Geopolymer liquid binder

GPC: Geopolymer concrete

GSB: Geopolymer Solid binder

OPC: Ordinary Portland cement

PPC: Portland Pozzolanic cement

PSC: Portland slag cement

7. Declarations

7.1. Author Contributions

Conceptualization: G.K. and S.S.M.; methodology: G.K. and S.S.M.; validation: G.K.; formal analysis: G.K.; investigation: G.K.; resources: G.K.; data curation: G.K.; writing—original draft preparation, G.K.; writing—review and editing, S.S.M.; visualization: G.K.; supervision: S.S.M.; project administration: S.S.M.; funding acquisition: G.K. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in article.

7.3. Funding and Acknowledgements

The authors acknowledge the funding and support from NIT Patna and the staff members of the Cement Concrete Laboratory of the Department of Civil Engineering, NIT Patna.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

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