Journal of Asian Concrete Federation
Vol. 8, No. 1, pp. 16-25, June. 2022
ISSN 2465-7964 / eISSN 2465-7972
DOI http://dx.doi.org/10.18702/acf.2022.6.8.1.16

Technical Paper

Experimental investigations on mechanical properties of normal and high strength high calcium geopolymer concrete

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(Received: January 1, 2022; Accepted: March 20, 2022; Published online: June 30, 2022)

Abstract: Alkali activated (Geopolymer) concrete is an excellent and viable alternative to Portland cement based concrete as it can be produced using industrial by-products such as Ground Granulated Blast Furnace Slag (GGBS) and fly ash (source of reactive alumino-silicates) along with less energy craving ingredients such as alkali activators. In this study, slag based geopolymeric concrete mixes of M40 and M80 grade were prepared using GGBS and fly ash in proportion of 70:30 by weight. Geopolymeric binder was activated using combination of Sodium hydroxide and Sodium Silicate. Activator modulus (i.e. SiO_2 / Na_2O) was maintained as 1 and Na_2O was kept as 7% and 8% by weight of total binder respectively for M40 and M80 grade geopolymeric concrete mixes. Both the concrete mixes were evaluated for fresh properties of concrete (slump and air content) along with mechanical properties of hardened concrete. Performance of geopolymeric mixes was compared with two conventional concrete mixes of equivalent grade (i.e. M40 and M80) in terms of aforementioned mechanical properties. Study concludes that slag based geopolymer concrete mixes of a particular strength were developed at significantly lower total binder content in comparison to cementitious binder required for development of conventional Portland cement based concrete of equivalent strength. Early age compressive strength of normal strength geopolymeric concrete mixes is higher in comparison to conventional concrete mix. Modulus of elasticity and Poisson's ratio of geopolymeric mixes of both normal and high grade are observed to be lower in comparison to their corresponding conventional concrete mixes of equivalent strength.

Keywords: Geopolymer; Activator Modulus; Alkali Activators; High Strength, Mechanical Properties

1. Introduction

Demand of cement for development of infrastructure is increasing by several folds across the world especially in developing nations, to meet the requirements of continuously increasing population. Production of concrete using conventional cementitious binders like Ordinary Portland Cement (OPC) leads to significant increase in global greenhouse gas emissions as production of 1 tonne of OPC leads to emission of around 900 to 1000 kg CO_2 into the atmosphere. To lower the significant carbon footprint of construction industry, efforts are being made all across the globe to develop cementitious binders using industrial by-products generated from different sectors of industries such as iron and steel industry, coal based power sector etc [1]. Owing to steep decline in availability of reserves for natural resources to be used as raw materials for production of clinker to be used in production of conventional binders, continuously increasing environmental concerns due to CO_2 emissions and accumulation of rapidly increasing industrial waste, alkali activated concrete has been identified as an excellent and viable alternative to Portland cement based concrete. Alkali activated concrete is gaining significant interest among construction related research fraternity as even though it is cement free concrete, geopolymeric binders have comparable cementing characteristics as in the case of conventional binders and they can be produced using industrial by-products such as Ground granulated blast furnace slag (GGBS) and fly ash

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(generally considered and dumped as waste) along with less energy craving ingredients such as alkali activators [2].

Significant increase in number of research publications along with conference and seminar in the area of alkali activated systems is a proof of huge surge in interest in this area across the globe [3]. Alkali activated binders are inorganic in nature and are produced by activating powdered materials containing reactive alumino-silicates (such as GGBS [4], fly ash [5], metakaolin [6]) using chemical activators containing alkali silicates [7], carbonates [8], hydroxides [9] in the presence of water at ambient temperature or elevated temperature, depending upon the chemical characteristics of the powdered material. The reaction product of activating a source of reactive alumino-silicates with alkali activator is amorphous glass phase of alumino-silicates containing three dimensional network of interlinked SiO_4^{-4} and AlO_4^{-5} tetrahedral units [2]. Presently, majority of the applications of alkali activated concrete are in developmental stage only. However, the superior performance of alkali activated concrete in terms of durability gives them an edge over conventional Portland cement concrete for use in structures such as bridges and runways [9].

Researchers across the globe have conducted several studies on fresh and hardened properties of geopolymer concrete using different binders and activators. It is understood that the alumina (Al_2O_3) and silica (SiO_2) present in the binder act as main component for geopolymerisation reaction which includes dissolution of alumina and silica in water along with alkali coming from activators leading to development of aluminosilicate gel, which provides the mechanical strength to geopolymer concrete mix [10]. Ojha et al [11] found that the workability of geopolymer concrete mix depends upon the ratio of cementitious binder to alkaline solution along with Na_2SiO_3/NaOH ratio. Increase in aforementioned ratios leads to higher water demand for development of workable geopolymer concrete mix due to viscous nature of Sodium Silicate. Malkawi et al [12] also studied the role of concentration of alkaline activator solution on the fresh properties of geopolymeric mortar mixes. Their study revealed that increase in the ratio of Na_2SiO_3/NaOH or increase in molarity of NaOH solution used in mix leads to reduction in the workability of fresh geopolymeric mix. Mo et al. [13], studied the effect of curing on hardened properties of geopolymer concrete and reported that samples cured at elevated temperature showed higher early age compressive strength in comparison to samples cured at normal temperature due to occurrence of vigorous geopolymeric reactions at early age. Iswarya et al [14] studied the role of ratio of slag and fly ash on hardened properties of geopolymer concrete observed that the compressive strength of geopolymer mix was higher for mixes with lower fly ash to slag ratio. This behaviour was attributed to denser microstructure of mix having higher proportion of slag. Deb et al [15] reported that the tensile strength of geopolymer concrete mix has direct relationship with its compressive strength. Therefore, the role of different variables (such as binder proportion, concentration of activator solution, water to binder ratio etc.) on tensile strength of geopolymer concrete was similar as it is in case of compressive strength. Modulus of elasticity and Poisson’s ratio are significant mechanical properties that determine the stiffness of hardened concrete mix. Modulus of elasticity of any concrete mix depends upon the temperature at which the concrete is cured, mechanical properties of aggregates used in the concrete mix, type and composition of binder along with curing time [16]. Several past research studies show that for a concrete mix of particular strength, geopolymer concrete shows lower values of modulus of elasticity in comparison to conventional Portland cement concrete of similar strength [17,18]. Such behaviour may be attributed to effect of aluminosilicate composition along with other processes involved in geopolymerisation reaction. However, Haq et al. [19] concluded from their studies that modulus of elasticity bottom ash based geopolymer concrete increases with increase in NaOH content of mix. Drying shrinkage plays a major role in occurrence of cracks in high strength concrete [20]. Several researchers have reported that geopolymer concrete mix of a particular grade exhibits higher values of drying shrinkage in comparison to OPC based concrete of similar grade. Lee et al. [21] conducted studies on shrinkage behaviour of alkali activated fly ash based geopolymer concrete mixes and reported that fly ash-slag based geopolymer paste showed higher drying shrinkage in comparison to OPC paste due to presence of larger volume of mesopore in alkali activated fly ash-slag paste than OPC paste. Majority of the previous studies conducted in the area of alkali activated (geopolymer) concrete were primarily focussed on normal strength concrete mix and assessment of a particular mechanical parameter of that concrete mix. Present study focusses on development of geopolymer and conventional concrete mixes of normal and high strength with systematic evaluation and comparison of fresh and hardened properties of both types of concrete mixes.

2. Experimental plan

In this study, geopolymeric concrete mixes of M40 and M80 grade were prepared using GGBS and fly ash in proportion of 70:30 by weight of total geopolymeric binder. Geopolymeric binder was activated using a combination of alkaline activators i.e. Sodium hydroxide and Sodium Silicate. Dosage of activators were evaluated based on two parameters namely activator modulus and total Na_2O (in terms of percentage by weight of total geopolymeric binder) being contributed from both activators. Both the geopolymeric concrete mixes were evaluated for fresh properties along with mechanical properties of hardened concrete such at different ages. To compare the performance of both normal and high strength slag based geopolymer mixes, two conventional concrete mixes of equivalent grades were prepared and mechanical properties of corresponding geopolymer and conventional concrete mixes have been compared.

3. Materials

For preparation of slag based geopolymeric concrete mixes, Ground granulated blast furnace slag (GGBS) and fly ash were used as source of reactive alumino-silicates in a proportion of 70:30 by weight. The chemical activators used to activate the mix of GGBS and fly ash were a combination of Sodium hydroxide and Sodium Silicate along with potable water. As per the experimental plan, to compare the performance of slag based geopolymer mixes, two conventional concrete mixes of equivalent grades were also prepared using OPC along with fly ash and silica fume as binder. Coarse and fine aggregates were kept same for both geopolymer and conventional concrete mixes. Physical characteristics of GGBS, OPC and silica fume were evaluated as per IS 4031 (Part 2): 1999 [22] and IS 4031 (Part 11): 1988 [23]. Chemical characteristics of GGBS, OPC and silica fume were evaluated as per IS 4032: 1985. Physical and chemical characteristics of fly ash were evaluated as per IS 1727: 1967 [25]. Physical and chemical characteristics of GGBS, fly ash, OPC and silica fume have been tabulated below in Table 1 and Table 2.

Table 1 – Physical Characteristics of GGBS, Fly ash, OPC and Silica fume

S. No.	Physical Parameters	GGBS	Fly ash	OPC	Silica fume
	Fineness (m^2/kg)	335	330	320	16701
	Specific Gravity	2.90	2.33	3.16	2.24

Table 2 – Chemical characteristics of GGBS, Fly ash, OPC and Silica fume

S. No.	Chemical Parameter	GGBS	Fly ash	OPC	Silica Fume
1.	Calcium Oxide (%)	37.66	5.80	60.73	-
2.	Silica (%)	34.60	48.66	20.38	95.02
3.	Reactive silica (%)	33.96	23.52	-	-
4.	Alumina (%)	18.38	26.72	4.95	-
5.	Iron Oxide (%)	0.98	8.87	3.96	0.80
6.	Magnesium Oxide (%)	5.15	1.43	4.78	-
7.	Na2Oeq (%)	0.60	0.74	0.52	-
8.	Loss on Ingnition (%)	0.40	4.76	1.50	1.16
9.	Total Sulphur as SO3 (%)	0.05	0.75	2.07	-
10.	Sulphide sulphur (%)	0.39	0.56	-	-
11.	Chloride (%)	0.024	0.026	0.04	-
12.	Manganese Oxide (%)	1.32	0.13	-	-

Physical and chemical characteristics of GGBS, fly ash, OPC 53G and silica fume (as shown in table 1 and 2) meets the requirements specified in IS 16714: 2018 [26], IS 3812: 2013 [27], IS 269: 2015 [28] and IS 15388: 2003 [29] respectively. The coarse aggregates meeting the specifications mentioned in IS 383: 2016 [30] were used in combined grading taking 20 mm and 10 mm fractions in the ratio of 55:45. Crushed fine aggregate of conforming to Zone-II of IS 383: 2016 was used. Physical characteristics of coarse and fine aggregates used for preparation of concrete mixes have been tabulated in Table 3.

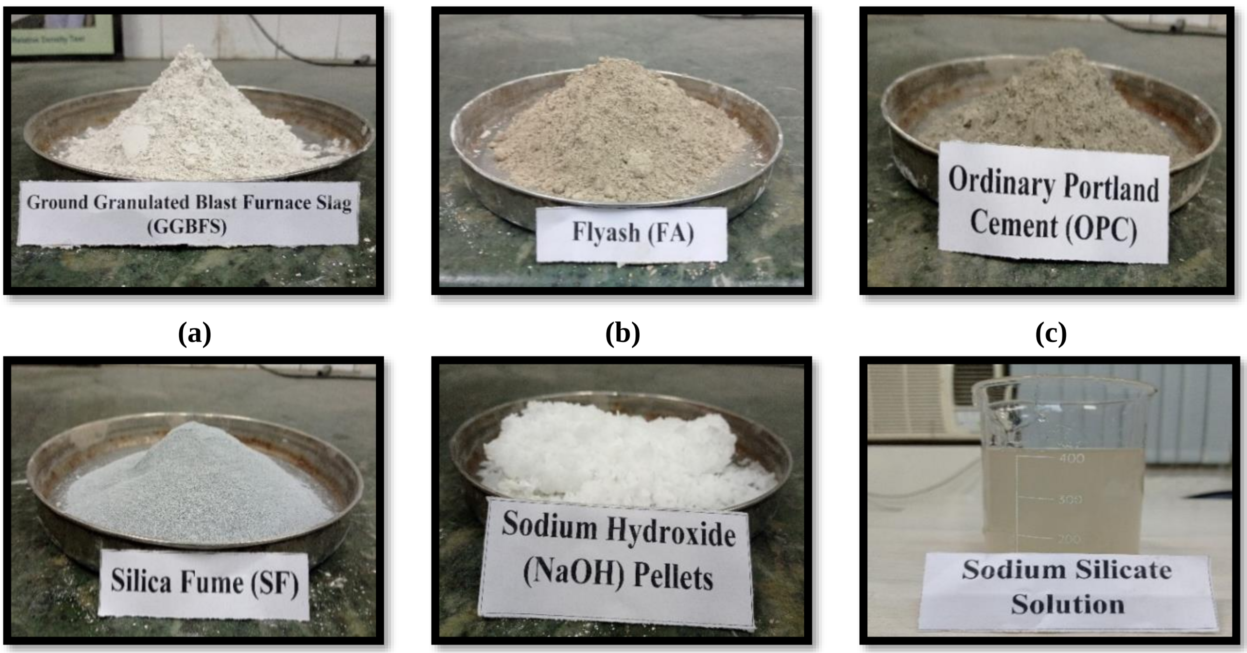
Potable water meeting the requirements of IS 456: 2000 [31] was used for preparing concrete mixes. Commercially available Sodium hydroxide and Sodium Silicate were used as activators for geopolymer concrete mixes. The purity of Sodium hydroxide (NaOH) used as activator was observed to be 97.16%. Along with Sodium hydroxide, Sodium Silicate Gel (Na_2SiO_3) was also used as activator. The composition of Sodium Silicate gel has been tabulated in Table 4. All the materials used for development of geopolymer and conventional concrete mixes has been shown in Fig. 1.

Table 3 – Physical Characteristics of coarse and fine aggregates

Property		Coarse aggregate		Fine Aggregate
		20 mm	10 mm	
Specific gravity		2.83	2.83	2.64
Water absorption (%)		0.3	0.3	0.8
Sieve Analysis Cumulative Percentage Passing (%)	20mm	98	100	100
	10 mm	1	68	100
	4.75 mm	0	2	95
	2.36 mm	0	0	87
	1.18 mm	0	0	68
	600 μ	0	0	38
	300 μ	0	0	10
	150 μ	0	0	2
	Pan	0	0	0
Abrasion Value		19	-	-
Crushing Value		19	-	-
Impact Value		13	-	-

Table 4 – Composition of Sodium Silicate gel

S. No.	Parameter	Results Obtained
1	Appearance	Light Grey Colour
2	Matter Insoluble in water, %	< 0.01
3	Relative Density (at 27° C)	1.55
4	Total Soluble Silicates (%)	48.10



(a) **(b)** **(c)**

(d) **(e)** **(f)**

Fig. 1 – Constituent binder (cementitious) and alkali activators used for development of geopolymer and conventional concrete mixes: (a) Ground granulated blast furnace slag (b) Fly ash (c) Ordinary Portland Cement (d) Silica Fume (e) Sodium Hydroxide (f) Sodium Silicate solution

4. Mix Composition

Two slag based geopolymeric concrete mixes keeping GGBS and fly ash in ratio of 70: 30 by weight of total cementitious binder were prepared and evaluated under this study. Mix trials of alkali activated mixes were conducted by varying the total Na_2O (% by weight of total cementitious binder) from 5% to 8% and keeping activator modulus (ratio of SiO_2 and Na_2O) as 1 and varying water to binder ratio to achieve mixes of varying strength. Based on those trials, two alkali activated concrete mixes were finalised having 28-day compressive strength of 48.93 MPa and 90.80 MPa were selected for further study as they qualify the criteria for concrete mix equivalent to M40 and M80 grade (concrete grades targeted under this study). Amount of water for geopolymeric concrete mixes mentioned in table 5 has been calculated after taking into account the water present in Sodium hydroxide and Sodium Silicate gel. Further, to compare the behaviour of geopolymeric concrete mixes with conventional concrete mixes, two concrete mixes equivalent to M40 and M80 grade were also prepared and evaluated for different fresh and hardened properties. Mix details of aforementioned four concrete mixes have been tabulated below in Table 5. Mixes were designed to have initial slump of at least 75 to 100 mm. PCE based super plasticizer was used to achieve desired level of initial workability in CC40 and CC80. While development of mixes, it was observed that slag based geopolymer concrete of a particular strength/grade was developed at significantly lower binder content in comparison to cementitious binder required to produce conventional Portland cement based concrete of equivalent strength/grade.

Table 5 – Mix details of alkali activated concrete mixes

Mix Parameter		Mix GC40	Mix GC80	Mix CC40	Mix CC80
Total cementitious Binder (kg/m^3)		350	380	362	525
Individual Binders (kg/m^3)	OPC	-	-	290	400
	Silica Fume	-	-	-	50
	GGBS	245	266	-	-
	Fly ash	105	114	72	75
Ratio of water to total cementitious binder		0.50	0.40	0.47	0.27
Na_2O (% by weight of total cementitious binder)		7	8	-	-
Activator Modulus (SiO_2/Na_2O)		1	1	-	-
NaOH (kg/m^3)		17.24	21.39	-	-
Na2SiO3 gel (kg/m^3)		74.20	92.12	-	-
Fine Aggregate (kg/m^3)		690	660.80	650	692
Coarse Aggregate – 10 mm (kg/m^3)		514.50	540	777	754
Coarse Aggregate – 20 mm (kg/m^3)		631	662	518	406
Water (kg/m^3)		132.48*	107.58*	170	140
Chemical Admixture (%)		Nil	Nil	0.70	1.00

* water mentioned in table 4 for GC40 and GC80 has been calculated after taking into account the water present in Sodium hydroxide and Sodium Silicate gel

5. Studies on fresh and hardened properties of concrete mixes

All the aforementioned concrete mixes i.e. GC40, GC80, CC40 and CC80 were prepared and evaluated for different fresh and hardened properties as discussed under section 4.1 and 4.2.

5.1 Fresh Concrete Properties

Fresh concrete properties such as initial workability (in terms of initial slump) and air content after preparation of mix were evaluated for all the 4 concrete mixes and test results are given below in Table 6.

Table 6 – Fresh properties of geopolymeric and conventional concrete mixes

S. No.	Type of mix	Mix	Initial workability in terms of slump	Air Content (%)	Dosage of chemical admixture (%)
1.	Geopolymeric	GC40	Collapse	1.00	Nil
2.		GC80	75 mm	1.30	Nil
3.	Conventional	CC40	95 mm	1.20	0.70
4.		CC80	80 mm	1.70	1.00

Dosage of super plasticizer to achieve desired level of initial workability (i.e. initial slump of at least 75 to 100 mm) has been mentioned in Table 6. In case of geopolymeric mixes, no superplasticizer was required during preparation of mix, as GC40 mix showed collapse behaviour when tested for slump. Whereas, GC80 concrete mix showed initial workability of 75 mm without any super plasticizer. Whereas, conventional concrete mixes CC40 and CC80 required 0.70 and 1.0 % of PCE based superplasticizer to have an initial slump of 95 and 80 mm respectively. All the four concrete mixes were homogenous in nature and showed no signs of segregation and bleeding. Air content of all the concrete mixes are comparable and are observed to be in the range of 1 to 1.7%.

5.2 Hardened Concrete Properties

Hardened concrete properties were evaluated for all the four concrete mixes. Compressive strength test was conducted on concrete cubes (150 mm × 150 mm × 150 mm) as per IS: 516 [32]. Flexural strength test (as shown in Fig. 2) was conducted on concrete beam (size 500 mm ×100 mm × 100 mm) as per IS: 516. Split strength test (as shown in Fig. 3) and modulus of elasticity along with Poisson's ratio (as shown in Fig. 4) were conducted on concrete cylinder (150 mm diameter and 300 mm height) as per IS: 516 (Part 1/Sec 1): 2021 [32] and IS: 516 respectively. Drying shrinkage test (as shown in Fig. 5) was conducted on concrete beam (75 mm ×75 mm × 300 mm) as per IS: 516 (Part 6) - 2020 [33]. Three specimens from each mix were tested for assessment of every parameter and average value of three specimens have been reported. The test results are tabulated in Table 7. Comparison of compressive strength of geopolymeric and conventional concrete mixes at 7 and 28 days has been shown in Fig. 6. Comparison of flexural and split tensile strength of geopolymeric and conventional concrete mixes at 28 days has been shown in Fig. 7.

Fig. 2 – Test set up for evaluation of flexural strength of concrete beam specimen

Fig. 3 – Test set up for evaluation of split tensile strength of cylindrical concrete specimen

Fig. 4 – Test set up for evaluation of Modulus of Elasticity and Poisson's ratio of concrete specimen

Fig. 5 – Test set up for evaluation of drying shrinkage of concrete beam specimen

Table 7 – Hardened properties of geopolymeric and conventional concrete mixes

Mix Type	Equi. Grade	Mix ID	Compressive Strength (MPa)		Flexural Strength (MPa)	Split Tensile Strength (MPa)	Modulus of Elasticity (N/mm2)	Poisson's Ratio	Drying Shrinkage (%)
			7 Days	28 Days	28 days	28 days	28 days	28 days	28 Days
Geopolymer	M40	GC40	43.29	48.93	5.07	4.09	22920	0.175	0.018
Conventional		CC40	29.12	45.72	4.42	3.59	32690	0.180	0.020
Geopolymer	M80	GC80	68.90	90.80	6.73	4.00	35118	0.195	0.019
Conventional		CC80	67.70	88.60	7.08	4.70	42160	0.210	0.019

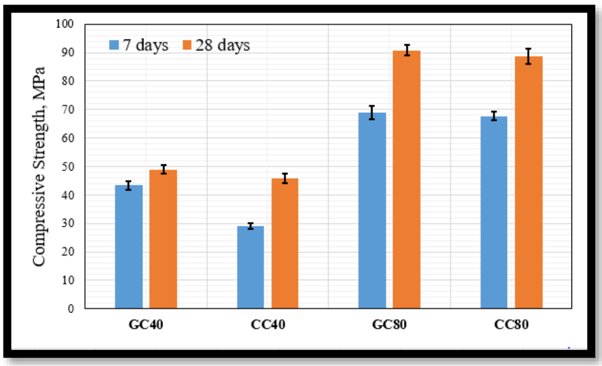


Fig. 6 – Comparison of compressive strength of geopolymer and conventional concrete mixes

Average compressive strength of geopolymer and conventional concrete mixes equivalent to M40 grade at 28 days is 48.93 MPa and 45.72 MPa, which is almost comparable. However, the compressive strength at 7 days for geopolymeric concrete mix is higher in comparison to conventional concrete mix. This shows that the dissolution of reactive alumino silicate ions (present in fly ash and slag) in alkaline media and geopolymeric reactions occurs rapidly and majority of strength gain (around 88%) occurs within first 7 days in geopolymer concrete mix, which is higher in comparison to extent of hydration and strength gain occurring in case of conventional concrete (around 64%) mix of equivalent grade. In case of high strength concrete mixes, compressive strength of both geopolymeric (GC80) and conventional (CC80) concrete mix 7 days were around 76% of their corresponding compressive strength at 28 days and compressive strength of both mixes at 7 and 28 days are similar and comparable. This behaviour can be attributed to lower amount of water and higher concentration of alkalis present in case of high strength geopolymer concrete in comparison to normal strength geopolymer concrete and therefore rate of dissolution of alumino silicate ions and occurrence of geopolymeric reactions is slower in case of high strength geopolymer concrete. Hence, the percentage strength gain after 7 days (76%) in case of high strength geopolymer concrete is lower than the percentage strength gain after 7 days (88%) in case of normal strength geopolymer concrete.

Flexural strength and split tensile strength of concrete has a direct relationship with its compressive strength. For concrete mixes equivalent to M40 grade, the flexural and split tensile strength values of geopolymeric concrete mix (GC40) are slightly higher in comparison to conventional concrete mix (CC40) of equivalent grade at 28 days. This observation is supported by the previous findings as Sarker et al. [1] also reported that flexural strength of alkali activated concrete is higher in comparison to flexural strengths of conventional Portland cement concrete of similar grade. However, the observations in case of high strength concrete mixes equivalent to M80 grade is opposite to the observations made for flexural and split tensile strength of mixes equivalent to M40 grade. For concrete mixes equivalent to M80 grade, the flexural and split tensile strength values of geopolymeric concrete (GC80) mix are lower in comparison to conventional concrete mix (CC80) of equivalent grade at 28 days. This increase in flexural and split tensile strength of high strength conventional Portland cement concrete is similar to findings of Arora et.al [34] wherein it was reported that flexural strength of silica fume concrete was higher by 10- 15% as compared that of Portland cement concrete for about 12-15 % silica fume addition. The silica fume in concrete mix leads to reduction in the development of cracks at micro level near the interface of cement paste and unreacted cement or pozzolanas [35, 36]. This phenomena leads to enhancement of flexural strength for a concrete mix with silica fume than a concrete mix without silica fume. In the other words silica fume besides reacting with free lime of cement and contributing to the development of the strength, bind themselves tightly with cement hydrates in the form of flocks and makes more space for the hydration products (C-S-H gel) of cement grains [37].The test results of split tensile strength are in good agreement with findings of Singh et.al [38] that claims that for lower strength concrete, tensile strength may go upto 10 % of compressive strength; however, for higher strength it reduces to about 5 % of compressive strength.

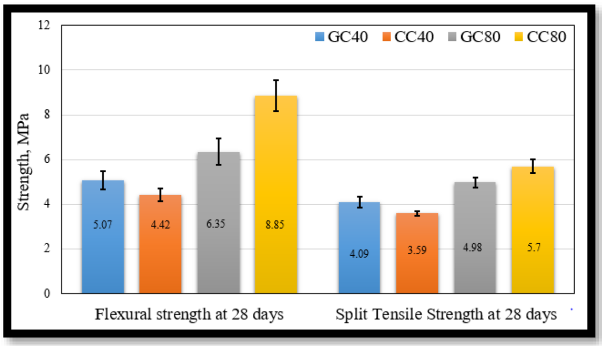


Fig. 7 – Comparison of flexural and split tensile strength of geopolymeric and conventional concrete mixes

Modulus of elasticity is an important engineering property that specifies the concrete stiffness. From table 6, it can be noted that modulus of elasticity and Poisson's ratio of both geopolymeric concrete mixes (i.e. GC40 and GC80 equivalent to M40 and M80 grade respectively) are lower than their corresponding conventional concrete mixes of similar grade. This observation is supported by findings of previous studies by different researchers [24-26] in which they have reported that geopolymer concrete shows a decrease in elastic modulus values when compared by the conventional concrete of the same compressive strength. The intrinsic modulus of C-A-S-H gel formed in slag based geopolymer concrete is comparable with the C-S-H gel formed in cement. But the intrinsic modulus of N-A-S-H gel formed in low-calcium fly ash gel based geopolymer concrete is much smaller than that of the C-S-H gel formed in cement. The lower value of modulus of elasticity for geopolymer concrete than conventional concrete can be attributed to the low intrinsic modulus of N-A-S-H gel and higher initial micro-cracks formulation in geopolymer concrete [27].

Drying shrinkage of both geopolymeric concrete mixes GC40 and GC80 (equivalent to M40 and M80 grade respectively) are observed to similar and comparable to their corresponding conventional concrete mixes i.e. CC40 and CC80 respectively. Similar values of drying shrinkage of geopolymer and conventional Portland cement based concrete may be due to significant proportion (70%) of slag (i.e. GGBS) in binder used for geopolymer concrete. The percentage of major oxides (i.e. CaO, SiO_2 and Al_2O_3) present in GGBS is comparatively closer to Portland Cement as compared to oxides present in fly ash. Therefore, the shrinkage behaviour of slag based geopolymer concrete will be similar to that of conventional Portland cement system which is being reflected in the experimental results. However, for fly ash based geopolymer concrete (having high proportion of fly ash), shrinkage behaviour will different from conventional Portland cement systems. In past studies by Lee et al [21], higher drying shrinkage values were reported for fly ash based geopolymeric concrete mixes in comparison to conventional Portland cement based concrete due to presence of large mesopore volume in alkali activated fly ash based geopolymer mix. However, the proportion of slag in overall binder of geopolymeric concrete mix in present study is significantly higher in comparison to fly ash. Therefore, the drying shrinkage of geopolymer mix of present study is comparable to drying shrinkage of conventional concrete mix.

6. Conclusion

The study presented in this paper is on high calcium geopolymer concrete mixes made up of binder containing GGBS and fly ash in proportion of 70: 30 (by weight) and activated using Sodium hydroxide and Sodium Silicate. Findings of the study cannot be generalised for all types of geopolymer concrete mixes as geopolymer concrete can be prepared by different types of binders, having different proportions and different activators. The fresh and hardened concrete properties of geopolymer mix will vary with the type of binder, type and dosage of activator. Based on experimental study, results and discussions; following conclusions can be made for high calcium geopolymer concrete in comparison to Portland cement concrete:

- Geopolymer concrete of a particular strength/grade can be developed at significantly lower binder content in comparison to cementitious binder required to produce conventional Portland cement based concrete of equivalent strength/grade which leads to development of sustainable concrete with low Co_2 footprint. Early age compressive strength of normal strength high calcium geopolymeric concrete mixes is higher in comparison to conventional concrete mix. Higher early strength in case of geopolymeric concrete mixes can be attributed to quick dissolution of reactive alumino silicate ions (present in fly ash and slag) in alkaline media and occurrence of geopolymeric reactions at early age in geopolymer concrete mix.
- Increase in flexural and split tensile strength of high strength conventional Portland cement concrete in comparison to high calcium

geopolymer concrete can be attributed to presence of silica fume which leads to reduction in the development of cracks at micro level near the interface of cement paste and unreacted cement or pozzolanas. For normal strength concrete both system shows similar results for flexural strength.

- The ratio of split tensile strength to compressive strength is same for both Portland cement concrete and high calcium geopolymer concrete. In case of normal strength concrete, tensile strength may go upto 10 % of compressive strength; however, for higher strength it reduces to about 5 % of compressive strength.
- Modulus of elasticity and Poisson's ratio of geopolymeric mixes of both normal and high grade are observed to be lower in comparison to their corresponding conventional concrete mixes. The lower value of modulus of elasticity for geopolymer concrete than conventional concrete can be attributed to the low intrinsic modulus of N-A-S-H gel and higher initial micro-cracks formulation in geopolymer concrete.
- In case of drying shrinkage, geopolymer mixes of normal and high strength showed drying shrinkage comparable to their corresponding conventional concrete mixes which can be attributed to higher proportion of slag in binder for geopolymer concrete.

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