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Study on Workability and Hardened Properties of Self Compacted GEOPOLYMER Concrete Cured at Ambient Temperature

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Abstract

Objective: To nullify the use of temperature curing in Self Compacted Geopolymer Concrete (SCGC). **Methods/Analysis:** SCGC is developed by activating Ground Granulated Blast Furnace Slag (GGBFS). The workability and compressive strength was studied by varying Sodium Hydroxide molarity from 8M to 12 M. Sodium Silicate and Sodium Hydroxide were used for alkaline solution. The water to geopolymer solid ratio was kept 0.25 for all mixes and the total powder content was 500 kg/m^3. The test specimens were cured at 60^{0}C, 70^{0}C, and at ambient temperature to study the effect of temperature on hardened properties. **Findings:** SCGC satisfied all workability criteria as per the EFNARC guideline. Results show that SCGC with 12M NaOH molarity produced maximum compressive strength. The SCGC specimen cured at 70^{0}C produced the highest hardened properties as compare to 60^{0}C and ambient temperature. As per results, SCGC can be developed at ambient temperature by using GGBFS as a sole binder. **Novelty/Improvement:** GGBFS enhances early age strength properties and the strength is comparable to heat cured SCGC as well as SCC based on OPC.

Keywords: Alkaline Solution, Ambient Curing Temperature, Silicon Dioxide, Sodium Hydroxide, Sodium Silicate

1. Introduction

Concrete is a second major contributor to the release of greenhouse gases in the environment[1]. In[2] has reported that manufacture of cement and emission of green house gases are expected to increase near to 100% up to 2020. It indicates the worst impacts on green house gases emission and hence on global warming[2]. In this view, use of supplementary cementitious materials with cement in the form of by-products from industries proved effective to improve the properties of concrete and also reduces the adverse impact on environment[3]. Geopolymeric concrete received the wide interest due to the benefits of environment for instance the reduction in carbon dioxide emission and reduced consumption of natural resources. The raw materials used for geopolymers do not require high energy consumption. The geopolymer binder produces 5-6 times lesser carbon dioxide emission than Portland cement[4-6]. The use of geopolymer concrete in construction industry reduces emission of carbon dioxide by utilizing the industrial waste and by-product which convert a hazardous material in to an important construction material[5]. Geopolymer concrete is developed by alkaline activation of alumino-silicate materials from geological source or by-product materials like metakaolin, Fly Ash (FA), rice husk ash, silica fume and blast furnace slag[6,7]. The mechanism of alkaline activation is uncertain and the chemical composition of the source materials as well as alkaline activators plays an important role to develop the final geopolymer product[8,9].

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FA with low calcium is most suitable to synthesize the geopolymer paste available in bulk in the world. FA is a fine powder of mainly spherical glass particles having pozzolanic properties which shall consist essentially of reactive silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3), the remainder being iron oxide (Fe_2O_3) and other oxides[10]. The increased use of coal in thermal power plants has increased the production of FA to an estimated more than 3 million tons per year which promote the development of geopolymer concrete. The other waste material which is widely available in the world is GGBFS, a by-product of the production of iron in a blast furnace and it is composed of calcium and magnesium silicates and alumino-silicates. A number of investigations have been studied on the use of GGBFS as a supplementary material in cement production since 1939 and to assess its performance[11]. The GGBFS can be used to develop high quality self compacting concrete[12]. Alkali activated slag concrete had lower resistance to carbonation and alkali-aggregate reaction than that of OPC concrete of similar grade. One tone of GGBFS releases only about 70 kg of carbon dioxide, which is only about 7% release of carbon dioxide of cement for the same quantity of material produced[13,14].

FA based geo-polymer concrete is required high temperature curing which is a challenge for cast in situ construction. The geopolymeric reaction can be accelerated by increasing the fineness of FA. In many experimental studies the FA reactivity in alkaline solution was increased by adding calcium[15-18]. The addition of calcium oxide (CaO) produces hydrated products such as calcium-silicate-hydrates (C-S-H) along with the alumino-silicate geo-polymeric gel[8,19]. It was observed decrease in setting time as well as increase in hardened properties with increase in CaO content[20]. Mechanical properties of ambient cured samples improved by adding calcium oxide and calcium hydroxide as a replacement of FA but in general it shows deteriorated properties when the samples cured at elevated temperature[17,21]. The addition of small amount of hydrated lime increased the early age strength of mixtures blended by FA or slag[22]. The compressive strength of geopolymer mortar increases with increase in content of GGBFS up to 70%. The fine particles of GGBFS resulted in dense mix and therefore the density of mortar formed using GGBFS resulted in increase of density of about 8%[23]. The hardening process is started by the formation of C-S-H and C-A-S-H, and rapid hardening continues on account of an accelerated geopolymerization[24]. The existence of calcium is important for development of early strength because of an improved aluminosilicate gel formation[8,17,25]. The Ca_2^+ present in Ordinary Portland cement and blast furnace slag are able to produce a co-existence of C-S-H gel and geopolymeric gel which is responsible for increase of mechanical strength of geopolymer concrete[26-27]. Higher amount of calcium and sodium compounds besides silicon, aluminium are responsible for the development of calcium- silicate hydrate (C-S-H), calcium-alumino-silicate hydrate (C-A-S-H) and sodium-alumino-silicate hydrate (N-A-S-H). Production of these additional products has produced more compact and dense microstructures[28,29]. Nath et al.[29] investigated that the geo-polymer concrete using FA and blended with GGBFS, OPC or Calcium Hydroxide reduced the setting time of paste to an equivalent value of OPC at ambient temperature curing condition. It also observed that compressive strength of the mixtures blended with the supplements increased from the age of one day. Geo-polymers blended with FA and small percentages of GGBFS, OPC or Calcium hydroxide proved a suitable binder to develop geopolymer concrete from low to medium strength at ambient temperature curing condition[29]. As the percentage of slag increases, its strength also increases and considerable strength can be achieved even at ambient curing[30]. The geopolymer concrete blended with 100% GGBFS attains maximum compressive strength and maximum split tensile strength at all curing periods and the values are greater than that of the conventional concrete[31]. Calcium sources are in general used to speed up the setting time of geopolymers blended with low calcium FA or meta-kaolin. It improved the mechanical properties of the final geopolymer product due to co-existence of C-S-H gel with the geo-polymeric gel[32].

Self Compacting Concrete (SCC) achieves advantages such as the enhancement of quality of concrete, reduction in construction time, easy pouring of concrete through congested reinforcing bars, full compaction with homogenization, and improvement in bond strength and reduction in noise pollution due to the absence of vibration. It also lowers the total costs, and provides safe working atmosphere to the masons[33,45]. The production of SCC used the same ingredients materials as used for the conventional concrete with different mix proportions and required the supplementary chemical and mineral admixtures. SCC usually required a higher amount of ultra fine powder and offers good flowability due to a lesser amount of coarse aggregate, lower water to binder ratio, superplasticizer and viscosity modifying agent[34,35]. The cementitious and mineral materials are used to improve workability and hardened properties and to decrease the cost of construction[36].

Self Compacted Geopolymer Concrete (SCGC) is a new type of concrete which provide the combined advantages of SCC and geopolymer concrete. Till today, very less research work has been carried out on SCGC. Memon et. al[37-41] were studied the fresh properties and compressive strength of FA (low calcium) based SCGC cured at high temperature varies from 60^0C to 90^0C. They studied the effects of temperature curing condition, dosage of superplasticizer and NaOH molarity as well as effect of mix composition on fresh properties and compressive strength of SCGC[37-41,42] Memon et al.[42] studied the effect of silica fume on the fresh and hardened properties of SCGC blended using[42]. The fresh and hardened properties of FA and GGBFS blended SCGC were investigated by Srishaila et al. and Anuradha et al. and concluded that mechanical properties increases as the percentage of GGBFS increases[43,44]. In recent years, there is an increasing awareness on the quantity and variety of hazardous solid waste production and its impact on environment and human health. Increasing concern about the environmental consequences of waste disposal has encouraged researchers to investigate the use of the wastes as potential construction materials. The intention of this experimental study was therefore to investigate the possibility and behavior of SCGC developed by using industrial waste (GGBFS) materials by examining its fresh and mechanical properties. As per the literature review, the majority of the experiments were on FA based geo-polymers samples cured using temperature curing for different duration of time. SCGC produced without using temperature curing has the potential to expand its application to the fields beyond precast construction. This also saves the energy and cost associated with temperature curing. Thus, the aim of this study is to develop SCGC cured at ambient temperature. Ground Granulated Blast Furnace Slag was activated by an alkaline solution mixture of Sodium Silicate and Sodium Hydroxide. The workability characteristics, compressive strength, split tensile strength and flexural strength of SCGC were studied.

2. Materials and Methods

2.1 Materials

The FA, GGBFS were used as an alumino silicate source materials. The same were purchased from local commercial supplier. Table 1 shows the chemical compositions of GGBFS and FA. Alkaline solution plays an important role in geopolymerization. The mixture of Sodium Hydroxide (NaOH) with Sodium Silicate (Na_2SiO_3) is usually used as alkaline activators. Sodium Hydroxide with 98% purity in the form of flakes and Sodium Silicate were obtained from local manufacturer. Locally available crushed aggregates of 14 mm size and river sand as fine aggregates used in the preparation of various mixes. To achieve good workability and required flowability of fresh concrete Master Glenium Sky 8784 superplasticizer supplied by BASF with relative density 1.10 was used.

2.2 Mix Proportions

Seven mixes, one control mix using FA as source material and six mixes using GGBFS as source material were prepared to study workability and strength properties. For all mixes, the water to geopolymer solid ratio (W/Gs) was 0.25 and total powder content was 500 kg/m^3. Mix samples MF, MG1, MG2, MG3, and MG4 were casted to study the effect of molarity of sodium hydroxide varied from 8M, 10M, 12M and 14M. Mixes MF, MG3, MG5 and MG6 were prepared to study the effect of curing temperature (ambient, 60^0C and 70^0C) on the hardened properties of the SCGC at12M. The ratio of Sodium Silicate to Sodium Hydroxide solution for all mixes was 2.5. Extra water of 25% and 6% superplasticizer by mass of the binder were used to achieve the desired workability. The mix proportions as per EFNARC guideline (EFNARC, 2002)[45] are given in Table 2.

Table 1. Chemical compositions of FA and GGBFS

Sample (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	LOI
FA	51.750	34.750	6.0	1.400	1.350	0.040	1.350	0.250	0.450
GGBFS	34.0	14.3	0.500	39.70	9.0	0.350	0.800	0.700	0.050

Table 2. Mix proportions

Mix	FA (Kg/m³)	GGBFS (Kg/m³)	Coarse Aggre-gate (Kg/m³)	Fine Aggregate (Kg/m³)	NaOH		Na-silicate (Kg/m³)	Extra water (%)	SP (%)	Curing Temperature (⁰C)
					Kg/m³	Molarity				
MF	500	-	785	1100	65	12	163	25	6	Ambient
MG1	-	500	785	1100	65	8	163	25	6	Ambient
MG2	-	500	785	1100	65	10	163	25	6	Ambient
MG3	-	500	785	1100	65	12	163	25	6	Ambient
MG4	-	500	785	1100	65	14	163	25	6	Ambient
MG5	-	500	785	1100	65	12	163	25	6	60
MG6	-	500	785	1100	65	12	163	25	6	70

2.3 Sample Preparation and Curing of Specimen

Dry materials of coarse and fine aggregare were mixed in mixture machine for 2.5 min followed by mixing of fine powdered like FA, GGBFS. A premixed alkaline liquid solution, superplasticizer and extra water added in the mixture after dry mixing. Wet mixing at least for 3 min required for homogeneous mixture. To access the fresh properties, workability tests as per EFNARC (2002)[45] were performed. Fresh concrete was mixed again and poured into cubes, cylinders and beams moulds and filled by its own weight without compaction. For each mix nine cubes, nine cylinders and nine beams were casted. The specimens with moulds were kept in the oven at 60⁰C, 70⁰C temperature for 24 hours without delay. One reference mix with 100% FA and other with 100% GGBFS were placed at ambient conditions at room temperature. After 24 hours of oven and ambient curing, specimens were demoulded and kept at room temperature for the air curing up to day of testing.

3. Test Methods

3.1 Fresh Properties Test

The behavior of fresh SCGC is totally different than normal fresh concrete. The concrete can be considered as Self Compacting Concrete (SCC) if it satisfied three characteristics of filling ability, passing ability and segregation resistance as per EFNARC (2002)[45] guidelines. Various methods are suggested by EFNARC to perform the workability tests. Slump flow test, Slump flow at 500 mm, V-funnel, L-box and J-ring tests are used to measure filling ability and passing ability of concrete mix. V-funnel at 5 min, L-box and J-ring test are used to study segregation resistance by measurement and visual observation. Various tests were performed as per EFNARC (2002)[45] and results were reported.

3.2 Hardened Properties

The samples of SCGC were tested to access the compressive strength, splitting tensile strength and flexural strength after oven curing of 24 hours and ambient curing at ages of 3,7 and 28 days. Compressive strength of all SCGC samples was tested on cube specimens of size 150 mm × 150 mm × 150 mm according to the test procedures given in IS: 516 (IS, 1959)[46] using a 2000-kN Digital compressive testing machine at a rate of 5.2 kN/s. The split tensile strength was tested by cylinder splitting test as per IS: 5816[47] on cylinder specimen of size 150 mm x 300 mm. Flexural strength determines the resistance of beam in bending. Beam specimens of size 150 mm × 150 mm × 700 mm were tested to access the flexural strength as per the procedure given in IS : 516 (IS,1959)[46].

4. Results and Discussion

Seven SCGC mixes were prepared to study the effect of Sodium Hydroxide molarity and curing temperature on fresh and hardened properties.

4.1 Fresh Properties

Mix with GGBFS as sole binder, workability in the form of slump flow, V-funnel etc. decreased as the mix become stiffer. The accelerated reaction and fast setting of SCGC increases the resistance against flow. Further the reduction of workability is due to reduced flowability of irregular shaped slag particles. The results of fresh properties of SCGC with Sodium Hydroxide molarity varies from 8M to 14 M are as shown in Figure 1 to 6. The results were compared with the control SCGC mix MF blended with 100% FA as sole binder. It was observed an increase in viscosity of alkaline solution with increase in Sodium Hydroxide molarity and hence mix became more cohesive which resulted in reduction of flowability and fluidity of SCGC mixes. It was also concluded[41,48] in their investigation on SCGC using FA. From Figure 1 to 4, it can be seen that flowability and passing ability in the form of slump flow value and V-funnel time of concrete were influenced due to GGBFS as a binder. Though both the binder were mixed with same amount of activator solution , the control mix MF with 100% FA at 12M has shown the more value of slump flow and lesser V-funnel time. Similar behavior was also described by Nath et al. in their investigation of workability of normal geopolymer concrete[20]. Similar results were observed for L-box test and J-ring test as shown in Figure 5 and 6. Control mix MF (100% FA) showed lower L-box ratio and good J-ring value than values of mix MG3 with 100% GGBFS at 12 M concentration. The workability results of 100% GGBFS mixes for all Sodium Hydroxide concentration are within EFNARC limits.

4.1.1 Slump Flow Test Results

Figure 1 shows the results of slump flow of various SCGC mixes. As per EFNARC guidelines, concrete possessing good filling ability if the slump flow value is between 650 mm to 800 mm. A 720 mm slump flow was observed for the reference mix MF (100% FA). Lowest slump flow value of 690 mm was observed for the mix MG4 with 14M molarity. It was observed reduction in the slump flow value with the increase in Sodium Hydroxide molarity for mixes with 100% GGBFS. With increase in Sodium Hydroxide molarity from 8M to 14M, viscosity of mix increases which further decreases the flowability of SCGC and hence lowers the slump flow value. There was 4.8% decrease in the slump flow value from 8M mix to 14M mix.

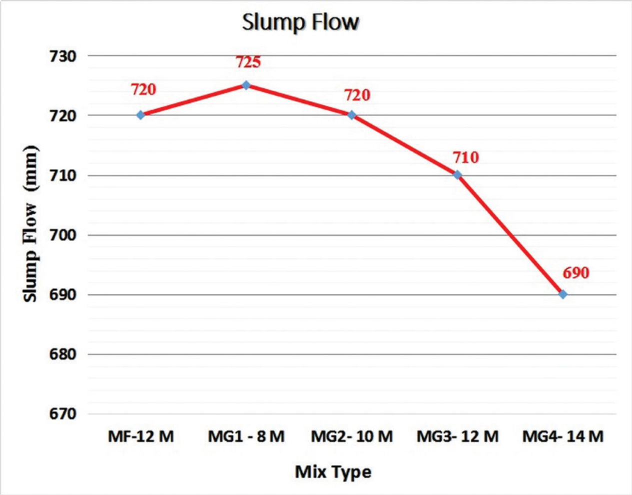

Figure 1. Effect of molarity of NaOH on Slump Flow.

4.1.2 T_{50}cm Slump Flow Test Results

With the slump flow diameter measurement, the time is recorded for the concrete mix to spread up to a 500 mm diameter. This flow time is called T_{50}cm slump flow. A lesser time suggests good flow ability as per EFNARC (2002)[45]. Figure 2 shows the results of T_{50cm} slump flow time. As per results, various SCGC mixes achieved the T_{50cm} slump flow value varies from 3.5s to 5s. The permissible values as per EFNARC (2002)[45] is between 2 sec to 5 sec. All mixes satisfy the EFNARC criteria. A minimum slump flow time of 3.5s was observed for the mix MG1with Sodium Hydroxide molarity of 8M. Maximum T_{50cm} slump flow time of 5s was observed for mix MG4 with Sodium Hydroxide molarity of 14M. With the increase the Sodium Hydroxide molarity viscosity of mix increases which further reduced the fluidity of concrete and hence results in increase of T_{50cm} time.

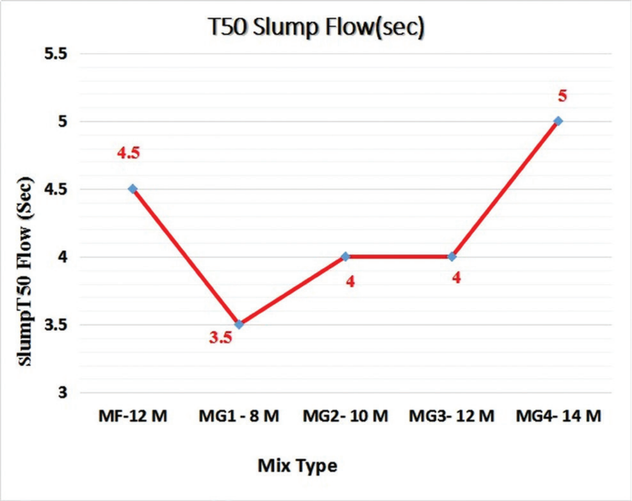

Figure 2. Effect of molarity of NaOH on T_{50cm} Slump Flow.

4.1.3 V-Funnel Test Results

The stability and flowability of SCGC mixes activated by 8M to 14M Sodium Hydroxide molarity were assessed by V-funnel test. Figure 3 and 4 show the results of V-funnel flow time and flow time at $T_{5\ min}$. As per results, the V-funnel flow time varies from 6 sec to 11 sec for various SCGC mixes. As per EFNARC (2002), the acceptable limits of V-funnel flow values are between 6 sec to 12 sec. Mix MG1 with 8M Sodium Hydroxide molarity achieved minimum flow time of 6 sec. A maximum flow time of 11 sec was achieved for mix MG4 with 14 M Sodium Hydroxide molarity. There was reduction in fluidity and flowability of SCGC with increase in the molarity which resulted in increase of V-Funnel flow time. Same behavior is observed for T_{5min} flow time.

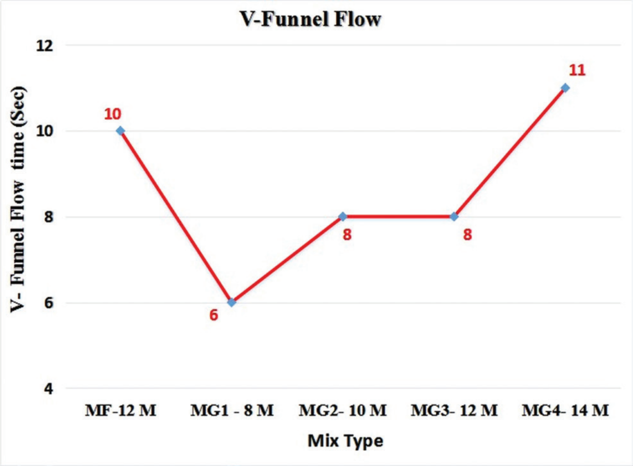

Figure 3. Effect of molarity of NaOH on V-funnel flow.

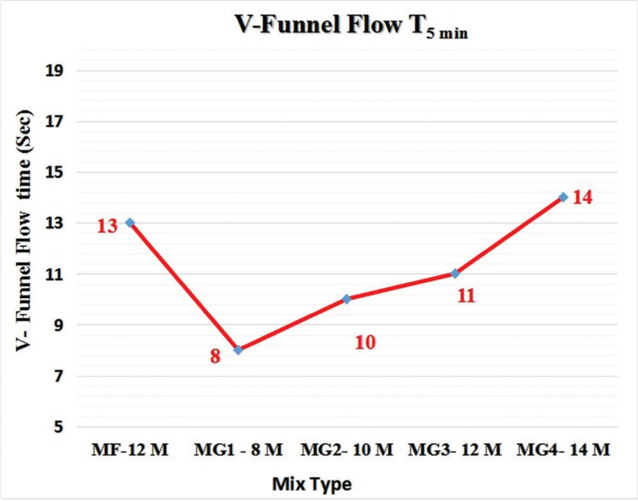

Figure 4. Effect of molarity of NaOH on V-funnel at $T_{5\ min}$.

4.1.4 Results of L-box Test

Figure 5 shows the results of L-Box. A mix is considered possessing good passing and filling ability if the L-box ratio is between 0.8 and 1.0. As per the visual observation, all SCGC mixes easily passed through the reinforcing bars of L-box without any blockage. It was observed decrease in blocking ratio from 8M to 14M due to increase in viscosity. The maximum blocking ratio of 0.97 for mix MG1 with 8M and minimum blocking ratio of 0.90 for mix MG4 with 14M was recorded. Visual observation showed good resistance to segregation for mix MG1.

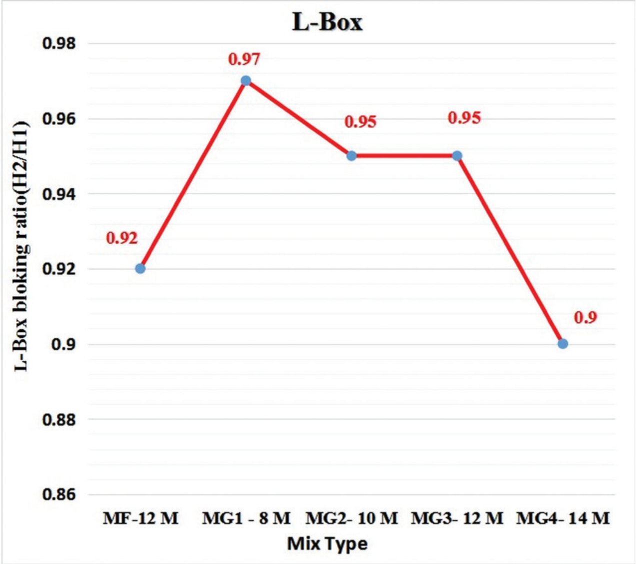

Figure 5. Effect of molarity NaOH on L-Box ratio.

4.1.5 J-Ring Test Results

J-Ring test is used to access flowing and passing ability of concrete mix. Figure 6 shows the results of the J-Ring test. Satisfactory range of blocking step is 0-10 mm as per EFNARC (2002)[45]. As per the visual observations and recorded values all five mixes showed good passing ability and J-Ring values. The J-Ring value of various SCGC mixes were within the acceptable limits of 0-10 mm as per EFNARC (2002)[45]. A minimum value of 5 mm was recorded for mix MG1 with 8M. The highest value of 8 mm was observed for mix MG4 with 14M. As the molarity increases from 8M to 14M, flowability and passing ability of fresh concrete reduces and hence increase in the J-Ring value was observed.

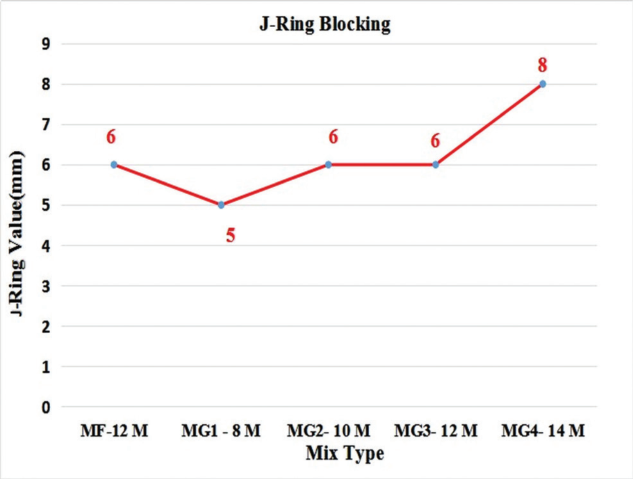

Figure 6. Effect of molarity of NaOH on J-ring blocking.

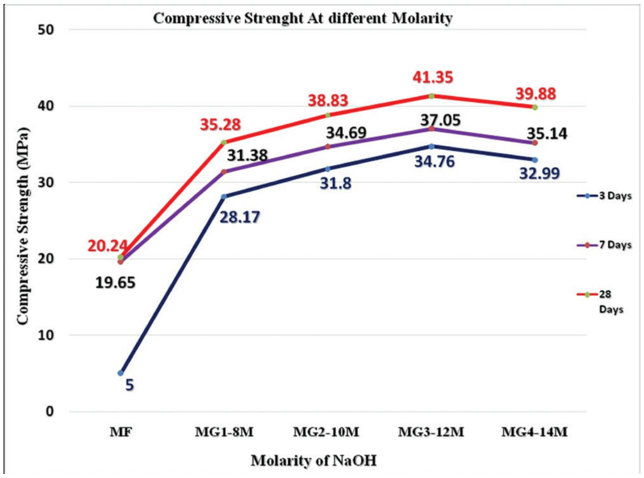

Figure 7. Variation of compressive strength with different NaOH molarity.

4.2 Hardened Properties

4.2.1 Compressive Strength

4.2.1.1 Effect of Morality of Sodium Hydroxide on Compressive Strength

Sodium Hydroxide is essential to activate the alumino-silicate source material to develop geopolymer concrete. It plays an important role in dissolution process and in bonding of solid particles. The increase in molarity of activating solution increases the solubility of alumino-silicate materials. With higher Sodium Hydroxide molarity, production of reactive bond increases which further increases the compressive strength of geopolymer concrete. This is due to the faster dissolution of alumina and silica from source material into the solution, thereby aiding the formation of larger amounts of alumino-silicate polymeric gel which accelerate the geo-polymerization. It was observed increasing trend in compressive strength of SCGC specimen as Sodium Hydroxide molarity increases from 8 M to 12M. After 12M it decreased with further increase in Sodium Hydroxide molarity. At 14M more hydroxide ions precipitate in aluminosilicate gel at very early age of geopolymerization and hence delayed next reaction process resulting in lower strength[42]. The results of compressive strength of SCGC mixes activated by different molarity are as shown in Figure 7.

If mix MF with 100% FA is considered as reference mix, it was observed 74.31%, 91.85%, 104.30% and 97.04% increase in compressive strength of mixes MG1, MG2, MG3 and MG4 respectively at 28 days. Mix MG3 with 12M achieved highest compressive strength of 34.79MPa, 37.05MPa and 41.35 MPa at 3, 7 and 28 days respectively. It was observed that there was an increase in compressive strength from 8M to 12M but decreased from 12M to 14M for all days of testing. It was observed 28.17 MPa, 31.8MPa, 34.76MP and 32.99MPa compressive strength in mixes activated by 8M, 10M, 12M and 14M respectively at 3 days. It was 12.89%, 23.39%, and 17.11% increase in strength of 10M, 12M and 14M mixes with compared to strength of 8M mix at 3 days. It was observed 31,38MPa, 34.69MPa, and 37.05MPa and 35.14MPa compressive strength of mixes with 8M 10M, 12M and 14M respectively at 7 days. It was 10.55%, 18.07%, and 11.98% increase in strength of 10M, 12M and 14M mixes with compared to strength of 8M mix. It was 35.28 MPa, 38.83MPa, 41.35MPa and 39.88MPa compressive strength of mixes 8M, 10M, 12M and 14M respectively at 28 days. It was 10.06%, 17.21%, 13.04% increase in strength of 10M, 12M and 14M mixes with compared to strength 8M mix. The compressive strength of mix MG2 was 12.89%, 10.55% and 10.06% higher than the compressive strength mix MG1 at 3, 7 and 28 days respectively. The compressive strength of mix MG3 was 9.31%, 6.80% and 6.49% higher than mix MG2 at 3, 7 and 28 days respectively. It was observed decreasing rate of increase in strength as molarity increases from 8M to12 M. The compressive strength of mix MG4 was decreased 5.09%, 5.16% and 3.56% with respect to mix MG3 at 3, 7and 28 days respectively. Increase of 12.43%, 11.93%, 11.61% and 13.49% compressive strength was observed at 28 days for mixes with 8M, 10M, 12M and 14M respectively with respect to compressive strength at 7 days.

4.2.1.2 Effect Of Curing Temperature on Compressive Strength

As[5] curing temperature plays an important role in the geo-polymerization process of geo-polymer concrete using FA. They have concluded that higher curing temperature accelerates the rate of geopolymerization process, which ultimately accelerates the hardening of geopolymer concrete[5]. Most of the investigations on geopolymer concrete blended with FA were adopted high temperature curing in the range of 60-90^{0}C. Previous experimental study on FA based normal and SCGC concluded that an increase in curing temperature beyond 70^{0}C did not increase the strength considerably. In this study, samples at12M were oven cured at 60^{0}C, 70^{0}C for 24 hours instantly after casting to compare with samples cured without oven temperature curing. High temperature curing improved the early age strength but at longer age the increase in strength is not significant. In contrast, strength developed progressively when samples were cured without temperature curing. The compressive strength of 100% FA mix and 100% GGBFS mix with 12 M Sodium Hydroxide molarity cured at ambient temperature was tested and compared. The compressive strength of 100% GGBFS mix cured at ambient temperature was also compared with the strength of the mixes cured at 70^{0}C and 60^{0}C temperature. The effect of temperature curing on compressive strength is shown in Figure 8.

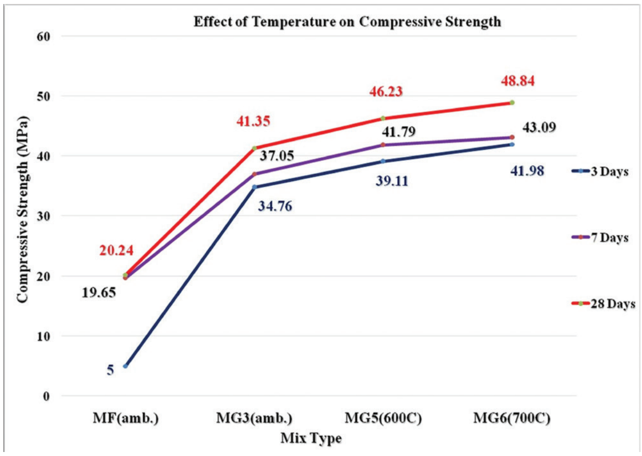

Figure 8. Variation of compressive strength with different curing temperature.

The reference mix MF (100% FA) was found to be very weak to produce a desired strength even after three days of casting when cured at an ambient temperature, while it is 34.76 MPa at 3 days for mix with 100% GGBFS at ambient temperature. As shown in Figure 8, mix with 100 % GGBFS at 12 M molarity, the compressive strength increased considerably from the early age of 3 days. At 3 days, ambient cured mixes reduced only about 11.12% and 17.20% of the strength achieved by the same samples cured at 60^{0}C and 70^{0}C and reduced 10.55% and 15.33% strength after 28 days. It was observed 20.24 MPa, 41.35MPa, 46.23MPa and 48.84 MPa compressive strength for mixes MF (100% FA), MG3 (100% GGBFS-amb.), MG5 (100% GGBFS-60^{0}C), and MG6 (100%GGBFS-70^{0}C) respectively at 28 days. It was increased by 104.30%, 128.41%, and 141.30% in comparison with the strength of the reference mix MF. Inclusion of CaO in GGBFS accelerates setting of geopolymer and hence increased strength at early age. The accelerated strength development of GGBFS based mix is due to the reaction of extra calcium present in GGBFS. When mixed with water, CaO generates heat which helps to begin condensation reaction in the FA based geo-polymer mix at room temperature. In[20] concluded that the geo-polymer paste with 50% GGBFS is more compact with less porosity than paste with10% GGBFS, which increases the strength of geopolymer mixes. The calcium compound increased with the increase of GGBFS percentage in the mix and formed a calcium-alumino-silicate (C-A-S-H) gel[20]. Hence it is concluded that addition of GGBFS supply additional calcium compound and produces additional binding product which modified the setting behavior of geopolymeric gel at early age[20]. GGBFS consist of the high CaO content apart from a high silica and alumina contents, while the CaO content in FA is very low. GGBFS is more amorphous which is more reactive as compared to FA which is crystalline phases of silica and alumina[49]. Geopolymerization of GGBFS formed a mixture of C-S-H gel from CaO and alumino-silicate gel from SiO_2 dissolution. In[50] concluded the same that there is a presence of C-S-H gel when an OPC blended FA was activated with water glass and Sodium Hydroxide solution[50]. It is also concluded[51,52] that, the co-existence of C-S-H with geo-polymer gel has also been observed for the blending of other calcium bearing binder with FA activated by alkaline solution[51,52]. Two different geo-polymerization gels blended together developed a geopolymer synthesis more likely as calcium-alumino-silicate (C-A-S-H) hydrate as concluded[53,54]. The gel with precipitation of (C-A-S-H) contributes to the hardening and early age strength development of the SCGC based on GGBFS. Though curing of the SCGC mix (MG5, MG6) blended by GGBFS and cured at high temperature (60^{0}C, 70^{0}C) develops early strength, the temperature curing is not available in cast-in-situ construction. However the same mix (MG3) can achieve the reasonable strength at ambient temperature condition slowly at longer duration just like OPC concrete.

4.2.1.3 Effect of Curing Temperature on Split Tensile Strength

The results of split tensile strength of SCGC mixes are as shown in Figure 9.

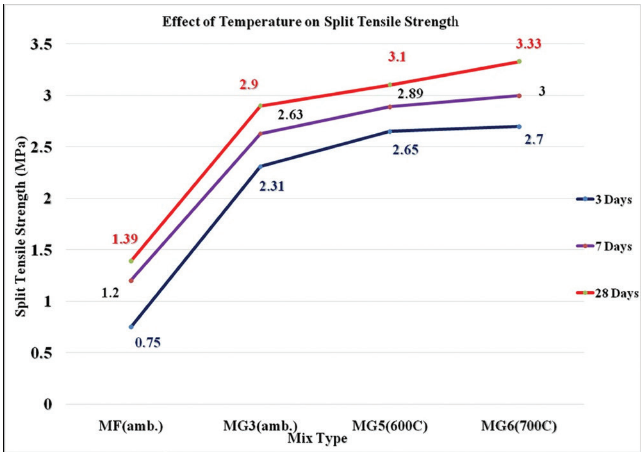

Figure 9. Variation of split tensile strength with different curing temperature.

It was observed increase in split tensile strength with increase in the curing temperature with the same trend as compressive strength. The split tensile strength of control mix MF (100% FA) achieved 1.39MPa, whereas mixtures MG3 (100% GGBFS-amb.), MG4(100% GGBFS-60^{0}C), and MG5 (100% GGBFS-70^{0}C), achieved the strength of 2.9 MPa,3.1MPa and 3.33 MPa, respectively at 28 days, increasing by 108.63 %,123.02 %, and 139.57% in comparison with strength of the reference mix. The split tensile strength of control mix MF with 100% FA at ambient temperature is very lower than the strength of the mix MG3 with 100% GGBFS at ambient temperature. This is also due to the high percentage of calcium and sodium in addition to silicon and aluminium which developed extra calcium-silicate hydrate or calcium-alumino-silicate hydrate and sodium alumino-silicate hydrates in mixes. These complementary products have resulted in the more compact and dense microstructures which increase strength of geopolymer.

4.2.1.4 Effect of Curing Temperature on Flexural Strength

The results of flexural strength test of SCGC mixes are as shown in Figure 10.

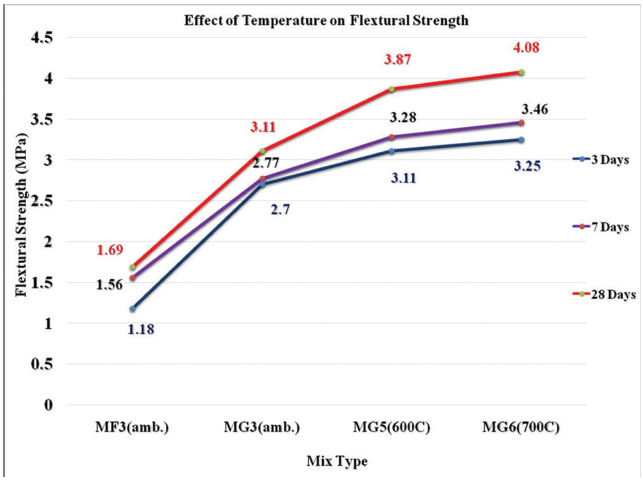

Figure 10. Variation of flexural strength with different curing temperature.

It was observed increase in flexural strength with increase in curing temperature. The flexural strength of control mix MF (100% FA) achieved 1.69MPa, whereas mixtures MG3 (100% GGBFS-amb.), MG4 (100% GGBFS-60 ^{0}C), and MG5 (100%GGBFS-70^{0}C), achieved the strength of 3.11 10MPa, 3.87 MPa and 4.08 MPa at 28 days respectively at 28 days, which increased by 84.02 %, 128.99 %, and 141.42% in comparison with the strength of the reference mix. The flexural strength of reference mix MF with 100% FA at ambient temperature curing is very lower than the strength of the mix MG4 with 100% GGBFS at ambient temperature. The development of extra calcium-silicate hydrate or calcium-alumino-silicate hydrate and sodium alumino-silicate hydrates are responsible for the increase in the strength.

5. Conclusions

- As the Sodium Hydroxide molarity increases from 8M to 12M, it was observed decrease in fluidity and flowability of SCGC mixes, though all mixes meet the requirements of SCGC as per the EFNARC guidelines,
- The mix with 12M Sodium Hydroxide molarity achieved highest compressive strength. After 12 M, increase in molarity decreases the compressive strength due to excess hydroxide ion concentration which lowers the rate of geo-polymer formation,
- The mix with 100% FA failed to achieve the early strength at ambient temperature,
- Improvement of mechanical properties of GGBFS based SCGC was observed with increase in the curing temperature varies from ambient to 60^0C-70^0C due to fast geo-polymerization,
- At ambient temperature, mix MG3 with 100% GGBFS developed 41.35 MPa, 2.9MPa, 3.11MPa compressive strength, split tensile strength and flexural strength respectively after 28 days of curing,
- It is feasible to develop SCGC at ambient temperature using GGBFS as sole binder,
- High temperature curing of the SCGC blended with GGBFS as a sole binder achieves high early strength but heat curing is not preferable in cast-in-situ construction. The same mix sample cured at ambient temperature achieves required strength gradually at longer age just like OPC concrete, which also reduces the consumption of energy and cost of heat curing, and
- Use of GGBFS to develop SCGC indirectly reduces the emission of green house gas CO_2 in the atmosphere released from the cement industries.

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