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Compressive Strength and Workability Characteristics of Low-Calcium Fly ash-based Self-Compacting Geopolymer Concrete

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Abstract**—**Due to growing environmental concerns of the cement industry, alternative cement technologies have become an area of increasing interest. It is now believed that new binders are indispensable for enhanced environmental and durability performance. Self-compacting Geopolymer concrete is an innovative method and improved way of concreting operation that does not require vibration for placing it and is produced by complete elimination of ordinary Portland cement.

This paper documents the assessment of the compressive strength and workability characteristics of low-calcium fly ash based self-compacting geopolymer concrete. The essential workability properties of the freshly prepared Self-compacting Geopolymer concrete such as filling ability, passing ability and segregation resistance were evaluated by using Slump flow, V-funnel, L-box and J-ring test methods. The fundamental requirements of high flowability and segregation resistance as specified by guidelines on Self Compacting Concrete by EFNARC were satisfied. In addition, compressive strength was determined and the test results are included here. This paper also reports the effect of extra water, curing time and curing temperature on the compressive strength of self-compacting geopolymer concrete. The test results show that extra water in the concrete mix plays a significant role. Also, longer curing time and curing the concrete specimens at higher temperatures will result in higher compressive strength.

Keywords**—**Fly ash, Geopolymer Concrete, Self-compacting concrete, Self-compacting Geopolymer concrete

I. INTRODUCTION

THE economic strength and even degree of civilization of any country is reflected by the growth rate of the infrastructures and highlighted by the production rate of concrete. Concrete is one of the most far used construction materials in the world. Portland cement (PC); an essential constituent of concrete is not an environmentally friendly material. The production of PC not only depletes significant amount of natural resources but also liberates a considerable amount of Carbon dioxide (CO_2) and other greenhouse gases in to the atmosphere as a result of decarbonation of limestone and the combustion of fossil fuels.

It is reported that the worldwide cement industry contributes around 1.65 billion tons of the greenhouse gas emissions annually [1]-[3]. Due to the production of PC, it is estimated that by the year 2020, the CO_2 emissions will rise by about 50% from the current levels [4], [5]. Therefore, to preserve the global environment from the impact of cement production, it is now believed that new binders are indispensable to replace PC. In this regard, the geopolymer concrete (GC) is one of the revolutionary developments related to novel materials resulting in low-cost and environmentally friendly material as an alternative to the PC [6], [7]. GC is an innovative binder material and is produced by totally replacing the PC. It is demonstrated that the geopolymeric cement generates 5–6 times less CO_2 than PC [8]. Therefore, the use of geopolymer technology not only significantly reduces the CO_2 emissions by the cement industries, but also utilises the industrial wastes and/or by-products of alumino-silicate composition to produce added-value construction materials [1], [9].

Earlier, most of the research study was focused on geopolymer synthesis from metakaolin [6], [10], [11], however since last decade, much research has been done on Fly Ash (FA) to investigate the possibilities of using coal FA as an alumina-silicate source material. FA, which is rich in silica and alumina, has full potential to use as one of the source material for Geopolymer binder [12]. Many research studies [13]-[16] have manifested the potential use of FA-based GC. For this reason, low-calcium FA has been chosen as a base material to synthesize geopolymer in order to better utilise this industrial waste.

In fact, all concretes almost rely essentially on being fully compacted.In case of large and complicated structures; it is sometimes become difficult to ensure full compaction. Despite the good mix design, inadequate compaction significantly lowers ultimate performance of concrete. Placement of the fresh concrete requires skilled operatives to ensure adequate compaction to attain the full strength and durability of the hardened concrete [17], [18]. As concrete is produced and placed at construction sites, under situations far from ideal, conventional vibrating concrete in such situations may cause risk to labour and there are always doubts about the strength and durability of concrete placed in such locations [19]. One of the solutions to overcome these difficulties is the employment of Self- Compacting Concrete (SCC) [18], [20].

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Open Science Index, Civil and Environmental Engineering Vol:5, No:2, 2011 publications.waset.org/3527/pdf

SCC is a type of concrete which can be compressed into every corner of the form work purely by means of its own weight. SCC has been developed to ensure adequate compaction and facilitate placement of concrete in structures with congested reinforcement and in restricted areas. It is generally accepted that SCC was developed first in Japan in the late 1980s in response to the lack of skilled labour and the need for improved durability. According to Ouchi [21], the need for SCC was first identified by Okamura in 1986 and the first prototype was developed in 1988. SCC offers many benefits and advantages over traditional concrete. These include an improved quality of concrete, reduced construction time, easier placement in congested reinforcements, uniform and complete consolidation, increased bond strength, reduced noise levels due to absence of vibration, lower overall costs, and safe working environment [17], [22], [23].

Self-compacting Geopolymer concrete (SCGC) is relatively a new concept and can be regarded as the most revolutionary development in the field of concrete technology. SCGC is an innovative type of concrete that does not require vibration for placing it and can be produced by complete elimination of ordinary Portland cement.

This paper presents the preliminary results of an ongoing research study on mechanical behaviour of low-calcium FA-based self-compacting Geopolymer Concrete. In this part of the study, workability characteristics and compressive strength of SCGC made from low-calcium FA were assessed. The test results substantiate the viability to develop SCGC.

II. RESEARCH SIGNIFICANCE

To date various research studies have been conducted by many of the researchers on the behavior of conventional SCC and that of FA-based GC in both fresh and hardened states, however, to the authors' knowledge no published work or research study has been conducted so far around the world on SCGC. There is a need to investigate the viability of using SCGC by examining its basic physical and mechanical properties. Therefore, this research is dedicated to develop FA-based SCGC by utilizing locally available constituent materials that would satisfy the requirements of concrete both in fresh and hardened state. The worth of this research study lies in its attempt to provide some performance data of SCGC, so as to draw attention to its possible use of SCGC.

III. EXPERIMENTAL DETAILS

A. Materials for Concrete Mixture

1. Fly ash

In this research study, Low-calcium (ASTM Class F) Fly ash obtained from Manjung Power Station, Lumut, Perak, Malaysia was used as a source material for the synthesis of SCGC. The chemical composition of FA as determined by X-Ray Fluorescence (XRF) analysis is shown in Table I.

2. Aggregates

A good quality, well graded coarse aggregate of maximum size 14 mm was used in the preparation of all test specimens. Natural Malaysian sand with the fineness modulus of 2.76 was used as fine aggregate. The grading curve of fine aggregate came under the umbrella of gradation zone-2. Fine aggregate was also sieved for the size less than 5mm.

3. Alkaline Solution

In geopolymerization, alkaline solution plays an important role. The most common alkaline solution used in geopolymerisation is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate (Na_2SiO_3) or potassium silicate (K_2SiO_3). In this study, a combination of sodium silicate and sodium hydroxide was chosen as the alkaline liquid. Sodium-based solutions were chosen because they are cheaper than Potassium-based solutions.

Sodium Silicate (Grade A53 with SiO_2 = 29.43%, Na_2O = 14.26% and water = 56.31%) obtained from Malay-Sino Chemical Industries Sdn Bhd, Malaysia was used in solution form while Sodium hydroxide supplied by QuickLab Sdn Bhd, Malaysia was in pellets form with 99% purity. Concentration of NaOH was kept 12M and in order to make 1 Kg of solution, 44.1% of pellets were dissolved in the 55.9% of water. Both the liquids were mixed together and alkaline solution was prepared.

In order to achieve superior workability and required flowability of the fresh concrete, a commercially available superplasticizer named as Sika Viscocrete-3430 supplied by Sika Kimia Sdn Bhd, Malaysia, and a specified amount of extra water was also used in the mix. The ordinary drinking water available in concrete laboratory was used for this purpose.

TABLE I
CHEMICAL COMPOSITION OF FLY ASH
AS DETERMINED BY XRF [24]

Oxide	(%) by mass	Requirements as per	
		BS EN 450-1:2005	ASTM C 618 Class F
Silicon dioxide (SiO_2)	51.19	min. 25%	-
Aluminum oxide (Al_2O_3)	24.0	-	-
Ferric oxide (Fe_2O_3)	6.60	-	-
Total $SiO_2 + Al_2O_3 + Fe_2O_3$	81.79	min. 70%	min. 70%
Calcium oxide (CaO)	5.57	-	-
Magnesium oxide (MgO)	2.40	max. 4%	max. 5%
Sulphur trioxide (SO_3)	0.88	max. 3%	max. 5%
Potassium oxide (K_2O)	1.14	-	-
Sodium oxide (Na_2O)	2.12	max. 5%	max. 1.5%

B. Mix Proportion

In this study, FA-based geopolymer was used as the binder instead of ordinary Portland cement based paste to produce concrete. The manufacture of SCGC was carried out by using the traditional trial and error concrete technology methods. In the beginning, numerous trial mixtures of SCGC were manufactured. A total of ten mixtures were made to assess the workability characteristics and study the influence of various parameters on the compressive strength. The details of these mixtures are given in Table II. The alkaline solution to FA ratio was kept constant at 0.5 whereas the ratio of sodium silicate to sodium hydroxide solution was kept 2.5 for all mix proportions.

TABLE II
DETAILS OF MIX PROPORTIONS

Mix Code	Fly Ash	C.Agg	F.Agg	Sodium Hydroxide		Sodium Silicate	Alkaline/ Fly ash	Super plasticizer		Extra water		Curing	
												Time	Temp.
	Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3	Mol.	Kg/m^3	Ratio	Kg/m^3	%	Kg/m^3	%	hrs	°C
M_1	400	950	850	57	12	143	0.5	28	7	40	10	24	70
M_2	400	950	850	57	12	143	0.5	28	7	48	12	24	70
M_3	400	950	850	57	12	143	0.5	28	7	60	15	24	70
M_4	400	950	850	57	12	143	0.5	28	7	80	20	24	70
M_5	400	950	850	57	12	143	0.5	28	7	48	12	48	70
M_6	400	950	850	57	12	143	0.5	28	7	48	12	72	70
M_7	400	950	850	57	12	143	0.5	28	7	48	12	96	70
M_8	400	950	850	57	12	143	0.5	28	7	48	12	48	60
M_9	400	950	850	57	12	143	0.5	28	7	48	12	48	80
M_{10}	400	950	850	57	12	143	0.5	28	7	48	12	48	90

C. Test Methods to assess Workability Characteristics

A concrete mix can only be categorised as SCC if the requirements for all the three workability properties are fulfilled. The three essential fresh properties required by SCC are filling ability, passing ability and resistance to segregation. A number of test methods have been developed to measure and assess these properties; however, no single test method is capable of assessing all the workability properties at once. As these properties are interrelated, most tests indirectly measure more than one property at a time. The European Guidelines EFNARC [22], has proposed five test methods to fully characterize an SCC mix. Table III lists the test methods along with their recommended values given by EFNARC.

TABLE III
TEST METHODS AND RECOMMENDED LIMITS AS PER EFNARC GUIDE LINES [22]

S.No.	Test	Permissible limits as per EFNARC Guide lines	
		Min.	Max.
1.	Slump flow by Abrams Cone	650 mm	800 mm
2.	$T_{50\ cm}$ Slump flow	2 s	5 s
3.	V-funnel	6 s	12 s
4.	L-Box (H_2 /H_1)	0.8	1.0
5.	J-Ring	0 mm	10 mm

1. Slump Flow Test

This is the simplest and most widely used test method for evaluating the flowability of SCC. This test is used to assess the flow rate of SCC in the absence of obstructions and gives a good assessment of filling ability. The basic equipment used in this test is the traditional slump cone used for the conventional slump test; however, the concrete placed into the mould is not rodded. To perform the test, slump cone is placed on a rigid and non-absorbent leveled plate and filled with concrete without tamping. After filling the slump cone, it is raised vertically and concrete is allowed to flow out freely. The diameter of the concrete in two perpendicular directions is measured and the average of the two measured diameters is recorded. There is no standardized threshold limit for the slump flow value, however, according to EFNARC guide lines, SCC is assumed of having a good filling ability and consistency if the diameter of the spread is in the range of 650mm to 800mm. This test is simple to perform and can give lots of information about a typical SCC mix. Visual observations during the test and/or measurement of the T_{50cm} flow time can give additional information on the segregation resistance.

2. $T_{50\ cm}$ Slump Flow

At the time of performing the slump flow test, the time taken in seconds from the instant the cone is lifted to the instant when the flow spread reaches a 500 mm circle is recorded. This flow time, termed as $T_{50\ cm}$ Slump flow, gives an indication of the relative viscosity and provides a relative assessment of the unconfined flow rate of the SCC mixture. A lower time indicates greater flow ability. It should be noted that T_{50} times will be less meaningful and perhaps more variable for highly viscous mixes than for mixes with lower T_{50} times. This test generally not be used as a factor in rejection of a batch of SCC but rather as a quality control diagnostic test.

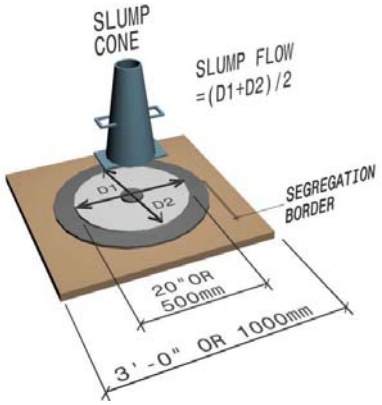


Fig. 1 Slump Flow Test

3. V-Funnel Test

This test is primarily used to measure the filling ability (flowability) of SCC and can also be used to evaluate segregation resistance. The equipment used in this test consists of a V-shaped funnel, as shown in Fig. 2. Various dimensions of V-Funnel are used but mostly the opening size at the bottom is 65 mm x75 mm or 75 mm x 75 mm.

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Open Science Index, Civil and Environmental Engineering Vol:5, No:2, 2011 publications.waset.org/3527/pdf

To perform this test about 12 liters (0.4 ft^3) of concrete is needed and the funnel is completely filled with concrete without tapping or compaction. After filling the funnel with concrete, the trap door at the bottom is opened and concrete is allowed to flow out under gravity and the time taken for the concrete to flow out completely through the orifice is recorded as the V-funnel flow time. This test is used to evaluate the ability of the SCC to flow through a continuously reducing section without segregation and blocking. The funnel flow time between 6-12 seconds is generally desired for SCC.

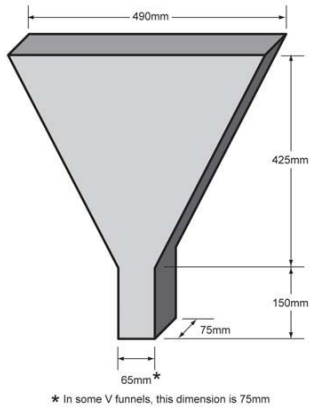


Fig. 2 V-Funnel Apparatus

4. L-Box Test

The L-box test is used to assess the filling and passing ability of SCC. This is a widely used test suitable for laboratory as well as site use. The L-box, as shown in Fig. 3, consists of a rectangular-section box in the shape of L, with a vertical and horizontal section, separated by a moveable gate, in front of which vertical reinforcement bars are fitted.

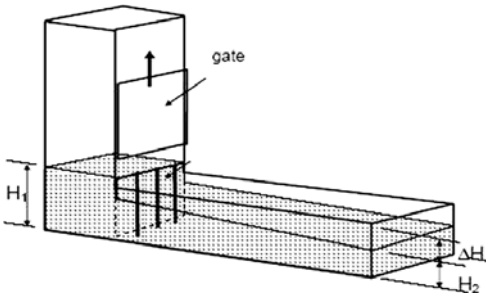


Fig. 3 L-Box Test Apparatus

To perform this test about 14 L (0.5 ft^3) of SCC is needed. Before commencing the test, the L-box is set on a firm levelled ground and inside surfaces of the box are moistened. After that, the vertical section of the box is filled with concrete and the gate separating the vertical and horizontal compartments is then lifted and the concrete is allowed to flow through closely spaced reinforcing bars at the bottom into the horizontal section of the box. The times for concrete to reach points 200 mm and 400 mm from the gate in to the horizontal section of the box are recorded. These are known as T-20 and T-40 times and are an indication for the filling ability. When the concrete stops flowing, the heights of the concrete at the end of the horizontal section (H_2) and in the vertical section (H_1) are measured to compute the blocking ratio (H_2/H_1). Nearer the value of H_2/H_1 to 1, the better will be the flow of the SCC. Various sources set different values for H_2/H_1 ratio but values between 0.8-1.0 are generally recommended.

5. J-Ring Test

This test is used to determine the passing ability of the SCC. The J-Ring, as shown in Fig. 4, is an open 300mm dia steel ring attached to vertical reinforcing bars at appropriate spacing. To conduct this test in conjunction with the slump flow test, the slump cone is placed in the center of the J-Ring and filled with concrete. The slump cone is lifted and concrete is allowed to spread horizontally through the gaps between the bars. Like in the Slump flow test, the diameter of the spread and the T_{50} time are recorded. The horizontal spread with the J-Ring to that without the J-Ring is then compared. Also, the difference in height of the concrete inside and that just outside the J-Ring is measured at four locations.

The difference between the slump flow and the J-Ring flow provides the blocking assessment and indicates the extent of the passing ability of a particular mixture. A difference less than 25 mm indicates good passing ability whereas a difference greater than 50 mm indicates poor passing ability.

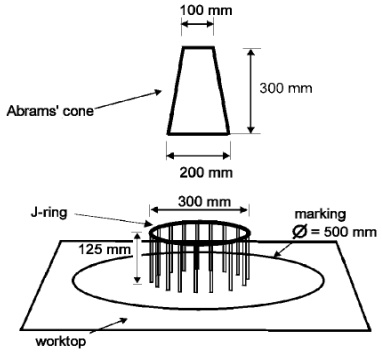


Fig. 4 J-Ring Test Apparatus

D. Mix Procedure and Test Set up

Mixing process was done in two stages. Initially, fine sand, crushed coarse aggregate in saturated surface dry condition and FA were mixed together in 100 liter capacity concrete mixer for about 2.5 minutes. At the end of this dry mixing, a well-shaked pre-mixed liquid mixture containing alkaline solution, superplasticizer and extra water was added in the concrete mixer and the wet mixing continued for another 3 minutes. Fresh concrete mix was then hand mixed for further 2 to 3 minutes to ensure the mixture homogeneity. The freshly prepared concrete mixture was then assessed for the essential workability tests required for characterizing SCC. For each mix slump flow, slump flow at T_{50}, V-funnel, L-box, and J-ring tests were carried out. After ensuring the necessary workability requirements as guided by EFNARC, the fresh concrete mixture was then cast in 100 mm x100 mm x100 mm steel moulds. Three cubes were prepared for each test variable. Immediately after casting, the test specimens were kept in oven at a specified temperature for a specified period of time

Open Science Index, Civil and Environmental Engineering Vol:5, No:2, 2011 publications.waset.org/3527/pdf

in accordance with the test variables selected. At the end of the curing period, the test specimens were taken out from the oven and left undisturbed for about 15 minutes in order to avoid a drastic change of the environmental conditions. The test specimens were then demoulded and left to air dry at room temperature for 24 hours and then tested for compressive strength.

IV. TEST RESULTS AND DISCUSSION

A. Workability Tests for SCGC

Workability characteristic plays an important role for SCC. It is a main property that defines SCC is highly workable in attaining consolidation and specified hardened properties. As stated earlier, to accomplish the workability properties, for each mix slump flow, slump flow at T_{50}, V-funnel, L-box, and J-ring tests were carried out. All the tests were performed by following The European Guidelines for SCC. The test results of workability properties are presented in Table. 4. The results of the quantitative measurements and visual observations showed that except for Mixture M_1, all the other concrete mixtures had good flowability and produced desired results and were within the EFNARC range of SCC, however, Mixtures M_3 and M_4 showed bleeding as well as segregation.

B. Compressive Strength of Self-compacting Geopolymer Concrete

The compressive strength is one of the most noteworthy properties of hardened concrete and is considered as the characteristic material value for the classification of concrete. In this study, compressive strength test was performed in accordance with BS EN 12390-3:2002 using 2000 KN Digital Compressive & Flexural Testing Machine in the Concrete Laboratory of Civil Engineering Department Universiti Teknologi PETRONAS. A set of three cubes for each mix were tested on the 1-day after specified curing period. The average compressive strength of the three cubes for all mix composition is presented in Table IV.

TABLE IV
WORKABILITY AND COMPRESSIVE STRENGTH TEST RESTULTS

Mix Code	Workability Test Results					Comp. Strength
	Slump flow	$T_{50\,cm}$ Slump flow	V-Funnel Flow time	L-Box (H_2/H_1)	J-Ring	
	(mm)	(sec.)	(sec.)	Ratio	(mm)	(MPa)
M_1	630	6.5	12.5	0.82	12	53.46
M_2	710	4.0	7.0	0.96	5	45.01
M_3	770	3.0	6.0	1.0	3	37.31
M_4	820	2.5	5.5	1.0	0	22.58
M_5	710	4.0	7.0	0.96	5	51.03
M_6	710	4.0	7.0	0.96	5	51.41
M_7	710	4.0	7.0	0.96	5	51.68
M_8	710	4.0	7.0	0.96	5	44.81
M_9	710	4.0	7.0	0.96	5	48.56
M_{10}	710	4.0	7.0	0.96	5	47.99
Acceptance Criteria for SCC as per EFNARC [22]						
Min.	650 mm	2 sec.	6 sec.	0.8	0 mm	
Max.	800 mm	5 sec.	12 sec.	1.0	10 mm	

1. Effect of Extra Water on Compressive Strength

Mixtures M_1, M_2, M_3 and M_4 were prepared to study the effect of extra water on the compressive strength of SCGC. Fig. 5 illustrates the effect of extra water on the compressive strength. As it was expected, the addition of water improved the workability characteristics of freshly prepared concrete mixtures; however, the addition of water beyond certain limit resulted in bleeding and segregation of fresh concrete and decreased the compressive strength of the concrete significantly. From Fig. 5, it is clearly observed that mixture M_1 with lower percentage of extra water showed highest compressive strength compared to mixtures M_2, M_3 and M_4. The compressive strength of SCGC was significantly decreased as the amount of extra water increased. The trend of these results was similar to those observed by previous research studies [14], [15], [25], [26]. This trend is similar to the well known effect of water-to-cement ratio on the compressive strength of ordinary Portland cement concrete, although the chemical reaction involved in the formation of both binders is entirely different.

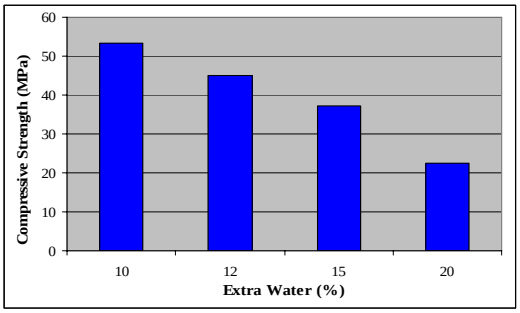


Fig. 5 Effect of Extra water on Compressive Strength

2. Effect of Curing Time on Compressive Strength

Previous research has shown that curing time and curing temperature significantly influence the compressive strength of GC. Palomo et al. [13], in their study on FA-based geopolymers have reported that the curing temperature and curing time significantly affected the mechanical strength of FA-based geopolymers. They concluded that higher curing temperature and longer curing time proved to result in higher compressive strength.

Mixtures M_2, M_5, M_6, and M_7 were prepared to study the influence of curing time on the compressive strength of SCGC. Fig. 6 shows the effect of curing time on compressive strength. From the Fig. 6, it is seen that longer curing time improves the geopolymerisation process resulting in higher compressive strength. It was observed that the compressive strength was highest when the specimens were cured for a period of 96 hours. However, the increase in strength after 48 hours was not significant. The results shown in Fig. 6 clearly demonstrate that longer curing time does not produce weaker material as claimed by van Jaarsveld et al [27]. The trend of these test results is similar to those observed by Hardjito et al. [3] in their study on FA-based GC.

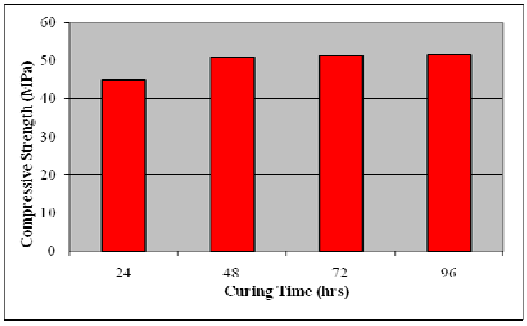


Fig. 6 Effect of Curing Time on Compressive Strength

3. Effect of Curing Temperature on Compressive Strength

Curing temperature is an important factor in the setting and hardening of the GC. Hardjito et al. [26], in their study on low-calcium FA-based geopolymer mortar have reported that curing temperature plays an important role in the geopolymerization process of FA-based geopolymer. They have concluded that higher the curing temperature, higher will be the rate of geopolymerization process, which eventually accelerates the hardening of geopolymer mortar.

In order to study the effect of curing temperature on the compressive strength of SCGC, Mixtures M_5, M_8, M_9, and M_{10} were prepared. Except temperature, all the other test parameters were kept constant. AS, curing of fresh GC is usually carried out at an elevated temperature in the range of 60-90°C; therefore, in this study the curing temperature was varied from 60 to 90°C. Fig. 7 shows the influence of curing temperature on the compressive strength. From the Fig.7, it was observed that mixture M_5 cured at 70°C produced the highest compressive strength as compared to mixtures cured at 60°C, 70°C and 90°C.

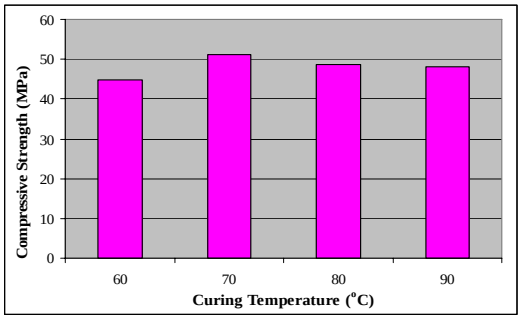


Fig. 7 Effect of Curing Temperature on Compressive Strength

V. CONCLUSION

In this experimental work, workability characteristics and compressive strength of low-calcium FA-based SCGC assessed. It was observed that it is possible to achieve self-compaction with FA-based GC. From the experimental results reported in this paper, the following conclusions are drawn:

1. Except for Mixture M_1, all the other concrete mixtures had good flowability and produced desired results for workability characteristics and were within the EFNARC range of SCC; however, Mixtures M_3 and M_4 showed bleeding as well as segregation.
2. The addition of extra water improved the workability characteristics of concrete mixtures; however, the inclusion of water beyond certain limit resulted in bleeding and segregation of fresh concrete and decreased the compressive strength of the concrete. The compressive strength of SCGC was significantly decreased as the amount of extra water exceeded 12% by mass of FA.
3. Longer curing time improves the geopolymerisation process resulting in higher compressive strength. The compressive strength was highest when the specimens were cured for a period of 96 hours; however, the increase in strength after 48 hours was not significant.
4. Concrete specimens cured at 70°C produced the highest compressive strength as compared to specimens cured at 60°C, 80°C and 90°C.

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