Research Article

Properties of Fly Ash and GGBS Based Geopolymeric Binder

P. Jayajothi*[1], R. Kumutha[2] and K. Vijai[2]

[1]Department of Civil Engineering, Dhirajlal Gandhi College of Technology, Salem, India
[2]Department of Civil Engineering, Sona College of Technology, Salem, India

Abstract
In this paper, the properties of geopolymeric binder prepared using the source materials such as Fly Ash and Ground Granulated Blast Furnace Slag (GGBS) without using any conventional cement have been investigated. The individual properties of the mortar such as setting time, flow, density, compressive strength, flexural strength and water absorption were determined as per relevant Indian and ASTM standards. The different parameters considered in this study are the proportion of binder components, the ratio of Na_2SiO_3 / NaOH and the alkaline liquid to binder ratio. The various combinations of fly ash and GGBS considered are 90% & 10%, 80% & 20%, 70% & 30%. The ratio of Na_2SiO_3/NaOH is taken as 2 and 2.5 and the alkaline liquid to binder ratio as 0.4. The test results reveal that the geopolymer mortar develops the strength even at ambient conditions. Compressive strength and flexural strength increases with an increase in the quantity of GGBS. It was also found that geopolymer mortars made with Na_2SiO_3/NaOH ratio as 2.5 & alkaline liquid to binder ratio as 0.4 produces higher strength. It can be concluded that the results of geopolymer mortars are high when compared with conventional mortars in terms of strength.

***Correspondence**
P. Jayajothi,
Department of Civil Engineering
Email: jayajothi21civil@gmail.com

Keywords: Geopolymer Mortar, Fly ash, GGBS, Binder, Alkaline liquid, Strength

Introduction

Concrete is the most widely used construction material in the world and Ordinary Portland Cement (OPC) is the major ingredient used in concrete. The production of cement releases large amount of carbon dioxide (CO_2) to the atmosphere that significantly contributes to greenhouse gas emissions. It is estimated that one ton of CO_2 is released into the atmosphere for every ton of OPC produced. In view of this, there is a need to develop sustainable alternatives to conventional cement utilizing the cementitious properties of industrial by-products such as fly ash and ground granulated blast furnace slag.

In 1978, Davidovits developed a binder called 'geopolymer' to describe an alternative cementitious material which has ceramic-like properties. Geopolymer technology is one of the new technologies attempted to reduce the use of portland cement in concrete. Geopolymers are environmental friendly materials that do not emit green house gases during polymerisation process. Geopolymer can be produced by combining a pozzolanic compound or aluminosilicate source material with highly alkaline solutions. Geopolymers are made from source materials with silicon (Si) and Aluminium (Al) content and thus cement can be completely replaced by marginal materials such as fly ash and ground granulated blast furnace slag which is rich in silica and alumina. Fly ash and GGBS reacts with alkaline solutions to form a cementitious material which does not emit carbon dioxide into the atmosphere.

Compressive strength development in ambient cured geo-polymer mortar using marginal materials / industrial by-products for sustainable development is studied by Manjunath et al (2011). The results reveal that the geopolymer mortar develops the strength even at ambient conditions without any conventional curing. Strength increases with an increase in the quantity of GGBS. Addition of small quantity of silica fume has no significant influence on the strength development [1].

Mechanical properties of newly developed repair material have been studied by Wanchai Yodsudjai. The compressive strength, flexural strength, bonding strength between geopolymer mortar and mortar substrate, setting time and chloride penetration are investigated comparing with those of conventional repair materials. It is found that the bond strength (accordance with the slant shear test-ASTM C882) and flexural strength is similar to that of the conventional repair materials at the age of 28 days [2].

Hardjito et al (2008) carried out tests on strength and setting times of low calcium fly ash based geopolymer mortar. The test results revealed that as the concentration of alkaline activator increases, the compressive strength of geopolymer mortar also increases. Specimens cured at temperature of 65˚C for 1 day showed the highest 28 days compressive strength [3].

Eduardo Vasconcelos et al (2012) have investigated the effectiveness of concrete retrofitting using CFRP and metakaolin based geopolymer mortars. Several compositions of geopolymer mortars were executed by varying the percentage of binder, sand/binder ratio and the concentration of sodium hydroxide. It was found that geopolymer mortars demonstrate very promising performances, having obtained a high mechanical resistance and a good adhesion to concrete [4].

Pacheco-Torgal et al. studied the bond Strength between concrete substrate and repair materials. Comparisons were made between Tungsten mine waste geopolymeric binder and commercial repair products. This study indicates that tungsten mine waste geopolymeric binders possess much higher bond strength than the commercial repair products. Scanning electron micrographs reveal that tungsten mine waste geopolymeric binders chemically bond to the concrete substrate. Cost comparisons were also made between tungsten mine waste geopolymeric binder and current commercial repair products [5].

Thokchom et al (2010) investigated the performance of fly ash based geopolymer mortar specimens in magnesium sulphate solution. Performance of the specimens was evaluated in terms of visual appearance, variation of pH of solution, change in weight, and change in compressive strength over the exposure period. At the end of 24 weeks samples experienced very little weight gain and recorded a loss of compressive strength by up to 56% [6].

In this study, an attempt has been made to prepare geopolymer mortars with fly ash and GGBS and their fresh and hardened properties such as setting time, flow, density, compressive strength, flexural strength and water absorption were determined as per relevant Indian and ASTM standards.

The materials used to make geopolymer mortar were fly ash, GGBS, sand and alkaline solution. The geopolymer mortar is produced by replacing the Portland cement by fly ash and GGBS and alkaline liquids are used for the binding of these materials. The alkaline liquids used in this study for the polymerization are the solutions of sodium hydroxide and sodium silicate. Distilled water was added for desirable workability.

Fly ash and GGBS are the aluminosilicate source materials used for the synthesis of geopolymeric binder in this research [7, 8]. Table 1 shows the chemical properties of these binders. In this study, low calcium fly ash (ASTM Class F) obtained from the thermal power plant in Mettur and GGBS obtained from Mangalore were utilized as the source materials. A combination of sodium hydroxide solution and sodium silicate solution was used as the alkaline activators. Specific gravity of fly ash is 2.38. Fine Aggregate (sand) used is clean dry river sand. The sand is sieved using 2.36 mm sieve to remove all the pebbles. Specific gravity of sand is 2.67 and its bulk density is 1536 kg/m³. It confirms zone II of IS 383-1970 requirements.

Table 1 Chemical properties of binders (%)

Binders	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**CaO**	**Na_2O**	**LOI**
Fly ash	64.11	18.58	4.32	0.24	1.21	0.21	0.64
GGBS	32.78	22.4	1.1	0.08	34.86	-	0.62

Mix Proportion

The density of mortar is 2100 kg /m^3. The ratio of binder to fine aggregate is fixed as 1:1.5. By assuming the alkaline liquid to binder ratios as 0.4 and by knowing the density of mortar the amount of binder, fine aggregate and quantity of alkaline liquids were determined.

The molarity of sodium hydroxide concentration is kept as 12 M. The different parameters considered in this study are proportion of binder components, ratio of Na_2SiO_3 / NaOH and alkaline liquid to binder ratio. The proportion of binder components (i.e) the various percentages of fly ash and GGBS is taken as 90% & 10%, 80% & 20%, 70% & 30%. The ratio of Na_2SiO_3 /NaOH is taken as 2 and 2.5 & alkaline liquid to binder ratio as 0.4. Extra water was added 10% by weight of cementitious material to get desirable workability for all the mixes. Table 2 shows the mix proportion for alkaline liquid to binder ratio 0.4.

Table 2 Mix proportion **-** Alkaline liquid to binder ratio: 0.4

Mix ID / Proportion of binders	**Flyash (kg /m³)**	**GGBS (kg /m³)**	**Sand (kg/m³)**	**NaOH (kg /m³)**	**Na_2SiO_3 (kg /m³)**	**Alkaline liquid (kg/m³)**
Na_2SiO_3 / NaOH = 2.5						
M_1 F_{90} G_{10}	651.72	72.41	1086.20	82.76	206.89	289.65
M_2 F_{80} G_{20}	579.30	144.82	1086.20	82.76	206.89	289.65
M_3 F_{70} G_{30}	506.89	217.24	1086.20	82.76	206.89	289.65
Na_2SiO_3 / NaOH = 2.0						
M_4 F_{90} G_{10}	651.72	72.41	1086.20	96.55	193.10	289.65
M_5 F_{80} G_{20}	579.30	144.82	1086.20	96.55	193.10	289.65
M_6 F_{70} G_{30}	506.89	217.24	1086.20	96.55	193.10	289.65

Mixing

To prepare 12 molarity concentration of sodium hydroxide solution, 480 grams (molarity x molecular weight) of sodium hydroxide flakes was dissolved in distilled water and makeup was done to one litre. The sodium hydroxide solution thus prepared is mixed with sodium silicate solution one day before mixing the mortar to get the desired alkaline solution. Distilled water is used to dissolve the sodium hydroxide flakes to avoid the effect of contaminants in the mixing water. The sand, fly ash and GGBS were dry mixed before adding the alkaline solution.

Research grade sodium hydroxide in flakes form with 98% purity and sodium silicate with Na_2O = 14.7%, SiO_2 = 30%, and water = 56% by mass was used in this research. Sodium hydroxide solution was used as alkaline activator because it is widely available and is less expensive than potassium hydroxide solution

Specimen and Testing Methods

5.1 Setting time

The setting times of fly ash and GGBS based geopolymeric binder was measured using Vicat needle. The geopolymer paste made with fly ash, sand, GGBS and activator solution was cast into the 40 mm height, 80 mm diameter conical mould in two layers. The period elapsing between the time when the solution is added to the geopolymer with fly ash and GGBS mixture and the time at which the needle fails to pierce the test block to a point 5.0 ± 0.5 mm measured from the bottom of the mould is measured as the initial setting time [9].

5.2 Workability

Workability was measured by the flow of the fresh geopolymer mortar on flow table for mortar. First, flow mould was placed in the middle of the flow table. A layer of fresh geopolymer mortar about 25 mm thick was placed in the mould and tamped with the tampers for 20 times. This was repeated for the second layer. Then the mould was lifted away and immediately the table was dropped from a height of 12.7± 0.13 mm for 25 times in 15 sec. Finally, the diameter of the geopolymer mortar along the six lines scribed in the table top was recorded.

5.3 Compressive strength

Compressive strength results were obtained using 70.6 x 70.6 x 70.6 mm^3 cubic specimens [10]. The Geopolymer mortar specimens were tested for compressive strength at the age of 1day and 28 days using the Compression Testing Machine. The specimens were subjected to a compressive force at the rate of 160 kN per minute until the specimen failed. The geopolymer mortars were weighed before testing for the calculation of density. The reported strengths were the average results of the three specimens.

5.4 Flexural strength

Flexural strength is determined by testing the prisms in bending according to ASTM standard [5]. Beams were subjected to single point loading. Flexural strengths were obtained using 160 x 40 x 40 mm^3 prismatic specimens. Totally 36 number of prisms were cast and tested after 28 days. Testing of a beam under single point loading is shown in Fig.1.

Figure 1 Testing of prism

5.5 Bond strength

The bond strength test is performed by the slant shear test in accordance with ASTM C882. The specimen for slant shear test is the cylinder with the 50 mm diameter and 100 mm height. A slant shear bond test is to measure the resistance to sliding between the repair material and the concrete substrate along an inclined surface. The interface is subjected to combined shear and compressive stress. At the appropriate age, the test specimen is loaded to failure in compression. Fig.2. shows the diagrammatic representation of slant shear specimens. The stress at fracture is determined by dividing the ultimate load by the elliptical area of the bonding surface to determine the bond strength.

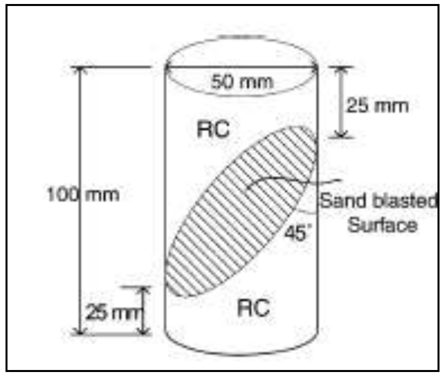

Figure 2 Diagrammatic representation of slant shear specimen

The concrete substrate was designed for M 30. Three cubes of size 150mm x 150mm x 150 mm were cast to find the compressive strength of concrete substrate and one beam of size 500mm x 100mm x 100 mm were cast to determine the flexural strength of concrete. Substrate concrete consists of cement, sand and aggregate of size 10mm down (i.e) chips. It was casted on half cylinder of size 50mm x 75mm. Fig.3. shows the slant shear specimen in compression testing machine.

Figure 3 Slant shear specimen in compression testing machine

5.6 Water absorption

Water absorption was measured using cube specimens of size 70.6 mm x 70.6 mm x 70.6 mm. The weights of the dried specimens were taken. The specimens were immersed in water at room temperature for 24 hours. The specimens were removed from water and the water is allowed to drain for 1 min by placing them on a wire mesh, removing visible surface water with a damp cloth and then the saturated weight was measured. From the difference in weight, the water absorption values were found out.

Results and Discussion

6.1 Setting time

The initial setting times of mortar specimens are shown in Fig.4. The test result reveals that the setting time gets decreased with an increase in quantity of GGBS. Geopolymer mortar sets early for Na_2SiO_3 / NaOH = 2.0 whereas the ratio of 2.5 takes comparatively longer time to set. Similarly geopolymer mortar made with an alkaline liquid to binder ratio of 0.4 sets faster. The initial setting time for geopolymer mortars is high when compared to conventional mortars. Initial setting time of geopolymers ranges from 145 – 255 minutes.

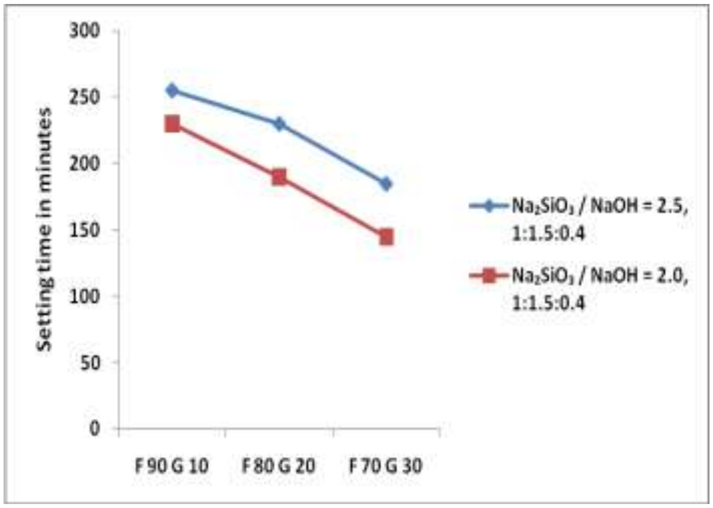

Figure 4 Effect of Na_2SiO_3 / NaOH on setting time

6.2 Workability

Flow percentage varies for all mortar specimens are shown in Fig.5. Flow percentage decreases with an increase in quantity of GGBS. Therefore, workability of mortar also decreases with an increase in GGBS content. Workability is high for Na_2SiO_3 / NaOH as 2.5 when compared to Na_2SiO_3 / NaOH as 2.0.

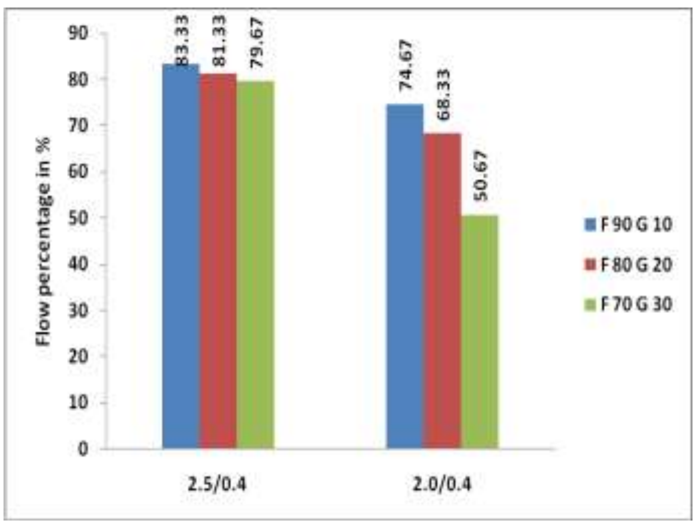

Figure 5 Flow percentages for mortar specimens

6.3 Density

Density values of mortar specimens are presented in Fig.6. Density of geopolymer mortar varies from 2065 – 2190 kg /m^3. It reveals that density increases with an increase in quantity of GGBS and it shows geopolymer mortar with higher density produces higher strength.

6.4 Compressive strength

The test results of compressive strength at 1 day and 28 days are given in Table 3. As the age of mortar increases, compressive strength of mortar also increases for all the mixes. Also compressive strength increases with an increase in quantity of GGBS. Specimens with 70% fly ash and 30% GGBS resulted in an enhanced compressive strength.

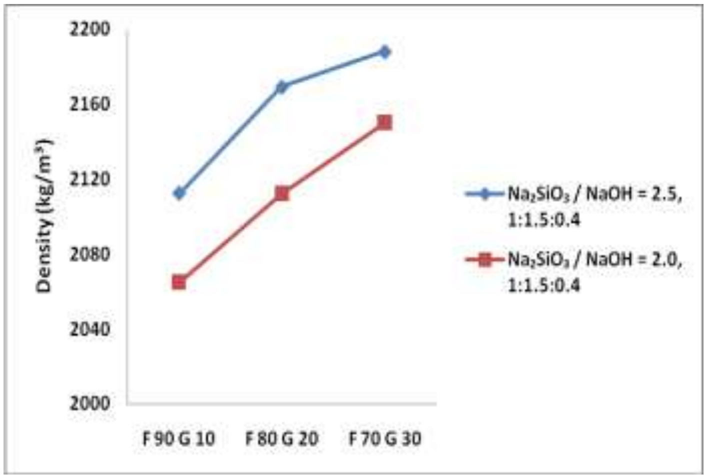

Figure 6 Density of mortar specimens

Table 3 Comparison of compressive strength

Mix grade	1 day	28days
M_1	4.4	28.21
M_2	13.42	33.54
M_3	14.96	50.6
M_4	3.02	20.6
M_5	5.08	30.31
M_6	11.09	44.22

Compressive strength of ambient cured geopolymer mortar at 28 days ranges from 20.6 – 50.6 MPa. The maximum compressive strength of 50.6 MPa is obtained for the mix M_3 and the minimum compressive strength of 20.6 MPa is obtained for the mix M_4.The compressive strength values are higher for Na_2SiO_3 / NaOH ratio of 2.5 as compared with a ratio of 2.0 and the increase in compressive strength was about 37%, 11% and 14% for M_1, M_2 and M_3 respectively with respect to M_4, M_5 and M_6. Effect of Na_2SiO_3 / NaOH on compressive strength is as shown in Fig.7. By keeping M_1 as reference the increase in compressive strength was about 19% & 79% for M_2 & M_3. Similarly increase in compressive strength was about 47% and 114% for M_5 and M_6 with respect to M_4.

6.5 Flexural strength

Flexural strength also increases with an increase in GGBS content. Flexural strength of ambient cured geopolymer mortar ranges from 3.26 – 3.74 MPa. The maximum flexural strength of 3.74 MPa is obtained for the mix M_3 for Na_2SiO_3 / NaOH = 2.5 and the minimum flexural strength of 3.26 MPa is obtained for the mix M_4 for an alkaline liquid to binder ratio of 0.4.

For Na_2SiO_3 / NaOH ratio of 2.5, the flexural strength obtained is comparatively higher when compared to a ratio of 2.0 and the increase in flexural strength was about 5%, 8% and 5% for M_1, M_2 and M_3 respectively with respect to M_4, M_5 and M_6. Effect of Na_2SiO_3 / NaOH on flexural strength is as shown in Fig.8. By keeping M_1 as reference the increase in flexural strength was about 7% & 9% for M_2 & M_3. Similarly increase in flexural strength was about 5% and 9% for M_5 and M_6 with respect to M_4.

6.6 Bond strength

Bond strength also increases with an increase in GGBS content. The average compressive strength of substrate concrete is 28.13 MPa. Bond strength of ambient cured geopolymer mortar ranges from 6.67 – 9.25 MPa. The maximum bond strength of 9.25 MPa is obtained for the mix M_3 for Na_2SiO_3 / NaOH = 2.5 and the minimum bond strength of 6.67 MPa is obtained for the mix M_4 for an alkaline liquid to binder ratio of 0.4.

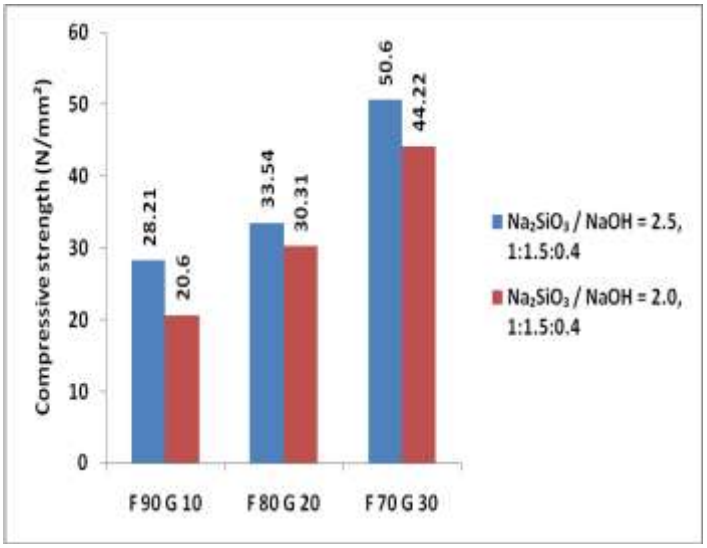

Figure 7 Effect of Na_2SiO_3 / NaOH on compressive strength

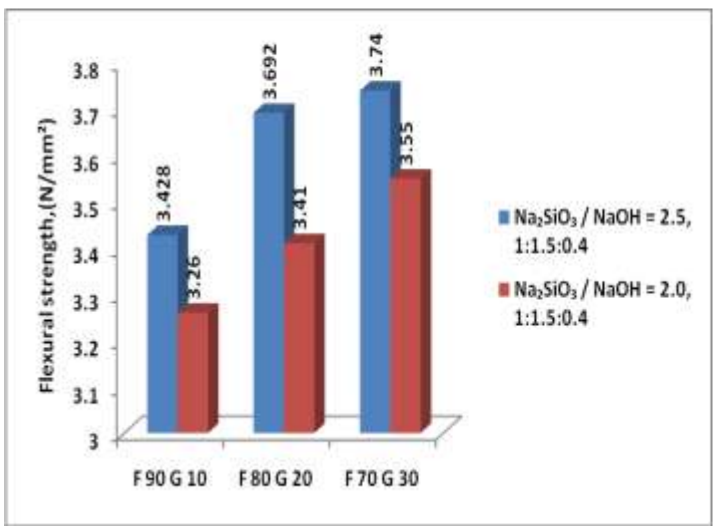

Figure 8 Effect of Na_2SiO_3 / NaOH on flexural strength

For Na_2SiO_3 / NaOH ratio of 2.5, the bond strength obtained is comparatively higher when compared to a ratio of 2.0 and the increase in bond strength was about 15%, 15% and 21% for M_1, M_2 and M_3 respectively with respect to M_4, M_5 and M_6. Effect of Na_2SiO_3 / NaOH on bond strength is as shown in Fig.9. By keeping M_1 as reference the increase in bond strength was about 9% & 21% for M_2 & M_3. Similarly increase in bond strength was about 8% and 15% for M_5 and M_6 with respect to M_4.

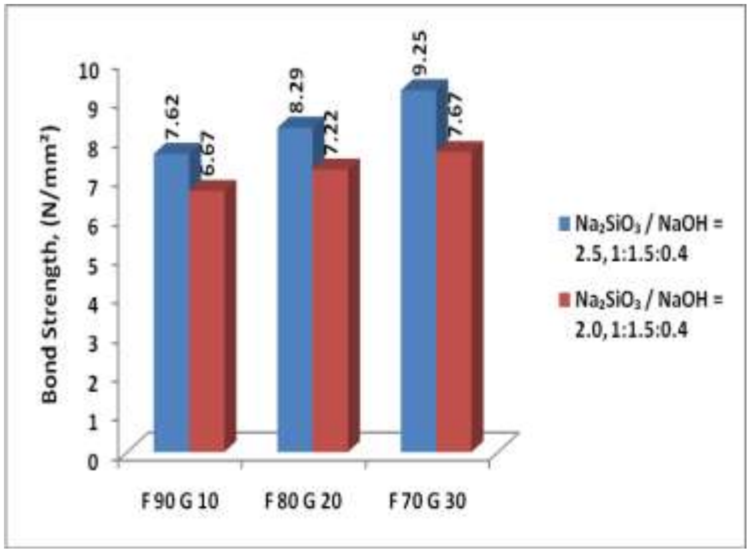

Figure 9 Effect of Na_2SiO_3 / NaOH on Bond strength

6.7 Water absorption

Water absorption values for all the geopolymer mortar mixes are presented in Fig.10. The water absorption values for geopolymer mortar ranges from 3.06% to 4.59%. From the test results it was found that for all the cases, as the content of GGBS increases water absorption values also increases. It is observed that specimens made with Na_2SiO_3 / NaOH ratio of 2.0, alkaline liquid to binder ratio 0.4 and 30% GGBS shows the maximum water absorption of 4.59%. Absorption of water is more for alkaline liquid to binder ratio 0.4 due to incomplete compaction leading to more voids results in reduced strength.

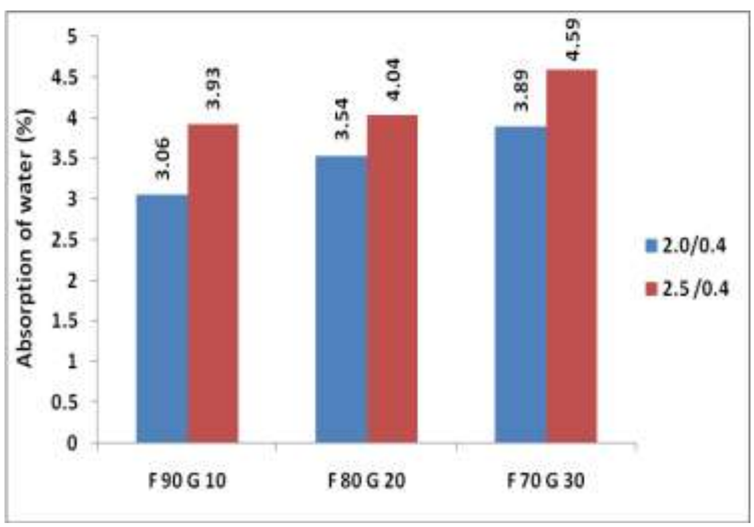

Figure 10 Water absorption for mortar specimens

Conclusions

The following conclusions can be drawn from this study:

1. The initial setting time for geopolymer mortars is high when compared to conventional mortars. Initial setting time of geopolymers ranges from 145 – 255 minutes.
2. Workability of geopolymer mortars is poor for alkaline liquid to binder ratio (0.4).

3. The density of mortar specimens is higher for higher $Na_{2S}iO_3$ / NaOH (2.5) and also for higher alkaline liquid to binder ratio. Geopolymer mortar specimens having higher density results in higher strength.
4. The compressive strength and flexural strength and shear strength increases when the quantity of GGBS increases. The geopolymer mortar specimens made of F_{70} G_{30} produces the maximum strength of all the mortar specimens.
5. Water absorption increases with an increase in quantity of GGBS. Absorption of water is more for alkaline liquid to binder ratio 0.4 due to incomplete compaction leading to more voids results in reduced strength.
6. For the ratios of Na_2SiO_3 / NaOH as 2.5 and alkaline liquid to binder ratio as 0.4 results in higher compressive and flexural strength.

References

[1] Manjunath, G.S., Mahesh Jadhav, (2011). “Compressive Strength Development in Ambient Cured Geo-polymer Mortar.” *International Journal of Earth Sciences & Engineering.*, Vol. 04, pp. 830-34.
[2] Wanchai Yodsudjai. Mechanical Properties of Newly Developed Repair Material.
[3] Djwantoro Hardjito, Chua Chung Cheak & Carrie Ho Lee Ing, (2008). “Strength and Setting Times of Low Calcium Fly Ash-based Geopolymer Mortar.” *Modern Applied Science.*, Vol. 2, pp. 3-11.
[4] Shweta Mane, Jadhav, H.S., (2012) “Investigation of Geopolymer Mortar and Concrete under High Temperature.” *International Journal of Emerging Technology.*, Vol. 2, Issue 12, pp. 384-90.
[5] Pacheco-Torgal, Eduardo Vasconcelos, and Sergio Fernandes, Barroso de Aguiar, (2011) “Concrete Retrofitting Using CFRP and Geopolymer Mortars.” *Construction and Building Materials.*, Vol. 25, pp. 3213-21.
[6] Thokchom, S., Ghosh, P., and Ghosh, S. (2010) “Performance of Fly ash Based Geopolymer Mortars in Sulphate Solution.” *Journal of Engineering Science and Technology.*, Review 3(1), pp. 36-40.
[7] IS : 3812 - 1981 Specification For Fly Ash For Use As Pozzolana And Admixture
[8] IS : 12089 - 1987 Specification For Granulated Slag For The Manufacture Of Portland Slag Cement
[9] IS : 1727 - 1967 *Indian Standard* Methods Of Test For Pozzolanic Materials
[10] IS : 4031 (Part 5) – 1988 Methods Of Physical Tests For Hydraulic Cement

Publication History
Received 24th Sep 2013
Revised 20th Oct 2013
Accepted 28th Oct 2013
Online 08th Jan 2014