Physical,Mechanical, properties of Fly ash based Geopolymer Mortar.

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Abstract:

This paper describes the microstructure characterization, strength, and durability of geopolymer mortar made by using low calcium fly ash (Class -F). Geopolymer mortars were prepared by using an alkaline solution (Sodium hydroxide (NH) and sodium silicate (NS)) with fly ash and sand. The fly ash to sand ratio is 1:1 with a constant rate of alkaline liquid /fly ash as 0.55 and NS/NH ratios as 1.5,2,2.5,3 Varying the ratio of NH concentrations as 2, 4, 6, 8M was prepared the geopolymer mortars for both the ambient and oven cured samples. The curing temperature of 60oC for 24 hours kept activating the geopolymerization. The results showed that the physical &Mechanical properties are increased and results in a good combination of eco-friendly material for cement compounds

Keywords: Fly ash,IST, FST & Normal consistency, workability & Compressive strength

Introduction:

Fly ash is nowcarefully used as a chief material for the construction industry. It is produced from coal combustion units mainly from thermal power stations and is a by-product of it. Generally,coal is a heterogeneous mixture of materials, and by the combustion of bituminous and sub-bituminous coal heated at a temperature of 1400-1600oC in power plants produces class F and Class C fly ashes from silos. Two types of fly ash conferred widely, i.e., class C(sub-bituminous) and class F (bituminous) fly ash. As per ASTM C 618, it is clear that the fly ash with silica, alumina, and iron oxide greater than or equal to 70% is class F fly ash. Greater than or equal to 50% is class C fly ash. Nowadays, construction companies and industries are looking for an alternative to cement, and so much potential research is going on the geopolymer binders. For the making of Geopolymer binders,the main components are the alkaline solution and source materials. Reference materials should have rich in silica and aluminum by various source materials such as GGBS, clays, fly ash, metakaolin, rice husk ash, perlite, spent coffee. The solution prepared by potassium or sodium-based pellets (based on the concentration). The use of fly ash in the geopolymer can reduce greenhouse gases and make environmentally eco-friendly materials responsible for sustainability [1-4,7,10-11,13-15].Mixing source material and solutions geopolymer can account for a 3D network formation [8].The geopolymer can also be useful for Structural health monitoring structures by using a metakaolin based adhesives for the deteriorating structures also [2].It can work for the stabilization of soils by using fly ash and slag based geopolymers [16-17].The geopolymer binders also have remarkable properties in getting early compressive strength and has low creep and shrinkage and resistance to durability attacks even[5-7,12].The remarkable properties depend on the fineness of the fly ash used in the construction. Based on the author he divided the fly ash into Coarser, medium and more refined type of fly ashes from Mae Moh power station for the study and revealed that fine fly ash has very high compressive strength as compared to other two types of fly ashes and he used high calcium fly ash for his experimentation[3].Bottom ash has also shown that it gets remarkable properties of 40-54.5MPa by using high calcium fly ash for geopolymer mortars also of mean diameter 15, 25, and 32µm,respectively [4].Not only strength can be gain but also the durability of GPC is more resistant exposed to chloride attack as compared to OPC [6]. The impact of alkali-silica reaction takes place on both types of fly ashes as compared to OPC and examined by using microstructural analysis SEM, XRD, FTIR, and compressive strength [5]. The crack formation can spot by using the Scanning electron microscope for geopolymer samples, and mineral compounds identifications can be made by using XRD, and the author said that Albite is responsible for strength enhancement for GPC specimens.

FTIR used for the analysis of the bond formation of GPC and ASR reaction takes place in the GPC [5]. Geopolymers are temperature resistant, and the elemental composition and mass loss can find by using EDS & TG/DTA.The main aim is to study and analyze its physical, mechanical, durability exposed to 5% sulphuric acid and followed by microstructural analysis by XRD, SEM. Based on all the tests and analysis by various techniques are detailed in this paper.

Geopolymer Mortar:

In the present research, we have fixed the Geopolymer mortar as 1:1 (Fly ash and sand) and 0.55 as the alkaline liquid (AL) to binder ratio. Here we have varied the molarities as 2, 4, 6&8M and sodium silicate to sodium hydroxide ratio as 1.5,2,2.5 and 3. The mix for preparing geopolymer mortars are described in the table: 1. To make the molarity of NaOH, generally, 40 grams of sodium hydroxide pellets are taken and dissolved in 1 liter of solution. Likewise, 2M (2*40), i.e., 80grams in a liter of resolution and 160 grams for 4M, 240 grams for 6M, and 320 grams of NaOH for 8M Solution. The solution prepared for varying molarities prepared for one day before the casting of the specimens. Here the mixture (fly ash and sand) are mixed uniformly before adding the solution to the mix. Then it is thoroughly mixed in an electrically operated mixer for getting uniformity for 10 minutes. The combination should be free from lumps so that it can be free from voids and pores, which maintain the natural hardening of the mortar. Here the vibratory machine is used for compaction of the specimens to remove any voids present in it. Here samples of dimensions 70.7 mm x 70.7 mm x 70.7mm cube are used for casting the samples. After one day, the specimens are demoulded and then kept in sunlight for curing in the day time, and afterward, the specimens preserved inside the room (lab) in the night time. The following parameters studied in the paper are

1. Change insodium hydroxide as 2M, 4M, 6M& 8M in Alkaline liquid Solution.
2. Sodium silicate to sodium hydroxide ratio = 1.5,2,2.5 and 3.
3. Geopolymer specimens placed inthe oven and ambient curing conditions

Experimental details:

Materials:

Low calcium fly ash was brought from Vijayawada thermal power plant (VTPS- Andhra Pradesh) India. The scanning electron microscope (SEM) shows the fly ash is mostly in spherical [3] in fig.1, and energy dispersive spectroscopy (EDS) shows the main chemical composition of the fly ash shown in fig.1. 38.6% SiO_2, 18.5% Al_2O_3, 14.7% Fe_2O_3, and 12.4% CaO. The mean diameter of fly ash particles is 10-25µm, with a Blaine fineness of 4050 cm^2/g and a specific gravity of 2.21. The alkali activators used here are sodium silicate (Na_2SiO_3) with 18.32% Na_2O,30.76 % SiO_2, and 50.82% H_2O and sodium hydroxide (NaOH) pellets with 98% purity. The sand was locally available from the sea and is generally in the Zone – II with fineness modulus of 2.39, and a specific gravity of sand is 2.62 for making geopolymer mortar.

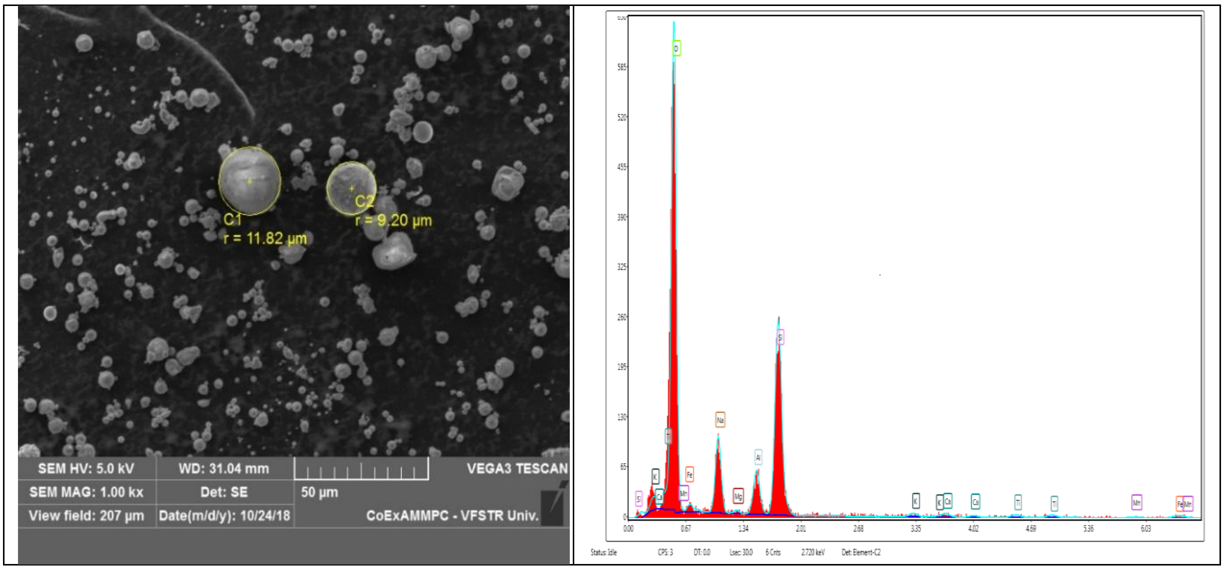

Fig:1 SEM and EDS of Fly ash

Mix proportions, mixing, and casting:

Here flyash to sand ratio was kept as 1:1 ratio, and NS/NH = 1.5,2,2.5,3 and alkaline liquid to binder ratio of 0.55 used for the mixing of geopolymer mortars. The effect of sodium hydroxide concentration on the geopolymer mortars is studied,which is four different concentrations viz., 2, 4, 6, 8 Molar(M). The details of the mix proportions shown in the table:1. Mixing of materials for geopolymer, done in a Hobart mixer for the proper dissolution of particles for a few minutes (approximately up to 3-5 minutes). Then the mixed materials are cast in 70.7mm x 70.7mm x 70.7mm mortar cubes and the cubes compacted by using a vibrating machine. The specimens kept in both the curing conditions (i.e., Ambient and oven cured). Samples kept inthe oven for 24hours, the temperature of 60^{o}C, ambientat a controlled environment of 27$\pm$3^{o}C until tested.

Table:1: Mix Proportion of Geopolymer Mortar

Mix ID	Ratio	Molarity	NS/NH Ratio	Fly ash	Sand	NH	NS	AL/B Ratio	AL
F1	1:1	2	1.5	860	860	189.2	283.8	0.55	473
F2	1:1	2	2	860	860	157.7	315.3	0.55	473
F3	1:1	2	2.5	860	860	135.1	337.9	0.55	473
F4	1:1	2	3	860	860	118.2	354.8	0.55	473
F5	1:1	4	1.5	860	860	189.2	283.8	0.55	473
F6	1:1	4	2	860	860	157.7	315.3	0.55	473
F7	1:1	4	2.5	860	860	135.1	337.9	0.55	473
F8	1:1	4	3	860	860	118.2	354.8	0.55	473
F9	1:1	6	1.5	860	860	189.2	283.8	0.55	473
F10	1:1	6	2	860	860	157.7	315.3	0.55	473
F11	1:1	6	2.5	860	860	135.1	337.9	0.55	473
F12	1:1	6	3	860	860	118.2	354.8	0.55	473
F13	1:1	8	1.5	860	860	189.2	283.8	0.55	473
F14	1:1	8	2	860	860	157.7	315.3	0.55	473
F15	1:1	8	2.5	860	860	135.1	337.9	0.55	473
F16	1:1	8	3	860	860	118.2	354.8	0.55	473

Testing details:

According to IS: 4031(Part IV) is used for the determination of the Normal consistency of the cement. By using the Vicats apparatus and the same way the geopolymer material (i.e., fly ash) tested for the determination of normal consistency, initial setting time, and final setting time of the fly ash by using alkaline liquid as the binder for mixing the Geopolymer material. Standard consistency is the same& finding of cement &taken material the plunger to penetrate to a depth of 33-35mm from the bottom of the mold.

Initial setting time and Final Setting time determine with the help of Vicat's apparatus as taking alkaline liquid as 0.85times standard consistency for getting the geopolymer. The compression testing machine determines compressive Strength for 7, 14, 28, 56, and 90 days for all the samples of taking three pieces for each set.

Workability test:

The workability of freshly prepared geopolymer mortar samples works out by using flow table test as per ASTM C 1437 and ASTM C 109, ASTM C 230/C, 230M-08 which has the flow table dimensions as top mold 7cm, bottom mold 10cm and height as 6cm respectively. The flow table gives the amount of water used for gauging and spreading of the mortar sample, which is piling at 25 drops in 15 sec should able to produce a 110±5% flow.

Compressive strength test:

CTM has capacity 100T, and mortar cubes are of different ages are tested under a digital machine, and the readings are recorded under a pacing value of 1.2KN/sec as per IS 516-1956 [19].

Test Results and discussion:

Normal Consistency: The values of normal consistency for the fly ash, as determined by the fly ash, are tabulated in table:2. It observes that the lower the molarity higher is the normal consistency for the geopolymer.Varying the ratio of sodium silicate to sodium hydroxide, we are getting a decrease in the consistency value. If we increase the molarity and proportion, the consistency is decreased and reached the amount of 27% for mix ID F16. Here a total of 16 mixes are taken for the determination of Fly ash-based geopolymer consistency. Mix ID F1-F4 are 2M, NaOH solution by varying NS/NH ratio as 1.5,2,2.5 and 3 and got the value ranging from 41-28% and similarly, for remaining molarities shown in the tabular form. Here Consistency has reached a similar amount for the cement as 28% for mix ID F15 due to the strong bonding and dissolution of the materials.

Initial setting time and Final setting time: Setting times of the geopolymer studied for all the mix id from F1-F16. We were varying both the molarities 2M, 4M, 6M and 8M and ratio of sodium silicate to sodium hydroxide as 1.5, 2, 2.5, and 3. Here for the determination of IST and FST is the same as per the IS 4031(part IV) as taking 0.85P as the alkaline liquid as a solution for mixing the geopolymer. The details of the IST and FST has shown in the table:2. Here IST and FST have varied from 598-75 minutes and 985 to 265 minutes for the MIX ID F1-F16. From the results, we observed that as the molarity is low, there is higher the IST and FST for the geopolymer paste. Still, Varying the sodium silicate to sodium hydroxide ratio, we have got decreased in the IST and FST for the lower molarities also. Higher the molarity we have observed, the less is the IST and FST for the NS/NH 1.5 and 2 and ratios NS/NH =2.5,3 we have got initial and final setting times readings before 2hours of the samples placed in the Vicats apparatus. We have got the penetration depth up to 33-35mm from the bottom of the Vicats mold. If we see ID, F1, F5, F9, F13, we have observed that the FST is approximately double the IST due to higher the IST, and similarly, FST is also more for these samples.

Table:2: Normal Consistency of Fly ash:

ID	Molarity	NS/NH Ratio	Fly ash (%)	Normal Consistency	IST	FST
F1	2	1.5	100	41	598	985
F2	2	2	100	40	298	550
F3	2	2.5	100	39	200	370
F4	2	3	100	38	108	305
F5	4	1.5	100	37	398	789
F6	4	2	100	36	195	450
F7	4	2.5	100	35	104	351
F8	4	3	100	34	85	285

F9	6	1.5	100	36	285	598
F10	6	2	100	35	171	362
F11	6	2.5	100	34	98	321
F12	6	3	100	33	75	265
F13	8	1.5	100	30	182	288
F14	8	2	100	29	158	264
F15	8	2.5	100	28	79	231
F16	8	3	100	27	71	211

Workability:

The workability for the geopolymer mortar finds by using the mini-slump cone test by using a flow table test for both the paste phase and mortar phase specimens. The freshly prepared geopolymer mortars are very much flowable and easy to work while mixing the materials and solutions at room temperature. For the workability by flow table test several authors have recommended the use of superplasticizers [8] which enhance the workability properties but in the present work describes the no use of any superplasticizers and it shows a good flowability for the different molarities and the difference in the ratio of sodium silicate to sodium hydroxide ratio. As we can see, table 4 describes the ID F1-F16 total of 16 samples, and each molarity, i.e., 2,4,6,8M constitutes 4 IDs and 4 different ratios as NS/NH= 1.5, 2, 2.5, 3. the slump value for lower molarity is not that much workable as compared there is an increase in the molarity. If you see the ratio, also there is an increase in the slump value upto 2.5 ratios, and then it decreases. No vast difference observed for the 2 & 4 molar samples, but an increase in the slump observed for 6, and 8 molar ratio and the maximum slump recorded as 188. The details of the flow are described in tables 3 & 4, respectively.

The flow can calculate as

$F=(D-D_o)/(D_o) \times 100\%$

Where D= spread of mortar flow at 25 drops

D_o= original diameter of the mortar sample

% of flow	20%	20-60%	60-100%	100-120%	120-150%	>150%
Flow	Dry	Stiff	Plastic	Wet	Sloppy	

Table :3 Flow table test for high workability

Table:4 Workability for Geopolymer

ID	Molarity	NS/NH Ratio	Fly ash (%)	GM Slump
F1	2	1.5	100	105
F2	2	2	100	110
F3	2	2.5	100	122
F4	2	3	100	120
F5	4	1.5	100	125
F6	4	2	100	138
F7	4	2.5	100	135
F8	4	3	100	140
F9	6	1.5	100	145
F10	6	2	100	150
F11	6	2.5	100	168

F12	6	3	100	160
F13	8	1.5	100	165
F14	8	2	100	170
F15	8	2.5	100	188
F16	8	3	100	180

Compressive Strength:

The Compressive strength of Geopolymer mortars specimens for 2M, 4M, 6M, 8M, and NS/NH = 1.5, 2,2.5, 3 in both in ambient curing and oven curing are as shown in Figure.1, 2, 3 and 4. The geopolymer mortar specimens tested for compressive test values varied from 6MPa to 52MPa.Ambient curing specimens with increasing the NaOH molarities from 2M to 8M have shown the values in the range from 6MPa to 43MPa.And it indicates that as the molarity increased, the compressive strength increased. For Oven cured specimens for varying molarities and varying sodium silicate to sodium hydroxide ratio of 1.5, 2, 2.5, 3, the values are in the range of 10MPa to 52MPa. Generally, for oven curing specimens, the 28 days Ambient cured samples strength at 7days of Oven fixing. The fig:2 shows the 2 molarity with varying ratios, and it shows the compressive strength from 6MPa to 18MPa.

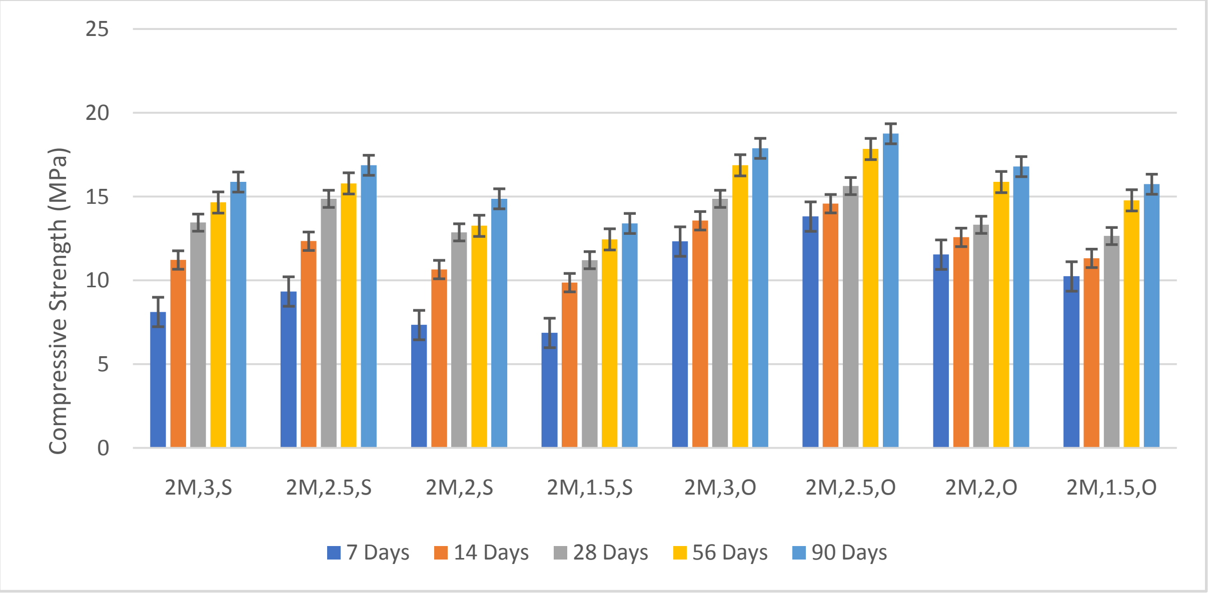

Fig: 2: Compressive Strength of Geopolymer Mortars 2M & NS/NH=1.5,2,2.5,3 for 7,14,28,56,90Days in Ambient(S) & Oven(O)

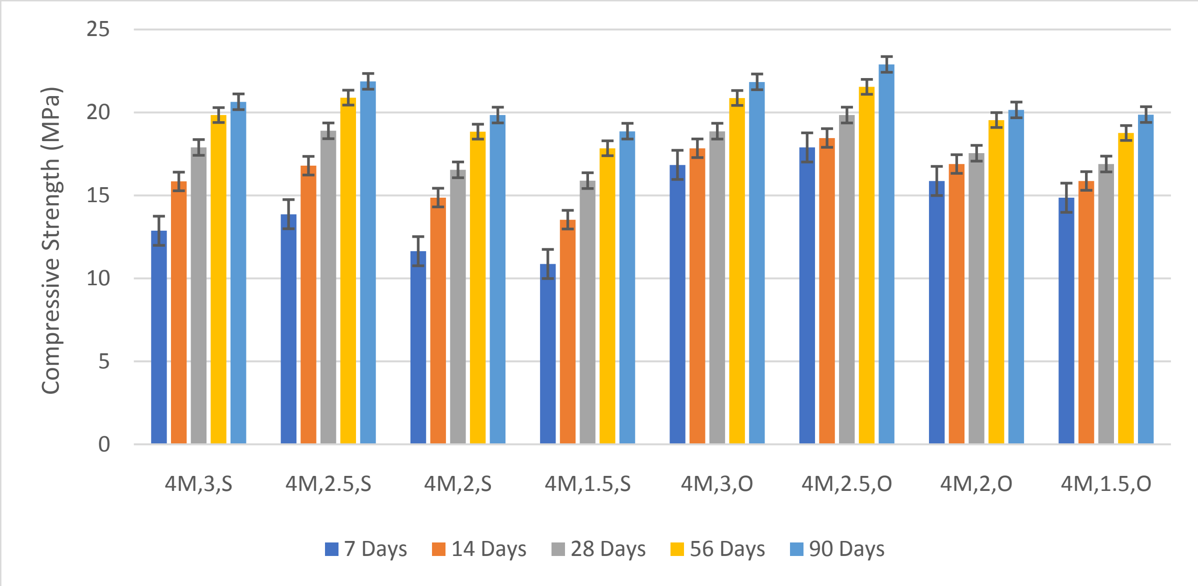

Fig: 3: Compressive Strength of Geopolymer Mortars 4M & NS/NH=1.5,2,2.5,3 for 7,14,28,56,90Days in Ambient(S) & Oven(O)

The fig:3 shows the 4 molarity with varying ratio and compressive strength value as 10MPa to 22MPa for the 7, 14, 28 ,56 and 90 days

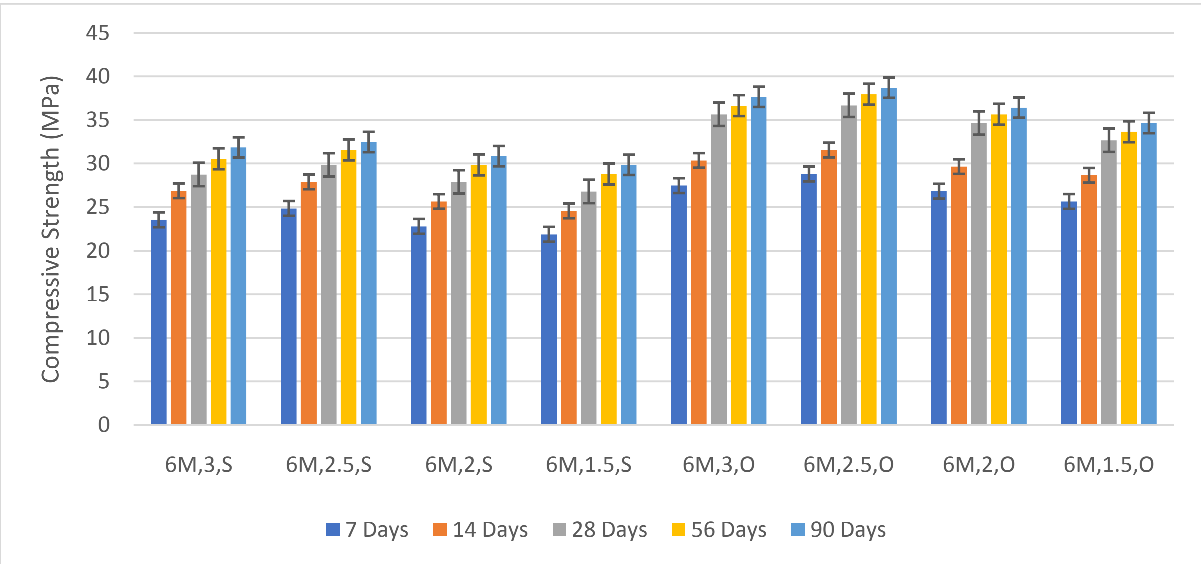

Fig: 4: Compressive Strength of Geopolymer Mortars 6M & NS/NH=1.5,2,2.5,3 for 7,14,28,56,90Days in Ambient(S) & Oven(O)

In the fig:4, we observe a large increase in the compressive strength as compared to 2M & 4M, and the results are as shown. Here we have got a large increase in the compressive strength upto 38MPa \for oven cured at 90 days and a minimum of 21MPa.

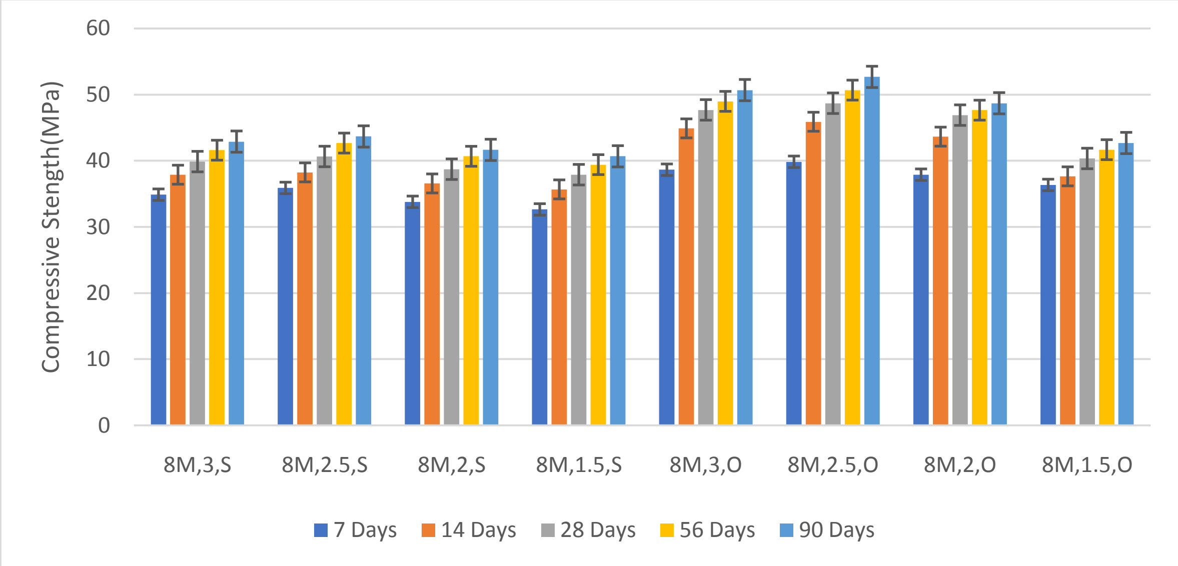

Fig: 5: Compressive Strength of Geopolymer Mortars 8M & NS/NH=1.5,2,2.5,3 for 7,14,28,56,90Days in Ambient(S) & Oven(O)

In fig:5 shows the variation of 8Molar geopolymer mortar specimens results, which, when cured at both ambient and oven cured, and the results show the maximum compressive strength of varying from 32MPa to 52MPa.

From the figures, it observed that compressive strength increases gradually by the incorporation of NaOH and Na2SiO3. However, the NS/NH ratio of 2.5 ratios only resulted in maximum compressive strength. Excessive OH- ions accelerated the dissolution process and resulted in a decrease in the polycondensation process, causing it to lose strength. It is also an essential factor to consider the age of the sample to find out its mechanical properties also. So for polymerization to takes place longer duration is preferable, and it gives its strength.

Conclusions:

1. The fly ash has spherical shells and is rich in aluminum and silicon can be seen in SEM and EDS.
2. The molarity of sodium hydroxide in the alkaline activator of a geopolymer does not affect normal consistency significantly, but NS/NH ratio changes the normal consistency of the geopolymer paste.
3. Initial and Final setting time decreases with an increase in the concentration of sodium hydroxide solution and also an increase in the ratio of NS/NH ratio.
4. Workability by flow table is increased with an increase in the concentration of sodium hydroxide and also increase in the ratio of NS/NH ratio.
5. Compressive strength results also increased for all the molarities at 2.5 ratios and it is a good combination as per the strength requirements.

References

[1] Keun-Hyeok Yang, Hey-Zoo Hwang, Seol Lee, "Effect of Water-Binder Ratio and Fine Aggregate - Total Aggeregate ratio on the Properties of Hwangtoh- Based Alkali Activated Concrete," *JOURNAL OF MATERIALS IN CIVIL ENGINEERING © ASCE*, vol. 22, no. 9, pp. 887-896, 2010.

[2] Jian He, Guoping Zhang, P.E, M.ASCE, Shuang Hou, C.S.Cai, "Geopolymer-Based Smart Adhesives For Infrastructure Health Monitoring: Concept and Feasibility," *JOURNAL OF MATERIALS IN CIVIL ENGINEERING © ASCE*, vol. 23, no. 2, pp. 100-109, 2011.

[3] P. Chindaprasirt, T. Chareerat, S. Hatanaka, T. Cao, "High-Strength Geopolymer Using Fine High-Calcium Fly Ash," *JOURNAL OF MATERIALS IN CIVIL ENGINEERING © ASCE*, vol. 23, no. 3, pp. 264-270,

2011.

[4] Chaicharn Chotetanorm, Prinya Chindaprasirt, Vanchai Sata, Sumrerng Rukzon, Apha Sathonsaowaphak, "High-Calcium Bottom Ash Geopolymer: Sorptivity, Pore Size, and Resistance to Sodium Sulfate Attack," *JOURNAL OF MATERIALS IN CIVIL ENGINEERING © ASCE,* vol. 25, no. 1, pp. 105-111, 2013.

[5] Kunal Kupwade-Patil, Erez N. Allouche, P.Eng., "Examination of Chloride-Induced Corrosion in Reinforced Geopolymer Concretes," *JOURNAL OF MATERIALS IN CIVIL ENGINEERING © ASCE,* vol. 25, no. 10, pp. 1465-1476, 2013.

[6] D. V. Reddy, P.E, M.ASCE, Jean-Baptiste Edouard, Khaled Sobhan, A.M.ASCE, "Durability of Fly Ash–Based Geopolymer Structural Concrete in the Marine Environment," *JOURNAL OF MATERIALS IN CIVIL ENGINEERING © ASCE,* vol. 25, no. 6, pp. 781-787, 2013.

[7] Dali Bondar, "Use of a Neural Network to Predict Strength and Optimum Compositions of Natural Alumina-Silica-Based Geopolymers," *JOURNAL OF MATERIALS IN CIVIL ENGINEERING © ASCE ,* vol. 26, no. 3, pp. 499-503 , 2014.

[8] Sudhakar M. Rao, Indra Prasad Acharya, "Synthesis and Characterization of Fly Ash Geopolymer Sand," *JOURNAL OF MATERIALS IN CIVIL ENGINEERING © ASCE,* vol. 26, no. 5, pp. 912-917, 2014.

[9] Muhammad Aamer Rafique Bhutta, Warid M. Hussin, Mohd Azreen, Mahmood Mohd Tahir, "Sulphate Resistance of Geopolymer Concrete Prepared from Blended Waste Fuel Ash," *Journal of Materials in Civil Engineering, © ASCE,* vol. 26, no. 11, pp. 04014080-1-6, 2014.

[10] Ginghis Maranan, Allan Manalo, Karu Karunasena, Brahim Benmokrane, "Bond Stress-Slip Behavior: Case of GFRP Bars in Geopolymer Concrete," *Journal of Materials in Civil Engineering,* vol. 27, no. 1, pp. 04014116-1-9, 2015.

[11] Patimapon Sukmak, Pre De Silva, Suksun Horpibulsuk, P.E, Prinya Chindaprasirt, "Sulfate Resistance of Clay-Portland Cement and Clay High-Calcium Fly Ash Geopolymer," *Journal of Materials in Civil Engineering, © ASCE,* vol. 27, no. 5, pp. 04014158-1-11, 2015.

[12] Ali Nazari, Jay G. Sanjayan, "Modeling of Compressive Strength of Geopolymers by a Hybrid ANFIS-ICA Approach," *JournalofMaterialsinCivilEngineering, © ASCE,* vol. 27, no. 5, pp. 04014167-1-8, 2015.

[13] S. T. Erdogan, "Properties of Ground Perlite Geopolymer Mortars," *Journal of Materials in Civil Engineering, © ASCE,* vol. 27, no. 7, pp. 04014210-1-10, 2015 .

[14] Arul Arulrajah, Teck-Ang Kua, Chayakrit Phetchuay, Suksun Horpibulsuk, Farshid Mahghoolpilehrood, Mahdi Miri Disfani, "Spent Coffee Grounds–Fly Ash Geopolymer Used as an Embankment Structural Fill Material," *Journal of Materials in Civil Engineering, © ASCE,* vol. 28, no. 5, pp. 04015197-1-8, 2016.

[15] Itthikorn Phummiphan, Suksun Horpibulsuk, P.E., Tanakorn Phoo-ngernkham, Arul Arulrajah, Shui-Long Shen, "Marginal Lateritic Soil Stabilized with Calcium Carbide Residue and Fly Ash Geopolymers as a Sustainable Pavement Base Material," *Journal of Materials in Civil Engineering, © ASCE,* vol. 29, no. 2, pp. 04016195-1-10, 2017.

[16] M. Albitar, P. Visintin, M. S. Mohamed Ali, O. Lavigne, E. Gamboa, "Bond Slip Models for Uncorroded and Corroded Steel Reinforcement in Class-F Fly Ash Geopolymer Concrete," *Journal of Materials in Civil Engineering, © ASCE,* vol. 29, no. 1, pp. 04016186-1-10, 2017.

[17] Yan-Jun Du, Bo-Wei Yu, Kai Liu, Ning-Jun Jiang, S.M.ASCE, Martin D. Liu, "Physical, Hydraulic, and Mechanical Properties of Clayey Soil Stabilized by Lightweight Alkali-Activated Slag Geopolymer," *Journal of Materials in Civil Engineering, © ASCE,* vol. 29, no. 2, pp. 04016217-1-10, 2017.

[18] Indian Standards: 383-1970, Specification for coarse and fine aggregates from natural sources for concrete, Bureau of Indian Standards, New Delhi, India.

[19] Indian Standards: 516-1956 (Reaffirmed 1999), Indian Standard Methods of Tests for Strength of Concrete, Bureau of Indian Standards, New Delhi, India.

[20] ASTM C 666–97, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, ASTM International, West Conshohocken, PA, USA.