International Journal of Engineering Research-Online
A Peer Reviewed International Journal
Email:editorijoer@gmail.com http://www.ijoer.in **ISSN: 2321-7758**

Vol.4., Issue.5., 2016 (Sept.-Oct.)

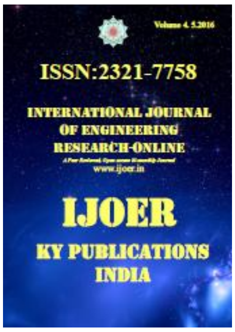
RESEARCH ARTICLE

ISSN: 2321-7758

STRENGTH STUDIES ON PERFORMANCE OF GEOPOLYMER CONCRETE

K.NAVEEN[1], Dr.K.JAYA CHANDRA[2], C.VIDYA SAGAR[3], P.NAVEEN[4]

[1] M.Tech Student, Department of structural Engineering, Sree Rama Engineering College, Tirupati, India
[2] Head of the Department of Civil Engineering & Professor , Sree Rama Engineering College, Tirupati, India,
[3,4]Assistant Professor, Department of Civil Engineering, Priyadarshini Institute of Technology and Sciences, Tirupati, India



ABSTRACT

The major problem that the world facing today is global warming. The cement industry is one of the major reasons for emission of greenhouse gases, such as CO_2 which causes global warming. A lot of energy and natural resources are consumed in production of Ordinary Portland cement (OPC). Geopolymer concrete (GPC) is one of the processes that reduces cement usage and increases the usage of industrial by-products in concrete. In the present study, OPC is fully replaced by pozzolanic materials and alkaline liquids such as Sodium hydroxide (NaOH) and Sodium silicate (Na_2Sio_3) to produce the Geopolymer concrete.

The present investigation is to study the effect of pozzolanic materials and concentration of NaOH. The experimental programme is divided into two phases. In Phase-1, two mixes were taken one is Fly ash based GPC and other is GGBS based GPC with 10M concentration and out of these two mixes the optimum mix GGBS based GPC is taken for further study. In Phase-2 the mix GGBS based GPC is considered and concentration of NaOH is varied (i.e. 6M, 8M, 10M, 12M and 14M) to study the compressive strength. The test specimens prepared were concrete cubes of size 100×100×100 mm and cured under sunlight. The GPC specimens were tested for their compressive strength at the ages of 7, 14, 28 and 56 days. The sorptivity and XRD analysis were also carried out after 28 days of curing. The results show that the GGBS based GPC specimens gives higher compressive strength and lesser sorptivity than the Fly ash based GPC in phase-1 study and in phase-2 with the increase in concentration of NaOH the compressive strength increased and sorptivity value decreased. The XRD analysis also carried out to study the minerals of GPC.

1. INTRODUCTION

1.1 General: The geopolymer technology was first introduced by Davidovits in 1978. His work considerably shows that the adoption of the geopolymer technology could reduce the CO_2 emission caused due to cement industries. Geopolymers are members of the family of inorganic polymers. The chemical composition of the geopolymer material is similar to natural zeolitic materials, but the microstructure is amorphous[1]. Any material that contains mostly silicon (Si) and aluminium (Al) in amorphous form is a possible source material for the manufacture of geopolymer.

Metakaolin or calcined Kaolin, low calcium ASTM Class F fly ash, natural Al-Si minerals, combination of calcined minerals and non-calcined minerals, combination of fly ash and metakolin, combination of granulated blast furnace slag and metakaolin have been studied as source materials[2]. The most common alkaline liquid used in geopolymerisation is a combination of sodium hydroxide or potassium hydroxide and sodium silicate or potassium silicate. In the past few decades, it has emerged as one of the possible alternatives to OPC binders due to their reported high early strength and resistance against acid and sulphate attack apart from its environmental friendliness. The temperature during curing is very important, and depending upon the source materials and activating solution, heat often must be applied to facilitate polymerization, although some systems have been developed that are designed to be cured at room temperature[3]. Geopolymer binders might be a promising alternative in the development of acid resistant concrete since it relies on alumina-silicate rather than calcium silicate hydrate bonds for structural integrity.

1.2 Necessity of Geopolymer Concrete

Concrete is one of the widely used materials all over the world. Ordinary Portland cement (OPC) is used as the primary binder to produce the concrete. The demand of concrete is increasing day by day for the need of development of infrastructure facilities. However, it is well known that the production of OPC not only consumes significant amount of natural resources and energy but also releases substantial quantity of carbon dioxide to the atmosphere. Environmental pollution is the biggest menace to the human race on this planet today. It means adding impurity to environmental. It has a severe effect on the ecosystem. There are many reasons which cause pollution. In our construction industry, cement is the main ingredient/ material for the concrete production. But the production of cement means the production of pollution because of the emission of CO_2 during its production[4]. There are two different sources of CO_2 emission during cement production. Combustion of fossil fuels to operate the rotary kiln is the largest source and other one is the chemical process of calcining limestone into lime in the cement kiln also produces CO_2. In India about 2,069,738 thousand of metric ton of CO_2 are emitted in the year of 2010. The cement industry contributes about 5% of total global carbon dioxide emissions[5]. And also, the cement is manufactured by using the raw materials such as limestone, clay and other minerals. Quarrying of these raw materials is also causing environmental degradation. To produce a ton of cement, about 1.6 tons of raw materials are required and the time taken to form the limestone is much longer than the rate at which humans use it. On the other side the demand of concrete is increasing day by day for its ease of preparing and fabricating in all sorts of convenient shapes. So, to overcome this problem, the concrete to be used should be environmental friendly. To produce environmentally friendly concrete, we have to replace the cement with the industrial byproducts such as fly-ash, GGBS (Ground granulated blast furnace slag) etc. In this respect, the new technology geopolymer concrete is a promising technique.

1.3 Objective and Scope

The main objective of this project is to study the performance of geopolymer concrete by considering two different pozzolanic materials and to investigate the effect of alumina-silicate source material and alkaline solution in Geopolymer concrete. The scope in geopolymer concrete is usage of recycled coarse aggregates as fresh coarse aggregates, SEM tests can be done for GGBS based GPC, Fine aggregates can be replaced by the industrial by-products.

2. EXPERIMENTAL STUDY

2.1. Materials

The cement industry is one of the major reasons for emission of greenhouse gases, such as CO2 which causes global warming. A lot of energy and natural resources are consumed in production of Ordinary Portland cement (OPC). Geopolymer concrete (GPC) is one of the processes that reduces cement usage and increases the usage of industrial by-products in concrete. In the present study, OPC is fully replaced by pozzolanic materials and alkaline liquids such as Sodium hydroxide (NaOH) and Sodium silicate (Na2Sio3) to produce the Geopolymer concrete.

The present investigation is to study the effect of pozzolanic materials and concentration of NaOH. The experimental programme is divided into two phases.

In Phase-1, two mixes were taken one is Fly ash based GPC and other is GGBS based GPC with 10M concentration and out of these two mixes the optimum mix GGBS based GPC is taken for further study.

In Phase-2 the mix GGBS based GPC is considered and concentration of NaOH is varied to study the compressive strength..These are the tests for slump cone,compression ,Sorptivity and XRD Test s.

The sorptivity and XRD analysis were also carried out after 28 days of curing. The results show that the GGBS based GPC specimens gives higher compressive strength and lesser sorptivity than the Fly ash based GPC in phase-1 study and in phase-2 with the increase in concentration of NaOH the compressive strength increased and sorptivity value decreased. The XRD analysis also carried out to study the minerals of GPC.

2.2. Mix design

As Geopolymer concrete is a new technology to the world, that it have not reached the stage of standards codes or mix design. The methods used to design, prepare and test the Geopolymer concrete are based on many previous journals.

Geopolymer concrete is nothing but a 100% replacement of cement with cementious materials and alkaline liquids. Initially, many number of trials were carried out by using different materials such as Rice husk ash, Metakaoline, Ground granulated blast furnace slag and Fly ash. In those trials, we found Fly ash and GGBS are suitable materials for the replacement of cement to get significant strength to OPC. The test specimens prepared were concrete cubes of size 100×100×100 mm and cured under sunlight. The GPC specimens were tested for their compressive strength at the ages of 7, 14, 28 and 56 days.

Phase-1 Mix proportions (kg/m^3):

S.no	Materials	Mix 1	Mix 2	Mix3
1	Fly ash	514.3	257.15	0
2	GGBS	0	257.15	514.3
3	Fine aggregate	672	672	672
4	20mm Coarse aggregate	705.6	705.6	705.6
5	10mmCoarseAggr egate	302.4	302.4	302.4
6	Sodium silicate	146.92	146.92	146.9 2
7	20mmCoarseaggre gate	18.22	18.22	18.22
8	Distilled Water	40.55	40.55	40.55
9	Molarity	10M	10M	10M

Phase-2 Mix proportions (kg/m3):

S.NO	Particulars of test	Coarse Aggregate	Fine Aggregate
1	Specific gravity	2.64	2.62
2	Water absorption	0.4	0.40%
3	Bulk density	1605 kg/m^3	1718kg/m^3
4	Loose bulk density	1477 kg/m^3	1518kg/m^3
5	Fineness Modulus	7.357	2.69

Mixing: Mixing of ingredients is done in a pan mixer of capacity 40 litres. First Fly ash or GGBS depends upon the mix, Coarse aggregate and fine aggregate are mixed thoroughly for three minutes in a pan mixer and the alkaline solution which is added with extra water to dry materials and mixed about for five minutes.The primary difference between geopolymer concrete and Portland cement concrete is the binder. The silicon and aluminium oxides in the low-calcium fly ash reacts with the alkaline liquid to form the geopolymer paste, that binds the loose coarse and fine aggregates and other unreacted materials to form the geopolymer concrete.

S.no	Materials	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8
1	GGBS	514.3	514.3	514.3	514.3	514.3
2	Fine aggregate	672	672	672	672	672
3	20mm Coarse aggregate	705.6	705.6	705.6	705.6	705.6
4	10mmCoarseAggregate	302.4	302.4	302.4	302.4	302.4
5	Sodium silicate	146.92	146.92	146.92	146.92	146.92
6	Sodium hydroxide	11.75	14.69	18.22	20.57	23.51
7	Distilled Water	47.02	44.08	40.55	38.2	35.26
8	Molarity	6M	8M	10M	12M	14M

2.3. Test specimens

Three cubical and cylindrical specimens of size 150 mm x 150 mm x 150 mm and length 300 mm, 150 mm diameter were cast and tested for each age and each mix for compressive strength and split tensile strength. The compressive and split tensile strength of Geopolymer Concrete was tested after 7, 28 and 90 days of curing. For impact test L/4 of cylinder i.e., 75 mm of length and diameter of 150 mm specimens were casted and cured for a period of 28 days. In case of sorptivity, the specimens having 100X100X100mm surface area were casted and cured for a period of 28 days and it is coated with non absorbent material on all sides except on side of contact with the water.

2.4. Curing of Test Specimens

After casting and demoulding, the test specimens were kept in normal water for curing at room temperature till the execution of the testing on the specimens.

3. METHODOLOGY

The strength studies on performence of geopolymer concrete are evaluated by using Compressive strength test, X-Ray Diffraction Test, and sorptivity as respective codes.

4. RESULTS AND DISCUSSIONS

4.1 Introduction: One of the most environmentally responsible ways of meeting the challenges of sustainability in construction is to reduce the production of OPC, by using the Fly ash and GGBS in concrete as a replacement of cement. The main objective of the present work of investigation is classfied in to two phases.

Phase-1: The effect of the Source materirial in geopolymer concrete which are rich in alumina-silica source such as GGBS and flyash.

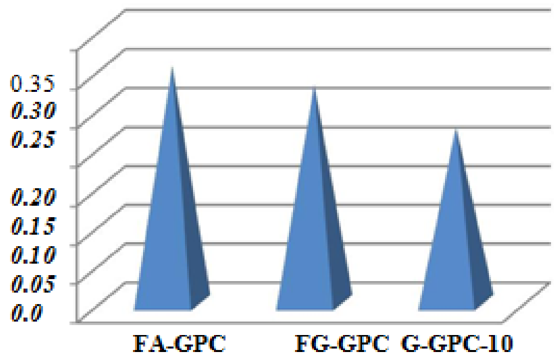
Phase-2: The effect of molarity of alkaline liquid in Geopolymer concrete by varing as 6M, 8M, 10M, 12M and 14M.

These are tests for geopolymers concrete Compressive strength, Sorptivity, XRD

4.2 Sorptivity: The sorptivity test has been conducted for the specimens of Phase-1 and Phase-2 after curing them for 28 days in sunlight.

Phase-1 Sorptivity test results:

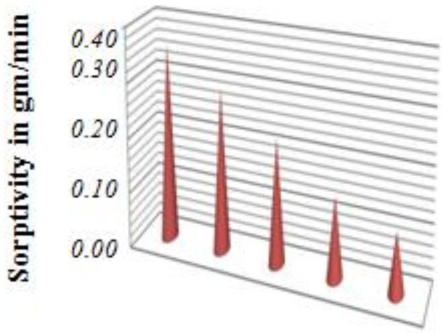
S.NO	*Morter Type*	*Dry wt.in grams(w)*	*Wet wt.in grams(w2)*	*Change in wt.in grams (w_2-w_1)*	*Sorptivity Value* 10^{-4} mm/min$^{0.5}$
1	FG-GPC	2362.3	2379	16.7	0.3
2	FG-GPC	2519.3	2534.7	15.3	0.28
3	G-GPC	2551.7	2564	12.3	0.23



Geopolymer concrete specimens G-GPC-10 manufactured with 100% GGBS resulted in lesser values of sorptivity when compared to the 100% Fly ash and 50% Fly ash + 50% GGBS based geopolymer concrete as in the case of FA-GPC and FG-GPC specimens respectively. This may be attributed to the fact that alkali content in the mix gives better reactivity with the GGBS resulting in denser microstructure.FA-GPC specimen recorded 0.30 mm/min0.5 sorptivity whereas specimens of G-GPC-10 showed comparatively lower corresponding values of 0.23 mm/min0.5 respectively.

Phase-2 Sorptivity test results:

S.NO	Morter Type	Dry wt.in grams(w_1)	Wet wt.in grams(w2)	Change in wt.in grams (w_2-w_1)	Sorptivity Value 10^{-4} mm/$min^{0.5}$
1	G-GPC-6	2423.7	2443.3	19.7	0.36
2	G-GPC-8	2449.3	2465.7	16	0.29
3	G-GPC-10	2551.7	2564	12.3	0.23
4	G-GPC-12	2578.7	2586.7	8	0.15
5	G-GPC-14	2604	2610	6	0.11



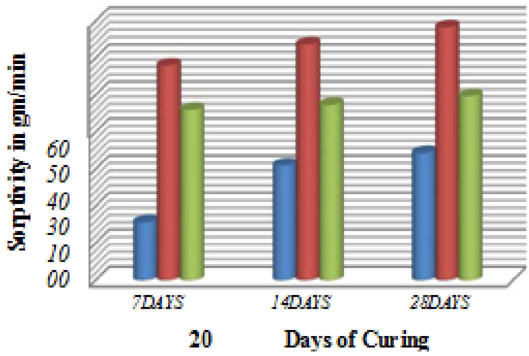
4.2. Mechanical properties

Compressive strength and splitting tensile strength of GPC were tested on cubes and cylinders with different percentages of steel and glass fibers for M20 grade mix are tabulated. The strength of GPC has been tested after 7, 14 and 28 and 56 days of normal curing.

4.2.1. Compressive strength:

Phase-1 Compressive strength results: In phase-1 of the project by varying the materials of the mix the compressive strength results are presented and the test results are taken for 7 days, 14 days and 28 days.

s.no	Types of specimen	Compressive Strength in MPa		
		7 days	14days	28days
1	FG-GPC	15.66	31	34.33
2	FG-GPC	46	47.33	49.7
4	G-GPC-10	58	63.33	68.33



Phase-11 Compressive strength results: In the phase-2 of the project the optimum mix of phase-1 material is taken that is GGBS based geopolymer concrete and by varying the molarity of the alkaline solution compression strength is presented for the 7 days, 14days, 28 days and 56 days.

s.no	Types of specimen	Compressive Strength in MPa			
		7 days	14days	28days	56days
1	G-GPC-6	29.33	33	42	443.33
2	G-GPC-8	35.33	36.33	54.33	56.66
3	G-GPC-10	58	63.67	68.33	69.87
4	G-GPC-12	63.7	68.33	70.66	71.66
5	G-GPC-14	65.7	71	75.33	76.33

Compressive strength was tested for the mixes with the addition of various percentage of fibers i.e., of 0%, 0.5%, 1%, 1.5% and 2% by volume and weight of cement in concrete. The samples were tested after curing periods of 7, 28 and 90 days. It was observed that there was a significant increase in compressive strength with the increase in percentage of fibers from 0% to 1.5% in all curing periods. After 7 days of curing, 1.5% fibers sample exhibited a compressive strength of 24.82 MPa, whereas after 28 days of curing it was 32.35 MPa and after 90 days of curing it was 37.64 MPa.

It is to be noted that the significant improvement in compressive strength is mainly due to the addition of fibers in concrete. From the results it is concluded that the fibers blending will enhance the initial crack stress, ultimate strength and toughness after cracking. Thus hybridization results in bridging of both micro cracks and macro cracks in the different stages by choosing an appropriate fiber to the concrete mix gives the best results. However, when the percentage fibers were increased to 2% a drastic fall in compressive strength was evidenced irrespective of the time of curing. The compressive strength values of the mixes with 2% addition of fibers were found to be 20.33 MPa, 29.32 MPa and 34.22 MPa respectively after 7, 28 and 90 days of curing.

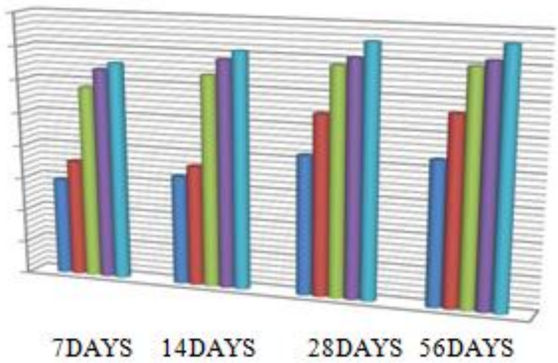


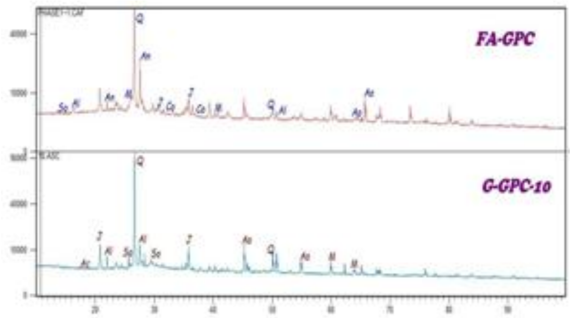
Figure 3. Compressive strength versus Age

X-RAY DIFFRACTION: Total four samples were tested for the X-Ray Diffraction (XRD) that is two samples in each phase. The samples that are tested,

Phase-1

FA-GPC (Fly ash based GPC)

G-GPC-10 (GGBS based GPC

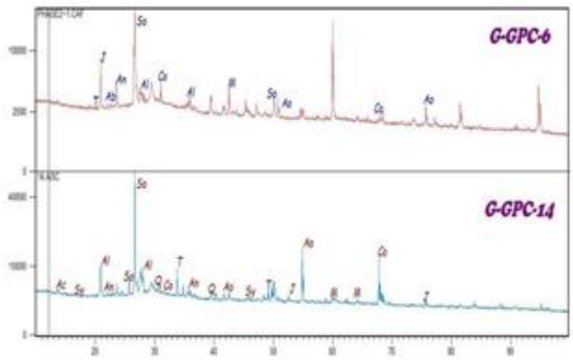


The G-GPC specimens exhibits peaks of Quartz. Peaks of Silicon Oxide are also observed.In the above Pie chart the Quartz and Silicon oxide are in higher contents GGBS based GPC than the FLY Ash based GPC.The mix G-GPC-10 containing Quartz and Silicon Oxide higher, than the FA-GPC, which helped in strengthening the concrete. Analcime is an extra compound that found in the G-GPC-10, which also increases the strength of the concrete.

Phase-2

G-GPC-6 (GGBS based GPC of 6 Molar)

G-GPC-14 (GGBS based GPC of 14 Molar)



The G-GPC specimens exhibits peaks of Quartz. Peaks of Silicon Oxide are also observed.In the above Pie chart the Quartz and Silicon oxide are in higher contents GGBS based GPC than the FLY Ash based GPC.The mix G-GPC-10 containing Quartz and Silicon Oxide higher, than the FA-GPC, which helped in strengthening the concrete.Analcime is an extra compound that found in the G-GPC-10, which also increases the strength of the concrete. XRD analysis of the G-GPC's Specimen showed the presence of Quartz, Analcime, Anorthite, Mullite, Jadeite and Albite.The G-GPC specimens exhibits peaks of syngenite. Peaks of Thenardite are also observed.Thenardite occured due to reaction between Na ions form the NaOH solution with sulfate ions leading to the formation of sodium sulfate decahydrate.The presence of the Anorthite phase indicates that calcium from the aggregate is reacting with the sodium silicate along with the alumina silicate forming Anorthite and Albite.Albite can be associated with the strength enhancement region of the geopolymer matrix.Thenordite is a compound which de-hydrates the material and resist the water absorption, it is also proved practically by the sorptivity test.

5. CONCLUSIONS

Based on the investigation, the following conclusions have been drawn.

1. The compressive strength attained by GGBS based Geopolymer concrete is more than the Fly ash based Geopolymer concrete.
2. The Sorptivity and XRD analysis proves that GGBS based GPC absorbs less water due to its crystalline structure.
3. The reaction of GGBS in geopolymer concrete with alkaline solution attains

higher strength and less sorptivity confirms GGBS is the best suitable material in Geopolymer concrete compared to fly ash.

4. The increase in molarity of NaOH leads to less voids and good crystalline structure that results in less water absorption.
5. NaOH plays a major role in attaining the strength of the concrete, hence it is recommended 10M concentrations for medium grade.
6. The rate of increase in strength after 10 Molar concentration is decreased. So, considering 10M and 12M as the optimum dosage for GPC mix.
7. Based on the molar concentration the grades of concrete can be designed and implemented in construction.
8. The geopolymer concrete can be innovative supplementary to OPC in construction material but judicious decisions are to be taken by engineers.

REFERENCES:

[1]. N A Lloyd and B V Rangan., Geopolymer Concrete with Fly Ash, Second International Conference on Sustainable Construction Materials and Technologies Volume 3, 2010, pp. 1493-1504.

[2]. V. Supraja, M. Kanta Rao., Experimental study on Geo-Polymer concrete incorporating GGBS, International Journal of Electronics, Communication & Soft Computing Science and Engineering ISSN:2277-9477, Volume2, Issue 2.

[3]. Kolli Ramujee and M. Potharaju., Development of Low Calcium Flyash Based Geopolymer Concrete, IACSIT International Journal of Engineering and Technology, Vol. 6, No. 1, February 2014.

[4]. More Pratap Kishanrao., Design of Geopolymer Concrete, International Journal of Innovative Research in Science, Engineering and Technology Vol. 2, Issue 5, May 2013

[5]. Prakash R. Voraa, Urmil V. Daveb., Parametric Studies on Compressive Strength of Geopolymer Concrete, Science directProcedia Engineering 51 (2013) 210 – 219

[6]. Mohd Mustafa Al Bakri Abdullah, Kamarudin Hussin, Mohamed Bnhussain, Khairul Nizar Ismail, Zarina Yahya and Rafiza Abdul Razak., Fly Ash-based Geopolymer Lightweight Concrete Using Foaming Agent, Int. J. Mol. Sci. 2012, 2013, 7186-7198; doi:10.3390/ijms13067186.

[7]. Shankar H. Sanni, Khadiranaikar, R. B., Performance of Geopolymer concrete under severeenvironmental conditions, International Journal of Civil and Structural Engineering, Volume 3, No 2, 2012.

[8]. Prof.M.A.Bhosale, Prof.N.N.Shinde., Geopolymer Concrete by Using Fly Ash in Construction, IOSR Journal of Mechanical and Civil Engineering (IOSRJMCE) ISSN : 2278-1684 Volume 1, Issue 3 (July-August 2012), PP 25-30.

[9]. Muhammad Aamer Rafique Bhutta, Ph.D., Warid M. Hussin, Ph.D., Mohd Azreen, Ph.D., and Mahmood Mohd Tahir, Ph.D.,Sulphate Resistance of Geopolymer Concrete Prepared from Blended Waste Fuel Ash, ASCE.

[10]. Ganapati Naidu. P, A.S.S.N. Prasad, S. Adiseshu, P.V.V. Satayanarayana., A Study on Strength Properties of Geopolymer Concrete with Addition of G.G.B.S, International Journal of Engineering Research and Development eISSN : 2278-067X, pISSN : 2278-800X.

[11]. 11. Mr. Bennet Jose Mathew, Mr. M Sudhakar, Dr. C Natarajan.Strength, Economic and Sustainability Characteristics of Coal Ash–GGBS Based Geopolymer Concrete,International Journal Of Computational Engineering Research (ijceronline.com) Vol.3

[12]. Daniel L.Y. Kong a, Jay G. Sanjayan., Effect of elevated temperatures on geopolymer paste, mortar and concrete, Cement and Concrete Research 40 (2010) 334–339

[13]. K. Vijai et al., Experimental Investigations On Mechanical Properties Of Geopolymer Concrete Composites, Asian Journal Of Civil Engineering (Building And Housing) Vol. 13, No. 1 (2012) Pages 89-96.

[14]. Gasca-Tirado J. Ramóna, Rubio-Ávalos J.C, Muñiz-Villarreal M.S, Manzano-Ramírez A, Reyes-Araiza J.L, Sampieri-Bulbarela S, Carlos Villaseñor-Mora, Pérez-Bueno J.J, Apatiga L.M, Amigó Borrás Vicenteg., Effect of porosity on the absorbed, reemitted and transmitted light by a geopolymer metakaolin base, Material Letter, 65 (2011) 880-883.

[15]. 15 K. Vijai, R. Kumuthaa and B.G.Vishnuram., Experimental Investigations on Mechanical Properties of Geopolymer Concrete Composites, Asian Journal of Civil Engineering (Building and Housing) Vol. 13, No. 1 (2012) Pages 89-96.

[16]. B. Vijaya Rangan. FlyAsh-Based Geopolymer Concrete,Proceedings of the International Workshop on Geopolymer Cement and Concrete, Allied Publishers Private Limited, Mumbai, India, December 2010, pp 68-106.

[17]. Mr. K. Madhan Gopal, Mr. B. Naga Kiran., Investigation on Behaviour of Fly Ash Based Geopolymer Concrete in Acidic Environment, International Journal of Modern Engineering Research (IJMER) Vol.3, Issue.1, Jan-Feb. 2013 pp-580-586.

[18]. S.V.A. Silva, J.N.J. Kithalawa Arachchi, C.L. Wijewardena, S.M.A. Nanayakkara., Development of Fly Ash Based Geopolymer Concrete.

[19]. Ammar Motorwala, Vineet Shah, Ravishankar Kammula, Praveena Nannapaneni, Prof. D. B. Raijiwala., ALKALI Activated FLY-ASH Based Geopolymer Concrete, International Journal of Emerging Technology and Advanced Engineering Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 3, Issue 1, January 2013)

[20]. Dali Bondar., Geo-polymer Concrete as a New Type of Sustainable Construction Materials, Third International Conference on Sustainable Construction Materials and Technologies.

[21]. Ammar Motorwala, Vineet Shah, Ravishankar Kammula, Praveena Nannapaneni, Prof. D. B. Raijiwala., Strength study on flyash based geopolymer concrete under heat curing, International journal of engineering trends in engineering and development, Issue 2, Vol. 4

[22]. Louise K. Turner, Frank G. Collins., Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete, Construction and Building Materials 43 (2013) 125-130.

[23]. Prabir K. Sarker, Rashedul Haque, Karamchand V. Ramgolam.,Fracture behaviour of heat cured fly ash based geopolymer concrete, Materials and Design 44, 580-586

[24]. Junjie Feng, Ruifang Zhang, Lunlun Gong, Ye Li, Wei Cao, Xudong Cheng., Development of porous fly ash-based geopolymer with low thermal conductivity, Materials and Design 65, 529-533.

[25]. BennyJoseph, GeorgeMathew., Influence of aggregate content on the behavior of flyash based geopolymer concrete, Scientia Iranica A (2012) 19 (5),1188–1194