REVIEW ARTICLE

Granulated Blast-Furnace Slag (GGBS) based Geopolymer Concrete - Review

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ABSTRACT: The geopolymer concrete has stepped in the construction industry as an alternate to the cement based concrete. Many of the research about geopolymer concrete states that it has potential to replace the cement based concrete in many countries depending on the locally available resources. The present review deals with the study of constituents of geopolymer concrete. Attempt has been made to collect information about the locally available constituents of geopolymer concrete and the ongoing research and few mechanical properties with and without fibres in concrete were discussed. The geopolymer concrete chosen is based on 100% ground granulated blast furnace slag (GGBS) cured in laboratory in typical tropical ambient environmental conditions.

KEYWORDS: Geopolymer Concrete, Bond strength, Durability, ambient curing, Fibres in Concrete.

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1. INTRODUCTION

Geopolymer concrete is produced by the alkali activation of fly ash or ground granulated slag combining with aggregates. The progress in the field of geopolymer concrete up to present time has been the fruit of an empirical approach, rather than the fundamental and scientific one. And because of empirical approach, the results from different studies cannot be related to one another. Geopolymers are a group of inorganic polymer produced by the result of reaction between an alkaline solution and an aluminosilicate as a source. The microstructure of hardened geopolymer material has an amorphous, three-dimensional structure similar to that of an aluminosilicate glass. However unlike a glass, these hardened geopolymer materials are produced at low temperature and as a result can integrate an aggregate skeleton and a reinforcing system, if required, during the forming process. The reactants needed to form a geopolymer are an alkali hydroxide, alkali silicate solution and an aluminosilicate fine binder. The binder needs to have a significant proportion of silicon and aluminium ions held in amorphous phases. Commonly used binders include class-F fly ash, ground granulated slag and metakaolin, but any fine amorphous aluminosilicate material can be used [1].

All types of concrete fail under compression when tested [2]. But compression strength itself is not the property of concrete to explain the performance of concrete. Concrete failure will always develop in weakest part of one of these three phases namely: aggregate zone, transition zone and hydrated cement paste. Thus, in order to increase the compressive strength of concrete, great care must be taken to strengthen all these three phases. It also depends on the microstructural features of concrete which govern the other properties like strength, elastic modulus and durability [3].

2. GEOPOLYMERIZATION MECHANISM

Similar to conventional organic polymerization, this process involves forming monomers in solution, then activating them to polymerize to form a solid polymer. This geopolymerisation process involves three separate but interrelated stages [4, 5]:

- Dissolution-During initial mixing the alkaline solution dissolves silicon and aluminium ions from the amorphous phases of the binder like fly ash or GGBS.
- Condensation- In this solution, neighboring silicon or aluminium hydroxide molecules undergo a condensation reaction where adjacent hydroxyl ions from these nearest molecules condense to form an oxygen bond connecting these molecules, and a free molecule of water.
- Polymerisation-Monomers and other silicon and aluminium hydroxide molecules condense to form rigid chains or nets of oxygen bonded tetrahedral with application of mild temperatures or even at ambient temperatures. All the three process of geopolymerisation [6] are shown in Figure 1.

3. GEOPOLYMER CONCRETE CONSTITUENT MATERIALS AND CASTING TECHNIQUE

3.1. Source Materials-Binder

Any material that contains mostly Silicon (Si) and Aluminium (Al) in amorphous form is a possible source material or binding material for the manufacture of geopolymer. Several minerals and industrial by-product materials have been investigated in the past and

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concluded that metakaolin or calcined kaolin, low-calcium fly ash, combination of calcined mineral and non-calcined materials, combination of fly ash and metakaolin, and combination of granulated blast furnace slag and metakaolin can be used as source materials [7].
However, Hardjito and Rangan [8] claims that calcined source materials like fly ash, slag (GGBS), calcined kaolin, and demonstrates a higher final compressive strength when compared to those made using non-calcined materials like kaolin clay, mine tailings, and naturally occurring minerals. According to Panagiotopoulou et al. [9] the amount of dissolution of GGBS is more than the amount of dissolution of fly ash as in Figure 2. Therefore, in the present study GGBS is used as a source material which is rich in silica and alumina [10]. The typical chemical composition of fly ash and GGBS is shown in the Table 1.

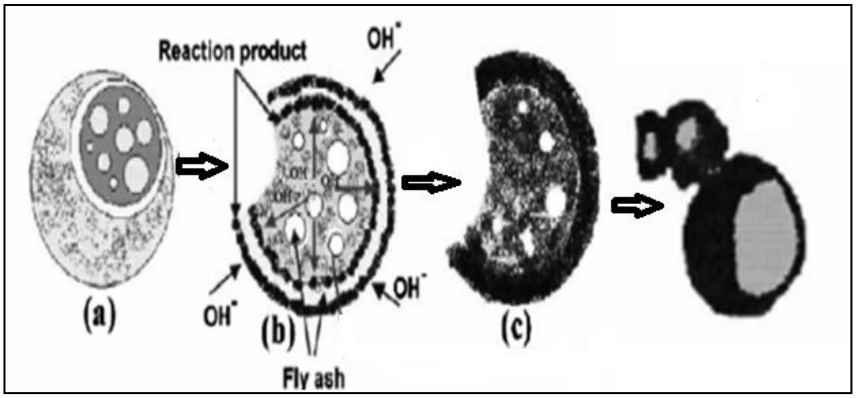

Figure 1. Typical geopolymerisation process on fly ash as binder reported by Abdullah et al[6]

Table 1 Typical Chemical composition of fly ash and GGBS (Sharma and Sivapullaiah [10])

Oxide	Fly ash	GGBS
SiO_2 (%)	54.4	29.2
Al_2O_3 (%)	28.6	13.8
CaO (%)	1.6	44.9
MgO (%)	1.4	6.2
Fe_2O_3 (%)	3.2	5.5
Na_2O (%)	0.3	0.3
K_2O (%)	1.7	1.0
TiO_2 (%)	1.8	2.1
LOI	5	-
CaO/SiO_2	0.03	1.54

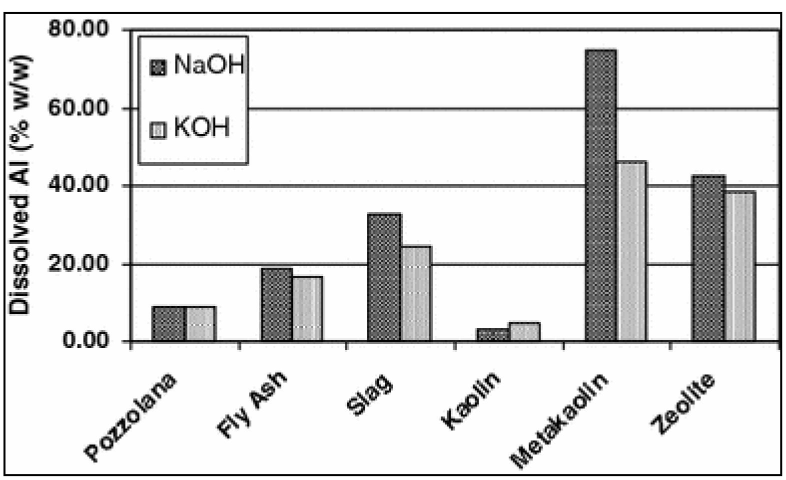

Figure 2 Dissolution of alumina from different sources in alkaline media (Panagiotopoulou et al [9])

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3.2. Binding Solution: Alkaline Solution

Binding solution used in geopolymerization process is an alkaline solution comprising of mixture of NaOH and Na_2SiO_3 in varying proportions. As explained in the mechanism this alkaline solution dissolves the binder to get alumino-silicate products which have the cementing property. According to Petermen [11] the activation of the selected pozzolanic material is the most significant factor in producing a mechanically-sound cementitious material via the geopolymerization process. The initial mechanism of reaction is driven by the ability of the alkaline solution to dissolve the pozzolanic material and release reactive silicon and aluminum into solution. The activators prompt the precipitation and crystallization of the siliceous and aluminous species present in the solution. OH^- acts as a catalyst for reactivity, and the metal cation serves to form a structural element and balance the negative framework carried by the tetrahedral aluminum.

Palomo et al. [4] concluded that the type of alkaline liquid as a precursor plays an important role in the polymerisation process. Reactions occur at a high rate when the alkaline liquid contains soluble silicate of sodium or potassium, in comparison with the use of only alkaline hydroxides. Xu and Van Deventer [5] confirmed that the addition of sodium silicate solution(Na_2SiO_3) to the sodium hydroxide (NaOH) solution as the alkaline liquid improved the reaction between the source material and the solution. The most common alkaline liquid used in geopolymerisation is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate. Furthermore, after a study of the geopolymerisation of natural Al-Si minerals by Hardjito et al. [12] and Panagiotopoulou et al. [9], found that generally the NaOH solution caused a higher extent of dissolution of minerals than the KOH solution. Hence in the present work NaOH and Na_2SiO_3 are used as binding solution. The activator solution was prepared one day prior to its use in specimen casting.

3.3. Admixtures

Various superplasticizers can be used to substantially improve the workability of fresh concrete without increasing the amount of water and hence reducing the risk of segregation. In order to improve the workability of fresh concrete, Raijiwala and Patil [13] used high-range water-reducing naphthalene based superplasticizer with the dosage from 0.6-2.0% of the weight of fly ash. Kumar et al. [14] used polycarboxylate ether based high performance superplasticizers in the concrete. The utilization of viscosity modifying admixture gives more possibilities of controlling segregation and homogeneity of the mix. However, in some cases, the use of superplasticiser may have an adverse effect on the strength of geopolymer. Therefore, the type and dosage of susperplastizer shall be used after trial mixes as the preliminary experiment. Though the previous works quote about the use of naphthalene based super plasticizer, in the present study such admixtures did not show any effect on the fresh concrete. But admixtures based on the polycarboxylate ethers showed the improvement in the workability of concrete and hence they are adopted in the present research.

3.4. Aggregates

It may be noted that any concrete requires fine aggregates and coarse aggregates so that a packing of these two inert filler materials creates minimum space for binder paste in the concrete mix and this is required from economic point of view also since binder portion is generally the most expensive in any concrete mix. Locally available crushed sand and crushed granite coarse aggregates are used at the saturated surface dry condition for geopolymer concrete mixes.

3.5 Mixing of Geopolymer Concrete

According to Nuruddin et al. [15] mixing process can be divided into two stages, dry mix and wet mix. Initially coarse aggregate, fine aggregate and GGBS will be mixed together in rotating pan mixer for 3 to 5 minutes. The alkaline solution is prepared by mixing sodium hydroxide solution with sodium silicate solution one day before making the geopolymer concrete to get the desired alkaline solution. The liquid part of the mixture, i.e., the alkaline solution, extra water and the superplasticizer, should be premixed thoroughly and then added to the dry mixture. The wet mixing can be done for 1.5 to 3 minutes. The process of mixing is depicted in figure 3. Fresh geopolymer concrete is then hand mixed to ensure the mixture homogeneity. The aluminosilicate gel is highly viscous and mixing agitation can easily encapsulate air into the matrix. Mechanical vibration of the formed molds serves to reduce this potential and greatly improves the overall strength of the hardened geopolymer concrete.

3.6 Curing of Geopolymer Concrete

Curing is a main important process for both strength and durability of geopolymer concrete. Geopolymer concrete needs to be cured in a high temperature to accelerate a reaction of geopolymerisation. Duration, temperature and type of curing have been investigated by various researchers like Olivia and Nikraz [16] and Mustafa et al. [17]. Curing process of geopolymer concrete can be achieved by: oven curing (30-90 °C), hot gunny curing (33-38 ºC), ambient curing (27-32ºC), and external exposure curing (39-44 ºC). Special curing techniques like steam curing at temperature of 60^0C for 24 hours followed by air curing in a control environment with a temperature of 23-2 ^{0}C until testing can also be followed. There is an increase in compressive strength with the increase in age for ambient cured specimens. According to Vijai et al. [18], the increase in compressive strength with age is very less as compared to that of specimens subjected to ambient curing for hot cured samples. The rate of increase in strength will be rapid up to 24 hours of curing time; beyond 24 hours, the gain in strength is only moderate. Therefore, heat-curing time need not be more than 24 hours in practical applications. Heat-curing can be achieved by either steam-curing or dry-curing. According to Rangan [19], 25-35°C range of temperature can be provided by the ambient curing conditions in tropical

climates. So, in the present study the adopted curing regime is only restricted to ambient curing.
As there are no standard codes established for the mix design of geopolymer concrete in any part of the world, so for the mix design process is carried on basis of some of the following thumb rules like density of concrete as 2400kg/m3, quantity of total aggregates as 80% of the total constituents, coarse aggregate content as 70-75% of total aggregates. A typical mix proportion as per Singh et al [20] is given in Table No.2.

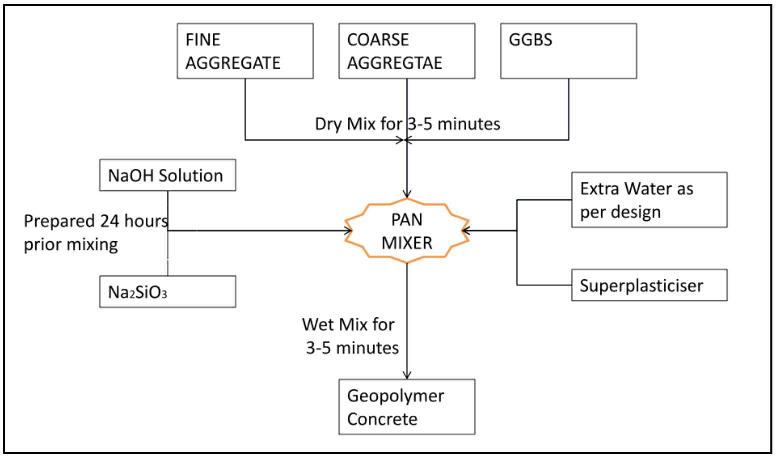

Figure 3 Mixing Process of Geopolymer Concrete

Table 2 Typical mix proportion of combination of fly ash and slag geopolymer concrete (Singh et al.) [20]

Constituent	Mix 1	Mix 2
Fly Ash (kg/m3)	343.00	300.00
Slag (kg/m3)	172.00	150.00
Coarse aggregate 10mm (kg/m3)	503.30	516.40
Coarse aggregate 20mm (kg/m3)	528.00	541.80
Fine Aggregate (kg/m3)	723.80	742.70
Activator Solution (kg/m3)	180.20	180.00
Superplastcizer (kg/m3)	7.70	6.70
water-geopolymer solids ratio	0.19	0.21
activator-binder ratio	0.35	0.40
Method of curing	Ambient	Ambient
Compressive Strength	30.26	35.38

4. MECHANICAL PROPERTIES OF GEOPOLYMER CONCRETE:

The mechanical properties of geopolymer concrete are dependent upon many variables like binder content, type of alkaline solution, molarity of alkaline solution, aggregate size distribution, and type of mixing and curing conditions. Generally, more than 75- 80% volume in geopolymer concrete is occupied by the aggregates. The aggregates are normally taken as inert materials dispersed throughout the matrix. Similar to the conventional concrete, geopolymer concrete can also be reinforced for improving its mechanical properties with different kinds of fibres and additives. With the present literature, it is being observed that geopolymer concrete upto M100 grade is possible with different mixing procedures.
Li and Liu [21] found that the incorporation of slag could significantly increase the compressive strength of the geopolymer at 30°C ambient curing. The incorporation of steel fibers in Geo-Concretes reduces the compressive strength at early ages. On the contrary, the splitting tensile strength, the flexural strength and the toughness increase significantly. According to Susan et al. [22], the strengths and the toughness of Ordinary Portland Cement Concretes with the same proportion of binder and fibers were lesser than the Geo-concretes reinforced with steel fibers. According to Sivakumar and Srinivasan [23], the mechanical properties like compressive, split tensile and flexural strength will be improved with added of polypropylene fibre. Test results of Srinivasan [23] showed that 100% GGBS binder composition with 0.25% polypropylene fibres has shown better performance.

5. DURABILITY ASPECTS OF GEOPOLYMER CONCRETE

When compared to conventional concrete systems, geopolymers are new materials which completely lack the long service and durability issues history that would enable an accurate prediction and control of structural deterioration. Performance requirements, drivers for deterioration and means of predicting and characterizing changes that will ultimately result in failure need to be assessed. Geopolymer cements are inherently resistant to chemical attack and thermal loading due to their reduced porosity and thermal conductivity characteristics. Many of the durability problems associated with plane cement concrete arise from its calcium content in the main phases. The C_3A reacts with sulfate ions in the presence of $Ca(OH)_2$ to form ettringite and gypsum, which in turn cause expansion and degradation of the cement into a non-cohesive granular mass. It is the low calcium content found within pozzolanic materials that prevents geopolymers from experiencing such negative effects. Since no limestone is used as a material, geopolymer cement has excellent properties within both acid and salt environments. Chanh et al. [24] concludes that geopolymer concrete is suitable for tough environmental conditions and seawater can be used for the blending of the geopolymer cement which can be useful in marine environments and on islands short of fresh water.

From Hardjito et al. [12] works it is clear that geopolymer concrete do not show any sign of sulfate attack or degradation in compressive strength, the unit mass, the length change, and in visual appearance. The Geopolymers are resistant to the corrosion and do not exhibit any sign of deterioration for long periods of time when exposed to environment of NaCl solution. However, geopolymer concrete exhibits a decrease in residual compressive strength when immersed in 10% Magnesium Sulphate solution which may be attributed to occurrence of micro cracks due to formation of gypsum and ettringite in the surface pores. According to Sanni and Khadirnaikar [25], the strength of GPC gradually decreases as the day of exposure to sulphuric acid increases. The degradation on strength is related to depolymerisation of aluminosilicate polymers in acidic media and the formation of zeolites. But in comparison with the different previous literatures many experiments and statements are contradictory about durability issues related to different exposure conditions of geopolymer concrete. Hence it is very much needed to study the durability issues related to it.

6. MICROSTRUCTURE OF GEOPOLYMER CONCRETE

While conventional cements are composed of portlandite [$Ca(OH)_2$] and calcium silicate hydrate (C-S-H) phases, geopolymer cement is based on an aluminosilicate framework. The microstructure of geopolymer specimens may be viewed as composites comprising of aluminosilicate gel phase and partially reacted binder particles. According to Alehyen et al. [26] the microstructure of geopolymer concrete shows a highly complex product morphology that consists of unreacted, partially reacted, and completely reacted fly ash spheres that are surrounded by a matrix which also includes quartz crystals and mullite needles originating from the fly ash. The bigger fly ash particles are almost dissolved or reduced to smaller size at higher silica content showing denser and finer microstructure as a result of geopolymerization, which indicates a higher degree of reaction resulting in increasing compressive strength. Therefore, the compactness of the microstructure indicates the proper dissolution of Si and Al due to which good binding has been developed between binder and aggregates; resulting in higher strength of concrete. However, many of the works related to microstructure are with geopolymer concrete with fly ash as binding material. Hence it is needed to understand the microstructural property of geopolymer concrete made with GGBS. Microstructure also helps to predict the reason for the failure of concrete with durability issues in different environments.

7. FIBER REINFORCED GEOPOLYMER CONCRETE (FRGPC)

Discrete discontinuous fibres are added to obtain fibre reinforced geopolymer concrete to bridge across the cracks that provide some post-cracking "ductility". The contribution of the fibres is to increase the toughness of the concrete under any type of loading. That is, the fibres tend to increase the strain at peak load, and offer a great deal of energy absorption in post-peak portion of the load versus deflection curve. The presence of fibres in the body of the concrete can be expected to develop the higher resistance of reinforced structural members against to cracking, deflection and other serviceability conditions. Bhalchandra and Bhosle [27] studied the effects of inclusion of glass fibres on density, compressive strength & flexural strength of hardened geopolymer concrete composite (GPCC). Based on the test results it was observed that the glass fibres reinforced geopolymer concrete have relatively higher strength in short curing time than geopolymer concrete & Ordinary Portland cement concrete. Ganesan et al. [28] showed from the experiments that addition of steel fibres improved the mechanical properties of GPC in the case of compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity and Poisson's ratio at 1% volume fraction of fibres. Amuthakkannan et al. [29] showed the improvement in tensile, impact and flexural strength with different fibre length and fibre content of basalt fibre. But still there is need to study the effect of fibres on geopolymer concrete as many of the works concentrated only on mechanical properties for fibre reinforced geopolymer concrete.

8. FIELD APPLICATIONS

Geopolymer concrete and its technology have just begun to capture the imagination of the building industry. Though the geopolymer concrete technology is in the developing stage, but presently it is being used already in some countries in the field application. It has also become commercial in the construction industry. For example, the British Company Banah UK sells its cement "Banah-cem" as geopolymer cement [32]. Zeobond, an Australian company markets its cement free binder concrete as 'E-Crete' which is a geopolymer concrete [33]. The world's first building using Geopolymer concrete for structural purpose is being built by Bligh Tanner and Wagners, designed by Hassell which is University of Queensland's Global Change Institute (GCI) in Australia [34].

9. CONCLUSION

Considerable progress has been made during the last two decades in the investigation of geopolymer concrete and information available is summarized in this paper. Fundamental knowledge on compressive strength and microstructure of GPC has already been obtained by the research carried out so far. However, intensive research is required to get optimum mix of geopolymer concrete with and without fibers, durability and microstructure of geopolymer concrete. While a larger focus has been on investigating mix design and workability of GPC mixes, studies are still required to get a good workable GPC, durability aspects and microstructure of GPC. Authors are pursuing the research in this subject area.

REFERENCES

[1]. Davidovits, J., 1994. Properties of Geopolymer Cements. Alkaline Cements and Concretes. Geopolymer Institute, KIEV, Ukraine.

[2]. Aitcin, P. C., 1998. High Performance Concrete. First ed. CRC Press, Taylor and Francis Group. New York.

[3]. Mehta, P. K., Montiero, P. J. M., 2006. Concrete: Microstructure, Properties, Materials. Third ed. McGraw-Hill Publications, New Delhi. pp-24.

[4]. Palomo, A., Grutzek, M.W., Blanco, M. T., 1999. Alkali-activated fly ashes: A cement for the future. Cement Concrete Research, 29(8) 1323-1329.

[5]. Xu, H., Van Deventer, J. S. J., 2000. The Geopolymerisation of Alumino-Silicate Minerals. International Journal of Mineral Processing, 59, 247-266.

[6]. Abdullah, M. M.A., Hussin, K., Bnhussain, K. N., Ismail, K. N., Ibrahim, W. M. W., 2011. Mechanism and Chemical Reaction of Fly ash Geopolymer Cement – A Review. International Journal of Pure and Applied Sciences and Technology. 6 (1) 35-44.

[7]. Deepak, R., Sulapha, P., Narayanan, N., 2010. Structure and Strength of NaOH activated concretes containing Fly ash or GGBFS as the sole binder. Cement and Concrete Composition, 32,399-410.

[8]. Hardjito, D., Rangan, B. V., 2005. Development and Properties of Low-Calcium Fly ash-Based Geopolymer Concrete, Research Report GC 1, Curtin University of Technology, Perth, Australia.

[9]. Panagiotopoulou, C., Kontori, E., Perraki, T., Kakali, G., 2007. Dissolution of aluminosilicate minerals and by-products in alkaline media. Journal of Material Science, 42(9) 2967-2973.

[10]. Sharma, A.K., Sivapullaiah, P. V., 2016. Ground Granulated blast furnace slag amended fly ash as an expansive soil stabilizer. Soils and Foundations. The Japanese Geotechnical Society; 56(2) 205-212.

[11]. Petermann, J.C., Athar Saeed., 2010. Alkali-Activated Geopolymers: A Literature Review. Air Force Research Laboratory Materials and Manufacturing Directorate. Tyndall Air Force Base, FL 32403-5323, July 2010.

[12]. Hardjito, D., Wallah, S. E, Sumajouw, D., Rangan, B.V., 2003. Geopolymer Concrete: Turn Waste into Environmentally Friendly Concrete. Keynote Paper, International Conference on Recent Trends in Concrete Technology and Structures, 10-11 September, Coimbatore, India. pp. 1-12.

[13]. Raijiwala, D.B., Patil, H. S., 2011. Geopolymer Concrete: A Concrete of Next Decade. Journal of Engineering Research and Studies.

[14]. Kumar, D. P, Krishnaraja, A. R., Sathishkumar, N. P., Sathish Kumar, T., 2014. Mechanical Behaviour of Geopolymer Concrete under Ambient Curing. International Journal of Scientific Engineering and Technology, 3 (2) 130 – 132.

[15]. Nuruddin, M. F., Kusbiantoro, A., Qazi, S., Darnawan, M. S., Husin, N. A., 2011. Development of Geopolymer Concrete with Different Curing Conditions. IPTEK, The Journal for Technology and Science, 22(1) February 2011.

[16]. Olivia, M., Nikraz, H. 2009., Durability of Low Calcium Fly Ash Geopolymer Concrete in Chloride Solution., Proceedings of the Sixth Asian Symposium on Polymers in Concrete, Shanghai, China, 153-161.

[17]. Mustafa Al Bakri, A. M., Kamarudin, H., Norazian, M.N., Ruzaidi, C. M., Zarina, Y. A. R., Rafiza., 2011. Microstructure Studies on the Effect of the Alkaline acyivators Ratio in Preparation of Fly-ash based Geopolymer. International Conference on Chemistry and Chemical Process. IPCBEE. Vol.10, Singapore.

[18]. Vijai, K., Hariharan, V., Kumutha, V., 2014. Investigation on Properties of Geopolymer Concrete using Fly Ash & GGBS., Chemical Science Review and Letters, 2(8) 620-625.

[19]. Wallah, S. E, Rangan, B. V., 2006. Low-Calcium Fly Ash-Based Geopolymer Concrete: Long-Term Properties, Research Report GC 2, Curtin University of Technology, Perth, Australia.

[20]. Singh, B., Rahman, M. R., Paswan, R., Bhattacharyya, S. K., 2016. Effect of activator concentration on the strength, ITZ and drying shrinkage of fly ash / slag geopolymer concrete, Construction and Building Materials, 118, 171-179.

[21]. Zongjin, Li., Sifeng, Liu., 2007. Influence of Slag as Additive on Compressive Strength of Fly Ash-Based Geopolymer. ASCE, Journal of Materials in Civil Engineering, 19(6) June 2007.

[22]. Susan, B., Ruby, D. G., Silvio, D., Erich, R., 2006. Performance of Geopolymeric Concrete Reinforced with Steel Fibres. IIBCC 2006 - Sao Paulo, Brazil. October 15 – 18.

[23]. Sivakumar, A., Srinivasan, K., 2014. International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, 8, 1275-1278.

[24]. Van Chanh, V. B., Trung, D., Tuan, D. V., 2008. Recent research on geopolymer concrete. Nguyen during the 3rd ACF International Conference.

[25]. Sanni, S., Khadiranaikar., 2012. Performance of geopolymer concrete under severe environmental conditions, International Journal of Civil and Structural Engineering, 3(2) 396-407.

[26]. Alehyen, S., Achouri, M. E., Taibi, M., 2017. Characterization, Microstructure and Properties of

fly ash based geopolymer. Journal of Materials and Environmental Sciences. 8(5)1783-1796.

[27]. Bhalchandra, A., Bhosle, A.Y., 2010. Properties of Glass Fibre Reinforced Geopolymer Concrete. International Journal of Modern Engineering Research Vol. 3, Issue. 4, Jul -Aug. 2013 pp-2007-2010.

[28]. Ganesan, N., Deepa Raj, S., Ruby, A., Divya, S., 2013. Fracture Properties of Fibre Reinforced Geopolymer Concrete. International Journal of Scientific & Engineering. Research, 4(5) 75-80..

[29]. Amuthakkannan, P., Manikandan, V., Winowlin Jappes, J. T., Uthayakumar , M., 2013. Effect of Fibre Length and Fibre Content on Mechanical Properties of short Basalt Fibres Reinforced Polymer Matrix Composites. Institute of Problems of Mechanical Engineering. Materials Physics and Mechanics, 16. Pp 107-117.

[30]. Olivia, M., Hamid, R., 2011. Strength and Water Penetrability of Fly Ash Geopolymer Concrete, Journal of Engineering and Applied Sciences, 6(7) 70-78.

[31]. Wallah, S. E, Rangan, B. V., 2006. Low-Calcium Fly Ash-Based Geopolymer Concrete: Long-Term Properties, Research Report GC 2, Curtin University of Technology, Perth, Australia.

[32]. http://www.banahuk.co.uk/info-centre/sustainability/

[33]. http://www.zeobond.com/products-e-crete.html

[34]. https://www.geopolymer.org/news/worlds-first-public-building-with-structural-geopolymer-concrete/