The Technology of Geopolymer - State of the Art

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Abstract **— The cement production has been increasing at an alarming rate due to higher paced industrialization and infrastructure development. Concrete jungles have replaced much of the earth's green cover and the cement production has been a major cause for the carbon-di-oxide emissions resulting in global warming. Geopolymers have been developed as cement-free concrete and the research in the field of Geopolymer has been gaining momentum because of the advantage it offers in terms of eco-friendliness, enhanced strength and higher durability compared to the conventional cement concrete. The formulation of Geopolymer concrete is very important and the properties of Geopolymer products is mainly determined by chemical composition of the raw materials and its processing and synthesis conditions This paper makes a brief attempt to present an overview of Geopolymer concrete, the reaction mechanism involved, its constituents, the parameters that affects the strength, and its behaviour at elevated temperature exposure.**

Keywords **— Geopolymer Concrete; Reaction Mechanism; Parameters affecting Strength; Behaviour at Elevated Temperature Exposure;**

I. INTRODUCTION

The utilization of concrete as a major construction material is adopted worldwide and the concrete industry is the largest consumer of natural resources suggested by Mehta[1]. This usage of concrete drives the massive production of cement globally which is estimated to reach 4.8 billion metric tons by 2030. The production of cement not only consumes a huge amount of natural resources i.e. limestone and fossils fuel but also contributes to 65% of global warming due to Carbon-di-oxide emission. This worldwide concern about the carbon dioxide emission has prompted the researches to develop alternative solutions. The solutions were either to replace cement partially with supplementary cementitious materials like fly ash, GGBS, Metakaolin, Silica Fume etc. or to develop alternate binders to Portland cement. Abundant research has been conducted on the fresh and hardened properties of concrete with partial replacement of cement by these materials and their use has been adopted in many construction solutions as they provide viable means of reducing the carbon footprint of concrete.[2.]The lesser use of cement were mainly achieved by their partial replacement by alkali activated alumino silicate materials. Though alkalies have been considered as a main cause of alkali aggregate reaction, it has been noted that the alkali activated alumino silicate cements suppress alkali aggregate reaction[3.]Further research in this area have led to the development of Portland cement-free concrete called "Geopolymer concrete"..

The term "Geopolymer" was first coined by the French chemist Joseph Davidovits in 1978. In Geopolymer concrete, the silicon and aluminium present in the source material can be activated by alkaline liquids to produce binders. These binders are called as Geopolymers. Geopolymer cement refers to a broader variety of binders which are alkali activated and includes metallurgical slag and other related materials. The benefits of using various pozzolanic matrix binder are that they tend to be economical, environmentally-friendly, more absorbent of liquids and produce a highly durable product.[4]

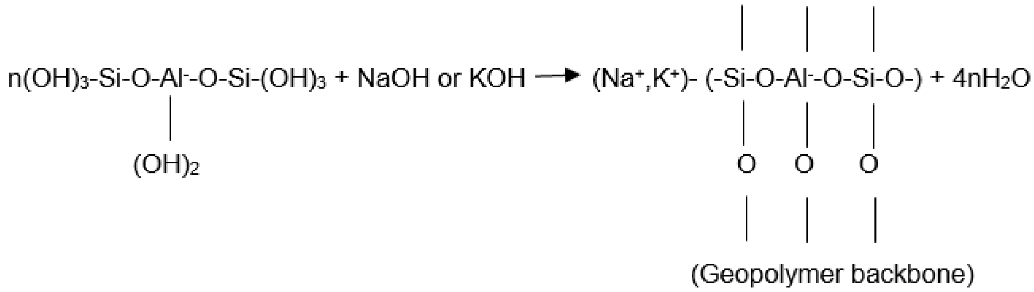
. The primary difference between geopolymer concrete and Portland cement concrete is the binder. It is noted that Calcium silicate hydrates are formed in Portland cement, whereas alumino silicate hydrates are formed in Geopolymer. The silicon and aluminium oxides in the source material reacts with the alkaline liquid to form the geopolymer paste that binds the coarse aggregates, fine aggregates, and other un-reacted materials together to form the geopolymer concrete.[5]

Geopolymers exhibit comparable performance to traditional cementitious material with an added advantage of reduced carbon footprint The main advantages of Geopolymer concrete over conventional cement concrete are faster strength development, lower carbon footprint and lower embodied energy, no water curing, higher acid resistance, high sulfate resistance, high-temperature resistance, enhanced fire resistance, higher protection to embedded steel, and overall higher durability.

II. GEOPOLYMER REACTION MECHANISM

The geopolymer binders are formed through a distinct series of reaction from the initial alkali activation of the pozzolanic material to final microstructure development. The major processes involved are dissolution of aluminosilicate species within an alkaline environment, polymerisation of minerals into short-span structural gel, precipitation of hydration products, and the hardening of matrix by growth of crystalline structures accompanied by water exclusion.[6]They are characterized by a two- to the three-dimensional Si-O-Al structure. The equations (1) and (2) represent the schematic formation of Geopolymer material.[3, 7]

$$\underset{\text{(Si-Al materials)}}{n(Si_2O_5,Al_2O_2)} + 2nSiO_2 + 4nH_2O + NaOH \text{ or } KOH \longrightarrow Na^+, K^+ + \underset{\text{(Geopolymer Precursor)}}{n(OH)_3\text{-}Si\text{-}O\text{-}\underset{\substack{|\\(OH)_2}}{Al^-}\text{-}O\text{-}Si\text{-}(OH)_3} \quad (1)$$



(2)

It is evident from equation (2) that water is expelled during the chemical reaction in the formation of Geopolymers. The water thus released benefits the performance of Geopolymer as it leaves behind discontinuous nanopores during curing and further drying periods.

The major steps in the polymerization process can be summarised as 1) dissolution of Al and Si atom from the source material in the presence of alkaline environment through the action of hydroxide ions. 2) Transportation or orientation of the precursor ions into monomers 3) Setting or polycondensation/ polymerization of monomers into the polymeric structure.[8] Fig.1 represents the overall polymerization reaction that occurs in Geopolymer.[9]

The various applications of Geopolymers depend on the Si: Al ratio. The amorphous network in Geopolymers is formed with various ratios of Si: Al. If the Si:Al -1:1, poly (sialate) will be formed, poly (Sialate-siloxo) for Si:Al -2:1,poly (Sialate-disiloxo) for ratio Si:Al-3:1 and Sialate link with ratio of Si: Al > 3:1.[10] . Research shows that Poly (Sialate) and Poly(Sialate-Siloxo) are being used as alternatives for OPC, and it exhibits strength similar to or higher than that of OPC concrete.

III. CONSTITUENTS OF GEOPOLYMER CONCRETE

Geopolymers consist mainly of two constituents namely the source materials and the alkaline liquids. The source material is based on alumina- silicate material and should be rich in silicon (Si) and Aluminium (Al). These materials could be natural minerals such as Clay, Kaolinite and industrial by-product such as Fly Ash, Metakaolin, Silica Fume, Slag, Rice-Husk Ash, Red Mud etc. The source material should be amorphous and degree of polymerization mainly depends on the extent of amorphous nature and fineness of aluminosilicate materials. The choice of the source materials for making Geopolymers depends on various factors such as the availability of the material, cost, type of application, and specific demand of the end users.

The alkaline liquids are usually sodium or potassium based alkali metals. The activators commonly used are NaOH, Na_2SO_4, water glass, Na_2CO_3, K_2CO_3, KOH, K_2SO_4, little amount of cement clinker and complex alkali component.[11] The most common alkaline liquid used is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate. Coarse and fine aggregate used by the concrete industry is suitable to manufacture Geopolymer concrete. Unlike conventional concrete, water has no role in the strength development of Geopolymer concrete. Water is added to the concrete for workability purposes. It is also noted that water cannot be added beyond a certain limit as it affects the strength. Hence in order to improve the workability, a high range water reducer superplasticizer and extra water (if required) may also be added to the mixture.

IV. STRENGTH GOVERNING FACTORS

It is noted that the compressive strength is a highly influential property of a concrete. The basic parameters that have to be considered in the formulation of Geopolymers are alkali binder ratio, alkali activators ratio, and water-geopolymer solids ratio, the molarity of sodium hydroxide, curing temperature, and curing time. The performance of Geopolymer concrete is governed by factors such as raw material processing condition (nature, composition, mineralogy of the material), the composition of solution (alkalinity, distribution of species), synthesis condition (homogenous mixing, curing temperature, curing time), Admixtures (superplasticizer, setting time retarders),microstructure pore distribution etc. The effect of some of these parameters on the strength of Geopolymer concrete is discussed. Many of the parametric properties cannot be generalized as it might vary according to the source material, its chemical and mineralogical composition, processing conditions etc. Hence a brief attempt is made in this paper to discuss the important strength governing factors with reference to the commonly used source materials.

A. Alkali – binder ratio

The normal range of alkali- binder ratio considered by different investigators is 0.25 to 0.75. The lower alkali-fly ash (binder is fly ash) ratio gives a higher compressive strength. This is mainly because of two reasons: 1) Lower the alkali fly ash ratio, higher will be the quantity of binder present. As the quantity of fly ash increases, the mixture will be denser, and hence there are fewer pores and better strength. Moreover greater the binder content more will be Al and Si atom that dissolute from the source material, resulting in a better-polymerized product. Lower alkali binder ratio normally results in the harsh and stiff mix, and superplasticizers are added to make it workable. 2) In higher alkali – fly ash ratio the amount of alkaline liquid increases, which in turn increases the water content in the solution and hence reduces the strength.

A study on the effect of alkali- binder ratio on the strength was carried out by Prakash and Urmil[12]. Two concrete mixes with the alkaline liquid to fly ash ratio of 0.35 and 0.4 were considered. The effect of alkaline liquid to fly ash ratio on compressive strength of concrete at 3 days has been evaluated and the result concluded that the ratio of alkaline liquid to fly ash, by mass, is not much effective in varying the compressive strength of the Geopolymer concrete if analysed in a short period

Another study was carried out in which the researcher reported the effects of alkaline solution/ binder ratio on the mechanical properties of Fly ash mortar [13.]Class F Fly ash was used as the raw material, and sodium hydroxide and liquid sodium silicate were used for the preparation of alkaline activators. Three alkaline solution-to-binder ratios (0.35, 0.5, and 0.65) were considered and the compressive strength at the end of 28 days was considered. The results showed that mortars with an alkaline solution to binder ratio of 0.35 had higher compressive strength, lower drying shrinkage, lower water absorption compared with other ratios.

B. Water to Geopolymer solids ratio

The normal range of water to Geopolymer solids ratio is 0.25 to 0.35. The Geopolymer solids are the sum of the mass of binder, the mass of sodium hydroxide solids, and mass of solids in sodium silicate solution (i.e mass of Na_2O and mass of SiO_2). The total mass of water is the sum of the mass of water contained in the sodium silicate solution, the mass of the water used for making the required molar solution of sodium hydroxide and the mass of extra water, if any, added to the mixture. The higher ratio gives segregated mix while lower ratio gives a viscous and dry mix.

Tests were performed to establish the effect of water-to-Geopolymer solids ratio by mass on the compressive strength and the workability of Geopolymer concrete[14]. The test specimens were heat-cured in an oven at various temperatures for 24 hours. The results concluded that the compressive strength of Geopolymer concrete decreases, as the water to-Geopolymer solids ratio by mass increases as shown in Fig. 2. This trend is similar to the well-known effect of water-to-cement ratio on the compressive strength of Portland cement concrete.

Another similar study was also carried out in which the water to Geopolymer solids ratio was varied in the order of 0.16 to 0.40[15]. Regarding the strength characteristics, the study concluded that as the ratio of water-Geopolymer solids ratio increases the compressive strength decreases .A study on the flow characteristics was also carried out in this research along with strength. It was noted that, at the water-Geopolymer binder ratio of 0.16, the mix was very dry and not workable. The mix took greater time for mixing, in the ratio ranging from 0.20 to 0.25. The studies showed that for ratio ranging from 0.30 to 0.35, the mix was cohesive and viscous, but had a better flow. The mix was highly workable and exhibited a flow like self-compacting concrete for ratios of 0.4. The effect of water/binder ratio on the strength of Geopolymer concrete is represented in Fig. 3.

C. Molarity of NaOH

Molarity of NaOH plays a vital role in the strength of Geopolymer concrete. The molarities used by the researchers vary between 8M to 18M.It is noted that as the concentration of NaOH solution increases the compressive strength also increases. The effect of NaOH molarities and Na_2SiO_3/ NaOH ratios on compressive strength of fly ash based Geopolymer were studied by Bakri et.al.[16] the study was carried out by molarities ranging from 6M to 16M. It was found that the compressive strength increases with increase in molarity till 12 M and then the strength decreases. It is illustrated in Fig. 4. Research work also shows that if the molarity is decreased beyond a certain extent, the concentration would not be sufficient for facilitating the Geopolymerisation reaction, and if the molarity is increased beyond a particular limit, it has an adverse effect on strength as it would cause the premature coagulation of silica resulting in reduced strength[17].

Another study suggests that higher concentration of NaOH has resulted in the reduction of compressive strength[18]. The Geopolymer concrete formulated for the study were Red mud and Rice Husk Ash (RHA) based. The strength decline could be attributed to various factors such as the high viscosity of NaOH resulting in the disruption of the leaching of Si and Al ions, excessive OH^- concentration causing premature precipitation of Geopolymeric gels, the presence of partially reacted/ unreacted RHA particles due to incomplete dissolution of Si and Al species.

D. The ratio of Sodium Silicate to Sodium Hydroxide

Sodium Silicate and Sodium Hydroxide are collectively called alkali activators system (AAS).In general, the AAS consists of a mixture of hydroxides and silicates of alkali. It is also noted that AAS can contain compounds such as sodium carbonate and sodium chloride, in addition to hydroxides and silicates of alkali elements[19].The activators solution provide an alkaline environment for the release of alumina and silica from the source material for the formation of Geopolymer. The ratios usually range from 0.17 to 3.0. Research also shows that sodium silicate can be used alone or along with other activators like NaOH or KOH. NaOH is commonly used compared with KOH, as it is cheaply available and the leaching of Al^{3+} and Si^{4+} ions are higher in sodium hydroxide solution in comparison with potassium hydroxide [20]. It is to be noted that when sodium silicate is used as activators, two important parameters has to be considered. One is the ratio between sodium silicate and sodium hydroxide (SS/SH) and the other being silica modulus (Na_2O/SiO_2). The effect of silica modulus of Na_2SiO_3 and its correlation with activators solution ratio has to be considered to maximize the strength and economic aspects of Geopolymer concrete[21].The effects of silica modulus (Na_2O/SiO_2) on the strength of pumice-based Geopolymer concrete were studied. The ratios adopted were 0.52, 0.6 and 0.68. The results concluded that the silica modulus ratio of 0.68 achieved the maximum compressive strength[22].

The influence of the Na_2SiO_3/ NaOH solution ratio on the compressive strength of the fly ash-based geopolymer paste, on Geopolymer concrete, has been carried out by researchers. It was found that increasing the Na_2SiO_3/NaOH solution ratio leads to more SiO_2species; therefore more Si-O-Si bond is formed, creating a stronger material.

The effect of alkali activators ratio on the strength of Geopolymer paste in which fly ash based Geopolymer paste is activated by alkaline solutions with six different ratios (0.5, 1.0, 1.5, 2.0, 2.5, 3.0) was reported by Bakri et.al[16] It was found that the strength increases with the increase of activators ratio till 2.5 and then the strength decreases. Hence the optimum ratio for alkali activators suggested by Bakri et.al[16] is shown in Fig. 5.

E. Curing Time and Temperature

Curing is the process which facilitates the Geopolymerisation reaction. In source materials like fly ash, the polymerization reaction is very slow and usually shows a slower setting and strength development. Hence it becomes essential to carry out the curing of Geopolymer concrete at elevated temperatures in the oven. The main types of curing in Geopolymer are ambient curing and oven curing. Previous research works have shown that both curing time and curing temperature significantly influences the compressive strength of

Geopolymer concrete. Many researchers have investigated the effect of curing time and curing temperature on the properties of Geopolymer concrete.

Longer the curing time, more improved is the polymerization process thereby resulting in higher compressive strength. The rate of increase in strength was rapid up to 24 hours of curing and the gain in strength is only moderate beyond 24 hours. Hence heat-curing time need not be more than 24 hours in practical applications.

Regarding the curing temperature, as temperature increases, the strength also increases. The optimum temperature and optimum duration of curing are essential in geopolymerisation. The optimum temperature of curing is 60^0C since the greater temperature causes the continuous moisture loss from the specimen surface resulting in a large number of voids and strength reduction. In an experimental study, the curing temperature was varied between 50^0C to 80^0C. The samples were cured for 24 hours in the oven and the test result showed that maximum compressive strength was obtained for 60^0C.[23]

The effect of curing time on the compressive strength of Geopolymer concrete was studied by Hardjito&Rangan[14.]The curing was carried out at a temperature of 60^0C in an oven for a period of 4 hours to 96 hours and the result is illustrated in Fig. 6.

The effect of curing time and temperature on the strength of the Geopolymer mortar was reported by Adam &Horianto[24.] In this research a study on fly ash based Geopolymer mortar was carried out by varying the curing temperature of 80^0C, 100^0C and 120°C, for the duration of 4, 6 and 20 hours. The fly ash was activated by sodium silicate and sodium hydroxide solution and the ratio between sodium silicate and alkaline activator was 1:2. The results showed that as the curing temperature and time increases, the compressive strength also increases and the highest compressive strength was obtained at the temperature120°C and curing period of 20 hours which was considered as optimum. The compressive strength of Geopolymer mortar of air cured, cured at 80^0C, 100^0C, 120^0C for 4, 6 and 20 hours are shown in Fig. 7 to Fig. 9.

F. Age of Concrete

Studies were carried out to understand the effect of age on the strength characteristics of Geopolymer concrete[25.]The heat cured specimens at various ages were tested in compression. The result showed that compressive strength does not very much with the age of concrete because the process of strength attainment is due to the fast polymerization process. This observation is in contrast to the well-known behaviour of OPC concrete, which undergoes hydration process and gains strength over time. The variation of compressive strength with the age of concrete is shown in Fig. 10.

G. Superplasticizers

The Geopolymer concrete has a stiff consistency in the fresh state. Even though sufficient compaction was achievable, an improvement in the workability was usually considered as desirable. Research shows that various practical difficulties such as low workability or shrinkage can be overcome by using admixtures[26]. Hence superplasticizers are added for workability purposes. Research shows that to study the effect of superplasticizer, the other parameters such as mix composition, curing period, curing time etc. were kept constant. The superplasticizer was added in proportion to the mass of fly ash. The specimens were tested for 7^{th}-day compression. The effect of commercially available naphthalene-based superplasticizer was studied. The result showed that the addition of superplasticizer had a negligible effect on the compressive strength up to 2% to the mass of fly ash, though it improved the workability of the fresh concrete. It was also noted that beyond 2% the compressive strength degrades [27].

The effect of different commercial superplasticizers such as naphthalene, melamine, and modified polycarboxylate on the strength and workability of geopolymer concrete was carried out by Nematollahi&Sanjayan[28].Class F fly ash was used and superplasticizer (SP) was added at a dosage of 1% by mass of Fly ash and activated by a single and multi-component activator. The result concluded that naphthalene based SP was effective when single activator was used, and modified polycarboxylate proved better in the case of multi-component activator.

H. Rest Period

The term 'Rest Period' is defined as the time taken from the completion of the casting of concrete specimens to the start of curing at an elevated temperature. This is very important in many practical applications. For instance, when the fly ash based Geopolymer concrete is used in precast concrete industry, ambient time should be available between casting of products and sending them to the curing chamber. It has been observed that one day rest period has resulted into a higher gain in compressive strength compared to the zero-day rest period. The literature review also shows that there has been very little increase in the strength if the specimens are cured after giving a rest period of one hour than zero rest periods.

V. EFFECT OF ELEVATED TEMPERATURE EXPOSURE ON GEOPOLYMER CONCRETE

Concrete members are exposed to elevated temperatures under many occasions. The behaviour of concrete exposed to elevated temperature is different from those at ambient temperature and need to be concentrated. Further, structural members when exposed to elevated temperatures behave differently compared with materials at elevated temperatures.

An experimental study was carried out on the fire resistance of fly ash based Geopolymer concrete by Pan & Sanjayan[29]. The specimens were heated to a temperature from 23^0C to 680^oC and then cooled and stress-strain relationship was investigated. It was noted that from a temperature range of 200°C to 290°C, the strength of Geopolymer specimen increased with a slight contraction in the size. On the other hand, for a temperature range between 380°C and 520°C, the strength increased with the specimen expansion. Further, it is also noticed that after elevated temperature exposure the specimen underwent a brittle failure.

The damage behaviour of Geopolymer and Geopolymer aggregate composites exposed to elevated temperature made with class F fly ash were studied by Daniel &Sanjayan[30]. Concrete samples were heated up to 800°C to evaluate strength loss due to thermal damage. After elevated temperature exposure, a strength increase of 53% has been exhibited by Geopolymer.

It was also noted that when geopolymer/aggregate composites were used, under elevated temperature there is a reduction in strength up to 65% even with identical geopolymer binder formulations. The reduction in strength is due to the apparent incompatibility of the behaviour of geopolymer matrix and the aggregates at elevated temperature i.e. The aggregates steadily expanded with temperature, reaching about 1.5 to 2.5% expansion at 800°C. Correspondingly, the geopolymer matrix undergoes a contraction of about 1% between 200°C and 300°C and a further 0.6% between 700°C and 800°C.

A study on the strength of geopolymer paste, mortar and concrete at ambient condition and after elevated temperature exposure were investigated byDaniel &Sanjayan[31].It was found that the strength of paste, mortar, and concrete is approximately the same before temperature exposure. After elevated temperature exposure, paste underwent 73.4% strength loss, mortar did not retain any residual strength and the concrete displayed a 58.4% strength loss.

The effect of certain parameters such as specimen sizing, aggregate sizing, aggregate type and superplasticizer type at elevated temperature were also taken into consideration in the studies carried out by Daniel &Sanjayan[31]. The aggregate types were basalt based and slag based. The admixtures considered for the study are superplasticizer of carboxylic ether based polymer and sulfonated polymer based. The research concludes with the identification of specimen size and aggregate size as the governing factors of the geopolymer behaviour at elevated temperature exposure (800°C).At ambient and elevated temperature condition, aggregates of sizes larger than 10 mm resulted in good strength performances. Basalt-based concrete experienced a 58.4% drop in strength while the slag aggregate based concrete reported a 64.6% drop after temperature exposure. Paste specimen cast into cubical mould recorded a 6.4% strength gain, whereas similar paste cast into cylindrical moulds reported a strength loss of maximum 73.4%. The research shows that the superplasticizer deteriorates strength of geopolymer matrix at ambient condition. It was also noted that superplasticizer is not beneficial for geopolymer concrete for elevated temperature performance.

Studies on Geopolymer mortar after exposure to elevated temperature were carried out by Pan et.al [32]. Two different types of fly ashes were used and specimens of strengths ranging from 5 to 60 MPa were prepared. It is noticed that at elevated temperature exposure, the gain or loss in strength of Geopolymer mortar is dependent on the strength of mortar at ambient temperature. There was a strength loss for a specimen having a compressive strength greater than 16 MPa, after 800°C temperature exposure, and again in strength was noted for a specimen having compressive strength less than 16 MPa. It was concluded that the strength gain is attributed to cindering of unreacted material leading to further polymerization. The strength loss is due to the thermal incompatibility between paste and aggregate at elevated temperature. It was also observed that after elevated temperature exposure, the lower initial strength Geopolymer mortars had greater ductility and mortar with high initial strength exhibited low ductility

Regarding the structural strength aspect, research work was carried out to study the effects of the loading rate and the testing temperature on the stiffness, the ultimate tensile strength of a fibre reinforced Geopolymer concrete was studied by Pernica et.al[33].The displacement rate was varied from 0.002 mm/s to 2 mm/s and the testing temperature was varied from the room temperature to 300°C. It is observed that with temperature increase, the ultimate strength and flexure stiffness decreased for all the specimens. Conversely, with the loading rate increase, the ultimate strength and stiffness also increased.

Daniel et.al[34]conducted tests on Geopolymer paste with two source materials such as metakaolin and fly ash after being exposed to an elevated temperature of 800°C.The significant colour change was observed in both fly ash and metakaolin specimens at 800°C.It was noted that the compressive strength of metakaolin based geopolymer paste specimen decreased slightly with micro-cracks in the order of 0.1mm to 0.2 mm on the surface at 800^0C. In fly ash based geopolymer, no cracks were developed and the compressive strength also increased slightly. At elevated temperature, the surface cracking and internal damage are mainly due to the moisture migrating to the surface, which further escapes from the surface. TGA analysis of the paste showed that the mass loss is maximum around 100°C and beyond 250°C, the mass loss is almost constant as the water within the paste escapes at a temperature below 200°C.

VI. CONCLUSIONS

This state of art paper presents a brief outlook on the research and development in the technology of Geopolymer concrete. The formulation of Geopolymer concrete has to be carried out after considering all the parameters discussed and if properly formulated the Geopolymer concrete is superior and economical than conventional one. The review also brings insights to the superior performance of Geopolymer concrete under elevated temperature. Hence in this present context, the technology has to be further extended and widened by extensive research as it holds a great promise to a more sustainable environment.

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REFERENCES

[1] Mehta, P. K. *Greening of the Concrete Industry for Sustainable Development*. Concrete International, 24, pp. 23-28, 2002.

[2] Mehta,P K. *High-Performance, High-Volume Fly Ash Concrete for Sustainable Development. Proceedings of International Workshop on Sustainable Development and Concrete Technology*. pp. 3-14, 2004.

[3] Davidovits, J. *High-Alkali Cement for 21st Century Concretes. Proceedings of Symposium on Concrete Technology, Past, Present and Future*. American Concrete International , vol. 144, pp. 383-397, 1994.

[4] Fernandez, J. A, Palomo A.& Criado M. *Microstructure development of alkali activated fly ash cement: a descriptive model*. Cement and Concrete Research, vol. 35, pp. 1204-1209, 2005.

[5] Rangan, B.V. *Fly Ash-Based Geopolymer Concrete. Proceedings of the International Workshop on Geopolymer Cement and Concrete*, pp. 68-106, 2010.

[6] Petermann, J.C. & Saeed, A. *Alkali-Activated Geopolymers*- A Literature Review, Technical Report, pp. 1-92, 2010.

[7] Jaarsveld, J .G. S. Deventer, J .S. J. & Lorenzen, L. *The potential use of Geopolymeric materials to immobilise toxic metals*. Mineral Engineering, vol. 10, pp. 659-669, 1997.

[8] Chang, N.V. Trung, B.D. Tuan,D. V. *Recent Research Geopolymer Concrete*. The 3rd ACF International Conference, pp. 235-241, 2008.

[9] Duxson, P. Fernandez, J. A. Provis, J. L. Lukey, G. C. Palomo, A. & Deventer, J.J. *Geopolymer Technology- The Current State of Art*. Journal of Material Science, vol. 42, pp. 2927-2933, 2007.

[10] Davidovits J. *Geopolymers and Geopolymeric materials*. Journal of Thermal Analysis, vol. 35, pp. 429-441, 1989.

[11] Xiong C J, Bin C H , Pei X , & Fang Z L. *A study on complex alkali-slag environmental concrete, Proceedings of the International Workshop on Sustainable Development and Concrete Technology*, pp. 297-307, 2004.

[12] Prakash R V & Urmil V D . *Parametric studies on Compressive Strength of Geopolymer Concrete*. Journal of Procedia Engineering, vol. 51, pp. 210- 219, 2013.

[13] Chi M. *Effect of Alkaline solution/binder ratio and curing condition on the mechanical properties of alkali-activated fly ash mortar*. Science and Engineering of Composite materials ,vol. 24, pp. 773- 784, 2016.

[14] Hardjito D & Rangan B V. *Development and Properties of Low Calcium Fly Ash-BasedGeopolymer Concrete*, Research Report,Curtin University, pp. 1-94, 2005.

[15] Patankar S V, Jamkar S S,& Ghugal Y M . *Effect of Water-to Geopolymer Binder ratio on the production of Fly ash based Geopolymer Concrete*. International Journal of Advanced Technology in Civil Engineering, vol. 2, pp. 79-83, 2013.

[16] Bakri A M M, Kamarudin H, BnHussain M, RafizaA R, Zarina Y. *Effect of Na_2SiO_3/NaOH Ratios and NaOH Molarities on Compressive Strength of Fly-Ash Based Geopolymer*. ACI Material Journal .vol. 109, pp. 503-508, 2011.

[17] Ken P W, Ramli M, Ban C C. *An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products*. Construction and Building Materials, vol. 77, pp. 370-395, 2015.

[18] He J, Jie Y, Zhang J, Yu Y, Zhang G. *Synthesis and characterization of red mud and rice husk ash-based geopolymer composites*. Cement Concrete Composites, vol. 37, pp. 108-118, 2013.

[19] Rajamane N P, Nataraja M C, & Jeyalakshmi R, *Pozzolanic industrial waste based geopolymer concretes with low carbon footprint*, The Indian Concrete Journal, vol. 88(7), pp. 49-68, 2014.

[20] Rattanasak U, & Chindaprasirt P. *Influence of NaOH solution on the synthesis of fly ash Geopolymer*, Minerals Engineering, vol. 22, pp. 1073-1078, 2009.

[21] Yusuf M ,Megat J M, Ahmad Z ,& Maslehuddin M. *Impacts of silica modulus on the early strength of alkali activated ground slag/ultra fine palm oil fuel ash- based concrete*. Materials and Structures, vol. 48(3), pp. 733-741, 2015.

[22] Yadollahi M M, Benli A ,& Demirboga R. *The effects of silica modulus and aging on the compressive strength of pumice based geopolymer composites*, Construction and Building Materials, vol. 94, pp. 767- 774, 2015.

[23] Bakri A M M, Kamarudin H, BnHussain M, Nizar I K, Zarina Y, Rafiza A R. *The effects of curing Temperature on physical and chemical properties of Geopolymers*, Journal of Physics Procedia, vol. 22, pp. 286-291, 2012.

[24] Adam A A & Horianto. *The effect of temperature and duration of curing on the strength of Fly ash based Geopolymer Mortar*, Journal of Procedia Engineering,vol. 95, pp. 410-414, 2014.

[25] Rangan B V ,Hardjito D ,WallahS E ,& SumajouwD M J. *Studies on flyash-based geopolymer concrete, Proceedings of the World Congress Geopolymer*, pp. 133-137, 2004.

[26] Diaz L E, Allouche E N, & Vaidya S. *Mechanical Properties of Fly ash based Geopolymer* , ACI Material Journal. Vol. 108(3), pp. 300-306, 2011.

[27] Hardjito D, Wallah S E ,SumajouwDody M J, & Rangan B V. *Factors Influencing the Compressive Strength of Fly ash based Geopolymer concrete*, Civil Engineering Dimension, vol. 6, pp. 88-93, 2004.

[28] Nematollahi B, & Sanjayan J G. *Effects of different superplasticizer and activator combinations on workability and strength of fly ash based Geopolymer*, Materials and Design, vol. 57, pp. 667- 672, 2014.

[29] Pan Z, & Sanjayan J G. *Stress Strain behaviour and abrupt loss of stiffness of Geopolymer at Elevated Temperature*, Cement and Concrete Composites, vol. 32, pp. 657–664, 2010.

[30] Daniel K L Y, Sanjayan J G, & Crentsil S K. *Comparative Performance of Geopolymers made with metakaolin and Fly ash after exposed to Elevated Temperature*, Cement and Concrete Research, 37(12), pp. 1583–1589, 2007.

[31] Daniel K L Y& Sanjayan J G. *Effect of Elevated Temperature on Geopolmer mortar, Paste and Concrete*, Cement and Concrete Research , 40, 334-339, 2010.

[32] Pan Z, Sanjayan J G ,& Rangan B V. *An Investigation of the Mechanism for strength gain or loss of Geopolymer mortar after exposure to Elevated Temperature*, Journal of .Material Science, vol. 44(7), pp. 1873-1880, 2009.

[33] Pernica D, Reis P N B, Ferreira J A M, & Louda P. *Effect of Test conditions on the bending strength of Geopolymer–reinforced composites*, Journal of Material Science, vol. 45(3), pp. 744-749, 2009.

[34] Daniel K L Y, & Sanjayan J G . *Damage behaviour of Geopolymer composites exposed to Elevated Temperature*, Cement and Concrete Composites, vol. 30, pp. 986-991, 2008.

FIGURE CAPTIONS

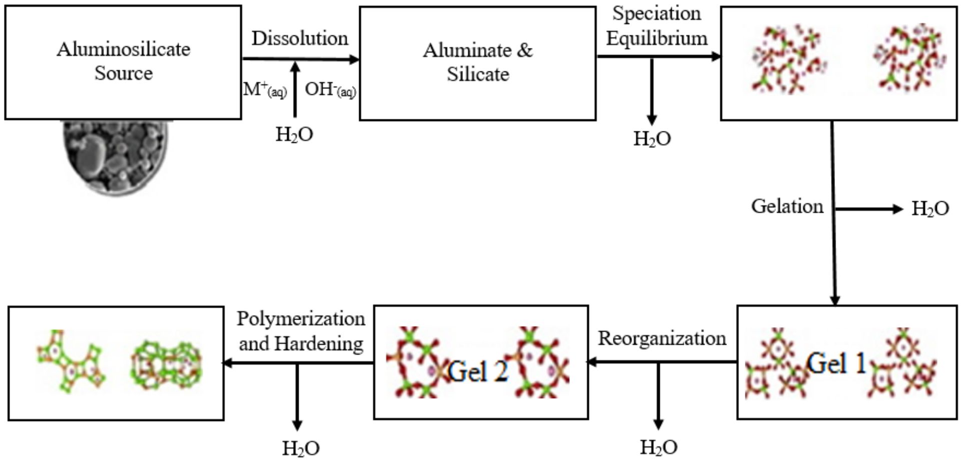

Fig. 1 Geopolymer reaction mechanism model[9]

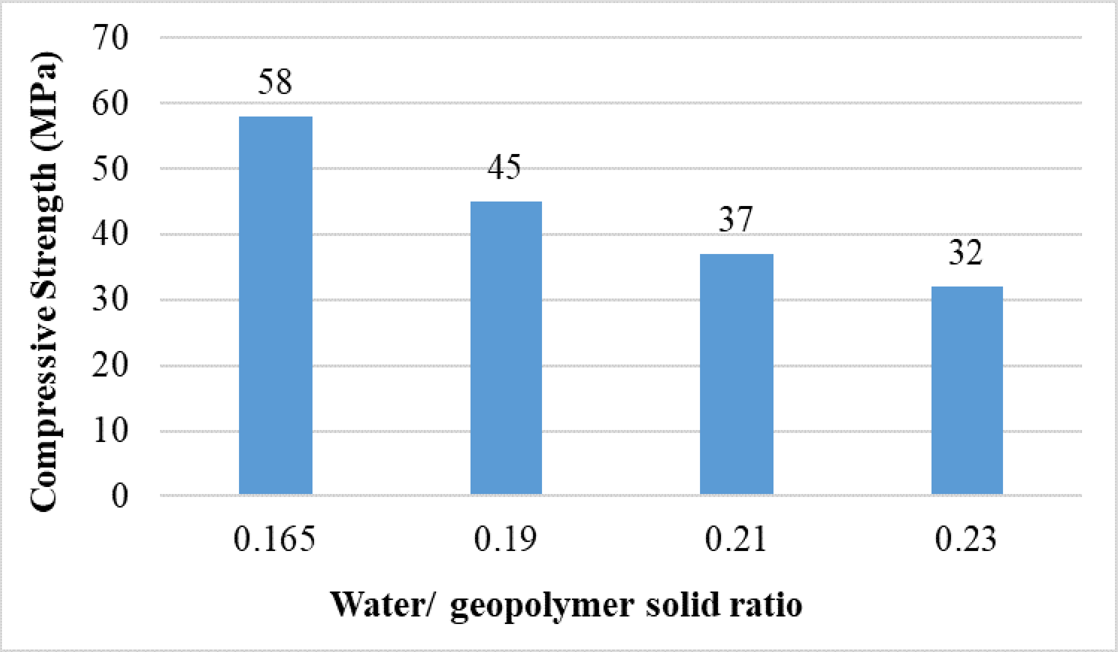

Fig. 2 Effect of water/ Geopolymer solid ratio on the Compressive Strength[5]

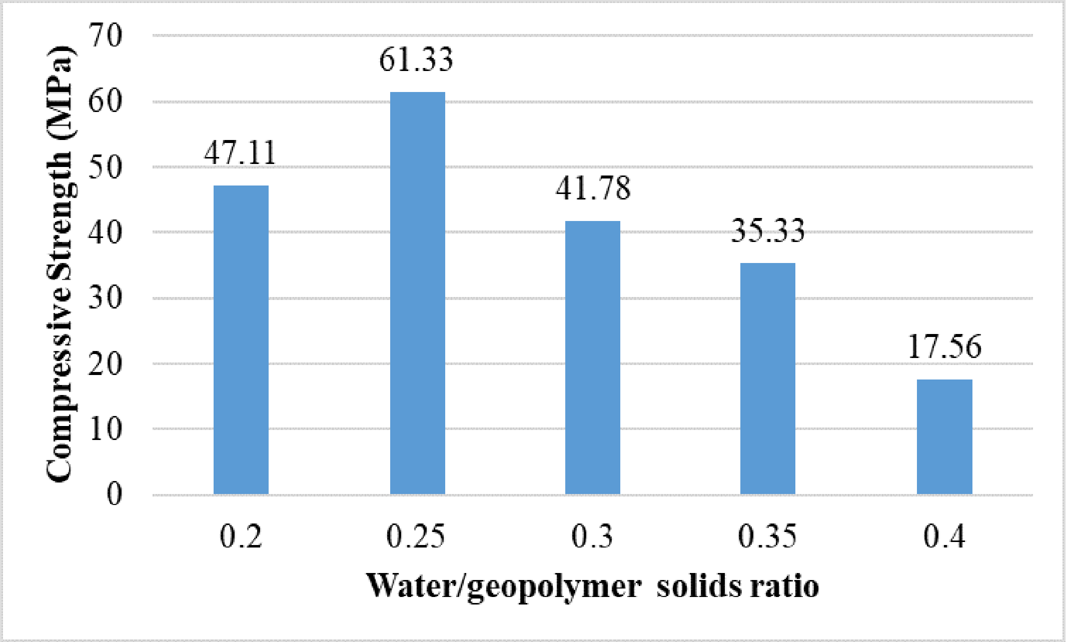

Fig. 3 Effect of Water/ Solids ratio on the Compressive Strength[15]

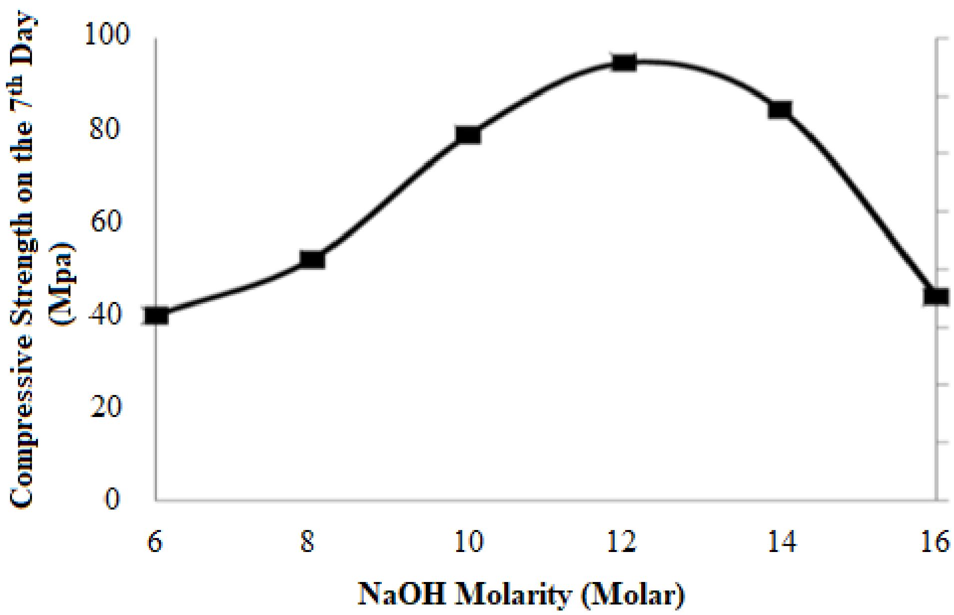

Fig. 4 Effect of Molarity on the Compressive Strength of Concrete[16]

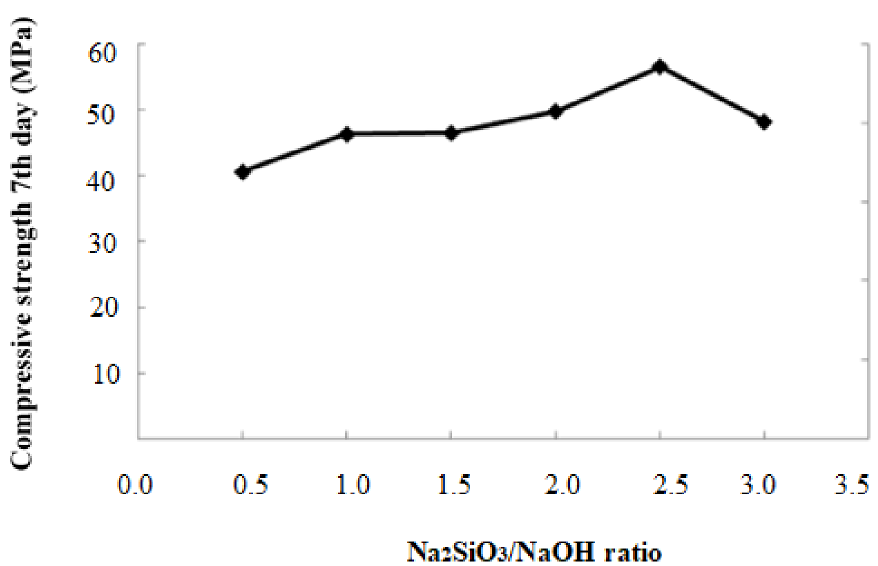

Fig. 5 Effect of Na_2SiO_3/ NaOH on the Strength of Concrete[16]

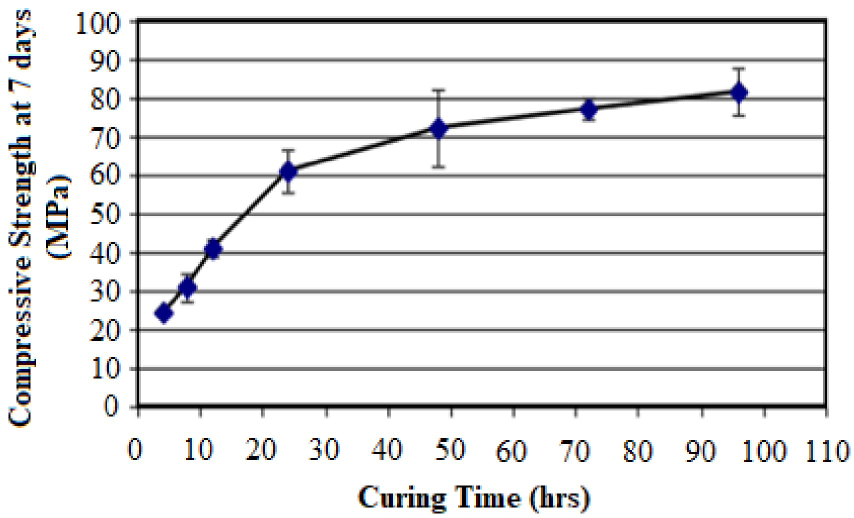

Fig. 6 Effect of curing time on the Compressive Strength of Concrete[14]

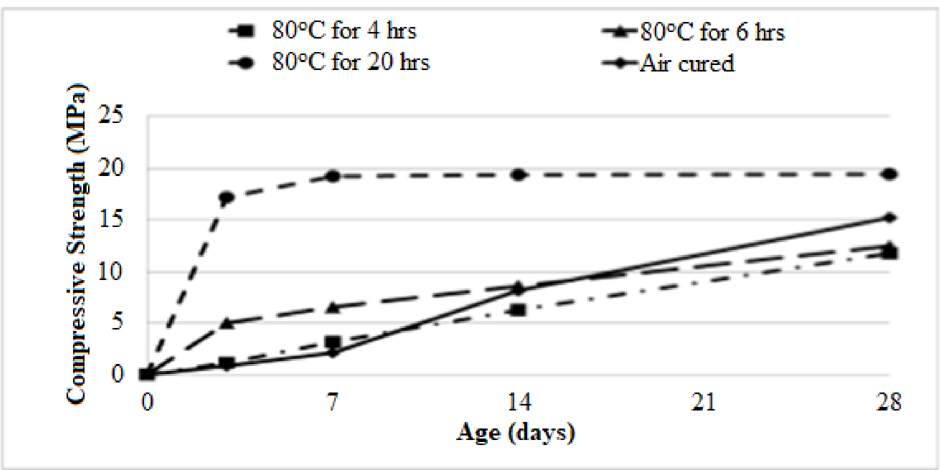

Fig. 7 Compressive Strength of Geopolymer mortar cured at 80^0C for 4, 6 and 20 hours[24]

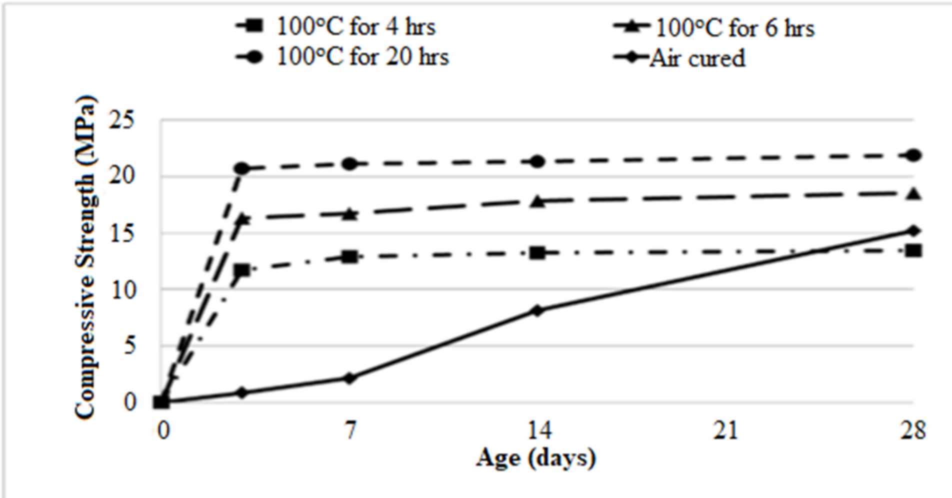

Fig. 8 Compressive Strength of Geopolymer mortar cured at 100^0C for 4, 6 and 20 hours[24]

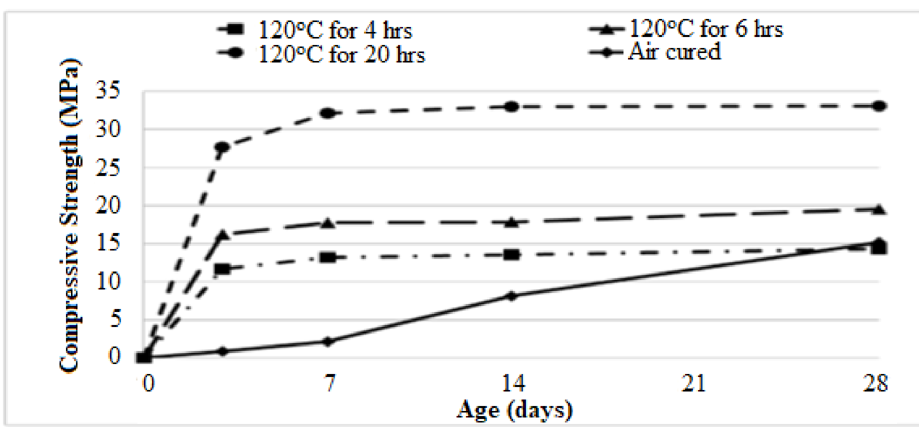

Fig. 9 Compressive Strength of Geopolymer mortar cured at 120^0C for 4, 6 and 20 hours[24]

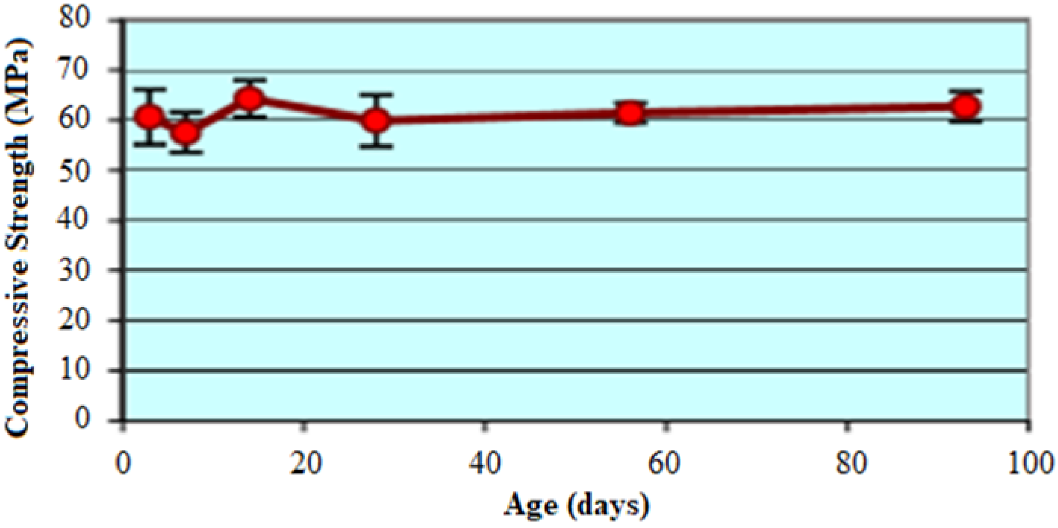

Fig. 10 Compressive Strength of Geopolymer Concrete at different ages[25]