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Methods of curing geopolymer concrete: A review

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ABSTRACT

Geopolymer concrete is a new approach of concrete production by exclusion of ordinary Portland cement entirely with pozzolanic material. Beside water, concrete is the largest consumed substances, which demand huge portion of Portland cement. During Portland cement manufacturing process, high emission of carbon dioxide (CO_2) is produced which results in polluting the surrounding environment. Moreover, a lot of energy is expended during cement production. Based on manufacturing situations, geopolymer concrete displays different behaviors and attributes. This paper succinctly discusses the different methods of curing of geopolymer concrete and figures out the best method of curing. Experimental findings revealed that condition of curing has a good influence on the mechanical properties of geopolymer concrete. Conventionally, ambience temperature curing of geopolymer concrete result in low strength development at an early age, while higher temperature curing results in significant strength improvement. Similarly, extended curing time enhanced the geopolymerisation mechanism and achieved greater strength. However, longer duration of curing at an elevated temperature result in failure of the sample.

1. Introduction

The development of science and technology is a continuing process for improvement of infrastructure all over the world. Every day new innovations in the construction industries are being created safely, economically and environmental sustainability. Besides water Concrete is the most utilized substance around the world (Hardjito and Rangan, 2005). Ordinary Portland cement (OPC) is customarily utilized as the main binder to manufacture Concrete. The difficulties related with the production of OPC are properly noted. The rate at which the carbon dioxide is discharge during the production of OPC is one- in- one that is for each 1 Kg of OPC produced 1 Kg of CO_2 will be emitted (Hardjito and Rangan, 2005). Production of geopolymer concrete does not require the use any OPC but, the binder is produced by the reaction of an aluminosilicate material with strong alkaline liquids. Collectively, geopolymer cement gel binds the aggregates and unreacted material to yield geopolymer concrete (Davidovits, 1991; Patankar et al., 2013).

Geopolymer concrete is a recent innovation for concrete production around the globe where by ordinary Portland cement (OPC) is completely substituted by aluminosilicate materials and actuated by strong alkaline solutions to serve as a binder in the concrete (Patankar et al., 2013). Geopolymer concrete hardened by heat at a temperature ranging from 60°C to 90°C (Duxson et al., 2007). The use of concrete is rapidly increasing every day as the need for shelter and economic activities are increasing, also due to the globalization and industrialization more infrastructural facilities were developed which make use of concrete. It has been recognized that the production of OPC releases huge quantity of energy and carbon dioxide to the surrounding environment. Therefore, it is essential to find a substitute binder so as to produce environmental friendly concrete (Vora and Dave, 2013). Class F fly ash is normally activated with sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) in fly ash based geopolymer concrete. Fernandez-Jimenez et al. (2006) mentioned that compressive strength of around 40 N/mm^2 was achieved by activating fly ash with NaOH at an elevated temperature curing between 80 to 90°C for a period of 1 day. Moreover, addition of Na_2SiO_3 into

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the mix and cured at the same conditions double the compressive strength results.

However, for alkali actuated fly ash geopolymer the method of curing have significant impact on the micro-structural and strength development. Class F fly ash geopolymer mixture hardens gently at surrounding temperature and reveals small strength gain at initial ages in contrast to oven cured specimens. Therefore, the geopolymerisation process is normally dependent on mode of curing. At higher temperatures ranging from 60 °C to 90°C the geopolymerisation is faster, but the oven curing can only be achieved in precast concrete structures. These attributes limit the broader utilization of fly ash based geopolymer to only precast concrete and believe to be a hurdle for on-site concrete applications (Duxson et al., 2007). The present paper reviews the method of curing of geopolymer concrete.

2. Research review

2.1. Heat/oven curing

In the geopolymerisation process of geopolymer concrete, water is given out during the chemical reaction and this water tends to vaporize as the specimens were subjected to heat during the curing process (Hardjito and Rangan, 2005). Similarly, the drying shrinkage becomes negligible due to the small quantity of water in the pores of the rigid specimens. Several efforts (Perera et al., 2007; Kani and Allahverdi, 2009; Rovnanik, 2010; Heah et al., 2011) were carried out for determining the influence of curing conditions on the physical and mechanical properties geopolymer paste and concrete. For near perfect geopolymerisation the curing temperatures were observed between 40°C to 85°C. Singh et al. (2015) reported that for an alkaline activated fly ash, curing temperature is very vital for achieving higher strength, specimens subjected to higher curing temperature exhibited higher mechanical strength than those of lower temperature this findings is in agreement with that of (Nuruddin et al., 2016). They also observed that longer duration of curing results in better strength but the increase of strength is negligible when curing time was extended beyond 24 hours. Rovnanik (2010) reported that curing temperature has an important influence on hardening and geopolymerisation of rock-based geopolymer. At an ambience and higher temperature the specimen virtually set in the first 4 hours. On the contrary, the setting was further postponed for a period of 4 days when the mixture was handled at temperature of at most 10 °C, but this does not affect the grade and properties of solidified geopolymer product at the age of 28 days. Accelerated strength formation was observed on rock based geopolymer cured at 40 to 80°C. It is worth mentioning that the influence of temperature is relied on duration of curing. Curing for a shorter period in oven did not yield to significant changes in strength development, but extended curing process to at least 20 hours was the caused for a noticeable rapid rate of reaction rate and resulted in early strength gained. However, elevated temperature especially at the initial stage leads to the growth of larger pores in the specimen which eventually influenced the mechanical strength.

Similarly, Adam and Horianto (2014) reported duration and temperature of curing influence on the strength of fly ash geopolymer paste. They found that the state of curing play a vital role on the strength development and micro-structural system of fly ash based geopolymer. The best heat curing zone obtained was 120°C for 20 hours of curing. However, they considered only mortar paste but its behavior in concrete was not cited. In another development, Kong and Sanjayan (2010) reported that temperature has great influence on strength development of geopolymer concrete and it relied upon the size of geopolymer paste and aggregates. Similarly the frequency at which aggregate expanded when subjected to higher temperature is influential in the performance of geopolymer concrete at elevated temperature. The investigation reveal that aggregate and specimen dimensions as the primary factors that control the behaviour of geopolymer concrete at advanced temperatures of about 800°C. In all, proper curing of geopolymeric materials is demanded to produce geopolymer concrete with best properties for sustaining their structural integrity (Van Jaarsveld et al., 2002).

Yewale et al. (2016) studied on the evaluation of efficient type of curing geopolymer concrete. In their work geopolymer concrete was manufactured with class F fly ash and it is activated by solutions of sodium hydroxide and sodium silicate. BB2 super plasticizer was incorporated in the mix for workability enhancement of geopolymer paste. Concrete cubes of 150 mm were cast. The specimens are cured by four different methods by using oven, steam, water and room temperature curing respectively. In oven curing, the temperature of curing was varied at an interval of 20°C starting from 40°C up to 140°C for 24 hours inside oven and tested after a rest period of 7 and 28 days after demolding. While for steam curing the cubes were placed in a steam at 60° to 110°C for 18 hours at the same rest period. Similarly the specimens were cured in water as per conventional method and room temperature. Experimental evidence reveals that the strength of geopolymer concrete cubes improved at higher temperature and the optimum strength was found to be 60°C oven curing. Similarly, Kumaravel (2014) also found that the compressive strength of concrete cured in oven is much better than that of ambient cured concrete and the optimum strength is found at 60°C for a day. In addition, Patankar et al. (2013) investigated the influence of water to binder ratio on workability of geopolymer concrete in terms of flow and compressive strength, the samples were placed in oven at 90°C for about 8 hours. They have maintained a constant ratio of 0.35 for activated solution to fly ash ratio. Experimental results showed that flow of geopolymer concrete increases at higher water-to-geopolymer binder ratio. On the other hand, the concrete strength decreases at higher water-to-geopolymer binder ratio analogous to water/cement ratio in conventional concrete.

Moreover, Pangdaeng et al. (2014) have reported the curing conditions of high calcium fly ash geopolymer concrete produce by addition of Portland cement. In this study geopolymer concrete was made by adding ordinary Portland cement (OPC) in small quantity with high Fly ash (FA) and subjected to various mode of curing. The OPC partially replaced fly ash by 0% to 15% at interval of 5% by total weight of the binder. The research outcome revealed that addition of OPC in the binder enhances the mechanical properties of the geopolymer concrete which is attributed to the formation of Calcium silicate hydrate C–S–H and Calcium aluminosilicate hydrate C–A–S–H gels. Furthermore, the mode of Curing significantly affect the properties of OPC blended geopolymer specimens. High early compressive strength development was noticed in a specimens cured in oven. Similarly, Patil et al. (2014) examined the influence of mode of curing on the mechanical properties of geopolymer concrete, in their work fly ash was activated by a solution of sodium hydroxide and sodium silicate. The results showed that 7 days strength of the oven cured specimen is almost six times than that of ambient cured specimens while at 28 days curing period, the strength increment was doubled. It was observed also that oven curing gives higher compressive strength values.

Vijai et al. (2010) have reported an improvement in mechanical strength of geopolymer concrete at higher temperature of curing and the optimum temperature was obtained at 60°C after 1 day of oven curing. The oven curing method was found to be the most suitable and efficient method of curing geopolymer concrete in terms of early development of strength. However, this method of curing is difficult to achieve for cast in situ applications. In another research Nuruddin et al. (2011) prepared three separate regimes of curing, namely hot burlap curing, ambient curing, and oven curing. Geopolymer concrete specimens were produced by activating fly ash and microwave incinerated rice husk ash (MIRHA) with 8 molar solutions of sodium hydroxide solution and sodium silicate. The hardened specimens were exposed to the stated curing regimes and then examined its mechanical and microstructural properties. The findings reveals that heat or oven curing was the best methods for achieving higher strength in comparison with the other methods used as shown in Fig. 1.

Similarly, the performance of oven exposure curing specimen was verified by field emission scanning electron microscopy (FESEM) image as shown in Fig. 2. Microstructural analysis by FESEM revealed that higher temperature is vital in accelerating the polymerization reaction of geopolymer concrete with a powerful bonding between the aggregate and geopolymer paste and thus strengthened micro crack path which later yield significance improvement in strength of concrete specimens.

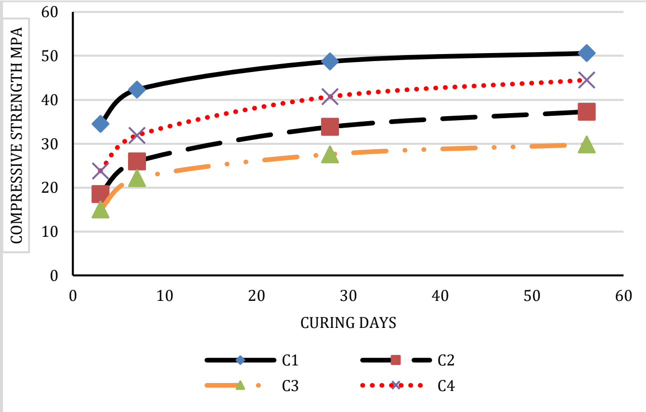

Fig. 1: compressive strength samples for oven curing (Nuruddin et al., 2011)

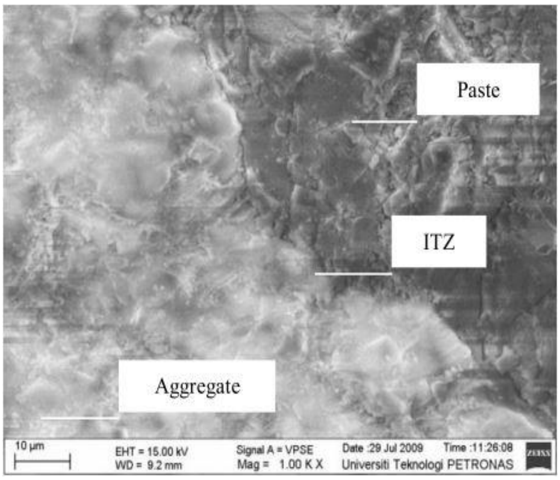

Fig. 2: Field emission scanning electron microscopy (FESEM) image for oven curing (Nuruddin et al. 2011)

2.2. Steam curing

There is a limited experimental work on steam curing of geopolymer concrete and among the few research studies, the work of Yewale et al. (2016) was one of the most important papers. They have found that strength of geopolymer concrete improves at higher temperature and the optimum strength was found to be 80°C temperature for steam curing, while for water curing, the strength obtained after 28 days was less than the characteristic strength due to the low development of strength at lower temperature. Moreover, Pangdaeng et al. (2014) have reported that addition of OPC in high calcium fly ash enhances the attributes of geopolymer concrete cure in steam and thus facilitated the hydration process due to the presence of OPC in the binder and thereby yields improvement in compressive strength. Similar work of Yunsheng et al. (2007) revealed that condition of curing have significance influence on the strength of slag based geopolymer concrete. Slag based geopolymer exhibited lower strength at ambient temperature compared to the steam cured specimens. During the first 2 hours of steam curing at 80°C, 9.4 MPa of compressive strength was achieved which is 19.14% higher than 3-days ambient curing. As the curing time was extended to 4 and 8 hours the strengths improved by 46.03% and 53.16% respectively. They also, obtained the maximum compressive and flexural strengths of slag based geopolymer of 75.2 MPa and 10.1 MPa, respectively. Similarly, Rangan (2008) and Lloyd and Rangan (2009) have placed thermocouples in three various specimens of geopolymer concrete and the internal temperature in the specimens were observed. The samples are cast in a small compression cylinder, a large tension cylinder, and a small compaction beam of 350 mm long by 85 mm square cross section. The thermocouples were placed at the surrounding platform were the steam curing process commenced and recorded up to 80°C. They have reported a mean temperature of 60°C and this was recorded as the optimum steam curing temperature of geopolymer concrete. Similarly, Kani and Allahverdi (2009) reported that hydrothermal steam curing contributed towards efflorescence reduction in geopolymer concrete. Three set of mix with different formulation were prepared and subjected to steam curing at 45 to 125°C for a period of 20 hours, another set of specimens were subjected to ambient curing for 7 days at 25°C. They noticed reduction in efflorescence at 65°C and above of steam curing which anticipated to be the cause for strength improvements of the geopolymer concrete specimens. However, they have not reported what happen at ambient curing.

Hardjito and Rangan (2005) produced precast geopolymer concrete products and exposed to steam-curing at 60°C for a day. A two-stage curing process was then used for maximum utilization of the form work so that more precast geopolymer precast elements could be produced. The products were cast and vapor-cured at the beginning for 4 hours and then put on hold so as to remove the precast elements from the formwork. The curing process was then recommencing for another 21 hours. They found that the two stage vapor curing stages did not cause any reduction in strength of the products. Similarly, Siddiqui (2007) produced reinforced precast geopolymer concrete box culverts.

He uses steam for curing of the culverts at 80°C for a period of 4 hours, at this period the concrete hardened and developed adequate strength for demolding of the culverts. The second curing regime was further commenced for another 20 hours at the same condition. He obtained good improvement in the compressive strength of the geopolymer concrete culverts despite the two-stage steam curing system employed. Furthermore, Kumaravel (2014) presented compressive strength result of geopolymer concrete in Fig. 2 produced by activating Class F Fly ash with 8 Molar solution of sodium hydroxide and cured in steam. Fig. 2 shows that steam curing possessed good compressive strength development at early age and suitable for cast in situ applications.

2.3. Ambient curing

Several attempts have been made for curing geopolymer at ambient conditions in the literature. Vijai et al. (2010) reported an experimental work on the mechanical and physical properties geopolymer concrete. The investigations were carried out on fly ash based geopolymer concrete and the mode of curing was varied. Class F fly ash was actuated by alkaline solution at a fixed ratio of solution to binder of 0.4 for a resting period of 5 days. The compressive strength test carried out showed a good improvement in geopolymer Concrete compressive strength with the age of curing for ambient cured specimens while for oven cured specimens, the change in strength with age of curing is negligible compared to the specimens subjected to ambient curing. However, oven curing was found to be efficient because of the low development of strength for ambient curing.

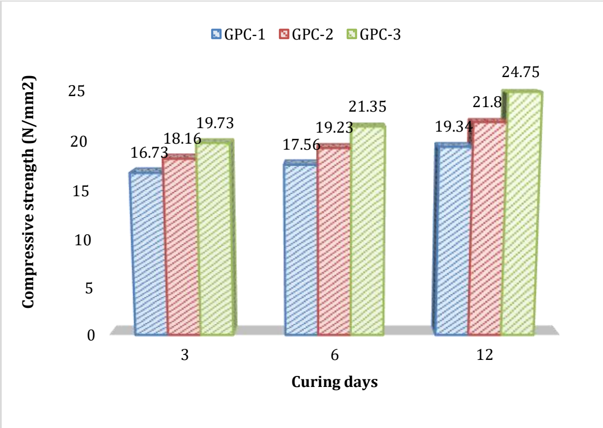

Fig. 3: Compressive strength development Vs age of steam curing (Kumaravel, 2014)

Nath and Sarker (2015) studied have focused on producing geopolymer Concrete that will be applicable for on-site constructions. In their work Fly ash of low calcium content was blended with small quantity of OPC to speed up the curing process of geopolymer concrete specimens at ambient condition in place of using heat for curing. They found that blending small amount OPC with fly ash causes quick setting time and slight decrease in workability. The strength gained at early-age has also improved significantly up to 28 days. Moreover, the microstructural analysis revealed a part of calcium-alumina-silicate gel hydrate (CASH) which is due to the presence of calcium ions in the OPC. Similarly, Nath and Sarker (2014) reported that blending Fly ash and slag in producing geopolymer concrete affected the setting time, workability and initial strength behaviour of geopolymer concrete cured in ambient state and the values obtained are similar to that of OPC concrete. They found that GGBS contributed in producing internal heat in the mixture which aid the geopolymerisation process at ambient curing and yield positive strength development at an early age. Similarly, the strength gain tends to follow the same pattern with that in

OPC concrete under the same curing condition. This considered being a new development for on-site utilization. However, optimum percentage of slag (GGBS) used was not being reported and other mechanical properties at this temperature were not analyzed.

Yewale et al. (2016) stated that the mechanical strength result of geopolymer concrete cured at room temperature is promising compared to water curing. Similarly, Kumaravel (2014) worked on various curing conditions of geopolymer concrete for cast in place applications. The geopolymer concrete was produced using low calcium fly ash and blast furnace slag as the binder material and reacted with alkaline solutions and aggregate to form the concrete. The hardened concrete specimens were subjected to three various mode of curing. He found that the rate of strength development for ambient cured geopolymer concrete resembles that of OPC Concrete and therefore be used for onsite constructions. Similarly, Nuruddin et al. (2011) found that the weight of fly ash geopolymer concrete correspond to that of OPC concrete. Analysis of microstructural properties of the specimens was shown in Fig. 4. From the Fig. 4; the geopolymer paste was slightly covered by the ITZ zone and contributed to better compressive strength formation of the geopolymer concrete samples. Appreciable bonding was observed between the aggregate and the paste which helps in improving the compressive strength. The strength development was observed to be low when compared to the samples cured by heat or oven.

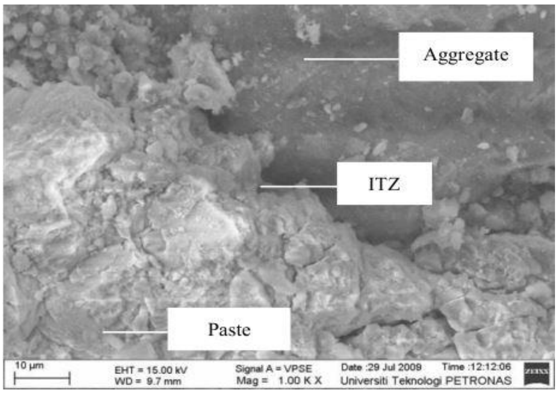

Fig. 4: Field emission scanning electron microscopy (FESEM) image for ambient curing (Nuruddin et al., 2011)

Temuujin et al. (2009) reported the influence of mechanical activation of fly ash on the behaviour of geopolymer concrete at ambient temperature. They found that geopolymer paste made with finer particles of the fly ash increases in reactivity and hence results in achieving higher strength at ambient curing. The strength reported to have almost double in comparison with the strength of geopolymer produced from unrefined fly ash. The prime contribution to increase in strength of the geopolymer is associated to the change of particles of fly ash and morphological transformation allowing a higher disintegration rate of the fly ash atoms. Similarly, Perera et al. (2007) reported that curing of metakaolin-based geopolymers at ambient temperature yields positive strength which is almost same to that of oven curing but the strength of heat cured specimens developed rapidly within a day. They also reported that humidity have influence on the curing process whereby the result is favorable at low humidity. In another findings Heah et al. (2011) reported ambient curing of metakaolin-based geopolymers gives a very low strength as compared to oven curing, he suggested a range of 40°C to 100°C curing temperatures as for rapid strength development. However, curing at advanced elevated temperature for a prolong period causes deterioration of the specimens due to the thermo-analysis of siliate –Si–O–Al–O– bond.

3. Conclusion

The present work has reviewed the methods of curing of geopolymer concrete. Several methods of curing has been attempted by various researchers which include oven heating, membrane curing, steam curing, hot gunny curing, hydrothermal curing, room temperature and water curing respectively. Among these attempted methods, oven curing proofed to be the most efficient method of curing of geopolymer concrete. The requirement for elevated temperature curing of the geopolymer concrete makes it a challenge that limits its application to only precast applications. Curing of geopolymer concrete is difficult using the oven on site. In addition, most of the researchers studied compressive strength only while other properties were not taken into consideration. Therefore, there is a scope of work needs to be done.

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