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A Review of the Compressive Strength Predictor Variables of Geopolymer Concrete

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REVIEW ARTICLE

Abstract- Having a prediction model for the geopolymer concrete (GPC) compressive strength gives Engineers an edge in project quality and cost control. Compressive strength of geopolymer concrete is dependent on various components that formed the concrete, and the curing regime. This paper is the outcome of a review of various variables (components and relationships) that influence the compressive strength of (GPC). The variables identified from the literature are; Concentration (Molarity) of the Hydroxide solution, Alkaline Liquid/Geopolymer Solids (Liquid/Binder) ratio, Sodium silicate to Sodium hydroxide ratio (SS/SH), curing time, curing temperature, Water/Geopolymer Solids ratio, age, fineness of the binder (pozzolan), rest period, admixtures and aggregates. A careful examination of the influence of each variable on compressive strength revealed that Hydroxide concentration, SS/SH, curing temperature, Alkaline Liquid/Geopolymer Solid ratio and Water/Geopolymer Solid ratio are the major determinants of GPC compressive strength.

Keywords- Geopolymer concrete, Compressive strength, Predictor variables, Alkaline activation

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1 INTRODUCTION

Although concrete is very crucial to modernization and enjoys extensive use, the cost of producing a good grade concrete is universally high especially with the use of Ordinary Portland Cement (OPC) as binder. Cement production continually increase due to unabating rise in construction works. Population boom and economic interest are drivers of demand and utilization of cement; yet the production leads to further pollution of our environment (Oyebisi *et al*, 2018). Komnitsas (2011) posits that with the rate at which the world population is increasing, it is necessary to focus on developments that are sustainable by considering factors such as environmental safety and energy utilization.

Using mineral admixtures to partially replace OPC is an effective way to reduce environmental pollution (Liu & Zheng, 2019). Recent alternatives to OPC include Alkali-activated cements, geopolymers and hybrid cements (alkali-activated cements with Portland cement clinker less than 30%). These are categorized as Possible Low Carbon Cements (Rivera *et al*, 2014). Although there is not yet any generally agreed nomenclature for these materials, referring to them as “alkali-activated materials”, “inorganic polymers” and “geopolymer” is common (Thapa & Waldmann, 2018).

According to Davidovits (2013), who invented and first coined the word geopolymers, these belong to the family of inorganic polymers similar to natural Zeolitic materials (Bachhav & Dubey, 2016) which are produced from chemical reaction of alumina and silicate oxides (Si_2O_5, Al_2O_3) with alkali poly-silicates producing polymeric Silicate Oxide Aluminate (Si–O–Al) bonds. Furthermore, Davidovits (2013) who considered the chemistry of alkaline activated materials and geopolymer said the two are not equivalent to each other, since some of the alkali-activated materials are not polymers.

However, the terms geopolymer and alkali activated material are somewhat interchangeably used in the literature (Luukkonen *et al*, 2018). Geopolymers stand out in the alternative technology area; this is not surprising considering that they have been the focus of many research works since the 1970s (Lehne & Preston, 2018). Geopolymer concrete (GPC) is a modern building material formed from reaction of inorganic molecules (Aleem & Arumairaj, 2012). Pozolans such as palm oil fuel ash (POFA), fly ash (FA), meta-kaolin and rice husk ash (RHA) that have high alumina and silica contents are activated by solution of alkaline to create the binding paste. The resulting geopolymer paste binds the loose coarse aggregates, fine aggregates and other unreacted materials together to form the geopolymer concrete (Gatti & Prasad, 2017).

Commercially produced alumina and silicate rich materials like meta-kaolin, industrial waste product such as slags and ashes can be combined with alkali and water to produce strong and durable concrete similar to OPC under controlled or ambient conditions (Zeobond Group; Oakes *et al*, 2019). GPC possesses many desirable qualities of which the compressive strength is the key consideration like the OPC concrete. An important index for assessing the GPC quality is Compressive strength

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(Dao *et al*, 2019; Fang *et al*, 2018); therefore, being able to predict the compressive strength of GPC correctly will further enhance its use and acceptability.

Strength prediction in concrete is being targeted as an active area of research. Researches are focused on exploring the behaviour and strength of concrete with the aim of increasing the efficiency of prediction (Hasan & Kabir, 2011). The prediction of concrete compressive strength according to Chopra *et al* (2016) has great significance because it offers opportunity to adjust concrete mix thereby preventing a scenario whereby design strength is not attained or by averting concrete that is excessively strong (leading to a disproportionately high cost) and also for more economic use of raw material, hence reducing construction cost.

Gupta (2007) stated that the prediction of concrete strength is important for use of concrete in construction as it gives an idea about the time for form work removal, project planning and quality assurance. The conventional method which involves trying various mixes and then adjusting the mix proportions until desired result is obtained is tedious, costly and time wasting (Onwuka *et al*, 2013). Since experimenting with concrete mixes is costly and time consuming, there is need to find new means and technique of reducing the effort required in order to save on cost and time while preserving quality and integrity of the concrete with high accuracy. Although literature concerning geopolymer cement concrete design is available, the influence of various mixtures and variables on the compressive strength has not been fully evaluated, because the level of previous works is limited (Lahoti *et al*, 2017).

Accurate prediction of compressive strength of GPC is quite difficult due to intricate and non-linearity of the problem. Correct and accurate prediction is predicated on good knowledge of the constituents that make up the GPC and how they relate with one another to ascertain the strength of the concrete. As noted by Brough & Atkinson (2000), the bond between cement paste and aggregate at the interfacial transition zone (ITZ) has a strong effect on the mechanical attributes of concrete. The geopolymer paste, the aggregates and the curing effect determines the compressive strength of the GPC. To properly predict the strength of geopolymer concrete, Aughenbaugh *et al.* (2015) concluded that the prediction model will need to incorporate information derived from knowledge of the binder and the resulting geopolymers formed.

2 STRENGTH PREDICTOR VARIABLES

Strength is the design property of the concrete. It is the most important characteristic of concrete although characteristics like, durability, volume stability, impermeability may be important in some concrete design. Strength is a reflection of the overall picture of concrete quality (Hasan & Kabir, 2011). According to Hassan & Kabir (2011), for concrete mix proportioning, water cement ratio is the most essential of all the factors which also include quality of aggregate and its grading, binder type, method used in mixing and forming and curing regime. Water cement (Water/binder) ratio is a strong determinant of concrete strength. Water required for exact chemical reaction in the GPC, is not much; surplus water only increases the workability but reduces strength. A major goal in concrete production is the compressive strength, which is dependent on how the various elements such as cement, water, coarse aggregate, fine aggregate, and modifiers are portioned (Orie & Osadebe, 2015). In applying support vector machines (SVM) model in the prediction of compressive strength of GPC, Gupta (2007) considered sand; coarse aggregates; percentage of fibres; percentage replacement of OPC by fly ash; percentage replacement of OPC by silica fume; water/cement ratio and compaction factor as the input variables in determining the 28th-day compressive strength.

Oakes *et al.* (2019) in their work on prediction of strength and procedures for mix design in geopolymer and activated cement mortars developed the prediction model as presented in equation (1) for the seventh day compressive strength of geopolymer mortar by incorporating 80% ground granulated blast-furnace slag (GGBS) and 20% meta-kaolin. Factors considered for the strength determination were Binder content, Total water (TW), Free Water/Binder (FW/B), Free Water/Activator (FW/A), Silica/Alumina (S/A) and Liquid/Solid (L/S) ratios.

$$F7 = -33.88 + (Binder * 0.4905) + (-280.4 * TW) + (-1153 * FW/B) + (-0.7 * FW/A) + (-168.8 * S/A) + (L/S * 2554) \qquad (1)$$

where: F7 is the seventh day compressive strength.

The load carrying capacity of any concrete structure is determined by compressive strength of concrete. Strength gain in concrete is related to the hydrated cement paste, ratio of cement to water (c/w), ratio of cement to aggregate, grading, surface texture, shape, and stiffness of aggregate particles and maximum size of aggregates. In using statistical methods to model the properties of concrete, Simon (2003) concluded that factors such as cement content, water/cement ratio, chemical admixture and percentage of pozzolan content determines the resulting concrete attributes such as strength, slump or even cost.

The Concrete Optimization Software Tool (COST), an online interactive system which model concrete compressive strength using Response Surface Methodology (RSM) considers water-cement ratio, fine aggregate, coarse aggregate, chemical admixture and percentage pozzolan utilization as the major variables for the determination of the required concrete strength. For Okoloekwe & Okafor (2007), Cement, Sand Content, Gravel and Water contents are the important variables in the determination of the compressive strength of any concrete. The following variables were considered by

Shariq *et al.* (2012) for optimization of 28 days compressive strength; water to cement ratio (w/c), coarse aggregate to total aggregate ratio (CA/TA) and total aggregate to cement ratio (TA/C). They used experimental and polynomial regression analysis to check how these variables influenced the compressive strength of the concrete. Ahmad & Alghamdi (2014) considered factors such as water/binder ratio, binder content, and fine/total aggregate ratio in developing an optimized polynomial regression model for compressive strength.

According to Suwan (2016)**,** ratio of sodium silicate to sodium hydroxide solutions (SS/SH ratio), the soluble silicate concentration (in molarity and percentage), and alkaline/geopolymer solid ratio (A/FA), curing method, temperature and duration are the important elements that are essential in forming geopolymeric gel. Alonso & Palomo (2001), opined that the rate at which polymer is formed is determined by variables such as initial solid content, curing temperature, alkali concentration among others. Awoyera *et al*. (2020) while estimating the strength of self-compacting geopolymer concrete produced by adding mineral admixtures using both genetic programming (GEP) expressed as equation (2) and the artificial neural networks (ANN) models, considered raw materials and fresh mix properties of GPC as predictors.

$$Cs = \frac{1}{\sqrt{F}}(4.96A - (\mathrm{T}_{50}\mathrm{V})) - (\mathrm{G} + \mathrm{S}_{\mathrm{f}}) - (\mathrm{S} + \mathrm{J}) \qquad (2)$$

where; Cs is compressive strength, F is amount fly ash, T50 is T50 flow, V is V funnel flow, S_f is Silica fume content, S is slump flow, J is J-ring reading, A is Age and G is GGBS content.

While using Taguchi method to measure the impact of different components on compressive strength of FA rubberized geopolymer concrete, Luhar & Luhar (2020) reported the factors to consider in compressive strength of GPC to include alkaline solution-FA ratio, ratio of Na_2SiO_3/NaOH, NaOH molar concentration, curing temperature, curing period, water content, rest period and quantity of superplasticizer as an additional material. They ranked curing temperature, NaOH concentration and Na_2SiO_3-NaOH ratio as first, second and third respectively from the ANOVA as the most important factors in optimizing the compressive strength of the GPC. Observation showed that an increase in values of these factors increases the compressive resistance of rubberized geopolymer concrete.

According to Junaid *et al*. (2012), the strength of GPC mix is dictated by the following key factors: Hydroxide/Sodium Silicate ratio, Alkaline Liquid/Geopolymer Solid ratio or Alkaline Liquid/Binder Ratio, Water/Geopolymer Solids and NaOH concentration. Also, for predicting the compressive strength of OPC concrete, the principal variables to consider for the mix according to Zain *et al*. (2008) are: water/binder ratio, quantity of cement, quantity of coarse and fine aggregates and density of the concrete. Chopra *et al* (2016) in their study on compressive strength of concrete with and without geopolymer (alkali activated Fly ash) came up with the prediction model in equation (3); parameters such as Water-cement ratio, Cement content, Water content, Percentage replacement of cement by geopolymer, workability, Coarse Aggregates and Curing ages were used for predicting the 28th day compressive strength of the GPC. Early age strength was also considered for predicting the latter age strength of geopolymer concrete.

$$fc_{28} = A0(W/CM)^{A1}\ (FA/CM)^{A2}(CA/CM)^{A3} \qquad (3)$$

where; fc_{28} is the 28th day compressive strength of concrete with or without geopolymer (fly ash); *W* is water content; *CM* is cement content; *FA* is the fine aggregate; *CA* is the coarse aggregate and *A0, A1, A2, A3* are the regression coefficients based on percentage reduction of OPC with geopolymer.

Various factors that impact on the making of geopolymer mortar according to Hameed *et al* (2017) are: Fly ash/Meta-kaolin content, type of superplasticizer, quantity of superplasticizer, ratio of fine to total aggregate composition, ratio of pozzolan to alkaline solution, NaOH and Na_2SiO_3, extra water content, ratio of NaOH to Na_2SiO_3, and curing regime (sunlight curing, laboratory curing and heat curing). Dao *et al.* (2019) approached the strength prediction of GPC utilizing particle swarm and genetic algorithms fuzzy systems; they considered Sodium hydroxide concentration which was varied from 10 to 14 M, alkaline activator to fly ash (AAS/FA) ratio ranging from 0.4 to 0.5, and Na_2SiO_3 to NaOH solution ratio (varied from 2 to 3) as the three parameters for the prediction. Hardjito, *et al*. (2004) considered the factors that affect the compressive strength of GPC and identified the following as important indicators in strength formation of the GPC; age of concrete, curing time, effect of superplasticizer, rest period prior to curing, water content in the mix, water/geopolymer solids ratio and molar H_2O/Na_2O ratio.

Lee & Shin (2019) when considering factors that determine the compressive strength of GPC, identified six variables comprising curing temperature, GGBS/binder weight ratios, the aggregate/binder ratio, alkaline solution/binder ratio, ratio of Na_2SiO_3/NaOH, and NaOH concentration as fundamental to the attainment of strength in GPC. When the six factors were subjected to ANOVA analyses using Taguchi orthogonal arrays in three levels, the result revealed that curing temperature and ratio of GGBS/binder ratio were the variables that mainly determined the compressive strength development; although their interaction effect is rather minor. Artificial Neural Network (ANN) was used by Rao & Rao (2012) in modelling the compressive strength of concrete using different aggregate to binder ratios. They considered age, water/ binder ratio, aggregate /binder ratio and percentage of FA substitution as the key predictor variables.

3 COMPRESSIVE STRENGTH PREDICTOR VARIABLES

3.1 EARLY STRENGTH

It had been demonstrated that early strength of GPC could be utilized for prediction of the latter strength as an independent variable. Thus, Kabir *et al* (2013) demonstrated that using power equation, 7th day compressive strength as the sole variable could be used for predicting the 14th and 28th day strength respectively.

3.2 CONCENTRATION OF ACTIVATORS / NAOH

Activators can either be solid or liquid and it can either be alkaline or acidic. Solid activators such as $Na_2SiO_3{\cdot}5H_2O$ and potassium carbonate have proved effective in GPC and advantageous in reducing the water-binder ratio (Askarian *et al*., 2018, Dong *et al*., 2020; Hadi *et al*., 2019). Although acidic activators such as phosphoric acid has been successfully used in the production of GPC, yielding high compressive strength (Shuai *et al*., 2020) and offering higher temperature resistance than alkaline activators (Celerier *et al*., 2019, Zhang *et al*., 2020a), yet sodium and potassium based alkaline activator still remain very popular in GPC production.

Various activators produce GPC having different fresh properties (Cong & Cheng, 2021); thus, activators may be chosen based on desired properties of which compressive strength is inclusive. According to Kupaei *et al.* (2014), the compressive strength of geopolymers is directly linked to the level of polymerization, which is strongly affected by the soluble silicate and aluminate of the geopolymeric scheme. While working on Oil Palm Shell Geopolymer Concrete (OPSGPC), Kupaei *et al* (2014) reported the impact of molar concentration of NaOH in the alkali activator on the compressive strength of GPC. They showed that increasing the molarity up to 14M caused an increment in the compressive strength; however, at 16M a decrease in the compressive strength of the OPSGPC was observed. More often than not, a gain in polymerization of the geopolymeric structures will result in greater compressive strength.

The NaOH concentration influences the dissolution process in the liquid state of the geopolymeric process (Panias, 2007; Memon, 2013). Increasing the NaOH concentration increases the GPC compressive strength; however not infinitely. As observed by Kumar *et al*, (2020) and Aldin (2017), the NaOH concentration affects the setting time and the GPC compressive strength. Reduced compressive strength and delay in setting time is experienced when concentration of NaOH is low. Fang *et al* (2018) also showed that gradual increase in compressive strength was obtained in alkali activated fly-ash slag (AAFS) concrete when the molarity of NaOH was increased; This was linked to the chemical action of the intrinsic Si, Al and Ca constituents occasioned by the increased breakage of the T-O-T bonds (T = Si or Al tetrahedral atom, O = shared octahedron atom) in fly-ash and Ca-O and Si-O bonds in GGBS, a direct effect of increasing NaOH alkalinity. Zhang *et al* (2019) showed that NaOH has the greatest influence on compressive strength of GPC, however its influence on the rate of strength gain is little subsequent to the initial heat curing. In figure 1, Vora & Dave (2013) showed that when NaOH concentration was increased from 8M to 14M, compressive strength increased from $32Nmm^{-2}$ to $46Nmm^{-2}$.

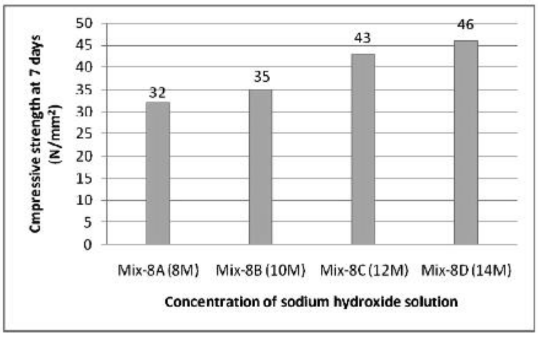

Fig. 1: Effect of Sodium Hydroxide Concentration on compressive strength (Vora & Dave, 2013)

After 28 days of hot curing, Rajesh (2014) found that GPC of 12M NaOH solution gives strength that is 1.25 times greater than GPC of other molarities. Hake (2016) also observed that at 80^0C curing, GPC of Sodium hydroxide concentration of 16M gives better strength than other molar concentrations. It was discovered that with increasing molarity of NaOH solution, there is corresponding increase in the compressive strength of GPC (Bidwe & Hamane, 2015; Chowdhury *et al*, 2018). However, Alonso & Palomo (2001) have shown that when the molarity of NaOH is too high, the tendency that a coagulated structure is formed increases and rapid setting could also be experienced which may not be desirable. According to Anuar *et al* (2011), production of geopolymer cement can be achieved by combining NaOH and Na_2SiO_3 solutions, with molar concentration ranging from 8M to 15M and between 30 to 50% weight/weight ratio of NaOH to Na_2SiO_3 respectively. Suwan (2016) suggested that higher NaOH concentration should be used for ambient-cured geopolymers than those that are heat cured, to ensure an extra level of reaction.

3.3 SODIUM HYDROXIDE / SODIUM SILICATE RATIO

Though arguable, NaOH had been found to perform better with regard to development of compressive strength in GPC than KOH (Okoye *et al*, 2015; Avanaki, 2020); and it is more widely used than KOH for production of GPC because NaOH actually has a higher capability to release silicate and alumina monomers. The compressive strength of GPC using NaOH and KOH was determined at different intervals of time and compared by Okoye *et al* (2019) in which NaOH performed better than KOH.

According to Srinivasan & Sivakumar (2013), using sodium NaOH solution is better for geopolymerization process than KOH solution because of its higher mineral's dissolution capability. However, NaOH is rarely used alone as alkaline activator in GPC production. NaOH

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compounded with Na_2SiO_3 solution is mostly utilized as activator solution for geopolymer synthesis due to their function in dissolving alumina-silicate minerals and initiation of geopolymeric gel formation (Wattanachai & Suwan, 2017). Na_2SiO_3 is also known as water-glass and may be procured in gel and solid forms. The addition of Na_2SiO_3 to NaOH solution supplies higher silicate content and is likely to make for faster polymerization (Srinivasan & Sivakumar, 2013). The ratio of silicon dioxide (SiO_2) to sodium oxide (Na_2O) that is present in the Na_2SiO_3 gel greatly influence the strength of GPC. A satisfactory result can be gotten with a ratio ranging from 2 to 2.5 (Sharma & Ahmad, 2017; Chowdhury *et al* ,2018; Poloju *et al*, 2020)**.** According to Fernández-Jimenez *et al* (2006), the inclusion of silicates in the alkali solution will in no small way improve the compressive strength of the GPC formed.

Generally, Na_2SiO_3 to NaOH ratio (SS/SH) determines the characteristic of the alkaline activator solution. Hardjito & Rangan (2005) state that a SS/SH ratio of 2.5 is sufficient to form GPC using conventional aggregates noting that a further increase in SS/SH will not change the compressive strength in any significant way. A lower SS/SH ratio delays the setting time and simultaneously lowers the compressive strength. This finding is illustrated in figure 2 (Aldin, 2017).

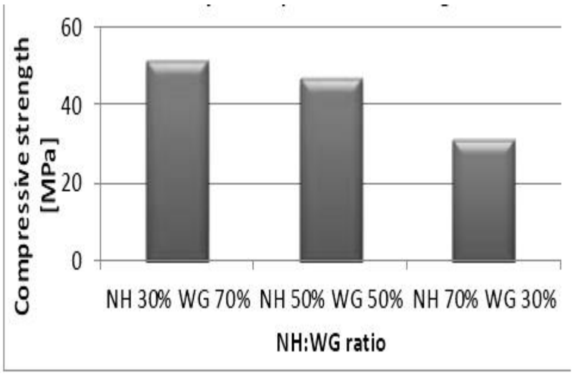

Fig. 2: Third day compressive strength of different ratios of 4M sodium hydroxide (NH) and Sodium silicate (WG) (Aldin, 2017)

Hameed *et al.* (2017) surmised that the effect of Na_2SiO_3 to NaOH ratio is very clear; by varying this ratio, compressive strength also varied and peaked when the ratio reaches 3:1 by mass. Sodium acts as charge balancing ions and therefore is important in the chemistry of geopolymerization. However, when Na_2SiO_3 to NaOH ratio was changed to 4:1, there was loss in compressive strength due to excess of Na_2SiO_3 which prevents evaporation of water and formation of structure. Therefore, Hameed *et al* (2017) concluded that for Meta-kaolin-based GPC, the optimum ratio of NaOH to Na_2SiO_3 was 1:3 by mass. Zhang *et al* (2019) noted that although the initial effect of SS/SH ratio on compressive strength of GPC is small, its influence is considerable on the rate of strength increase over the long term.

3.4 CURING TIME

Curing is very important to strength development in concrete whether it is geopolymer or OPC concrete. Effect of curing duration on early strength development in GPC is very crucial. Curing has been found to improve polymerization process in GPC, resulting in high compressive strength (Castillo, 2021). However, the strength gain was observed rapid only up to 24 hours curing period (Hardjito, 2004; Vora & Dave, 2013). Forty-eight (48) hours was obtained as the optimal curing time by Luhar & Luhar (2020) when experimenting on rubberized geopolymer concrete samples. It was discovered that extending the curing period beyond 48 to 72 hours resulted in reduction in strength owing to water evaporation from the surface of the specimen**.** Davidovits (2013) noted that when geological material as KANDOXI, a special metakaolin is utilized as the root material to produce geopolymer, curing for a shorter period of time and at a lower temperature is sufficient to achieve satisfactory results.

3.5 CURING TEMPERATURE

Unlike OPC concrete that requires low temperature and water for curing, geopolymer concrete requires higher temperature. When geopolymers are cured at elevated temperature, their properties become like that of ceramics with some added benefits (Kong & Sanjayan, 2010). Increasing the curing temperatures from over 40°C to 70°C could distinctly cause a betterment in the compressive strength of (FA based) geopolymer paste at the early and later stages. It was impossible to measure the compressive strength at low curing temperature (10°C to 30°C) as at the 3rd day while the strength remains low even at the 28th day (Suwan, 2016). When curing temperature was raised from 40°C to 70°C, more geopolymeric gel was formed in the matrices due to increase in chemical reaction. However, when the curing temperature was increased from 75°C to 90°C no significant gain in compressive strength was observed (Hardjito & Fung, 2011). This showed that the temperature for curing cannot be increased indefinitely. While Hassan *et al* (2019) suggested 75°C for 26 hours as optimal curing temperature, Vora & Dave (2013) expressed that raising the temperature of curing beyond 75°C only translated into a marginal rise in the compressive strength.

Memon *et al* (2011) studied the influence of curing temperature on compressive strength of GPC. The result showed that oven curing of specimens at 70°C for 48 hours increased the compressive strength, while the specimens that were cured at 80ºC and 90ºC have their compressive strength decreased. When curing temperature is too high (e.g., over 70°C) or curing duration too long (e.g., over 24 hours), a decrease in compressive strength of GPC may result. Research on Metakaolin-based geopolymer done by Rovnaník (2010) on the effect of curing temperature and curing time have specimens cured at various temperatures (10, 20, 40, 60 and 80ºC) for 4 hours in electric oven revealed that increasing the temperature leads to accelerated formation of compact structure and accelerates early age geopolymerization reaction. It takes 24 hours for the specimens cured at 60 and 80ºC to reach their final stage of strength. Hameed *et al* (2017) reported that lower curing temperature thus impacted negatively on the strength values of geopolymer. It was shown that GPC cured at 70ºC gives significantly better strengths compared to those cured at 50ºC for the same duration.

Heah *et al. (*2011) concluded that heat curing at a temperature below 100°C contribute significantly to the geopolymeric reactions and is thus advantageous for the strength development in kaolin-based GPC. They observed that optimal strength was obtained at 60°C. Higher temperature and prolonged curing caused distorted reaction which led to subsequent failure of sample resulting from partial and rapid water evaporation and micro cavities formation (Sambucci *et al*, 2021). Research has shown that adding Portland cement to the GPC fundamentally affects the setting characteristics and early strength development. The mechanical and microstructural properties of GPC could be enhanced by heat liberated via the exothermic reaction of OPC hydration (Pangdaeng *et al.* 2014). Despite the advantage of heat curing, geopolymer concrete can be cured at room temperature especially when a combination of Na_2SiO_3 and NaOH solution is used as activator (Huang *et al.*, 2018; Bhutta *et al.*, 2019) . According to Yewale *et al.* (2016) and Jindal, (2019), when GPC is cured at room temperature, the strength is better than when cured in water. For mass precast production, oven curing and sunlight curing system in summer are considered reasonable for curing especially when OPC is incorporated into fly ash, POFA and meta-kaolin based geopolymer concretes. This is favourable and economical in hot weather countries (Hameed *et al*, 2017; Detphan *et al*, 2021).

3.6 ALKALINE LIQUID TO GEOPOLYMER SOLID RATIO

Alkaline liquid to geopolymer solid (pozzolan) ratio is very important in strength formation of GPC. Increasing the alkaline solution to pozzolan ratio increases the strength of the GPC up to an extent, after which there will be a reduction in the compressive strength. This lessening in compressive strength of GPC is premised upon more water that is needed in preparing the activator coupled with significant rise in amount of pores resulting from heat curing. This phenomenon is similar to Portland cement concrete for which increase in water to cement ratio decreases compressive strength (Sharma & Ahmad, 2017). When the alkaline activator solution increased relative to the geopolymer solid, compressive strength of the concrete and mortar decreased; however, workability improves (Nagajothi & Elavenil, 2018).

Fang *et al.* (2018) reported that decreasing the alkali activator to binder (AL/B) ratio caused compressive strength increase. Thus, it can be summarized that the alkaline liquid/geopolymer solid ratio have a strong influence on the early-age (less than 14 days) compressive strength development in alkaline activated fly-ash slag (AAFS) concrete, but will not so much influence the compressive strength at 28th day. Al Bakri *et al.* (2011), Chowdhury *et al* (2018), & Hamzah *et al* (2020) reported that geopolymerization in a fly-ash-based geopolymer is maximized at an activator to FA ratio of 0.4 although Ganesan *et al* (2019) suggested 0.3 as the optimum alkaline liquid to solid ratio. It was also suggested by Rangan (2008) that the alkaline liquid to FA ratio should be ranged from 0.30–0.45 as presented in Table 1.

Table 1. Effect of alkaline liquid to pozzolan/ fly ash (AL/FA) ratio (Rangan, 2008)

AL/FA	**Compressive Strength (MPa)**	**Workability**
0.30	58	Hard
0.35	45	Moderate
0.40	37	Moderate
0.45	32	High slump

3.7 WATER TO GEOPOLYMER SOLID RATIO

Increasing the water/geopolymer solid ratio will decrease the compressive strength of GPC (Castillo *et al*, 2021). A test conducted by Vora & Dave (2013) showed results similar to how water/cement ratio will impact on OPC concrete strength. According to Ferdous *et al* (2013), alkaline liquid/geopolymer solid (FA) ratio and the amount of geopolymer solid in the matrix are the two variables that majorly affects the water/geopolymer solid ratios. It is obvious that decreasing water/geopolymer solid ratio will better the strength of GPC (Ramujee & Potharaju, 2014). Thus, the water-cement ratio in concrete produced with Portland cement, compressive strength and water/geopolymer solids ratio in GPC are inversely related as shown in Figure 3.

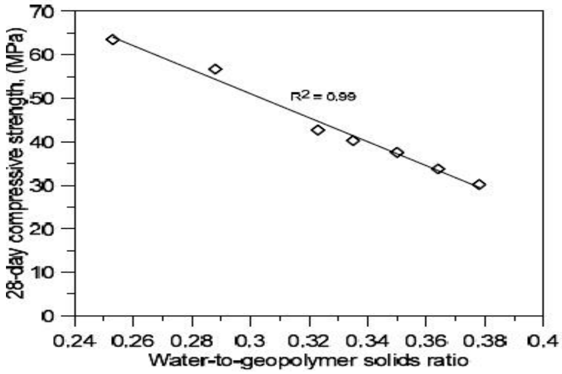

Fig. 3: Effect of Water to Geopolymer solid ratio on Compressive strength of GPC. (Ferdous *et al.*, 2013)

If the dissolved solids in the alkaline solution are to be taken as part of the solids content of the material, then proportioning should be based on water to solids ratio. Hardened characteristic of GPC mix like microstructure, porosity and strength are adversely influenced by excess water, so minimizing it would be beneficial. (Ramujee & Potharaju, 2014). From figure 3, Ferdous *et al* (2013) demonstrated that a lower compressive strength of GPC will result from a higher water to geopolymer solid ratio.

The total mass of water in a GPC mix is the summation of all the masses of water in Na_2SiO_3 and NaOH solutions, and that of water added to the mix. The geopolymer solids is the addition of the masses of binder, sodium silicate solids such as SiO_2 and Na_2O in sodium silicate solution and sodium hydroxide flake. Although the chemical reactions involved in the formation of the binders of ordinary Porland cement and GPC concretes are entirely different, the variation in compressive strength of GPC as the mass ratio of water/geopolymer solids varies is similar to the established outcome of water/cement ratio on the compressive strength of OPC concrete (Hardjito *et al*, 2004)

3.8 FINENESS OF BINDER (POZZOLANS)

The particle size of the source material is a major determinant of the compressive strength in fly ash GPC (Assi *et al*, 2018). Both physical and chemical reactions get better with increasing surface area. Initial setting time and geopolymeric gel phase are controlled by physical and chemical reactions involved in geopolymer formation such as rate of dissolution, ions conveyance and alumina-silicate variety formation; which improved through smaller particles possessing higher surface area (Chindaprasirt *et al*, 2010;Petermann *et al*, 2010; Ahmari *et al*, 2012) Increasing Fly ash fineness increased the mass density of geopolymer concrete because greater Si-Al bond for polymerization could take place with more surface area (Jamkar *et al*, 2013; Patankar *et al* , 2015).

The fineness of FA (geopolymer solid) affects the strength of the GPC as fineness is pivotal in the activation of geopolymer concrete. Compressive strength and workability are both influenced by increase in fineness. Sharma & Ahmad (2017), observed that a determined strength could be achieved requiring less heating period of time with finer particles which increase the reaction rate. Sičáková & Števulová (2017) confirmed that for fly ash based geopolymer, mixture using ground fly-ash of size 31.0μm rather than unground one with a size of 74.0μm is obviously better in all factors. At 28th day, they found out that density increased by about 18%, total water absorption improved by about 25%, flexural strength gained around 25%, and compressive strength shoot up by about 10%

3.9 REST PERIOD

The time interval between casting a GPC specimen and commencement of curing is referred to as Rest Period. It is a very crucial factor when considering practical applications. In precast concrete industry, sufficient time should be available between casting and heat curing. As ascertained by Vaičiukynienė *et al* (2017) and Hardjito *et al* (2004), a higher compressive strength can be achieved with a day rest period than without any rest period. The study by Oyebisi *et al* (2019) revealed that 4 days rest period is better than other days for strength performance of all classes of concrete examined.

3.10 ADDITION OF PLASTICIZER / ADMIXTURE

Superplasticiser addition to geopolymer concrete resulted in improved workability while reducing the water requirement (Sambucci *et al*, 2021). According to Vora & Dave (2013), higher compressive strength was achieved with 2% dose of superplasticiser inclusion in concrete mix compared to higher superplasticiser dosage of 3%. When the superplasticiser was increased to 4%, the compressive strength of the GPC reduced. Thus, they confirmed that the workability of fresh GPC could be improved by adding naphthalene-based superplasticiser. Research by Hardjito *et al* (2004) revealed that the addition of superplasticizer to about 2% of the mass of geopolymer solid improved the workability of fresh GPC but the impact on the compressive strength had been very little. Beyond 2%, there is some degradation of the compressive strength. Using retarder such as Plastocrete RT6 Plus insignificantly increases the compressive strength of geopolymer concrete, therefore Umniati *et al* (2017) concluded that the addition of retarder has no significant effect on the compressive strength of the GPC. Also, barium chloride dehydrate retarder was found not to have any effect on the compressive strength of GPC at 7th, 28th and 90th days (Aldin, 2017). When borax was introduced into the geopolymer paste, the initial setting time was expedited but the final setting time was delayed. Increasing the content of borax in geopolymer is likely to lower the compressive strength; hence its use should be limited to 2.5% w/w of the pozzolan (Wongkvanklom *et al*, 2018). Graphene has been shown to improve the mechanical and micro-structural properties of geopolymer paste (Matalkah and Soroushian, 2020). 1% graphene was shown to be beneficial to the strength of geopolymer mix (Ranjbar *et al*., 2015). Gulsan *et al*. (2019) also concluded that the strength of GPC can be improved by incorporating nano-silica in it.

3.11 AGGREGATES (COARSE AND FINE)

Aggregates in GPC serve the same purpose as in OPC concrete. However, there is possibility of aluminosilicate reactivity (ASR) with the activating alkaline solution which should be avoided (Mermerdas *et al*, 2017). Mermerdas *et al*, (2017) noted that the adhesion between the binder and the aggregates' surface area, surface texture and angularity of the aggregates determine the compressive strength of geopolymer mortar. The angular nature and texture of the fine aggregates played an essential part in the strength development due to the filling and packing characteristics. Shape, grade, and maximum size are the principal characteristics of fine aggregate that influence the compressive strength of fresh and hardened concrete (Bashar *et al*, 2014). Angular shaped aggregates have better surface to volume ratio than smooth aggregates, enabling stronger interlock and bond between the particles. However, a workable matrix will require an increase in the binder content (Bashar *et al*, 2014).

Mane & Jadhav (2012) in their study of FA geopolymer using different grades of fine and coarse aggregates subjected to high temperatures discovered that using coarse granite aggregate is better than using basalt aggregates for the manufacture of GPC in terms of strength development. In the same vein, crushed sand yields higher strength as compared to river sand as fine aggregate in the manufacture of GPC. Nuaklong *et al.* (2016) in the study on strength and durability of GPC using crushed limestone aggregate and recycled concrete aggregate (RCA) discovered that recycled aggregates are comparable with crushed limestone aggregates in GPC. Geopolymer concrete comprising (RCA) gave 76–93% of the compressive strength of ones utilizing crushed limestone as aggregate. Thus, recycled aggregates can replace natural coarse aggregate in GPC (Krishnan & Purushothaman, 2017). Gravel ranging from 12.5mm to 25 mm in size offered a maximum compressive strength. From figure 4, it was ascertained that coarse aggregate size does not influence the effect of curing regime on GPC. Regardless of the aggregate size, oven curing still guaranteed more compressive strength than ambient curing (Guades, 2016).

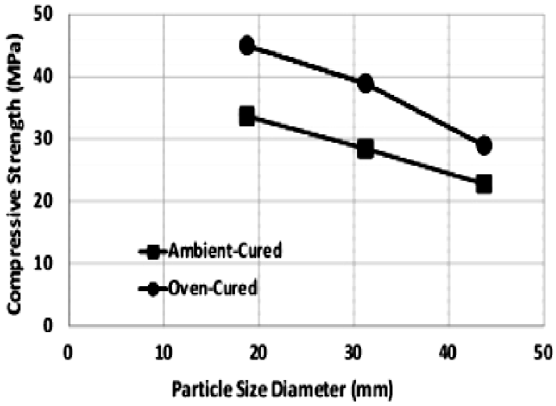

Fig. 4: Relationship between compressive strength and aggregate particle size of GPC (Guades, 2016)

In order to obtain high strength concrete, it is usually appropriate that coarse aggregate be limited to a maximum size of 19mm, though this will require extra binder due to additional surface area. Because of the higher cement content, the fine aggregate can more often contain less particles passing 300µm and 150µm sieve. A comparison between textured and smooth surface aggregates of similar rock mineralogy showed that concrete made with rough or textured aggregates have higher strength at early age than the one with smooth surfaced aggregates. To allow for maximum interaction and bonding with the geopolymer binder paste, the fineness modulus of 4.5 or 5.0 is considered best for the combined aggregate material (Chindaprasirt *et al*, 2010).

4 CONCLUSIONS

A realistic approach to strength prediction in GPC should take cognizance of both the chemical and physical features of the constituent materials, including the vitreous composition and the particle sizes. This review has considered the activator system, the aggregates and the curing process, all of which impact on the compressive strength of the GPC. In conclusion, the following should be noted:

1. NaOH Concentration: Increase in NaOH concentration yields an increase in the compressive strength of the GPC (a range between 8M to 16M is suggested).
2. Sodium silicate to sodium hydroxide solutions ratio (SS/SH): This ratio generally defines the characteristics of the activator system. A range between 2.0 and 3.0 is sufficient to obtain a good compressive strength. Increasing SS/SH further may yield no considerable strength increase.
3. Curing temperature: Elevated curing temperature of 60^{0}C to 70^{0}C is beneficial for GPC. Addition of OPC to GPC has been shown to make its curing under ambient condition possible.
4. Aggregates: Compressive strength of GPC is also a function of the bond between the binder and the aggregates while the aggregates' bonding capability depends of its surface texture, surface area and angularity. (Angular aggregate is better than smooth/rounded one. Coarse aggregate not exceeding 19mm is also preferable).
5. Alkaline liquid to geopolymer solid ratio: This ratio is very crucial in strength formation of GPC. Reducing the ratio of alkaline liquid to geopolymer solid increases the strength of GPC up to a certain limit, beyond which the compressive strength decreases. An alkaline liquid/geopolymer solid ratio in the range of 0.30 – 0.45 is recommended.
6. Fineness of Binder Solid (pozzolan): Finer binder solid had been shown to be more reactive, thereby increasing strength development in GPC.

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