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# Geopolymer Concrete: Properties, Durability and Applications-Review

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ABSTRACT

Concrete is one of the most reliable, durable, and desired construction materials. It became the second most used material after water in the world. Many studies and investigations reported that the amount of $CO_2$ released into the atmosphere is nearly 1 ton in the production of 1 ton of cement, which contributes to 5-7 % of total $CO_2$ emissions worldwide. Geopolymer concrete (GPC) is a new development in the world of concrete, which does not need to use cement. The most used materials in geopolymer are by-products such as fly ash, ground granulated blast furnace slag, silica fume, etc. Industrial waste materials are a great problem for human health, environment, and scarcity of land, therefore, reusing them in GPC manufacturing can be seen as a great advantage. Fortunately, most of the recent research concludes that most by-products exhibit similar or better durability, mechanical and physical properties when compared to ordinary concrete. Therefore, GPC became a good sustainable engineering material with many advantages over conventional concrete, such as high early strength, excellent resistance to chemical attacks and steel reinforcement corrosion, elimination of water curing, low cost, etc. This paper reviews the process of geopolymer concrete, constituents, types, properties, durability, and particular applications.

## 1. Introduction

Establishing factories and industries is the main factor for the development of any country, and it has become a huge source of incomes. The industrial sector currently increased worldwide which is the great sources of $CO_2$ emissions, which are harmful for the environment in various ways and the results are global warming, greenhouse gases, etc. To conserve water from contamination by any disposal and protect lands, the industries should reduce waste by recycling or reusing and reducing $CO_2$ by capturing and storage. Related to civil engineering, construction has been one of the rapidly growing fields.

A lot of effort is put in reducing the use of cement, one of the changes is partial replacement of cement by other cementitious materials such as by-product materials e.g., fly ash, slag. These types of cements are called blended cements, because they are mixed with ordinary cement. Another new technology is the complete replacement of cement by a natural or waste materials (Law et al., 2015), which is rich in silica and alumina, it can be applied as a binder instead of cement in concrete.

This new innovation is called Geopolymer, firstly formed by French chemist Joseph Davidovits in 1978 (Davidovits, 1994). Geopolymer concrete (GPC) is a good alternative for conventional concrete, it provides excellent mechanical properties and durability such as strong resistance to acids, thermal and freezing-thawing attacks.

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## 2. GPC (Geopolymer concrete)

Geopolymer is a new development class of concrete. It is a new idea to avoid using cement and completely replace it, thus become an eco-friendly material. This system is based on an inorganic Aluminosilicate binder, that is any source material that is rich in alumina (Al) and silica (Si) can be used, especially by-products such as; fly ash, slag, natural rocks, etc. The source material is mixed with an alkaline activator (usually KOH or NaOH) to liberate Al and Si atoms, with an additional source of silica ($Na_2SiO_3$ commonly used) to activate the atoms. In the chemical reaction of GPC water is not involved, it is expelled during curing, which resultes in no water content. Therefore, the hydration reaction that occurs in ordinary concrete is released and the hydration production (Calcium-Silicate-Hydrate, Calcium Hydrate) is also released. These results show great advantages in terms of the mechanical properties (Sathia et al., 2008), alkali-aggregate reaction, lower sorptivity (Shaikh, 2014) and other chemical attacks. Geopolymerization process involves a chemical reaction under strongly alkaline conditions, the product is in the form of a strong gel with an amorphous (Non-Crystalline) microstructure based on Al-Si system. It can exhibit the ideal properties e.g. hardness, longevity and chemical stability. The important fact is that high-alkali binder does not generate an alkali-aggregate reaction. Its structure consists of three-dimensional links of $SiO_4$ (Silate) and $AlO_4$ (Tetrahedra) with shared oxygen atoms. Figure 1 shows the formation process of geopolymer (Davidovits, 1994).

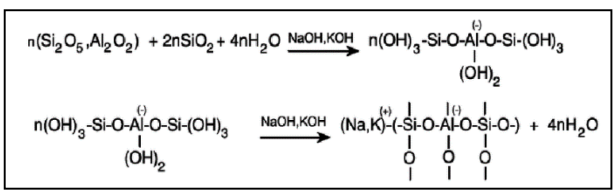

**Figure 1.** Schematic formation of geopolymer (Davidovits, 1994)

## 3. Constitution of GPC

The main ingredients of the GPC are source material and alkaline solution, also aggregate (both coarse and fine), water and admixture.
GPC = Aluminosilicate by-products (precursors) + Alkaline Activator + Aggregate + Water + Admixture.

### 3.1. Source (base) material

The base material used is a dry and very fine powder, its fineness is almost higher than cement, which helps in better reaction and bonding. Pozzolanic compound or other Aluminosilicate material can be used in the production of a geopolymer that is used instead of cement and acts as a binder in concrete. Natural materials such as kaolinite, clay and other alternatives especially by-product materials e.g. Fly ash (Bakri et al., 2012; Hariz et al., 2017), Ground granulated blast-furnace slag (GGBS), silica fume, rice-husk ash (Bakri et al., 2012), red-mud (Burduhos Nergis et al., 2018), metakaolin, etc. can be used. Various industry by-products and hazardous wastes can be used to manufacture geopolymers (Hajimohammadi and van Deventer, 2017; Bagheri et al., 2018; Hu et al., 2018).

In order to promote more environmental-friendly production using waste materials more than naturals have been suggested to minimize $CO_2$ emissions, using less energy and conserving more land. Also using locally available source materials helps in minimizing the total cost.

### 3.2. Alkaline activator

The liquid solution is another main ingredient of geopolymer. Alkali activation is a process of mixing Aluminosilicate material with an alkaline activator, it produces a paste that sets and hardens. This process is done with the availability of some amount of water. Bakri et al. (2012) stated that, the most common used alkaline liquids are mixture of sodium hydroxide with sodium silicate ($Na_2SiO_3$) or potassium hydroxide (KOH) with potassium silicate ($K_2SiO_3$). Selecting the types of activators mainly depend upon availability and reactivity. NaOH is cheaper and more reactive compared to KOH (Sathia et al., 2008).

### 3.3. Aggregates

Aggregates are the other main ingredients of GPC. In normal concrete, coarse aggregate and fine aggregate are usually used by 65 % and 35 %, which occupy almost 70 % of concrete volume (Chowdhury et al., 2021). The ratio of aggregates is also same for GPC, while the studies by Kashani et al. (2019) reported that the use of fine aggregates to coarse aggregates at a ratio of 0.53:0.47 to achieve self-compactness without decreasing required strength. Locally available aggregates are recommended to use in geopolymer in order to become more economical. Table 1 shows the type and some physical properties of both coarse and fine aggregates used in GPC by different researchers.

### 3.4. Admixtures

To maintain the workability of the GPC, it is better to use admixtures other than using extra water. Some commonly used superplasticizers are Sulfonated naphthalene formaldehyde and Sulfonated melamine formaldehyde (Chowdhury et al., 2021). High-Range-Water-Reducer admixtures such as naphthalene-based superplasticizer (Sathia et al., 2008; Joseph and Mathew, 2012; Singh et al., 2015), MasterGlenium ACE_450

**Table 1**
Types and physical properties of aggregates

| Author | Aggregate | Type | Nominal size (mm) | Specific gravity |
|---|---|---|---|---|
| (Mesgari et al., 2020) | Coarse | Recycled GPC | 12 | 2.85 |
| | Fine | Sydney sand | - | 2.6 |
| (Joseph and Mathew, 2012) | Coarse | Crushed granite rock | 20 | 2.72 |
| | Fine | Natural river sand | 4.5 | 2.64 |
| (Gupta et al., 2021) | Coarse | - | 20 | 2.81 |
| | Fine | - | 4.75 | 2.66 |
| (Jamkar et al., 2013) | Coarse | Crushed basalt | 12.5 | 2.639 |
| | Fine | Natural river sand | 4.75 | 2.563 |
| (Mucsi et al., 2014) | Coarse | Metallurgical converter slag | 22.4 | - |
| | Fine | Andesite | 4 | - |
| (Jawahar and Mounika, 2016) | Coarse | Crushed granite stones | 10, 20 | - |
| | Fine | Natural river sand | - | - |

(Safari et al., 2020) were used to increase relative slump without any decrease in compressive strength. Admixtures such as sucrose ($C_{12}H_{22}O_{11}$) is used as retarder since it is absorbed by Al, Ca and Fe ions to form insoluble metal complexes. Also citric acid ($C_6H_8O_7$) acts as accelerator reducing the setting time (Kusbiantoro et al., 2013; Singh et al., 2015).

Admixtures in the ratio of 1-2 % (Rattanasak et al., 2011), 1-2.5 % (El-hassan and Ismail, 2017), and 2 % (Joseph and Mathew, 2012; Safari et al., 2020) were added by mass of the source material.

## 4. Production of GPC

Similar to the hydration reaction of ordinary Portland cement (OPC), geopolymerization is also an exothermic reaction, it releases a large amount of heat during mixing. The process can be divided into three stages:

1. Preparing the alkaline solution by mixing NaOH and $Na_2SiO_3$ or KOH and $K_2SiO_3$ with availability of some amount of water. To completely dissolve the chemical substances in each other this preparation should be at least 24 hours prior (Bakri et al., 2012; Safari et al., 2020).
2. Mixing dry materials such as source material and aggregates then mixing with the prepared chemical solution and adding the admixtures to maintain workability, then moulding. In this state (fresh state) the concrete can easily handle up to 120 minutes without any sign of setting and without any degradation in its compressive strength.
3. Leaving the samples at room temperature for 24 hours. Then solidification through curing the samples after de-moulding them either at ambient temperature or by heating using oven. Most of the researches are agree on oven curing in 60º C to 100º C for 24 to 96 hours (Kumar et al., 2015). In this stage the water is totally eliminated and the material shows its final form.

The production process of GPC is summarized in the Figure 2 (Hassan et al., 2019; Masoule et al., 2022).

## 5. Types of GPC

### 5.1. Fly ash-based geopolymer

Fly ash is a pozzolanic waste material, pozzolans are siliceous or siliceous and aluminous materials. Generally, fly ash is generated in the coal-fired power plant. Its particles are glassy and spherical, based on its sources and composition can be classified into two classes; class F of fly ash which is produced from burning of bituminous or anthracite coal also contains less than 7 % lime (CaO), the second type is class C which is normally produced from burning of sub-bituminous or lignite coal, contains more than 20 % lime. Fly ash is available in huge quantities worldwide. Class F of fly ash has been investigated as a suitable material for geopolymer because of its pertinent silica and alumina composition, less water demand, and wide availability (Nath and Sarker, 2014; Jawahar and Mounika, 2016). Fly ash has strong and glassy silica-alumina chains, these chains are broken by alkali activators. Using fly ash in geopolymer is a good choice due to its ability to maintain good workability, durability and compressive strength. The main chemical compositions of fly ash classes are tabulated in Tables 2 and 3, respectively.

### 5.2. Slag-based geopolymer

Slag is a waste material that produced during the melting of iron ore (Burduhos Nergis et al., 2018). Slag has different types such as Granulated Corex slag (GCS), steel slag, blast furnace slag (BFS), GGBS, etc. It can be used in manufacturing different types of materials also used to create binders in different types of concrete and mortars with a very good mechanical property by geopolymerization. Compared to fly ash, slag is more preferable to use in producing geopolymer, because its behaviour is more similar to OPC and it has the same main chemical composition like OPC but in different proportions while fly ash has slowly pozzolanic reaction. The main chemical compositions of GGBS, GCS, and BFS are shown in the Table 4.

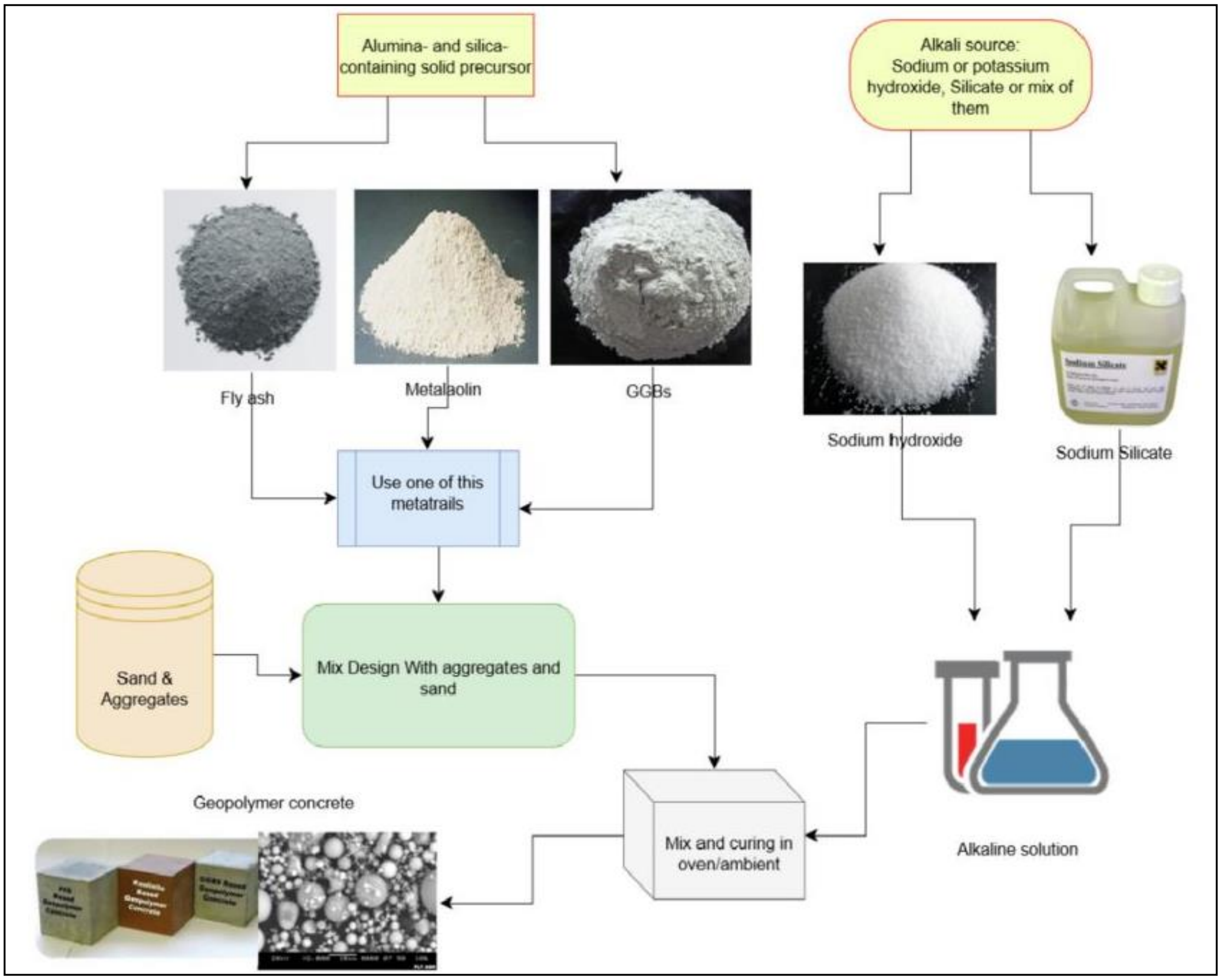


**Figure 2.** Production process of GPC (Hassan et al., 2019; Masoule et al., 2022)

**Table 2**
Chemical composition of fly ash

| Fly ash | Author | Chemical Composition % | | | | | |
|---|---|---|---|---|---|---|---|
| | | $Al_2O_3$ | $SiO_2$ | CaO | $Fe_2O_3$ | MgO | $SO_3$ |
| Class F | (Sathia et al., 2008) | 30.08 | 61.16 | 1.75 | 4.62 | 0.18 | 0.19 |
| | (Huseien et al., 2016) | 28.80 | 57.20 | 5.16 | 3.67 | 1.48 | 0.1 |
| Class C | (Muthadhi et al., 2016) | 31.23 | 32.62 | 17.12 | 8.48 | 3.49 | 0 |
| | (Wardhono et al., 2017) | 17.89 | 4.75 | 12.65 | 59.11 | 0 | 0.86 |

**Table 3**
Chemical composition of fly ash classes

| Fly ash (Burduhos Nergis et al., 2018) | Chemical Composition |
|---|---|
| For class F | $Al_2O_3 + SiO_2 + Fe_2O_3 \geq 70$ % |
| For class C | $Al_2O_3 + SiO_2 + Fe_2O_3 \geq 50$ % |

**Table 4**
Main chemical composition of GGBS, GCS, and BFS

| Material | Author | Chemical Composition % | | | | | |
|---|---|---|---|---|---|---|---|
| | | $Al_2O_3$ | $SiO_2$ | CaO | $Fe_2O_3$ | MgO | $SO_3$ |
| GGBS | (Huseien et al., 2016) | 10.9 | 30.80 | 51.80 | 0.64 | 4.57 | 0.06 |
| | (Jawahar and Mounika, 2016) | 16.24 | 30.61 | 34.48 | 0.584 | 6.79 | 1.85 |
| GCS | (Mehta and Siddique, 2016) | 18.36 | 32.51 | 33.31 | 1.49 | 11.08 | - |
| BFS | (Mehta and Siddique, 2016) | 11.50 | 33.80 | 38.30 | 0.60 | 9.0 | - |

5.3. Red -mud -based geopolymer

Red mud is another source material that can be used in GPC. It is generated in huge amount from aluminium production plant, its pH is about 10.5-12.5 (Rai et al., 2012). Burduhos Nergis et al. (2018) stated that 2 ton of red mud are deposited for every ton of aluminium. Red mud is rich in silica and alumina, thus it can be used to create geopolymer and its ions dissolved in NaOH at 175 ºC, resulted in produce of $Al_2(OH)_2$ (Burduhos Nergis et al., 2018). It has excellent quality with low cost and $CO_2$ emissions but the main problem of red mud is that it cannot be reused, hence it becomes a huge problem for environment in future (Rai et al., 2012). Table 5 shows the main chemical composition of Red-mud.

5.4. Metakaolinite based-geopolymer

Metakaolin is a type of refined kaolin clay calcined at temperature between 650 °C and 750 °C (Burduhos Nergis et al., 2018). It is an aluminosilicate material which can be used in manufacturing of geopolymer concrete (Parathi et al., 2021). Its ions can be dissolved in NaOH at 100-150 ºC (Rovnaník, 2010). It can emit 80-90 % less $CO_2$ than OPC. Metakaolin-based GPC has higher strength and durability compared to OPC concrete (Guo et al., 2020). Granizo et al. (2007) stated that the chemical constituents of metakaolin directly influence the mechanical properties of GPC. The main chemical composition of three types of kaolin (Granizo et al., 2007; Heah et al., 2011) and metakaolin (Rovnaník, 2010; Mehta and Siddique, 2016; Zain et al., 2017) are shown in the Table 6.

The difference between cementitious materials (silica fume, natural pozzolans, metakaolin, fly ash, slag, limestone and OPC) based on chemical compositions ($Al_2O_3$, CaO and $SiO_2$) are shown in a ternary diagram in the Figure 3.

**Table 5**
Main chemical composition of red-mud

| Material | Author | Chemical Composition % | | | | | |
|---|---|---|---|---|---|---|---|
| | | $Al_2O_3$ | $SiO_2$ | CaO | $Fe_2O_3$ | MgO | $TiO_2$ |
| Red-mud | (He et al., 2013) | 14 | 1.20 | 2.50 | 30.9 | - | 4.5 |
| | (Kaya and Soyer-Uzun, 2016) | 14.02 | 11.67 | 1.10 | 37.1 | 0.23 | 5.78 |
| | (Mehta and Siddique, 2016) | 0.45 | 89.34 | 0.76 | 0.4 | 0.49 | - |

**Table 6**
Main chemical composition of kaolin and metakaolin

| Author | Material | Chemical composition % | | | | |
|---|---|---|---|---|---|---|
| | | $Al_2O_3$ | $Si_2O_3$ | CaO | $Fe_2O_3$ | MgO |
| (Granizo et al., 2007) | Kaolin 1 | 36.3 | 49.8 | 0 | 0.6 | 0.2 |
| | Kaolin 2 | 36 | 47 | 0.8 | 0.5 | 0 |
| (Heah et al., 2011) | Kaolin | 35 | 52 | <0.05 | 1.0 | 0.70 |
| (Rovnaník, 2010) | Metakaolin | 40.94 | 55.01 | 0.14 | 0.55 | 0.34 |
| (Mehta and Siddique, 2016) | Metakaolin | 40.48 | 48.31 | 0.04 | 2.62 | 0.36 |
| (Zain et al., 2017) | Metakaolin | 37.20 | 55.90 | 0.11 | 1.7 | 0.24 |

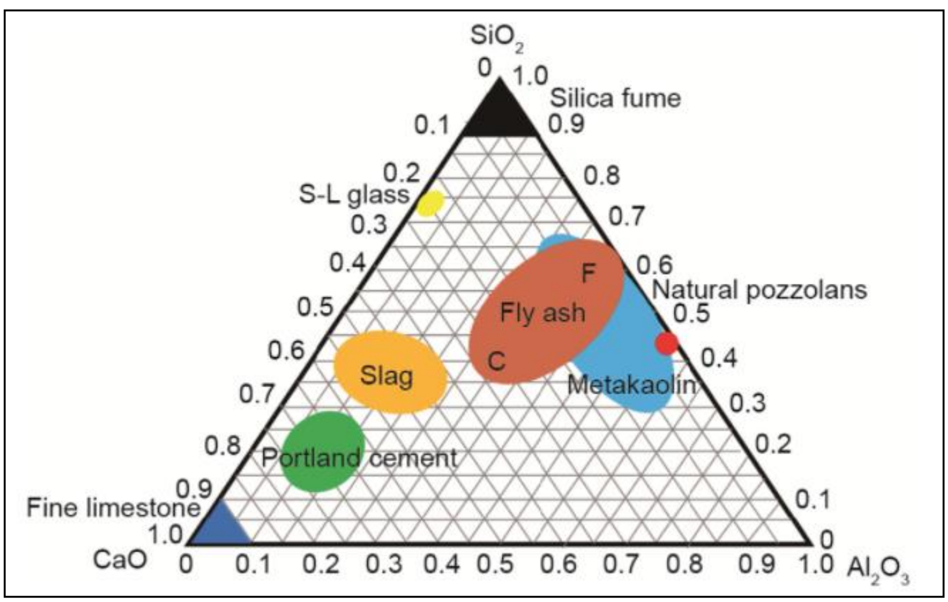


**Figure 3.** $Al_2O_3$ – CaO – $SiO_2$ ternary diagram for cementitious materials (Wang et al., 2020)

## 6. Mechanical properties

The behaviour and properties of any concrete should be studied from preparing the ingredients to its full life-cycle in order to learn how to deal with the possible issues. According to previous studies when compared to conventional concrete, GPC has more excellent properties such as, high early strength and durability. Sathia et al. (2008) reported that the time of hardening in GPC is very short, 90 % of its strength is obtained within 7 days and after that there are no more variation in compressive strength. There are a lot of factors that have a great influence on the compressive strength of the GPC. The main effective factors are: concentration of the alkaline activator, curing time and temperature. Also, Burduhos Nergis et al. (2018) added other factors like; molar ratio of $SiO_2$ to $Al_2O_3$, $Na_2O$ to $SiO_2$, $H_2O$ to $Na_2O$, type and quantity of the admixture, particle dimensions, calcium quantity and fineness of the source material and aggregates.

### 6.1. Alkaline solution

The main factors affected the mechanical properties of GPC regarding the alkali solution are; $Na_2SiO_3$ to NaOH ratio, ratio of alkali to binder (Raijiwala and Patil, 2011). Bhikshma (2012) worked on fly ash-based geopolymer, used different alkaline to binder ratio. The experimental results showed that all compressive, tensile and flexural strength increased with increasing alkaline to fly ash ratio, in Figure 4.

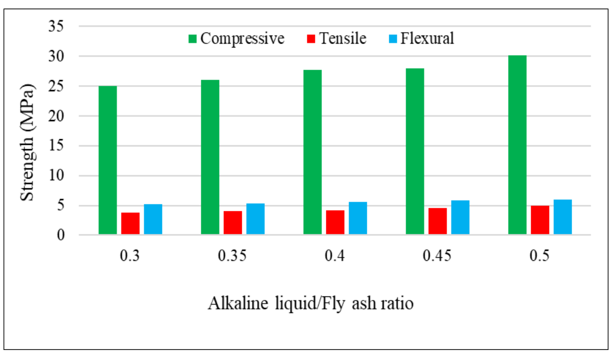


**Figure 4.** Effect of Alkaline liquid/fly ash ratio on compressive strength (Bhikshma, 2012)

The explained factors can increase the compressive strength in a limited range, beyond that range it will have adverse effect. In addition, compressive strength decreases with increasing $H_2O$ to $Na_2O$ ratio. Because the water evaporates during curing and it leads to increased porosity, decreased density and poor compressive strength. Moreover, Huseien et al. (2016) stated that increasing the ratio of water to geopolymer, resulted in decreasing compressive strength. Wu et al. (2019) reported that increasing of $SiO_2$ to $Al_2O_3$ ratio resulted in decreasing of compressive strength.

### 6.2. Liquid concentration

Concentration (in terms of molarity M) of the alkaline activator is one of the factors which influence the mechanical properties of GPC (Hardjito et al., 2004; Raijiwala and Patil, 2011). Compressive strength increases with increasing concentration of the liquid, alkaline to binder ratio and $Na_2SiO_3$ to NaOH ratio. Because higher concentration means higher -OH ions thus rapid disintegration and higher solubility of silica-alumina chains of source material in the solution. Hence contribute the production with larger number of active groups resulted in higher early compressive strength (Sathia et al., 2008; Jawahar and Mounika, 2016).

Practically, Burduhos Nergis et al. (2018) used concentration 4, 8, and 12 M, Raijiwala and Patil (2011) applied 8, 10, 12, 14, 16, and 25 M and Huseien et al. (2016) used 2, 4, 6, 8, 10, 12, 14 and 16 M, they tested the samples for 28 days. Their results showed that the compressive strength of GPC increases with increasing liquid concentration in a specific range, in Figure 5.

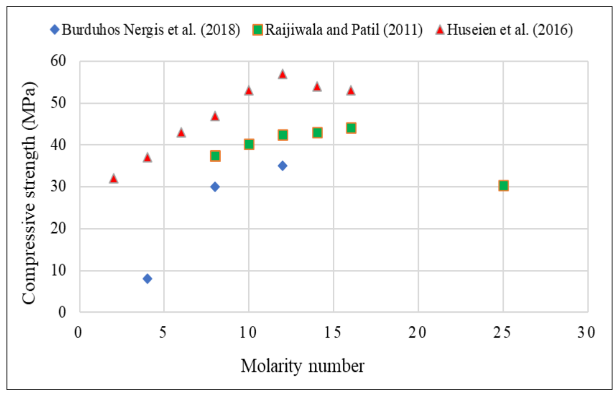


**Figure 5.** Effect of NaOH concentration on compressive strength

Through reviewing the previous studies and investigations on geopolymer, there should be an optimum level for the liquid concentration and $SiO_2$ to $Al_2O_3$ ratio and $H_2O$ to $Na_2O$ ratio. Most of the researchers found the optimum level in 12 Molarity of the concentration and (2.5 to 4) for $SiO_2$ to $Al_2O_3$ ratio of precursor materials (Bakri et al., 2012; Safari et al., 2020).

### 6.3. Curing time and temperature

There is a difference between curing in OPC concrete and GPC; in OPC concrete water is used to cure the samples but in geopolymer system the samples can be cured in room temperature (ambient curing) or by heat (steam or dry curing) to facilitate the geo-polymerization rate. The temperature during curing depends upon source material and activating solution. Increasing curing temperature results in accelerated geopolymerization process, decreased setting period and contribution to higher compressive strength in short time (Shaikh, 2014;

Burduhos Nergis et al., 2018). Vijai et al. (2010) studied effect of different curing times and temperatures and used ambient and hot curing for 7 and 28 days, respectively. The results showed that the compressive strength increased with increasing curing temperature and curing period. The results are shown in Figure 6.

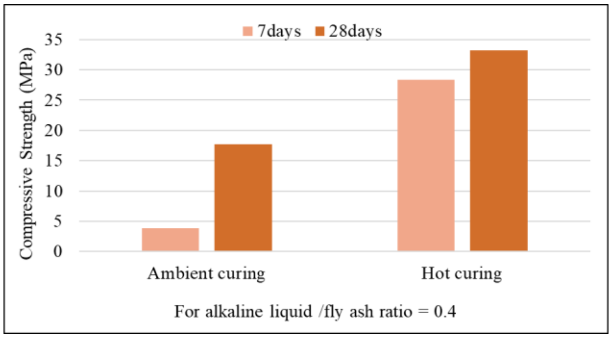


**Figure 6.** Effect of curing time and temperature on compressive strength (Vijai et al., 2010)

Zhang et al. (2016) showed that compressive and flexural strength increased with increasing curing temperature 25 ºC to 100 ºC, but beyond 100 ºC they were decreased, in Figure 7.

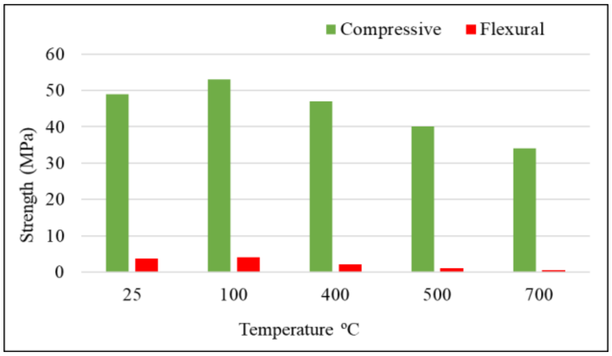


**Figure 7.** Effect of curing temperature on compressive and flexural strength (Zhang et al., 2016)

Raijiwala and Patil (2011) worked on geopolymer, fixed 16 molarity concentration for all samples then tested in different curing time. The compressive strength, split tensile, and flexural strength increased with time of curing, Figure 8.

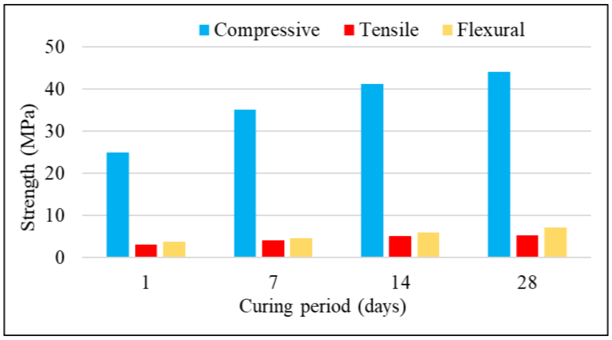


**Figure 8.** Effect of curing temperature on compressive, tensile and flexural strength (Raijiwala and Patil, 2011)

6.4. Fineness

The fineness of the source material was also studied by some researchers. Chowdhury et al. (2021) used fly ash in geopolymer concrete with specific surface area of 250-500 $m^2/kg$ and (542, 430, 367, 327, 265) $m^2/kg$ were used by Jamkar et al. (2013). They concluded that, the fineness of the source material is directly related to the density of the geopolymer material. The finer particle size of source material, the larger the specific surface area and the higher the reactivity (Gupta et al., 2017; Al-Mashhadani et al., 2018; Assi et al., 2018). The fineness of the aggregates is also significant in order to evaluate the performance of geopolymer materials. Table 7 shows the type and fineness modulus of fine aggregate used in different studies.

**Table 7**
Types and fineness modulus of fine aggregate

| Author | Type of fine aggregate | Fineness Modulus |
|---|---|---|
| (Nuaklong et al., 2016) | Natural river sand | 2.6 |
| (Joseph and Mathew, 2012) | Natural river sand | 2.36 |
| (Jamkar et al., 2013) | Natural river sand | 3.16 |
| (Gupta et al., 2021) | - | 2.83 |
| (Aly et al., 2019) | Natural sand | 2.25 |

## 7. Durability

The durability of concrete is an important issue that should be considered in the performance of the structure throughout its lifecycle. The durability of concrete mainly depends upon its permeability characteristics. When concrete is impermeable, it means that it can resist penetration by any aggressive ions, thus reduce damaging of the concrete, maintenance cost and extend its life-cycle expectancy. Most of the researches reported the excellent durability in geopolymer system due to less steel corrosion, creep, drying shrinkage, acid attacks, chloride attack, water sorptivity (Shaikh, 2014), porosity, and high temperature resistance up to 600 ºC, heat insulation, strong interfacial bonding and higher sustainability. The mass loss in geopolymer paste due to exposure of $H_2SO_4$ is about 3 % which is less than ordinary Portland cement (Sathia et al., 2008). All the parameters which affect the properties and performance of the GPC also affect the durability. Higher water absorption occurs with increasing NaOH molarity and reducing fine aggregate content while by curing at lower temperature (ambient), the water absorption decrease when compared to curing at elevated temperature (Huseien et al., 2016). Furthermore, using more $Na_2SiO_3$ leads to lower water absorption and better corrosion resistance. However, using higher alkaline solution to binder ratio will have negative effect and increase water absorption.

Sathia et al. (2008) stated that increasing $H_2O$ to $Na_2O$ ratio decreases the compressive strength due to increasing porosity.

Huseien et al. (2016) studied the effect of sodium hydroxide molarity on water absorption in geopolymer mortar. The test results after 24 hours showed that water absorption decreases with increasing NaOH concentration, Figure 9.

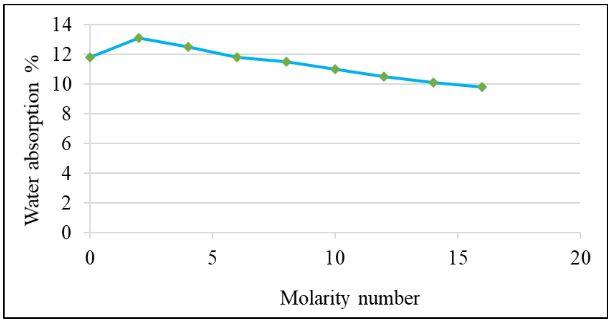


**Figure 9.** Relation between molarity and water absorption (Huseien et al., 2016)

Raijiwala and Patil (2011) studied the effect of NaOH molarity and curing time on durability of GPC, used 8, 10, 12, 14, 16, and 25 M and tested in 1, 7, 14, and 28 days for weight loss amount. The results showed that the weight loss decreased with increasing molarity and curing period until 16 M but after that it was increased, Figure 10.

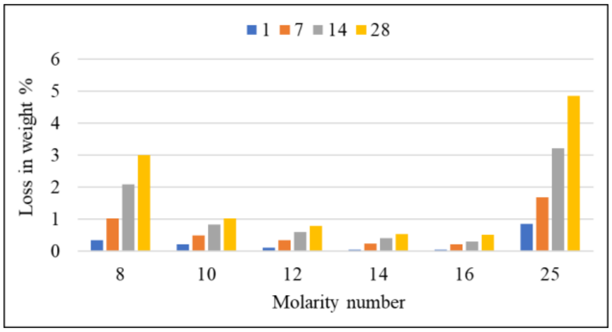


**Figure 10.** Effect of molarity and curing time on weight loss in compressive strength (Raijiwala and Patil, 2011)

Davidovits (2013) showed that the expansion due to alkali-aggregate reaction in OPC is much higher than GPC, it is shown in the Figure 11.

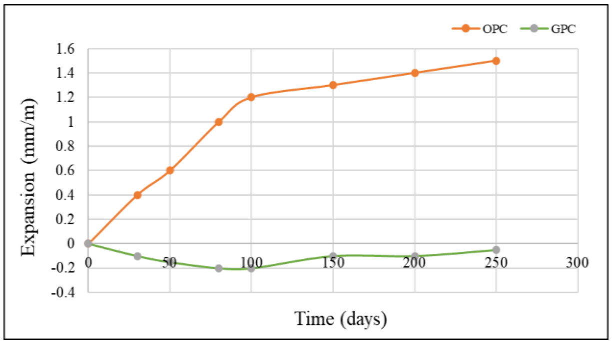


**Figure 11.** Expansion due to alkali-aggregate reaction (Davidovits, 2013)

Compared to OPC-based concretes, fly ash-based geopolymer has less tendency for shrinkage and cracking and has much less effect of fire when exposed to fire. Sarker et al. (2014) reported that GPC has more resistance to loss compressive strength at high temperature than OPC concrete, when both of them were exposed to fire from 23 ºC to 1000 ºC. The variation is shown below in Figure 12.

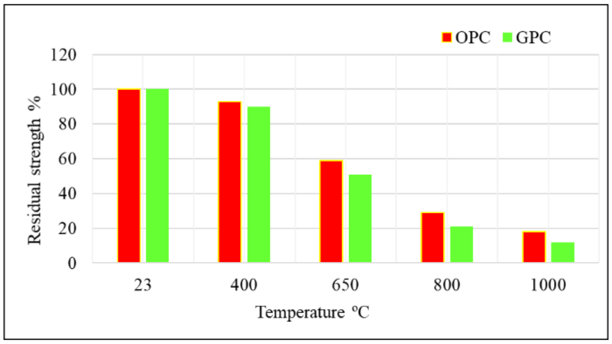


**Figure 12.** Residual of compressive strength after exposure to fire (Sarker et al., 2014)

Lavanya and Jegan (2015) studied durability of OPC concrete and GPC, they evaluate the reduction in compressive strength and density when exposed to magnesium sulphate and sulfuric acids. The reductions were less in GPC compared to OPC concrete, Table 8.

**Table 8**
Reduction in compressive strength and density for plain and geopolymer concrete (Lavanya and Jegan, 2015)

| Type of exposure | Type of concrete | Loss in compressive strength % | Decrease in density % |
|---|---|---|---|
| Sulfuric acid | OPC | 18 - 28 | 5 - 7 |
| | GPC | 12 - 20 | 2.5 - 4 |
| Magnesium sulphate | OPC | 5 - 25 | 4 - 6 |
| | GPC | 5 - 12 | 2 - 3 |

Hardjito et al. (2004) investigated the durability of geopolymer concrete by evaluating its resistance to sulphate attack. They performed a series of tests, the test samples were soaked in 5 % sodium sulphate ($Na_2SO_4$) solution for a period of time. After 12 weeks from immersion, the samples were tested. The results showed no significant changes in the compressive strength, its mass and in the length of the specimens.

Astutiningsih et al. (2010) studied the effect of seawater on compressive strength of fly ash-based geopolymer concrete. The geopolymer concrete samples were cured at room temperature for 24 hours, then removed from their moulds and left at room temperature for 14 days, while the normal concrete samples were cured in water for 28 days to maintain complete hydration. After curing the samples, all samples were immersed for 7, 28, 56, and 90 days in ASTM seawater. The compressive strength of both kinds of concretes were measured and compared. See figure 13 and 14.

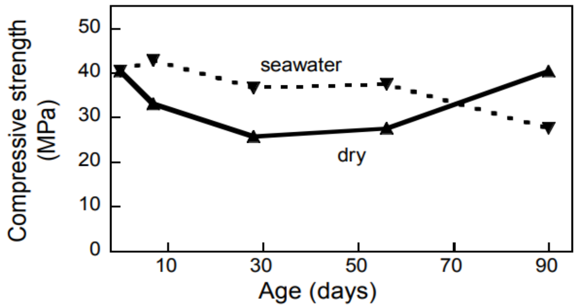


**Figure 13.** Effect of seawater immersion on compressive strength of geopolymer (Astutiningsih et al., 2010)

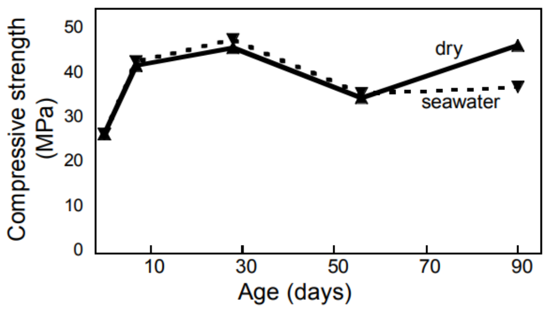


**Figure 14.** Effect of seawater immersion on compressive strength of cement-based concrete (Astutiningsih et al., 2010)

Other studies have been performed to evaluate the short and long-term durability of geopolymer composites in different ways. For example, Bakharev (2005) studied resistance of geopolymer materials to acid attacks, acetic and sulfuric acids. Thokchom et al. (2009) and Albitar et al. (2017) examined the effect of water absorption, sorptivity, porosity on durability of geopolymers. (Farhana et al., 2015) studied the relationship between porosity and water absorption in geopolymer concrete. Law et al. (2015) investigated on water sorptivity and chloride permeability of geopolymer concrete. Pasupathy et al. (2018) observed on fly ash-based geopolymer under atmospheric condition for 8 years. Aygörmez et al. (2020) worked on durability of geopolymer composite at one year, and Gupta et al. (2021) studied effect of varying admixture dosage on durability geopolymer concrete composite.

## 8. Applications

Geopolymer cement can be used in construction, transportation infrastructure and offshore applications. GPC can be used in precast industries due to high early strength and less breakage during transporting. Using GPC for water retaining (water tank) is considerable due to excellent autogenous healing behaviour while in Portland cement concrete autogenous healing due to deposition of calcium hydroxide is not desirable.

GPC can be used in light pavements, there is no appearance of bleeding on the concrete surface. Practical example to this, paving a slab for a weighbridge at the Port of Brisbane-2010 with geopolymer concrete (Sathia et al., 2008).

GPC can be used in creating precast bridge decks which provide a serviceable wearing deck, effectively used for the beam-column junction of reinforced concrete structure, in manufacturing reinforced-concrete pipes, for repairing and rehabilitation work (Aleem and Arumairaj, 2012), in marine structure due to its excellent resistance to chemical attacks. It can also be used as water proof, fire proof, and thermal insulator and as retaining wall for a private residence. Geopolymer cement is very suitable to create massive concrete panels, expanded (foam) panels, and fibre reinforced sheet (Davidovits, 1994).

It is also good choice for heat insulation, prestressing, pavements, 3D printing, repairing and rehabilitation work (Aleem and Arumairaj, 2012; Singh et al., 2019). Aleem and Arumairaj (2012) stated that constructing boat ramp in-situ by GPC was better choice than using conventional concrete.

## 9. Limitations

1. Until now any standard specification to mix design geopolymer system has not been fixed. Because many parameters can affect the system such as curing time, curing temperature, concentration of the chemical liquid, alkali to binder ratio, etc.
2. Geopolymer can be produced only by pre-mixing, thus using high alkalinity chemical solutions such as NaOH is hazardous and has safety risk to humans during mixing and handling, hence it is difficult to create (Safari et al., 2020).
3. In large-scale application, great amount of heat will be released during dissolution of NaOH in water, thus it will be difficult for controlling.
4. The demand for using GPC instead conventional concrete is still limited due to its quality performance.
5. The cost of chemical solution used for activation is very high.
6. Difficulties in applying steam-curing is not practical, especially for large-scale projects.

## 10. Conclusions

Through reviewing the existing literature, we conclude the following points:

1. GPC is a good alternative to conventional concrete. It becomes an eco-friendly construction material and as a result using cement reduced required energy and $CO_2$ emissions, utilizing industrial waste materials such as ashes which are widely available.
2. Regarding to the economic aspects, utilizing local source materials helps in reduction of the total cost.

3. GPC can be used in various fields instead of cement-based concrete with providing excellent durability and mechanical properties.
4. Related to the disadvantages, GPC is not recommended to use in mass concrete due to release a huge amount of heat at early stages; and it needs preparation of an alkaline solution at least one day prior, thus it is a time-consuming material.
5. There are possibilities to exhibit drying shrinkages due to high heat-development at early ages and similar to normal concrete GPC is weak in tension. It is very important to improve the behaviour and overcome such weaknesses of the material. Thinking about reinforcing GPC by other materials such as fibres is a good idea to decrease crack propagation and increase the energy absorption capacity.
6. Despite the effective parameters such as concentration, curing time and temperature controlling, all the process from selecting the materials until final stages is necessary to present a perfect production.

**References**


Astutiningsih, S., Nurjaya, D.M., Ashadi, H.W., Swastika, N., Durability of Geopolymer Concretes upon Seawater Exposure, Adv. Sci. Technol., 69, 2010, 92-96,

Aleem, M.I.A., Arumairaj, P.D., Geopolymer Concrete - A review, International Journal of Engineering Sciences & Emerging Technologies, 1, 2012, 118-122,

Astutiningsih, S., Nurjaya, D.M., Ashadi, H.W., Swastika, N., Durability of Geopolymer Concretes upon Seawater Exposure, Adv. Sci. Technol., 69, 2010, 92-96,

Aleem, M.I.A., Arumairaj, P.D., Geopolymer Concrete - A review, International Journal of Engineering Sciences & Emerging Technologies, 1, 2012, 118-122,

Albitar, M., Mohamed Ali, M.S., Visintin, P., Drechsler, M., Durability evaluation of geopolymer and conventional concretes, Constr. Build. Mater., 136, 2017, 374–385,

Al-Mashhadani, M. M., Canpolat, O., Aygörmez, Y., Uysal, M., Erdem, S., Mechanical and microstructural characterization of fiber reinforced fly ash based geopolymer composites, Construction and building materials, 167, 2018, 505-513,

Assi, L. N., Deaver, E. E., Ziehl, P., Effect of source and particle size distribution on the mechanical and microstructural properties of fly Ash-Based geopolymer concrete, Construction and Building Materials, 167, 2018, 372-380,

Aly, A. M., El-Feky, M. S., Kohail, M., Nasr, E. S. A., Performance of geopolymer concrete containing recycled rubber, Construction and Building Materials, 207, 2019, 136-144, Aygörmez, Y., Canpolat, O., Al-mashhadani, M.M., Assessment of geopolymer composites durability at one year age, J. Build. Eng., 32, 2020, 101453,

Bakharev, T., Resistance of geopolymer materials to acid attack, Cem. Concr. Res., 35, 2005, 658–670,

Bakri, A.M.M. Al, Kamarudin, H., Bnhussain, M., Nizar, I.K., Rafiza, A.R., Zarina, Y., The Processing, Characterization, And Properties of Fly Ash Based Geopolymer Concrete, Reviews on Advanced Materials Science, 30(1), 2012, 90–97,

Bhikshma, V., Koti Reddy, M., Srinivas Rao, T., An Experimental Investigation on Properties of Geopolymer Concrete (No Cement Concrete), Asian Journal of Civil Engineering (Building and Housing), 13(6), 2012, 841-853,

Burduhos Nergis, D.D., Abdullah, M.M.A.B., Vizureanu, P., Tahir, M.F.M., Geopolymers and Their Uses : Review, IOP Conf. Series: Materials Science and Engineering, 374(1), 2018, 012019,

Bagheri, A., Nazari, A., Hajimohammadi, A., Sanjayan, J. G., Rajeev, P., Nikzad, M., Mendis, P., Microstructural study of environmentally friendly boroaluminosilicate geopolymers, Journal of Cleaner Production, 189, 2018, 805-812,

Chowdhury, S., Mohapatra, S., Gaur, A., Dwivedi, G., Soni, A., Study of various properties of geopolymer concrete – A review, Materials Today: Proceedings, 46, 2021, 5687-5695,

Davidovits, J., Properties of geopolymer cements, In Kiev (Ed.), First international conference on alkaline cements and concretes, Kiev, Ukraine: Kiev State Technical University, 1, 1994, 131-149,

Davidovits, J., Geopolymer Cement A Review, Geopolymer Sci. Tech, 2013, 1–11,

El-Hassan, H., Ismail, N. Effect of Process Parameters on The Performance of Fly Ash / GGBS Blended Geopolymer Composites. J. Sustain. Cem. Mater., 2017, 1–19,

Farhana, Z.F., Kamarudin, H., Rahmat, A., Al Bakri, A.M.M., The relationship between water absorption and porosity for geopolymer paste. Mater. Sci., 803, 2015, 166–172,

Granizo, M. L., Blanco-Varela, M. T., Martínez-Ramírez, S., Alkali activation of metakaolins: parameters affecting mechanical, structural and microstructural properties, Journal of Materials Science, 42(9), 2007, 2934-2943,

Guo, L., Wu, Y., Xu, F., Song, X., Ye, J., Duan, P., Zhang, Z., Sulfate resistance of hybrid fiber reinforced metakaolin geopolymer composites, Composites Part B: Engineering, 183, 2020, 107689,

Gupta, R., Bhardwaj, P., Mishra, D., Prasad, M., Amritphale, S. S., Formulation of mechanochemically evolved fly ash based hybrid inorganic–organic geopolymers with multilevel characterization, Journal of Inorganic and

Organometallic Polymers and Materials, 27(2), 2017, 385-398,

Gupta, N., Gupta, A., Saxena, K. K., Shukla, A., Goyal, S. K., Mechanical and durability properties of geopolymer concrete composite at varying superplasticizer dosage, Materials Today: Proceedings, 44, 2021, 12-16,

Hardjito, D., Wallah, S.E., Sumajouw, D.M.J., Rangan, B.V., On the Development of Fly Ash-Based Geopolymer Concrete, ACI Materials Journal, 101(6), 2004, 467-472,

Heah, C. Y., Kamarudin, H., Al Bakri, A. M., Binhussain, M., Luqman, M., Nizar, I. K., ... & Liew, Y. M., Effect of curing profile on kaolin-based geopolymers, Physics Procedia, 22, 2011, 305-311,

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

Huseien, G.F., Mirza, J., Ismail, M., Hussin, M.W., Arrifin, M.A.M., Hussein, A.A., The Effect of Sodium Hydroxide Molarity and Other Parameters on Water Absorption of Geopolymer Mortars, Indian Journal of Science and Technology, 9(48), 2016, 1-7,

Hajimohammadi, A., van Deventer, J.S.J., Solid reactant-based geopolymers from rice hull ash and sodium aluminate, Waste and Biomass Valorization, 8(6), 2017, 2131-2140,

Hariz, Z., Mohd, A., Al, M., Kamarudin, H., Nurliyana, A., Ridho, B., Review on Various Types of Geopolymer Materials With The Environmental Impact Assessment, MATEC Web of Conferences, 97, 2017, 01021,

Hu, W., Nie, Q., Huang, B., Shu, X., He, Q., Mechanical and microstructural characterization of geopolymers derived from red mud and fly ashes, Journal of Cleaner Production, 186, 2018, 799-806,

Hassan, A., Arif, M., Shariq, M. Use of geopolymer concrete for a cleaner and sustainable environment – A review of mechanical properties and microstructure, Journal of cleaner production, 223, 2019, 704-728,

Joseph, B., Mathew, G., Influence of aggregate content on the behaviour of fly ash based geopolymer concrete, Scientia Iranica, 19(5), 2012, 1188-1194,

Jamkar, S. S., Ghugal, Y. M., Patankar, S. V., Effect of fly ash fineness on workability and compressive strength of geopolymer concrete, The Indian Concrete Journal, 87(4), 2013, 57-61,

Jawahar, J.G., Mounika, G. Strength Properties of Fly Ash and GGBS Based Geopolymer Concrete, Asian Journal of Civil Engineering, 17(1), 2016, 127-135,

Kusbiantoro, A., Ibrahim, M. S., Muthusamy, K., Alias, A., Development of sucrose and citric acid as the natural based admixture for fly ash based geopolymer, Procedia Environmental Sciences, 17, 2013, 596-602,

Kumar, S.G., Aleem, M.I.A., Dinesh, S., Application of Geopolymer Concrete, International Research Journal of Engineering and Technology (IRJET), 2(9), 2015, 96-99,

Kaya, K., Soyer-Uzun, S., Evolution of structural characteristics and compressive strength in red mud–metakaolin based geopolymer systems, Ceramics International, 42(6), 2016, 7406-7413,

Kashani, A., Ngo, T. D., Mendis, P., The effects of precursors on rheology and self-compactness of geopolymer concrete, Magazine of Concrete Research, 71(11), 2019, 557-566,

Lavanya, G., Jegan, J., Durability Study on High Calcium Fly Ash Based Geopolymer Concrete, Advances in Materials Science and Engineering, 2015, 731056,

Law, D.W., Arham, A., Thomas, A., Patnaikuni, I., Wardhono, A., Long Term Durability Properties of Class F Fly Ash Geopolymer Concrete. Materials and Structures, 48, 2015, 721–731,

Mucsi, G., Rácz, Á., Molnár, Z., Szabó, R., Gombkötő, I., Debreczeni, Á. Synergetic use of lignite fly ash and metallurgical converter slag in geopolymer concrete. Mining Science. 2014, 21, 43-55,

Muthadhi, A., Vanjinathan, J., Durai, D., Experimental investigations on geo polymer concrete based on class C fly ash, Indian journal of Science and Technology, 9(5), 2016, 1-5,

Mehta, A., Siddique, R. An overview of geopolymers derived from industrial by-products, Construction and Building Materials, 127, 2016, 183-198,

Mesgari, S., Akbarnezhad, A., Xiao, J. Z., Recycled geopolymer aggregates as coarse aggregates for Portland cement concrete and geopolymer concrete: Effects on mechanical properties, Construction and Building Materials, 236, 2020, 117571,

Masoule, M. S. T., Bahrami, N., Karimzadeh, M., Mohasanati, B., Shoaei, P., Ameri, F., & Ozbakkaloglu, T., Lightweight geopolymer concrete: A critical review on the feasibility, mixture design, durability properties and microstructure, Ceramics International, 2022,

Nath, P., Sarker, P. K., Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition, Construction and Building materials, 66, 2014, 163-171,

Nuaklong, P., Sata, V., Chindaprasirt, P., Influence of recycled aggregate on fly ash geopolymer concrete properties, Journal of Cleaner Production, 112, 2016, 2300-2307,

Pasupathy, K., Berndt, M., Sanjayan, J., Rajeev, P., Cheema, D.S., Durability Performance of Precast Fly Ash–Based Geopolymer Concrete under Atmospheric Exposure Conditions, J. Mater. Civ. Eng, 30(3), 2018, 04018007,

Parathi, S., Nagarajan, P., Pallikkara, S. A., Ecofriendly geopolymer concrete: a comprehensive review, Clean

Technologies and Environmental Policy, 23(6), 2021, 1701-1713,

Rovnaník, P., Effect of Curing Temperature on the Development of Hard Structure of Metakaolin-Based Geopolymer, Constr. Build. Mater., 24(7), 2010, 1176–1183,

Raijiwala, D.B., Patil.H.S., Geopolymer Concrete: A Concrete of Next Decade, Journal of Engineering Research and Studies, 2(1), 2011, 19-25,

Rattanasak, U., Pankhet, K., Chindaprasirt, P., Effect of chemical admixtures on properties of high-calcium fly ash geopolymer, International Journal of Minerals, Metallurgy, and Materials, 18(3), 2011, 364-369,

Rai, S., Wasewar, K., Mukhopadhyay, J., Yoo, C. K., Uslu, H., Neutralization and utilization of red mud for its better waste management, Arch. Environ. Sci, 6, 2012, 13-33,

Sathia, R., Ganesh Babu, K., Santhanam, M., Durability study of low calcium fly ash geopolymer concrete, The 3rd ACF international conference, 2008, - ACF/VCA 2008.1153–1159,

Shaikh, F.U.A., Effects of Alkali Solutions on Corrosion Durability of Geopolymer Concrete, Advances in Concrete Construction, 2(2), 2014, 109-123,

Sarker, P.K., Kelly, S., Yao, Z., Effect of Fire Exposure on Cracking, Spalling and Residual Strength of Fly Ash Geopolymer Concrete, Mater. Des., 63, 2014, 584–592,

Singh, B., Ishwarya, G., Gupta, M., Bhattacharyya, S. K., Geopolymer concrete: A review of some recent developments, Construction and building materials, 85, 2015, 78-90,

Singh, N.B., Saxena, S.K., Kumar, M., Rai, S. Geopolymer Cement : Synthesis, Characterization, Properties and Applications, Mater. Today Proc., 15, 2019, 364–370,

Safari, Z., Kurda, R., Al-Hadad, B., Mahmood, F., Tapan, M., Mechanical Characteristics of Pumice-Based Geopolymer Paste, Resour. Conserv. Recycl., 162, 2020, 105055,

Thokchom, S., Ghosh, P., Ghosh, S., Effect of water absorption, porosity and sorptivity on durability of geopolymer mortars, J. Eng. Appl. Sci., 4, 2009, 28–32.

Vijai, K., Kumutha, R., Vishnuram, B.G. Effect of Types of Curing on Strength of Geopolymer Concrete, International Journal of the Physical Sciences, 5(9), 2010, 1419-1423,

Wardhono, A., Law, D. W., Sutikno, Dani, H., The effect of slag addition on strength development of Class C fly ash geopolymer concrete at normal temperature, In AIP Conference Proceedings, 1887(1), 2017, 020030. AIP Publishing LLC,

Wu, Y., Lu, B., Yi, Z., Du, F., Zhang, Y. The Properties and Latest Application of Geopolymers the Properties and Latest Application of Geopolymers, IOP Conf. Series: Materials Science and Engineering, 472(1), 2019, 012029,

Wang, A., Zheng, Y., Zhang, Z., Liu, K., Li, Y., Shi, L., Sun, D. The Durability of Alkali-Activated Materials in Comparison with Ordinary Portland Cements and Concretes: A Review, Engineering, 6(6), 2020, 695–706,

Zhang, H. Y., Kodur, V., Wu, B., Cao, L., Wang, F., Thermal Behavior and Mechanical Properties of Geopolymer Mortar after Exposure to Elevated Temperatures, Construction and Building Materials, 109, 2016, 17-24,

Zain, H., Abdullah, M. M. A. B., Hussin, K., Ariffin, N., Bayuaji, R., Review on various types of geopolymer materials with the environmental impact assessment, In MATEC Web of Conferences, EDP Sciences, 97, 2017, 01021.

# Geopolimerni beton: svojstva, izdržljivost i primena – Pregled

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INFORMACIJE O RADU

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Ključne reči:
Geopolimer
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Izdržljivost
OPC

I Z V O D

Beton je jedan od najpouzdanijih, najtrajnijih i najtraženijih građevinskih materijala. Postao je drugi najkorišćeniji materijal posle vode na svetu. Mnoga istraživanja su pokazala da količina ispuštenog $CO_2$ u atmosferu iznosi 1 tonu tokom proizvodnje 1 tone cementa, što doprinosi 5-7 % ukupnoj emisiji $CO_2$ u svetu. Geopolimerni beton predstavlja novinu u proizvodnji betona koja ne zahteva upotrebu cementa. Materijali koji se najviše koriste u geopilimeru su nusproizvodi, kao što si leteći pepeo, usitnjena granularna šljaka iz visoke peći, silicijumska prašina i drugi. Industrijski otpadni materijali predstavljaju veliki problem za ljudsko zdravlje, životnu sredinu i nedostatak zemljišta, stoga se njihova ponovna upotreba u proizvodnji geopolimernog betona može smatrati velikom prednošću. Dosadašnje istraživanje pokazuje da većina nusproizvoda pokazuje sličnu ili bolju izdržljivost, kao i mehanička i fizička svojstva u poređenju sa običnim betonom. Zbog toga je geopolimerni beton postao dobar održivi materijal sa mnogo prednosti u odnosu na konvencionalni beton, kao što su visoka brza čvrstoća, odlična otpornost na hemijske napade i koroziju čelične armature, eliminacija očvršćavanja u vodi, niska cena i drugi. Ovaj rad pruža pregled geopolimer betona, njegovog sastava, tipova, trajnosti i posebne primene.