

## Development, synthesis, classification and characterization techniques of geopolymer cement - a review

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**Abstract:** The manufacture of Ordinary Portland Cement (OPC) involves significant energy consumption, dust emission into the atmosphere, and the release of carbon dioxide gas (CO<sub>2</sub>) release. This leads to climate change and environmental concerns. A geopolymer binder is an inorganic polymer produced when aluminosilicates and alkalis undergo a polycondensation reaction. They have three-dimensional aluminosilicate frameworks that are amorphous or semi-crystalline and are made by the accompanying tetrahedral (SiO<sub>4</sub>)<sup>4-</sup> and (AlO<sub>4</sub>)<sup>5-</sup>. They can be synthesized using a variety of industrial by-products and natural aluminosilicate materials such as blast furnace slag, fly ash, rice husk ash, and metakaolin. Geopolymers exhibit excellent mechanical properties such as compressive strength and resistance to chemical attack. Geopolymers' durability and mechanical performance have attracted a lot of attention recently in the building and research sector because utilizing geopolymers as a sustainable alternative to OPC would significantly reduce GreenHouse Gases (GHG) emissions. Numerous studies have reported that geopolymer cement is a possible substitute for OPC in sustainable building materials since it has been shown to have better mechanical qualities, increased durability, and reduced carbon emissions. The present review highlights the synthesis techniques and classification of geopolymer cement based on materials utilized in their production, geopolymer concrete characterization techniques based on fresh and mechanical properties, and the durability performance since the last decade. The review also features the current development and applications of geopolymer cement. This review will provide the need for continuous research and development efforts to maximize geopolymer performance, enhance its properties, and expand its application ranges in the construction industry.

**Keywords:** Ordinary Portland Cement; geopolymer cement; aluminosilicate; Greenhouse gas; mechanical performance.

### 1. Introduction

Since its inception approximately 2,000 years ago, cement manufacturing has experienced incredible progress. Although cement was used in concrete, industrial cement production began in the middle of the 19<sup>th</sup> century <sup>1</sup>. The amount of cement produced worldwide has reached 2.8 billion tonnes annually and is expected to rise to almost 4 billion tonnes (Fig.1). Significant growth is expected in countries like China and India, as well as in the Middle East and Northern Africa <sup>2</sup>. Ordinary Portland Cement (OPC) is the most popular type of cement used in all general concrete constructions due to its high resistance to shrinkage and cracking properties <sup>3,4</sup>.

However, the manufacture of OPC involves significant resource consumption and high atmospheric emissions of carbon (IV) oxide (CO<sub>2</sub>),

both of which can potentially have adverse environmental effects <sup>5</sup>. 2.8 tonnes of raw materials total, gasoline included, and other resources are required to generate one tonne of OPC, and as a result, 1 ton of CO<sub>2</sub> is produced <sup>6</sup>. The enormous demand for energy and raw materials necessary to produce OPC compels the building and construction sector to turn to Supplementary Cementitious Materials (SCM) <sup>7</sup>.

Sustainable building practices and the effective use of the few available resources have become increasingly important <sup>8</sup>. More efficiently than structures designed to function, sustainable buildings use energy, water, materials, and land resources. More and more "green" projects are being undertaken by the construction industry, which has led to the development of numerous green buildings across the globe <sup>9,10</sup>. Numerous studies recently

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caused by the OPC To attain environmental efficiency while preserving similar or higher mechanical performances<sup>7</sup>.

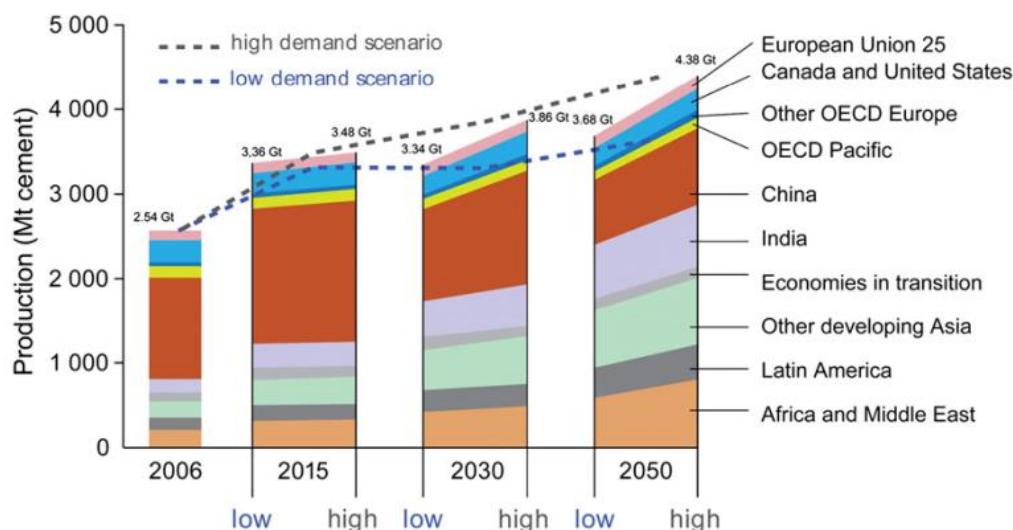


Fig.1. Global cement production<sup>1</sup>

However, the manufacture of OPC involves significant resource consumption and high atmospheric emissions of carbon (IV) oxide ( $\text{CO}_2$ ), both of which can potentially have adverse environmental effects<sup>5</sup>. 2.8 tonnes of raw materials total, gasoline included, and other resources are required to generate one tonne of OPC, and as a result, 1 ton of  $\text{CO}_2$  is produced<sup>6</sup>. The enormous demand for energy and raw materials necessary to produce OPC compels the building and construction sector to turn to Supplementary Cementitious Materials (SCM)<sup>7</sup>.

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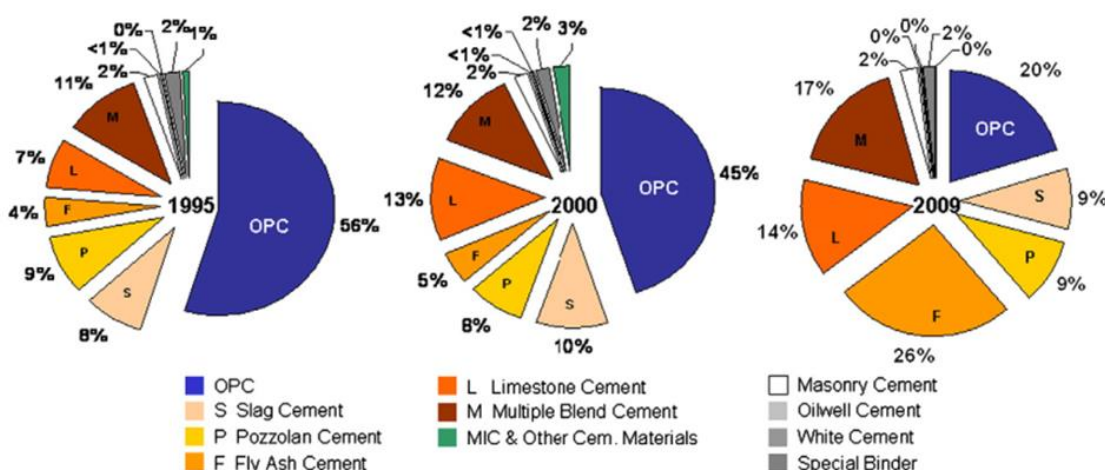


Fig.2. Cement types produced by Holcim 1995–2009<sup>1</sup>

Over the past 20 years, the cement industry has discussed the necessity of climate change for the environment by reducing its emissions of greenhouse gases per metric tonne of cement using various methods<sup>11</sup>. One such strategy is reducing the

proportion of calcined material in cement, which could provide a workable alternative in terms of energy needs and amounts of off-gases generated, as seen in Fig.2<sup>1</sup>. Given the high cost of calcined ingredients and the frequent lower cost of

alternatives, cement manufacturers view this as an appealing option. The step in the cement manufacturing process that requires the most energy and produces the most significant CO<sub>2</sub> emissions is the clinker-producing process<sup>12</sup>. Industrial by-products like blast furnace slag, a by-product of making iron, coal fly ash, a by-product of thermal generating stations, or other pozzolanic minerals, such as volcanic materials, are used in blended cement to replace a portion of the clinker. The ground clinker and these by-products are combined to create a homogenous mixture<sup>13</sup>.

Studies by Luo et al<sup>14</sup> researched replacing Portland cement with red mud derived from the Bayer process. The authors calcined red mud at various temperatures between 200 and 1000 °C. To create a paste, Portland cement was partially substituted with a sample of red mud calcined at a particular temperature. After that, pastes of varying ages were allowed to hydrate. The hardened pastes were evaluated for shape, chemical composition, and compressive strength at each age. The authors concluded that, after 28 days, 15% of the cement paste made of calcined red mud had a much better compressive strength than pure cement paste. Gartner & Sui<sup>15</sup> researched four alternative cement clinker technologies presently being developed by industry and/or academia. However, the widespread application of other materials to replace OPC will ultimately hinge on how profitable it is compared to traditional OPC-based concrete technologies and the pertinent sustainability and environmental concerns.

Recently, a significant step towards creating environmentally friendly cement to complement the OPC blended cement is the development of geopolymer cement. One kind of amorphous aluminosilicate cementitious material is geopolymer<sup>16</sup>. Geopolymer cement is a binding material like ordinary Portland cement. Geopolymer cement solidifies at ambient temperature to form materials that are essentially low-temperature ceramics with typical ceramic strength and temperature resistance<sup>17</sup>. They are created by activating aluminosilicate materials with an alkaline solution. Industrial waste and by-products are being utilized in synthesizing geopolymer cement, significantly reducing their carbon footprint<sup>18</sup>. Geopolymers are growing in popularity as viable substitutes for OPC in developing environmentally friendly building materials for offshore applications, building, and transportation infrastructure<sup>19</sup>. Additionally, it exhibits remarkable resistance to many durability difficulties that might befall ordinary concretes<sup>20</sup>.

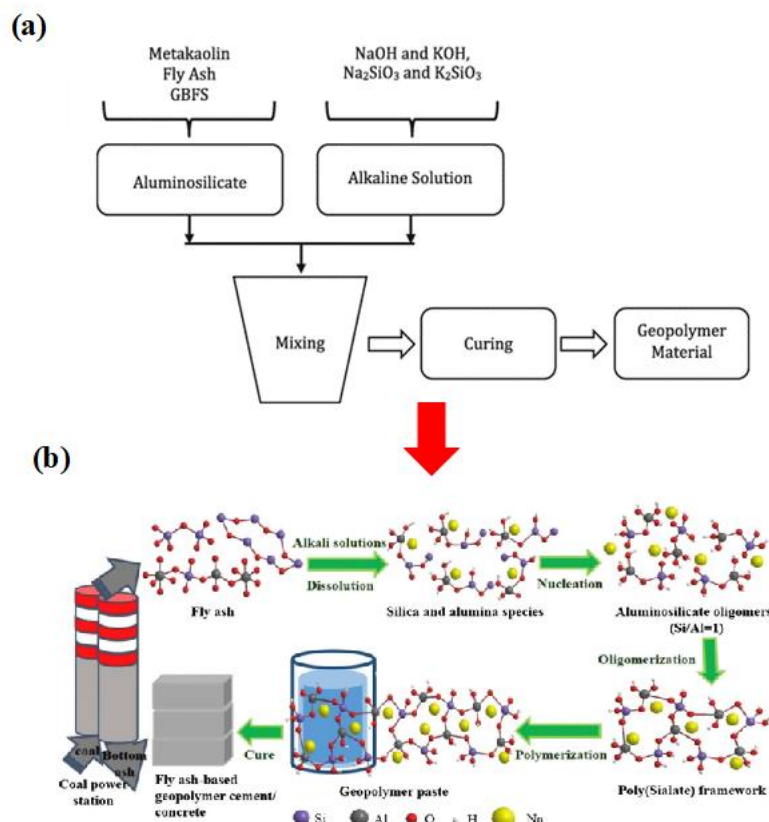
Geopolymer technology use in the construction sector creates improved environmental effects at the

construction material level<sup>21</sup>. Previous research has indicated that when geopolymer concrete is used as a substitute material, it is less environmentally harmful than OPC concrete<sup>18</sup>. Concrete made using fly ash-based geopolymers has become more utilized as an environmentally acceptable alternative to OPC<sup>22,23</sup>. Recent research studies by Golewski<sup>24</sup> revealed that replacing cement binders with fly ash lowers water absorption levels, mainly when the replacement is up to 35%. However, the amount of fly ash integrated determines the characteristics of the concrete.

This review paper summarizes the synthesis of geopolymer cement using various sustainable materials and techniques. Furthermore, the study highlights the chemistry and the reactions involved in synthesizing geopolymer cement, as well as the construction sector, which now uses geopolymer cement. Lastly, the review summarizes the essential properties utilized in analyzing geopolymer cement and its comparison with ordinary Portland cement.

## 2. Synthesis and Geo-Polymerization Reaction of Geopolymer Cement

Geopolymers are formed when aluminosilicate precursors react with alkaline activators through the geo-polymerization process, leading to the development of a three-dimensional network composed of silicon-oxygen and aluminum-oxygen tetrahedra joined by an oxygen bridge<sup>17,25</sup>. This polymeric chain structure has a lower pH than OPC and is calcium hydroxide-free. Geopolymers are regarded as an environmentally friendly technology because they offer several benefits, such as reduced carbon emission, exceptional mechanical strength, increased durability, and resistance to both acid and thermal influences compared to OPC<sup>26,27</sup>. The properties of geopolymers vary depending on the raw material's chemical composition, the kind of alkaline catalyst used, and the curing temperature. Therefore, understanding the chemical characteristics of geopolymer cement is essential for enhancing its properties, refining manufacturing processes, and advancing sustainable construction practices<sup>28,29</sup>. Generally, Geopolymers are an amorphous aluminosilicate consisting of a silicate monomer (-Si-O-Al-O-) repeating unit and the synthesis of a geopolymer reaction occurs via three steps namely: (i) Dissolution of Si & Al atoms because hydroxide ions are present; (ii) Conversion of the precursor ion into the monomer is seen during condensation, and (iii) polycondensation forms polymeric structures. Fig.3 shows the steps used in the synthesis of geopolymer cement.



**Fig.3.** (a) Block diagram of the synthesis steps of geopolymer cement <sup>25</sup> (b) Polymeric network of geopolymerization process <sup>30</sup>

Geo-polymerization reactions entail a heterogeneous chemical reaction involving solid aluminosilicate oxides at low temperatures and alkali metal silicate solutions at highly alkaline conditions. The resultant polymeric structures are amorphous to semi-crystalline and comprise Si-O-Al and Si-O-Si bonds <sup>31</sup>. The ability of the aluminum ion to induce crystallographical and chemical changes in a silica backbone, either through 6-fold or 4-fold coordination, drives the geo-polymerization reaction, which is a chemical integration of minerals <sup>32</sup>.

Duxson et al. <sup>33</sup> stated that a geopolymer reaction is a series of steps that include dissolving the aluminosilicate precursor in an alkali hydroxide solution to create aluminate and silicate ions, polymerizing these ions to form a solution of oligomers with low molecular weight, and then a high molecular weight three-dimensional geopolymer gel is formed. This geopolymer gel's formation is thought to be related to the geopolymer setting. While several researchers have different theories regarding the reaction mechanism involved in geopolymerization, most agree that the process can be broken down into three main stages <sup>33-37</sup>. The first step is where aluminosilicate is dissolved in a concentrated alkali solution to form an alumina

tetrahedron unit and free silica. An inorganic geopolymer gel phase is formed because of the movement, gelation, or solidification of materials, alumina, and silica hydroxyl condensation reaction <sup>38</sup>. The hydrolysis process takes place in the second step, and water seeps out of the structure. In the third step, a geopolymer is produced when the gel phase condenses to create an aluminosilicate network in three dimensions as it solidifies <sup>36,37</sup>. The diffusion of the dissolved species into the solution and the hardening of the inorganic gel to form the final products cannot be observed since the procedure cannot be stopped, and the products cannot be isolated <sup>39</sup>. Therefore, the dissolution of aluminosilicate materials is the only stage that can be scientifically studied.

The formation of geopolymer concrete currently utilized in the construction industry is shown in Fig.4. As it can be seen in Fig.4, there are materials referred to as precursors, which are geopolymers or alkali-activated materials, are made from a variety of materials, typically industrial by-products. The precursors are activated by alkali solutions such as hydroxides and silicates to form geopolymer cement. Fig.4 gives a summary of the steps and ingredients for the development of geopolymer concrete.



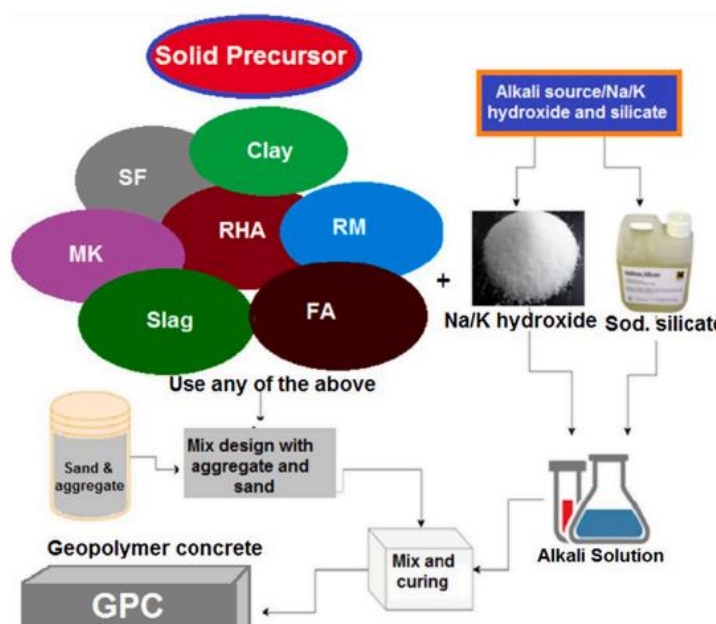
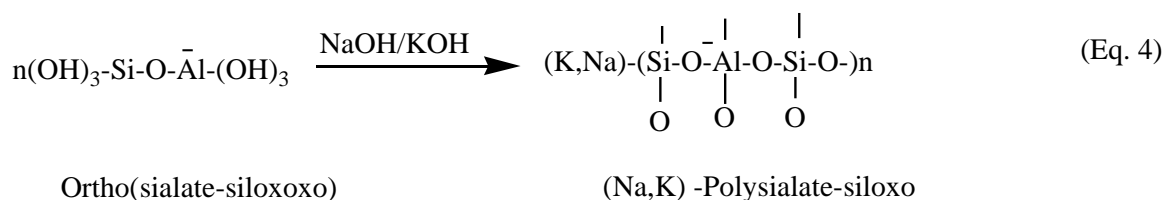
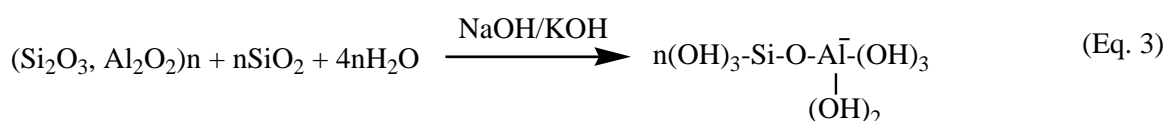
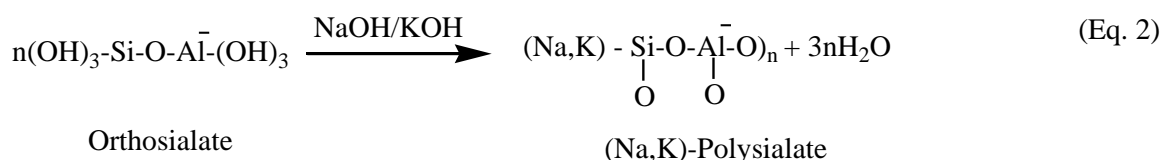
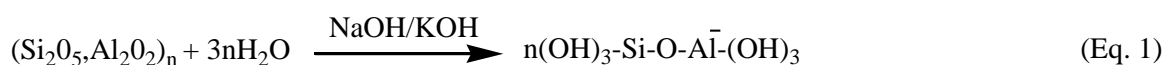


Fig.4. Steps utilized in the formation of geopolymerization concrete <sup>40</sup>

In the case of dissolution kinetics, according to Obonyo et al. <sup>41</sup> and Cao et al. <sup>42</sup>, after the dissolution of the complex silicon and aluminum bonds by an alkaline activator, the released silicon and aluminum ions undergo a polycondensation

reaction in the presence of water. The silicate and aluminate species recombine to create a three-dimensional, cross-linked polymer network known as geopolymer, as represented by the reaction mechanism in Equation 1 – 4.



However, Geopolymers can vary in properties and characteristics based on raw material conditions for selection and processing, including low shrinkage, low heat conductivity, fast or slow setting, acid resistance, and fire resistance. However, these properties are not included in every formulation of geopolymeric material. There is no standard application for inorganic polymers. The varying properties of raw materials prevent the broad

adoption of geopolymers, unlike Portland cement, which is produced with consistent chemical composition and characterization. To address the issue caused by the variability of raw materials composition, the molar ratio may be a viable solution to quality control. Numerous studies have demonstrated a strong correlation between the performance of geopolymers and the molar ratio, particularly the Si/Al ratio <sup>43-45</sup>. Davidovits <sup>32</sup>

categorized a geopolymer structure based on the Si/Al ratio as: poly-sialate (-Si-O-Al-O-) with Si/Al = 1, poly-sialate-siloxy (-Si-O-Al-O-Si-O-) with Si/Al = 2, and poly-sialate-disiloxo (-Si-O-Al-O-Si-O-Si-O-) with Si/Al = 3. Wang et al.<sup>46</sup> recommend that the optimal molar ratios of Na/Al and Si/Al for low-carbon cement and concrete products be 1.0 and 2.0, respectively. This ratio can help formulate an aluminosilicate precursor and activator based on molar ratios to achieve optimal geopolymer performance. It can also serve as a potential non-dimensional index that would allow for chemical quality monitoring of geopolymer products.

## 2.1 Classification of Geopolymer Cement based on Raw Materials used

Geopolymer cement is characterized by its primary components comprising aluminosilicate precursors and alkaline activators. The most common aluminosilicate precursors include metakaolin, fly ash, silica fumes, Rice Husk Ash (RHA), red mud, and Ground Granulate Blast Furnace Slag (GGBFS)<sup>47</sup>. The activators used comprise alkaline solutions such as potassium hydroxide or sodium hydroxide as well as potassium silicate or sodium silicate. The chemical composition of these constituents has a crucial role as they interact to initiate and drive the geopolymerization process<sup>48,49</sup>.

**Table 1.** Raw materials utilized for geopolymer synthesis<sup>11</sup>.

Geopolymer Raw material	Category	Conditions	Production processes
Fly ash	Industrial waste	5- 70 % replacement	Separation from flue gases
Metakaolin	Product	5- 50 % replacement	Calcination, beneficiation
Rice husks ash	Agricultural waste	The surface area is 152 m <sup>2</sup> /g or roughly 50–60 m <sup>2</sup> /g.	Derived from flue gases
GGBS	Industrial waste	Crushed	Separation or collection from flue gases
NaOH	Product	50 %	Electrolysis of brine;
Sodium silicate	Product	37 % solution	Manufacturing of furnace liquor, soda ash or sand mining

### 2.1.1 Kaolin-based geopolymer cement

Kaolin is the primary source of metakaolinite when calcined at temperatures between 650 °C and 750 °C. Phyllosilicate comprises alumina and silica layers stacked on each other in octahedral and tetrahedral coordination, respectively<sup>38</sup>. A common feature of clay minerals is their crystalline layer structure with no electrical charge, which causes the particle size to become acceptable and plate-like morphology<sup>50</sup>. It also allows the particles to pass over one another easily, resulting in the development of physical attributes, including pliability, soapiness, and ease of cleavage<sup>51</sup>. The main component of kaolin is hydrated aluminum disilicate (Al<sub>2</sub>SiO<sub>5</sub>(OH)<sub>4</sub>), also known as kaolinite. Other minerals containing kaolin

are quartz, muscovite-like micas and rutile<sup>47</sup>. Table 2 shows the chemical composition of kaolin.

Between 650 and 900 °C, hydroxyl ions bonded to kaolin cause it to lose 14% of its mass. During this heat treatment, its structure is broken down, causing the alumina and silica layers to lose their long-range order and become puckered<sup>51</sup>. As a result of this dehydroxylation and disorder, the formation of an amorphous material with pozzolanic and latent hydraulic reactivity that can be utilized in cementing applications, as well as a highly reactive transition phase<sup>52</sup>. Geopolymers based on metakaolin are attainable through manufacture reliably and with high predictability, as shown in Fig.5.

**Table 2.** Chemical composition of kaolin.

Chemical compound	Eisa et al. <sup>53</sup>	Moradikhou et al. <sup>54</sup>	Okashah et al. <sup>55</sup>	Khalil et al. <sup>56</sup>
Al <sub>2</sub> O <sub>3</sub>	34.97	31.7	37.44	39.00
SiO <sub>2</sub>	57.81	54	55.99	54.20
CaO	0.05	0.00	0.02	1.37
MgO	0.54	0.00	0.40	0.15
SO <sub>3</sub>	0.03	0.00	0.05	0.45
K <sub>2</sub> O	0.00	4.05	2.93	0.27
TiO <sub>2</sub>	0.00	1.41	1.27	0.80
Fe <sub>2</sub> O <sub>3</sub>	1.72	4.89	1.43	0.92
Na <sub>2</sub> O	0.00	2.32	0.00	0.22
MnO	0.00	0.11	0.00	0.00



**Fig.5.** Production of geopolymer concrete from Kaolin <sup>38</sup>

### 2.1.2 Fly Ash based geopolymer cement

Using ashes in cement is a "green" idea since it reduces the need to use natural resources for construction purposes <sup>39</sup>. The economical factor is significant and influences the choice of ash to be used in the construction process in addition to its superior mechanical, chemical, and physical qualities, positive environmental impact, and low CO<sub>2</sub> emissions <sup>57</sup>. As a by-product of burning pulverized coal, fly ash is the most used ash in geopolymer cement synthesis due to its abundant availability and chemical composition <sup>42</sup>. Fly ash is categorized into class F and class C groups according to its chemical composition, physical properties, and place of origin <sup>8</sup>. Class F fly ash has a chemical

composition of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and Fe<sub>2</sub>O<sub>3</sub> ≥ 70% and is produced by burning bituminous or anthracite coal. Class C coal often comes from burning lignite or sub-bituminous coal, and it possesses the following chemical makeup: SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and Fe<sub>2</sub>O<sub>3</sub> at least 50% <sup>51</sup>. These oxides give it strength, durability, and heat resistance by defining its mechanical, chemical, and thermal characteristics <sup>58</sup>. Table 3 shows fly ash's chemical composition, which is made up of silicone dioxide, aluminum oxide, and calcium oxide, with 60 to 90% of the particles in amorphous phases. These pozzolanic properties of fly ash make it an excellent precursor for geo-polymerization due to the formation of a strong and durable binder <sup>59</sup>.

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

Chemical compound	Badkul et al. <sup>60</sup>	Girish et al. <sup>61</sup>	Bellum et al. <sup>62</sup>	Rifaai et al. <sup>63</sup>	Tahir et al. <sup>64</sup>	Das et al. <sup>65</sup>
Al <sub>2</sub> O <sub>3</sub>	31.43	26.1	25.08	17.1	13.1	28.25
SiO <sub>2</sub>	56.99	46.8	58.23	51.6	30.8	50.00
CaO	1.43	2.91	2.87	14.2	22.3	1.79
MgO	0.45	1.9	1.21	2.2	4.0	0.89
SO <sub>3</sub>	0.11	1.54	1.16	1.6	2.67	0.38
K <sub>2</sub> O	1.00	0.62	0.87	1.6	1.60	0.46
TiO <sub>2</sub>	2.35	1.88	0.83	0.9	0.89	1.54
Fe <sub>2</sub> O <sub>3</sub>	5.08	15.82	4.56	5.2	22.9	13.5
Na <sub>2</sub> O	0.00	0.46	0.41	1.4	0.04	0.32
MnO	0.03	0.21	2.94	0.00	0.152	0.00
P <sub>2</sub> O <sub>5</sub>	1.00		0.2	0.00	0.00	0.98

### 2.1.3 Rice Husk Ash (RHA) based geopolymer cement

RHA is a by-product produced in the processing of rice. The burning conditions mainly influence the physical characteristics of RHA. Rice husk ash has many uses, such as an excellent insulator <sup>66,67</sup>. It has also been used in steel foundries, residential insulation production, and refractory brick production, among other industrial processes <sup>68</sup>. It is an active pozzolan with several packages in the concrete and cement sector. The microstructure and properties of rice husk are specifically influenced by the duration and temperature of burning, indicating that burning rice husk at temperatures below 700°C results in the production of amorphous silica with a large surface area <sup>69</sup>. However, the properties of

RHA may change depending on several factors, including holding time and burning temperature. Higher temperatures yield more crystalline silica, and longer retention times reduce the amount of unburned carbon in the RHA, which is produced at <sup>70</sup>. The resulting ash is further finely crushed to increase its surface area and improve its reactivity during geopolymerization <sup>16</sup>. An alkaline solution is added to activate the geopolymerization process. Table 4 shows the RHA, which has the highest concentration of silica content.

RHA's mineralogy mainly determines how reactive it is; more amorphous silica in RHA makes it more reactive than more crystalline silica phases. Additional materials such as slag may be included to

improve its mechanical and durability properties <sup>71</sup>. The application of RHA in geopolymer cement enhances the binder system's reactivity and contributes to its strength development <sup>72,73</sup>. Silica gives RHA - based geopolymer cement strength and durability, forming a stable aluminosilicate network,

while calcium oxide increases the early strength <sup>67</sup>. Numerous studies have examined RHA use as Supplemental Cementitious Material (SCM), mainly when used in partial substitution of cement per weight of cement in amounts between five percent and thirty percent.

**Table 4.** Chemical composition of RHA.

Chemical compound	Das et al. <sup>74</sup>	Pandey and Kumar <sup>58</sup>	Das et al. <sup>75</sup>	Amin & Abdelsalam <sup>76</sup>	Zareei et al. <sup>77</sup>
Al <sub>2</sub> O <sub>3</sub>	0.70	0.15 – 1.75	0.28	0.26	0.04
SiO <sub>2</sub>	87.22	87 – 95.04	96.26	96.20	86.73
CaO	2.12	0.41 – 2.69	0.58	0.47	0.39
MgO	1.18	0.2 – 2.3	0.27	0.35	0.08
SO <sub>3</sub>	0.04	0.01 – 1.21	0.20	0.15	1.32
K <sub>2</sub> O	1.12	0.83 – 6.25	0.45	0.67	0.01
TiO <sub>2</sub>	1.68	0.62 – 2.5	1.37	0.57	0.61
Fe <sub>2</sub> O <sub>3</sub>	0.20	0.05 – 2.09	0.05	0.12	9.76
Na <sub>2</sub> O	1.06	0.25 -8.5	0.00	1.15	0.54



**Fig.6.** Geopolymer production from RHA <sup>72</sup>

#### 2.1.4 Ground Granulated Blast Furnace Slag (GGBFS) based geopolymer cement

GGBFS is a glass granular by-product of the blast furnaces produced during the manufacture of iron in the steel industry when molten blast furnace slag at a temperature of approximately 1500 °C is rapidly chilled by immersion in water <sup>78</sup>. GGBFS is primarily composed of silicates and calcium aluminates. Its typical chemical composition includes calcium oxide, about 40%; silica, about 35%; alumina, about 13%; and magnesia, about 8%, as shown in Table 5 <sup>79</sup>. It has an amorphous structure and can be used to manufacture different types of materials. Owing to its inexpensive, strong defense against chemical deterioration and the ability to maintain superior thermal properties, this material is advantageous for the concrete industry. Through the polymerization process, a binder, mortars, and several varieties of concrete can be created with strong mechanical characteristics <sup>80,81</sup>. GGBFS undergoes a dissolution reaction in an alkaline solution to form SiO<sub>4</sub><sup>4-</sup> and AlO<sub>4</sub><sup>5-</sup> species. These species undergo a further rearrangement and polycondensation reaction to form potassium

aluminosilicate hydrate (K-A-S-H), which hardens to form a stable polymeric network of silica (SiO<sub>2</sub>) and alumina (AlO<sub>3</sub>), which provide it strength and durability. The presence of sodium (NaO) and potassium oxides (KO) speed up geopolymerization, although they may result in efflorescence. While minor oxides influence reactivity and color, magnesium oxide (MgO) improves durability and sulfate resistance. These oxides ensure strength, durability, and heat resistance, which also shape mechanical, chemical, and thermal properties.

#### 3. Characterization techniques of geopolymer concrete

Geopolymer concrete properties have been investigated using several techniques in terms of their mechanical, chemical, and physical characteristics. This review examines the performance of geopolymers synthesized from different precursors. The properties that are discussed in this review are (i) fresh geopolymer properties, (ii) mechanical properties, (iii) durability performance of geopolymer concrete, and (iv) resistance to attack properties.



**Table 5.** Chemical composition of GGBFS.

Chemical compound	Nawale & Patankar <sup>82</sup>	Badkul et al. <sup>60</sup>	Bellum et al. <sup>62</sup>	Das et al. <sup>83</sup>
Al <sub>2</sub> O <sub>3</sub>	16.19	16.56	12.14	14.30
SiO <sub>2</sub>	37.73	32.54	32.25	32.46
CaO	38.42	36.55	44.70	43.10
MgO	7.30	8.03	4.23	3.94
SO <sub>3</sub>	1.26	1.28	0.84	4.58
K <sub>2</sub> O	0.00	0.55	0.00	0.33
TiO <sub>2</sub>	0.00	0.41	0.00	0.55
Fe <sub>2</sub> O <sub>3</sub>	1.68	2.93	1.10	0.61
Na <sub>2</sub> O	0.00	0.77	0.87	0.02

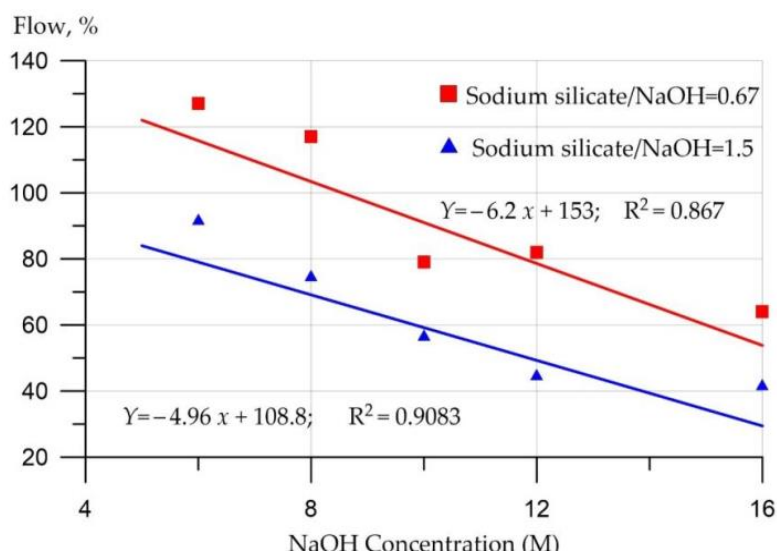
### 3.1 Fresh geopolymer concrete properties

The key fresh properties of geopolymer concrete are workability and setting time. These properties are crucial in determining its performance in building and construction applications by defining the ease of handling and placement before hardening<sup>84</sup>.

#### 3.1.1 Workability

The precursors' characteristics directly impact the workability and setting time of fresh geopolymer paste, which may be thought of as a suspension-dispersion system with several phases and scales<sup>85</sup>. The amount of water needed to make the concrete workable primarily depends on the characteristics and size of the fine aggregate particles<sup>66</sup>. In the case of fly ash, Umniati et al.<sup>86</sup> and Junior et al.<sup>87</sup> indicated that the workability of geopolymer increases when the fly ash and sand ratio were increased. Also, when the silicon oxide to sodium oxide ratio increased, the cohesiveness and slump ability of the sodium silicate solution improved. Ahmed et al.<sup>85</sup> used the slump cone test to assess various samples of fly ash-based geopolymer concrete, and the slump value of geopolymer

concrete specimens was found to be 72% greater than that of cement concrete because of their dense flow character. Further research by Mehta & Siddique<sup>88</sup> tested the workability of low-calcium fly ash-based geopolymer concrete at various NaOH molarities and silicon oxide to aluminum oxide ratios by mass. The authors noted that when the dosage of NaOH rose, the workability of geopolymer concrete reduced, as shown in Fig.7. Also, according to the experimental findings by Davidovits<sup>89</sup> and Agustini et al.<sup>90</sup> on the workability of geopolymer concrete using fly ash and allowed to cure in ambient settings, concluded that, when the slag mix increased in geopolymer concrete based on fly ash, the slump and flow characteristics decreased. This became more apparent as the percentage of the blend increased. Fumed silica, a silicon and ferrosilicon industries alloy by-product, has been reported to give concrete a more spherical shape, making it denser and more workable. Fumed silica can change a specimen's chemistry and porosity by forming dihydrogen during synthesis when sodium silicate is activated<sup>91</sup>.

**Fig.7.** Effect of NaOH concentration on the workability of geopolymer concrete<sup>88</sup>

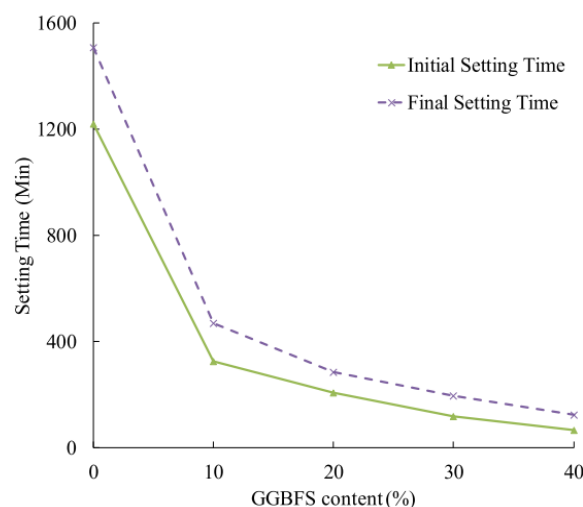
Research by Ghorbel & Samet <sup>92</sup> reported that kaolin-based geopolymer concrete has low workability because kaolin particles have a plate-like shape that increases surface area and water consumption. Kaolin particles have a higher aspect ratio, which results in increased interparticle friction and reduced fluidity, making the mix stiffer, more difficult to handle, and requiring higher shear stress during mixing and placement than spherical fly ash particles. Additionally, the high alumina content in kaolin enhances geopolymerization and increases viscosity, further reducing workability. Hassan <sup>93</sup> also assessed the workability of geopolymer concrete based on GGBFS using the slump cone test. He used GGBFS, fly ash, water, coarse and fine aggregate, and alkaline liquid produced by combining sodium silicate and sodium hydroxide in geopolymer concrete, and his findings demonstrated that adding GGBFS decreases the geopolymer concrete's workability. In the case of RHA as a precursor for geopolymer synthesis, Das et al. <sup>74</sup> reported that RHA significantly decreased the workability of wet concrete due to a high water demand brought on by the increased volume of replacement concrete from its low density. The author concluded that an increase in the amount of RHA decreased the workability for both RHA by weight and volume.

### 3.1.1 Setting time

Setting time is essential in determining how long the concrete is workable to lay and compact into its desired shape. It should be sufficient for the concrete to harden so that it can be handled and cast before it begins to set <sup>94</sup>. Compared to regular cement, the setting time of geopolymers is more challenging to modify. It is influenced by the water-to-solid ratio (w/s), the kind and concentration of the alkaline activator, the curing circumstances, the inclusion of accelerators and retarders, and the chemical makeup and particle size of the solid raw materials.

Research by Nath & Sarker <sup>95</sup> substituted fly ash with 10 - 30% slag in studying the setting time of GGBFS and fly ash geopolymer. The authors also utilized three distinct ratios of sodium hydroxide to silicate (1.5, 2.0, and 2.5), as well as three different binder ratios to the alkaline solution of 0.35, 0.40, and 0.45 while maintaining NaOH molarity at 14 M. They found that the setting time was reduced from more than 24 hours when it is 100% fly ash to 290 minutes, 94 minutes, and 41 minutes when 10%, 20%, and 30% of the slag content was used respectively. Furthermore, the binder ratio to alkaline solution significantly increased the setting time for every increment of the alkaline solution. In contrast, a decrease in the sodium silicate to sodium hydroxide ratio from 2.5 to 1.5 resulted in a more extended setting.

In another study by Jang et al. <sup>96</sup>, the authors used GGBFS and superplasticizers based on polycarboxylate and naphthalene to assess the compositional impacts on setting time. Delay by 50 and 70 minutes was done on the initial and final setting times, respectively; however, by adding 4% of polycarboxylate-based superplasticizer and raising the superplasticizer based on naphthalene from 1% to 4%, the setting time was unaffected, while an increase in GGBFS from 0% to 30% significantly affected the setting time. The effects of adding GGBFS, the impact of changing the ratios of sodium silicate to sodium hydroxide, alkaline solution to binder, and free water on the characteristics of fly ash geopolymer were assessed by Hadi et al. <sup>97</sup>. The authors discovered that the first and final setting time reduced as the amount of slag in the mix increased because of the higher concentration of soluble silica present in alkaline solution which impacted the crystallization and polymerization processes as shown in Fig.8.



**Fig.8.** Effects of GGBFS content on the initial and final setting time of geopolymer concrete <sup>97</sup>

Kumar et al. <sup>98</sup> investigated the effect of GGBFS on the geopolymer reaction of fly ash and its final

hydrated products. The binder ratio to the alkaline solution was 0.35; sodium hydroxide at a constant

molarity of 6 M was used, and 0%, 5%, 10%, 15%, 20%, 25%, 35%, and 50% GGBFS were used in place of fly ash. The authors observed that the setting time was 295 minutes at 100% fly ash content and 105 minutes at 5% GGBFS content. However, at 25, 35, and 50% GGBFS content, the setting time gradually dropped from 105 minutes to 45 minutes. Ghorbel & Samet <sup>92</sup> reported that the setting time of kaolin-based geopolymer varies with activator content and curing circumstances but is often faster than fly ash-based geopolymers but slower than GGBFS-based mixtures. The setting and strength development is greatly accelerated by heat curing at 60 to 80°C. Although the work duration is less than that of fly ash-based systems, it can be modified by adding retarders or changing the ratio of the alkali activator. López et al. <sup>43</sup> compared the RHA-based geopolymer's setting time to that of regular geopolymer concrete. The authors reported that RHA-based geopolymer concrete takes longer to set. This is mainly because rice husk ash is less reactive than other aluminosilicate sources like fly ash or metakaolin and dissolves more slowly in alkaline solutions, delaying the geopolymerization. The porous structure of RHA also prolongs the setting time since it slows the rate at which silica dissolves and raises the demand for an activator solution.

### 3.2 Mechanical properties

Developing an appropriate geopolymer concrete with sustainable building properties requires the mechanical characterization of the produced geopolymer cement <sup>4</sup>. Compressive strength, splitting tensile strength, and flexural strength are the two most popular methods for mechanical characterization. Numerous studies have been conducted about the variables impacting the strength characteristics of geopolymers. Geopolymers exhibit high compressive strengths and cures even more quickly than regular cement. The mechanical properties of compressive strength and flexural and splitting tensile strength for fly ash, GGBFS, kaolin and RHA based geopolymers are discussed in sections 3.2.1 and 3.2.2, respectively.

#### 3.2.1 Compressive strength

Concrete's compressive strength is frequently used to describe how it behaves under compression. In contrast, the initial elastic modulus represents how strength develops with the shape and age of the stress-strain relationship <sup>85,99</sup>. The wet-mixing time and curing temperature, curing duration, and particle size impact the compressive strength of geopolymer concrete <sup>100</sup>. A research study done by Ryu et al. <sup>101</sup> on fly ash-based geopolymer concrete found that after one day, heat-cured low calcium fly ash-based geopolymer concrete achieved a high compressive strength. Also, approximately 91% of the ultimate strength is generated when cured between 80°C and 90°C in less than 24 hours. Further research work by Demie et al. <sup>102</sup> and Erfanimanesh & Sharbatdar <sup>103</sup> on the effect of geopolymer particle size to water ratio and the impact of fly ash to slag ratio on compressive strength of geopolymer concretes. The authors concluded that the compressive strength of the concrete is inversely related to the ratio of geopolymer particles to water. Cyr et al. <sup>104</sup> examined the effects of the mass ratios of fly ash to sand, sodium oxide to silicone, and water to fly ash on the geopolymer concrete compressive strength. They reported that the ratio of sodium hydroxide to sodium silicate for geopolymer concrete was more beneficial in terms of compressive strength than the silicone oxide to sodium oxide ratio.

A research study by Suresh & Nagaraju <sup>105</sup> on the qualities of concrete composed of ground-granulated blast furnace slag revealed the GGBFS sample's compressive strength rose as the waste percentage rose. When 10% of the cement was replaced with GGBFS, the maximum compressive strength was noted, as shown in Fig.9. Regarding days of curing, according to research work by Suresh & Nagaraju <sup>105</sup>. The cementitious content may need to be raised to achieve the same 28-day strength at higher GGBFS percentages. Compared to identical concrete built with Portland cement, GGBFS concrete gradually builds strength. The drop in early strength will be particularly pronounced at low temperatures and high GGBFS levels. For the same 28-day strength, GGBFS concrete will have lower strength at early ages but greater strength over time.

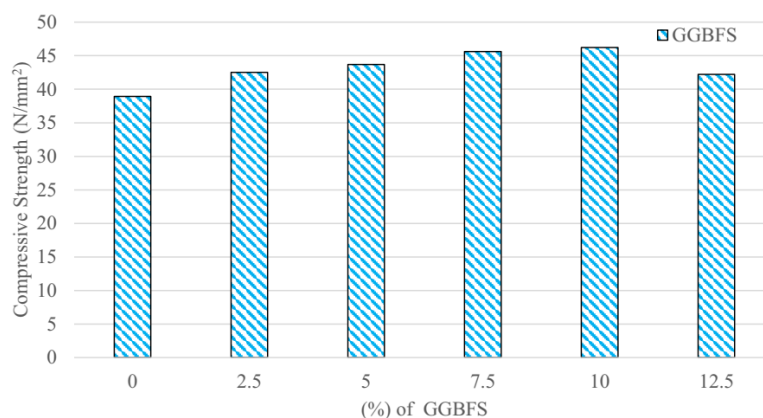


Fig.9. Compressive strength test results on varied proportions of GGBFS <sup>106</sup>

Further research work on the comparison between the compressive potency of different proportions of Fly Ash (FA) and GGBS at different curing time tests by Jawahar & Mounika <sup>107</sup> concluded a significant increase in compressive strength with an increasing percentage of GGBS in all curing times as

shown in Table 6. The safety and stability of a constructed structure are significantly impacted by its compressive strength and the raw materials, and the curing conditions affect the compressive strength of the geopolymer concrete.

**Table 6.** Compressive strength of geopolymer concrete with different fly ash and GGBS proportions <sup>107</sup>.

Mechanical properties	Age (Days)	Mix type		
		FA50GGBS50	FA25GGBS75	FA0GGBS100
Compressive strength (f' <sub>c</sub> MPa)	7	40	44.4	52.3
	14	46.5	48.2	56.2
	28	53.5	55.3	58.6
	56	63	74	83
	112	65	77	87

Research studies on the compressive strength of RHA have indicated that, as the RHA content rises to a particular point, concrete's compressive strength with RHA added as a partial cement replacement increases, as shown in Table 7. This is because of the pozzolanic reaction between the amorphous silica in RHA and calcium hydroxide (Ca (OH)<sub>2</sub>), which creates more calcium silicate hydrate (C-S-H) gel. Nonetheless, in the remaining trials, the compressive strength of concrete using RHA as a partial cement

replacement rises to a particular ideal level <sup>39</sup>. When RHA content is increased beyond this ideal replacement level, compressive strength tends to decrease. Lower C-S-H gel formation results from an inadequate supply of calcium hydroxide to maintain the pozzolanic reaction. A high RHA content can also raise porosity and water demand, reducing the density and mechanical performance of the concrete <sup>108</sup>.

**Table 7.** Compressive and modulus of rupture (MR) of concrete with RHA proportions.

Max. replacement of cement by RHA (%)	Comp. strength without RHA to 28 days (MPa)	Comp. strength with RHA to 28 days (MPa)	MR without RHA to 28 days (MPa)	MR with RHA to 28 days (MPa)	Reference
40	48.5	42.9	-	-	58.
30	56	66	-	-	57.
20	42.35	50.41	4	4.34	51.
25	83.36	93.28	-	-	39.
20	36.1	37.7	4.17	4.72	61.
15	14.1	13.8	-	-	48.
20	43	55	4.9	5.9	62.

Duxson et al. <sup>33</sup>, a study to determine the effect of curing temperature on the compressive strength of kaolin-based geopolymer cement, demonstrated that while treating a fresh mixture at higher temperatures speeds up the development of strength, the compressive strength decreased after 28 days when compared to results for mixtures treated at room temperature or slightly lower. The authors reported that the compressive strength increases with longer curing times and higher curing temperatures but decreases with additional water. Therefore, water impacts the final product's strength, while curing temperature and duration will impact compressive strength.

### 3.2.2 Flexural strength and splitting tensile strength

The flexural strength and splitting tensile strength of geopolymer concrete are directly proportional to the compressive strength of <sup>109,110</sup>. Research done by Jawahar & Mounika <sup>107</sup> on the impact of different proportions of GGBFS and fly ash in a geopolymer concrete on splitting tensile and flexural strengths at various stages of cure showed a rise in flexural and splitting tensile strengths when the percentage of GGBFS increased from 50% to 100%. Shaikh <sup>111</sup> measured the flexural strength of steel fiber-reinforced geopolymer composite at 7, 14, and 28 days of curing and reported that the flexural strength increased with aging. At 28 days, the author recorded a 70% increase in the flexural strength of fibre-reinforced geopolymer composite. The author also measured the reinforced geopolymer composite splitting tensile strength and recorded a similar trend. Shaish et al. <sup>112</sup> and Zhang et al. <sup>113</sup> investigated the



geopolymer concrete's flexural strength when strengthened with PolyPropylene (PP) fiber at one and three days of curing. A 0.75 percent addition of PP fiber at both curing ages yielded a double increase in flexural strength.

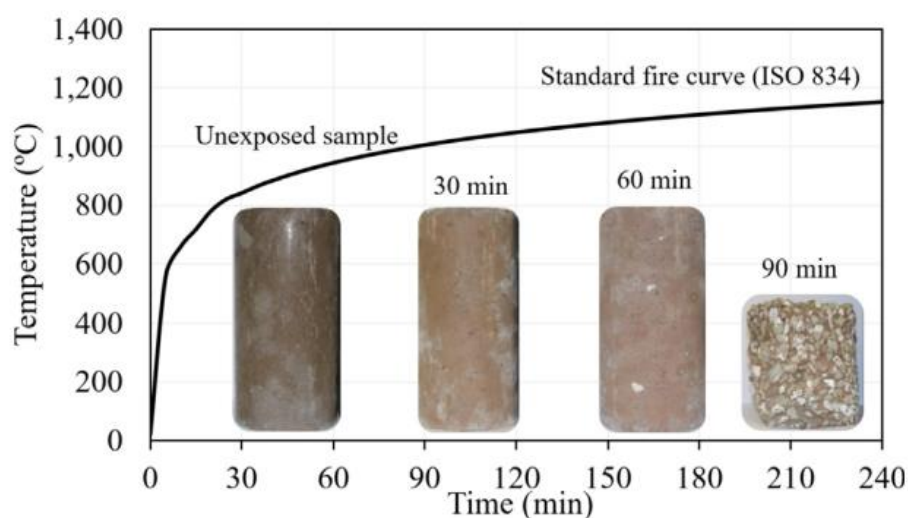
Saravanan & Elavenil <sup>114</sup> substituted 50% of fly ash with GGBFS and noticed an improved flexural and splitting tensile strength. The specific heat curing affects the flexure-to-compression ratio and tensile-to-compression ratio compared to curing at ambient temperature <sup>91</sup>. Lee et al. <sup>115</sup> conducted an experimental test to determine geopolymer concrete tensile strength by varying fly ash to sand at 7, 14, and 28 days of curing. They reported that the tensile strength gradually decreased as the sand-to-fly ash ratio increased. Khater <sup>116</sup> examined the impact of replacing cement with 0–20% kaolin and observed the flexural strength and splitting tensile strength at 7, 28, and 90 days. The author noted that the flexural strength and splitting tensile strength of concrete containing kaolin were higher than that of the control mix at all replacement levels and ages. Heah et al. <sup>117</sup>, in their study on kaolin-based geopolymers, stated that the geopolymer structure using kaolinite source material alone produced weak structure and, therefore, low flexural and splitting tensile strength. This is because kaolin geopolymers do not undergo complete geopolymerization and are not incorporated into the polymeric structure. Billong et al. <sup>118</sup> studied the performance of hardened RHA geopolymer paste, focusing on tensile and flexural strength. The hardened products were tested after 7 and 28 days of curing, and the authors reported that the RHA-based geopolymer improved flexural and tensile strength compared to the control mixture, which had no RHA. The authors noted that the presence of RHA impacted the geopolymer's Si/Al ratios, which affected the polycondensation process.

### 3.3 Durability performance of geopolymer concrete

Durability performance is the concrete's capacity to resist exposure environments, such as abrasion, chemical attack, and weathering action while maintaining its expected engineering characteristics. For OPC concrete in severe environments, long-term durability has always been a significant challenge <sup>119</sup>. Geopolymer concrete is well known for its outstanding resilience to several types of chemical and environmental deterioration <sup>120</sup>. This review evaluates the degradation of geopolymer concrete by analyzing: (i) resistance to fire, (ii) water absorption, (iii) resistance to sodium chloride solution, sulfate attack, and abrasion.

#### 3.3.1 Heat resistance

Heat exposure is often one of the most important variables influencing concrete's characteristics, color, shape, and surface appearance <sup>121</sup>. The impact of high temperatures on fly ash, metakaolin, and GGBFS used to make High Strength Geopolymer Concrete (HSGC) was conducted by Gupta et al. <sup>122</sup> at intervals of 100 °C from 100 °C to 700 °C. The authors reported that the primary cause of the decrease in strength in the geopolymer concrete mixes is the incompatibility of the aggregates and geopolymer matrix with heat. This led to the formation of internal cracks caused by the matrix from the aggregate's separation. It is essential to study the fire endurance of concrete and the elements influencing it since fire safety is one of the most crucial components of building concrete structures. A research study by Nuaklong et al. <sup>123</sup> to evaluate the fire resistance characteristics of a combination of high-calcium fly ash geopolymer and rice husk ash is shown in Fig.10. The visual observation shows that after 30 minutes of exposure to high temperatures, reddish brown to dark brown surface color changes occurs in geopolymer concrete. In addition, according to research by Nath & Sarker <sup>95</sup> regarding fly ash geopolymer concrete's fire resistance, the samples turned red at a temperature between 800 and 1000°C due to iron oxide in fly ash.



**Fig.10.** Fire exposure effects on Geopolymer concrete after 30-, 60-, and 90-min <sup>123</sup>

Zareei et al. <sup>77</sup> evaluated the heat resistance property of RHA-based geopolymer concrete and observed that the geopolymer concrete showed an improved heat resistance; this is attributed to the high silica content in RHA. The authors reported that silica enhances geopolymerization, creating a dense, thermally robust matrix that resists spalling and cracking at temperatures between 600 and 1000°C. According to Nnaemeka & Singh <sup>124</sup>, kaolin-based geopolymer concrete has improved heat resistance because high aluminosilicate content in kaolin stops microcracks and thermal deterioration when activated. The tiny particle in kaolin improves geopolymerization, leading to increased durability.

### 3.3.2 Water absorption

In the case of water absorption, concrete and structural reinforcement degrade due to water penetration. Water seeps into the concrete's cracks and carries elements that could lead to the deterioration of concrete or, in the case of chloride ions, the corrosion of steel reinforcing <sup>34</sup>. Much research has been done to compare the water absorption of conventional concrete developed with OPC and concrete created with modified cement formulations and geopolymers. A research work by Saloni et al. <sup>73</sup> evaluated the water absorption of GeoPolymer Cement (GPC) using fine RHA at different amounts in place of OPC. They observed that there was a drop in water absorption for every curing time as the fine RHA fraction increased to 15%. Venkatesan & Pazhani <sup>125</sup> also studied the water absorption of geopolymer samples made from rice husks and found that adding RHA decreased the water absorption value to a minimum of 10% replacement. RHA creates a micro-filler effect, making the concrete more compact and less prone to liquid penetration. Further research by Mohseni et al. <sup>126</sup> evaluated the durability properties of fiber-reinforced geopolymer composites based on RHA.

The authors reported that the water absorption of the geopolymer samples decreased when fibers were incorporated, which significantly offset the adverse effects of lightweight aggregate replacement.

Research work by Nagajothi et al. <sup>127</sup> used fly ash and GGBFS aluminosilicate material with an alkaline solution, which indicated that the decrease in the percentage of water absorption in GPC is smaller than that of conventional OPC. This was attributed to the pores filled with fine slag particles. Further work by Abbass & Singh <sup>67</sup>, Gupta et al. <sup>122</sup>, and Mansourghanaei et al. <sup>121</sup> on several modified formulations of GPC using various materials indicated that geopolymer concrete exhibited reduced water absorption, slower water penetration, and lower sorptivity when compared to OPC concrete. Ojha & Aggarwal <sup>128</sup> performed the water absorption studies of three samples of low calcium geopolymer concrete based on fly ash and OPC. The authors concluded that geopolymer concrete based on low calcium fly ash has a lower weight gain than OPC concrete, as shown in Table 8. Higher water absorption rates of OPC concrete were attributed to larger voids.

In contrast, reduced water absorption values in geopolymer concrete with a low calcium fly ash content were attributed to forming a more compact microstructure, resulting in fewer vacancies. Nnaemeka & Singh <sup>124</sup>, in their study, reported that the tiny particle size and high aluminosilicate content in kaolin lowers the water absorption of kaolin-based geopolymer concrete by limiting pore connection through the formation of a dense and compact matrix when activated. The decreased water absorption increases durability and resistance to damage caused by moisture. The authors concluded that kaolin can be used to enhance the long-term performance of geopolymer concrete in damp or humid environments.

**Table 8** Water absorption results in low calcium fly ash geopolymer, and OPC concretes <sup>128</sup>.

Concrete type	Initial weight (g)	Final Weigh (g)	Gain (%)	Average Gain (%)
OPC	8615	8739	1.439	1.428
	8512	8633	1.421	
	8490	8611	1.425	
Low calcium FA-GPC	8097	8211	1.407	1.409
	8120	8235	1.416	
	8160	8220	1.406	

### 3.3.3 resistance to chloride and sulfate attack

Numerous chemical reactions between the harsh environment and the calcium-containing components of the concrete might cause degradation <sup>129</sup>. Chloride and sulfate attack is one kind of harmful chemical attack that occurs in concrete when sulfate and chloride ions enter the pore structure by hydrostatic pressure or capillary action <sup>119</sup>. Research work by

Çevik et al. <sup>130</sup> indicated an increase in the weight of GPC following two weeks and a month, during which GPC and OPC specimens were exposed to seawater. However, OPC showed a weight decrease after the same amount of time; as a result, the compressive strength of the OPC specimen dropped more than that of the GPC specimen. The increase in specimen weight due to solution absorption was

impacted by salt in the concrete matrix's pores. Kumar et al.<sup>131</sup> investigated fly ash-based geopolymer and OPC concrete by immersing them in seawater containing 5% sodium chloride solution and fly ash-based GPC in a 5% sodium sulfate solution, respectively. The results showed that the fly ash-based geopolymer concrete specimens are more stable in seawater environments than those of OPC specimens, which experienced significant mass loss. These results show that the geopolymer concrete specimens have more excellent chemical resistance to NaCl solution and sodium sulfate than OPC concrete specimens. This is due to the binding capacity of geopolymer concrete with chloride and sulfate ions that block their penetration and distribution across the body, which strongly correlates with its resistance to chloride attack<sup>120</sup>.

Nnaemeka & Singh<sup>124</sup> investigated the chemical resistance of geopolymer concrete made from fly ash and kaolin. The authors reported that the resistance of the geopolymer concrete containing Kaolin was significantly higher than that of the OPC concrete (control) and higher than that of the geopolymer concrete containing only fly ash. Prabu et al.<sup>68</sup> discovered that adding RHA up to 30% replacement level for OPC improves the corrosion-resistant properties and lessens chloride and sulfate penetration. Ahsan & Hossain<sup>72</sup> reported that adding RHA to geopolymer concrete improves its impermeability, lowering the penetration of chloride ions and the danger of corrosion in reinforced structures. Furthermore, the authors stated that RHA-based geopolymer concrete maintains structural integrity in harsh conditions due to its exceptional resistance to sulphate-induced degradation. Bellum et al.<sup>62</sup> investigated GGBFS-based geopolymer concrete. They reported that GGBFS-based geopolymer concrete is highly durable in marine and industrial environments where exposure to chlorides and sulfates is a concern. Additionally, the authors stated that GGBFS helps to prevent corrosion of steel reinforcing by creating a denser microstructure drastically lowering permeability and preventing the infiltration of chloride.

### 3.3.4 resistance to abrasion

Abrasion is considered one of the key techniques to characterize concrete surface wear durability. The hardness of the geopolymer binder, aggregate toughness, and compressive strength impact the geopolymer concrete's resistance to abrasion<sup>119</sup>. Çevik et al.<sup>130</sup> studied the durability and the resistance to wear of pavement fly ash based geopolymer concrete slabs of dimensions 500 mm × 500 mm × 100 mm cured for 28 days. The study revealed that the upper surface's average abrasion was 1.08 mm, and the average abrasion on the bottom surface was 0.92 mm. Wongsu et al.<sup>132</sup> research on lightweight fly ash geopolymer concrete's resistance to abrasion with river sand, pumice, natural limestone, and clay brick aggregates.

The authors identified that the specimens showed a weight loss as the proportion of sodium hydroxide to sodium silicate rose in the geopolymer concrete samples after 28 days. Further research work by Luhar et al.<sup>133</sup> on the abrasion resistance of high calcium fly ash geopolymer concrete showed that the wear depth decreased when the number of rubber fibers in the concrete samples increased. This indicated that adding rubber fibers increased the material's abrasion resistance. This is all attributed to the GPC composition, design techniques, curing schedule, and mixing procedure for the preparation of the geopolymer<sup>120</sup>.

A research study by Faried et al.<sup>80</sup> stated that GGBFS-based geopolymer concrete performs better than OPC concrete in its abrasion resistance. The authors reported that GGBFS improves the geopolymer matrix by hardening it and adjusting its pore structure, which increases its resistance to erosion and surface wear. Another study by Bellum et al.<sup>62</sup> confirmed that material loss under mechanical stress is decreased by the dense, long-lasting hydration products that are formed by the high calcium and aluminosilicate content of GGBFS. Therefore, geopolymer concrete based on GGBFS is well-suited for hydraulic structures, high-traffic areas, and industrial floors where long-term abrasion resistance is essential for durability and structural integrity. In the case of kaolin-based geopolymer, Ghorbel & Samet<sup>92</sup>, in their study on the pozzolanic activity of kaolin, concluded that the mix composition and curing conditions have an impact on the abrasion resistance of kaolin-based geopolymer concrete. This is because it contains less calcium compared to other geopolymer precursors. A study by Kaze et al.<sup>134</sup> indicates that kaolin-based geopolymer concrete's surface hardness and wear resistance can be improved by adjusting the alkali activator concentration and adding acceptable reactive additives. Abbass & Singh<sup>135</sup> studied RHA-based geopolymer concrete's durability in rigid pavements. The authors reported that RHA-based geopolymer concrete exhibits good abrasion resistance, especially when mixed with cementitious ingredients like slag or fly ash. The authors also stated that the concentration of the alkaline activator and the curing conditions affect how the geopolymer works.

## 4. Current Development and Applications of Geopolymers

Geopolymers are necessary replacement materials that can be employed to promote recycling and sustainability. There are several significant effects of using GPC over OPC regarding environmental preservation, cost, and end quality of the products developed<sup>136</sup>. Geopolymers have been applied in advanced precast technology in several buildings and construction sectors, which include (i) application of geopolymer concrete in railway sleepers, (ii)

geopolymer concrete in highway infrastructure, and (iii) geopolymer concrete for protection of reinforced concrete against corrosion. Currently, geopolymers are used in railway sleepers as a long-lasting and sustainable alternative, enhancing structural performance and reducing environmental impact<sup>137</sup>. Research work by Deivabalan & Tamilamuthan<sup>138</sup> compared OPC concrete and fly ash-based geopolymer sleepers and concluded that geopolymer concrete sleepers performed comparably to OPC concrete sleepers. The authors concluded that under the flexural test, the experimental results confirmed that geopolymer concrete was comparable to OPC in all aspects of testing. Srividya et al.<sup>139</sup> used conventional prestressing techniques to create prestressed geopolymer concrete sleepers, which passed cyclic load tests and met standard requirements. They found greater bond strength and no steel slippage at maximum load. These sleeper specimens have been successfully used in mainline rails, proving to be environmentally friendly and an excellent alternative to OPC concrete<sup>140</sup>.

In highway infrastructure, several investigations have demonstrated the potential use of geopolymer<sup>141,142</sup>. Almutairi et al.<sup>136</sup> conducted the first tests using geopolymer concrete in highway infrastructure, particularly in light pavement applications such as cycle lanes and precast walkways. Their research concluded that the geopolymer concrete showed no signs of strain, cracking, or flaws. Mustafa et al.<sup>143</sup> investigated geopolymer made from fly, palm, and para wood ash for highway infrastructure restoration. Laboratory tests showed that geopolymer concrete had more compression and bonding strengths, making it an excellent material for highway infrastructure.

Regarding roadway infrastructure, geopolymer concrete is currently limited; initiatives are underway to include it in regional highway authority standards due to its exceptional performance<sup>141,142</sup>. In 2024, an Indian company constructed the first cement-free geopolymer road using 2,000 metric tons of fly ash and GGBS. This new development has encouraged industrial waste, highlighting the potential of geopolymer cement in highway infrastructure as a long-lasting and sustainable substitute for conventional materials.

Recently, geopolymer concrete has been used in offshore and coastal constructions where the corrosive ocean environment and saltwater erode concrete exposed to harsh marine conditions<sup>136</sup>. Repairing this damage is expensive, prompting researchers to focus on increasing marine concrete structures' anticorrosion properties and durability<sup>144</sup>. Geopolymer binders are a strategy that has been utilized to enhance the longevity of maritime concrete structures. A research work by Zhang et al.<sup>145</sup> proposed applying geopolymer coatings to mitigate the durability issues of conventional

coatings, suggesting that geopolymer coatings, with their good adhesion, low permeability, and anticorrosive properties, could safeguard marine structures. Therefore, there are several benefits to utilizing GPC in the building and construction sector as a novel and environmentally friendly material seen as a potential substitute for OPC. In addition, geopolymer reduces the significant quantity of CO<sub>2</sub> emissions when OPC is produced. Geopolymer concretes are exceptionally durable and are anticipated to alleviate the durability difficulties associated with conventional concretes. The decision between GPC and OPC should be made after thoroughly examining the specific conditions and use in each application building and construction system.

## 5. Future research in the development of geopolymer concrete

Further studies have concentrated on improving the efficacy, sustainability, and efficiency of GPC to advance the development of geopolymer concrete has focused on the reduction of energy costs and greenhouse gas emissions. Furthermore, geopolymer concrete has a lot of potential in the building industry because of its environmental benefits. Additionally, the quest for automation capabilities, fast rate of production, and accuracy in execution has led to the utilization of geopolymer concrete in 3D printing technology. Moreover, geopolymers developed from nanomaterials such as graphene possess outstanding mechanical, optical, electrical, catalytic, and biological properties. The growing scientific emphasis in the construction industry is on 3D printing technology, which provides incredible strength and resistance to abrasion and challenging conditions. In this context, the advancement of this cutting-edge technology is promising and compliant with sustainable development, representing a cutting-edge tactic to reduce threats to human health and the environment.

The growing scientific emphasis on developing geopolymers based on graphene nanomaterials has also emerged as a specialty with potential contributions to the construction industry. Graphene oxide is the most utilized nanomaterial in structural applications that modify the microstructural properties of cement-based materials. Graphene oxide addition to geopolymer concrete enhances its durability since the microstructure becomes denser, and brittleness and nano-cracks are decreased. Studies exploring advanced approaches to nanomaterials in geopolymer concrete possess the capacity to offer insightful information on their composition and behavior, resulting in advancements in their mechanical properties. At the same time, adding graphene oxide to slag geopolymer concrete was studied to significantly improve its mechanical properties, resulting in a 20% increase in flexural strength<sup>146</sup>.



Finally, incorporating graphene nanoflakes into concrete with geopolymer based on fly ash increases compressive and flexural strength. However, the bending strength is reduced. Thus, it is vital to determine the appropriate graphene concentration in geopolymer concrete to obtain the desired properties. With the increasing need for efficient and long-lasting building materials, further studies on geopolymer concrete will be essential in improving optimized construction, leading to a reduction in environmental degradation and efficient use of materials in the construction sector.

## 6. Conclusion

The choice between conventional OPC concrete and geopolymer concrete includes the need for efficiency, environmental influence, and economic factors. While traditional OPC is widely available, geopolymer cement presents significant advantages regarding excellent mechanical properties in building materials and its eco-friendly nature. Pursuing more sustainable and effective materials keeps pushing the creation of novel research and development in construction materials.

Based on present investigations, the utilization of waste, such as industrial and agricultural waste, is thought to be an appealing substitute for OPC concrete. 80% less carbon dioxide is released into the atmosphere during the manufacture of concrete, which could be achieved by using geopolymer concrete rather than OPC concrete. Additionally, Temperature and cure time significantly impact the reactivity of geopolymers, while their durability is significantly affected by the water content and particle size. Moreover, the use of alkaline activators is crucial to the environmental impact. Therefore, careful consideration is required when selecting an appropriate supply of alkaline activators for the geopolymer concrete combination. Finally, recent developments in geopolymer concrete, like nanomaterial-based geopolymers and 3D printing, require further research. Additional research with various aluminosilicates and activators is needed.

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