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Geopolymer for Pavement Construction: A Review

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Abstract. Requirement of suitable construction materials in the area of highway engineering and many other civil engineering construction sites is of utmost importance for a developing country like India. Fly Ash, a byproduct of the thermal power generation plant that is obtained from burnt coal. This is abundantly available across the globe. It is rich in Si and Al. When reacted with a strong base it produces aluminosilicate gel that acts as the binding material for the soil. It is an excellent alternative construction material over the existing plain cement concrete for road construction. Nowadays, geopolymers made of coal ash are environmental friendly substitutes for Portland cement. In many applications, it not only reduces greenhouse gas emissions but also utilizes large volumes of industrial wastes like fly ash, metakaolin, mine tailing, and metallurgical slag. A brief review of geopolymer fundamentals, the formation of the structure, preparation of raw materials, and the properties of geopolymers and its advantages over ordinary Portland cement concrete is presented in this article. Also, different factors like particle size, curing with and without temperature exposure, the molar concentration of alkaline activators, silicate to aluminum molar ratio, and Ca content which affect the strength of the modified soil are highlighted. The newly developed concept of geopolymer formation cured at relatively low temperature (30°C to 50°C) or cured at ambient temperature may be useful in pavement construction. Finally, it is concluded that factors including the conservative view of new materials have a wide application and it is expected to be an essential part of the sustainable development of our country

Keywords: geopolymer; pavement; fly ash; alkali activator;

1 Introduction

The most common soil stabilizers used nowadays are OPC (ordinary Portland cement), lime, and fly ash (FA). FA, a byproduct of burning anthracite or bituminous coal, is a waste and commonly used as a substitute in Portland cement for making concrete. The rest of the raw fly ash is disposed of in landfills. There is always a risk to water sources due to heavy metals present in the fly ash. Fly ashes procure from coal combustion systems contain Ca. Generally, most of the FA available globally is low-calcium fly ash (ASTM Class F). FA can only partially substitute portland cement since SiO_2 and Al_2O_3 in fly ash still need $\text{Ca}(\text{OH})_2$ from portland cement hydration for its pozzolanic reaction to yield calcium aluminate hydrate and calcium silicate hydrate. However, due to the CO_2 emissions produced during the manufacturing of the aforementioned soil stabilizers, which contribute to greenhouse gases, other soil

stabilizers are being sought out and recommended. In the recent past, another form of cementitious materials called geopolymer has been discovered [18]. The geopolymer method is the latest concept on soil stabilization and a few researchers worked in the field of pavement engineering for its application. There is no convenient guidance for the usage of geopolymer in the soil, despite some research that has determined that it could be used for ground improvement [1].

This review paper planned to present a capsulization of factors that affect the strength of geopolymers and bulk utilization of fly ash for pavement construction. The contents of this article are based on the review of various literature to find out the utilization of geopolymer technology in pavement construction. Also, these works addressed issues related to environmental friendly construction materials to beat sustainability issues. The most concomitant construction activities in India have been increasingly shifting towards new techniques like geopolymerization due to its low CO₂ emissions from its production process, bulk utilization of industrial waste which causes a severe problem for the environment, and replacement of previously used OPC due to its high carbon emission in the manufacturing process.

The geopolymerization of FA attempts environmental benefits, such as curtailing consumption of natural resources and a decline in the net production of CO₂. Again, a geopolymer grid has been proven to stabilize, solidify, and enclose metallic and radioactive wastes and industrial wastewater [24]. It also possesses excellent mechanical properties, acid resistance, and fire resistance. These are the properties that make the geopolymers a potential construction material. Due to these excellent characteristics, it has been catching the attention of researchers internationally in the past 2 decades [19]. However, the commercial application of geopolymers is still confined at present.

The polymerization process associates a substantially fast chemical reaction under the alkaline condition on Si-Al minerals that result in three-dimensional polymeric chains and ring structure consisting of Si-O-Al-O bonds. Geopolymerization is based on the alumino-silica chain. Geopolymers are a synthetic inorganic polymer produced by the alkali activation of aluminosilicates. In a high pH environment, the soil particles are conventional to be dispersed, at the same time the soil particles are flocculated when the pH value is low [36]. Fly ash contains a high volume of amorphous silica and alumina, so it is suitable as source material for generating a geopolymer. Fly ash is normally mixed with an alkali solution to obtain alumina and silica precursors. When it comes into contact with the alkali solution, the disintegration of silicate species starts [13].

2 Background Information

2.1 Fly Ash, lime, and cement stabilization for road construction applications

Fly ash is considered an extensive universal pollutant as a result of the excess amount of generation and hazardous nature. With the advancement in the techniques and various Government policies, it has acquired a status of value-added materials. In India,

around 70-75% of electricity is generated by coal-based thermal power plants. Every year nearly 30-40% of fly ash remains unutilized in India. The risk has been further heightened after the central government opened up the coal sector for commercial mining by private bodies, which indirectly paves for the generation of more FA. India is one of the major producers of coal and as well as fly ash. The utilization of FA in rail and road embankments in earthquake-prone areas requires a thorough understanding of its strength characteristics. Here there is a scope to find out various ways of utilization of FA which will be beneficial for the future generation.

The utilization of fly ash for pavement construction has also raised phenomenally in India with annual utilization of about 8.82 million tons in road construction, which constitutes about 16 percent of total utilization. Hence consumption of FA for pavement and embankment construction is thus justifiably called high-volume ash utilization. The typical approach for the redemption of soft subgrade has consisted of removal of poor soil and its replacement with a large quantity of crushed rock. The high cost of removal of poor topsoil and transportation of aggregates, along with increasing interest in re-usable industrial by-product has prompted an investigation to find out a solution that complements the need for highway construction. The use of FA for stabilization of soft sub-grade as a replacement to the soil is one of these solutions. The relevant works of literature from the past researchers are reviewed and summarized below.

The addition of lime and FA with soil enhances California Bearing Ratio (CBR) to (84.6%) [4]. To develop highway infrastructure in the country, there are approximately about 15–20 MT of FA consumed in the construction of pavement and flyover embankments per year. The specific gravity of class C FA is more as compared to class F FA and the class C fly ashes show a very large gain in strength [15]. The fly ash samples are consist of more than 50% amorphous alumino-silicate spheres and a very less amount of iron-rich spheres [32]. The pozzolanic hardening properties of cement additives gives additional strength to the road pavements [8]. FA decreases the swelling potential of expansive soils. The significant strength gain occurs after a relatively long period which is required for the formation of the cementitious phase [14].

Lav [33] investigated the microstructural formation of FA stabilized with lime and cement. It was found that the final hydration product that results in the strength gain of lime incorporation with FA is similar to that of the cement inclusion with FA. The pozzolanic activity of lime addition with FA was seen to be increasing up to 360 days but a steep gain of strength was recorded during 28 days to 180 days of curing. In OPC, FA is only used to improve workability and reduction of temperature during curing but does not use significantly for strength enhancement [42]. In geopolymers, FA is the main component for strength development because it is the source of aluminosilicates.

2.2 Typical geopolymer

Geopolymers are generally prepared by blending aluminosilicate pozzolanic materials with alkaline solutions to develop a homogenous paste. To achieve a particular strength heat curing is required either in an oven above room temperature or other means of heat curing. Typical curing temperatures from various studies are 40 to

90°C for 6 to 48 h, to accelerate the formation of a geopolymer and enhance strength. After the required temperature exposure, the geopolymer cured constantly at room temperatures until meeting the testing days [12]. The characteristics of properly-cured geopolymers are of the same line or better than those of OPC [36]. Presently, geopolymers can be manufactured as precast reinforced-concrete products like sewer pipes, railway sleepers, wall panels, and culverts [21][50][9]. Murmu [40] studied the effect of curing on the unconfined compressive strength (UCS) of black cotton soil and FA admixtures treated with 5M NaOH (SH) solution and cured in ambient temperature for 0, 7, 14, 28, and 90 days. They found out that the UCS value increment with a rise in the curing period, which is due to the creation of a geopolymeric binder from the reaction of silica and alumina in the existence of a strong base [52]. According to IRC [25], an improved sub-base layer has to satisfy a minimum UCS of 750 kPa at the end of 28 days of curing and a granular material stabilized with lime fly ash should require to reach a minimum UCS of 1500 kPa at the end of 28 days curing. Similarly, it recommended a minimum CBR of 8 for a soil to be used as the subgrade. The schematic formation of a geopolymer precursor was given by Davidovits [16]. A geopolymer can take one of the three basic forms [16]:

- the repeating unit of Poly (sialate), [-Si-O-Al-O-]
- the repeating unit of Poly (sialate-siloxo) [-Si-O-Al-O-Si-O-]
- the repeating unit of Poly (sialate-disiloxo), [-Si-O-Al-O-Si-O-Si-O-]

The chemical reaction process may go forward with these three steps that are the condensation or transportation or orientation of precursor ions into monomers followed by the dissolution of silica and alumina atoms from the raw material in the presence of hydroxide ions and then polycondensation of monomers into polymeric structures [16][62]. Geopolymerization associates the dissolution of aluminosilicate from the precursor succeed by short-ranged polymerization to create a Si–Al based geopolymer backbone [59]. The superior properties of geopolymer concrete are higher compressive strength, long working life before stiffening, nontoxic, impermeable, higher heat resistance, sets at room temperature, bleed free, and resist all inorganic solvents [23].

3 Factors Affecting The Strength of Fly Ash-Based Geopolymer

3.1 Effect of particle size

The particle size of raw material is a very essential parameter to increase the strength of a geopolymer after activation. Thus, the fineness results in greater strength [31]. Specifically, after 7–14 days increment in the fineness of FA ensured in a significant gain in strength improvement of paste and alike at around 1–3 days, the strength development is enhanced with the use of finely ground FA [52]. According to them to get comparatively high strength for an ambient cured geopolymer paste, sodium hydroxide (SH) concentrations of 9.5–14.0 M along with SH-activated ground fine FA with an average particle size of 10.5 microns are suitable. The SH concentration requires to be higher with temperature curing to attain a greater rate of strength development of geopolymers in the case of coarser fly ashes. The gel formation for the geopolymerization process started within colloidal form differing in sizes from less

than 1 μm to about 20 μm [49]. To analyze the effect of the particle size of FA on unconfined compressive strength of geopolymer stabilized BCS, Murmu [41] has taken two distinct sizes of FA i.e., FA finer than 75 μ and 425 μ . According to the authors, in an alkaline solution, the finer fly ash particles give a faster reaction in comparison with the coarser particles. The degree of dissolution of aluminosilicates in alkaline solutions with high pH is largely dependent on morphology, composition, and the particle size of the precursor [7].

3.2 Effect of Geopolymer cured at ambient temperature

The various works from literature proved that the curing temperature is a powerful factor for the strength gain of the geopolymer. But at the same time, it is tested that under ambient temperature curing conditions, an FA-based geopolymer gains strength at a very steady rate for a longer period like 90 days or more. However, when cured at high temperatures strength and other mechanical properties are evidently improved. But, the motivation mostly is to find out the proper method for geopolymerization at ambient curing temperature to achieve the required strength for real field applications like pavement base and sub-base construction. Somna [52] recommended an ambient curing temperature of 25-28°C for NaOH-activated ground FA geopolymer pastes with a concentration of 9.5–14.0 M for relatively high strength. The UCS and CBR values of FA geopolymer stabilized black cotton soil containing 5 to 20% FA cured at a room temperature of $25 \pm 2^\circ\text{C}$ for a minimum of 14 days got a satisfactory result for sub-base as well as sub-grade application [40]. According to Khatar [29] in a hot environment (average temperature 36-42°C and max temperature of 48°C), another heat source due to sunlight drives to a greater rate of polymerization by which strength increases to the desired level.

Effect of different curing conditions

Alike curing period and curing temperature, curing condition is also a very important factor in strength variation of geopolymer. Nuruddin [43] studied two different ambient curing conditions for geopolymers in hot weather. First, geopolymer curing under the shade outside the laboratory and the second one, the prepared sample is concealed by a translucent plastic sheet and then exposed to direct sunlight. The strength of the geopolymer for the former one was greater than that of later, because of the alternative temperature curing of the Sun. In line, results were achieved by keeping geopolymer samples in direct sunlight and covering with water-proof sheets or hot gunnies [44]. Again there are two different curing conditions available that are open and protected curing conditions. Former produce solid bodies characterized by intensified leaching of certain oxyanionic metalloids, high porosity, and low compressive strength. On the contrary, later promotes less porous systems, binder development, and lead to higher strength. This enforces restrictions to leaching in the time of geopolymerization formation which obstructs releases of oxyanionic metalloids in comparison to the former method [27]. Self-internal temperature from a bulk volume could be a heating source for geopolymer concrete production [57]. According to their

test data, temperature-induced during the curing of geopolymer concrete are a function of volume mix. By capturing the heat evolved by an exothermic reaction in the formation of geopolymer concrete, they remove additional curing requirements. As reported by Mostafa and Brown [38] both the Ca-based additive geopolymer's and OPC have nearly equal heat measure evolution.

3.3 Effect of low temperature cured geopolymer

The reaction of FA was immensely slow at ambient temperature. The structure of geopolymers can be semi-crystalline or amorphous, depends on the condensation temperature. One can differentiate between these two types of structure of geopolymer by temperature variation among them. Semi-crystalline polymers are obtained at 150–1200°C, whereas amorphous polymers are obtained at 20–90°C. Muniz [39] observed that 60 °C heat curing is the best for the geopolymerization process and also for the physical and mechanical properties. Nonetheless, the process of geopolymerization is very slow with low absorption of the SS solution on the surface of the metakaolin at 30 °C. As a result, both gel and network formation obstructed due to the entrapped water in pores and build up a higher amount of macroporosity. Palomo [45] proclaimed that the different fly ash activated with 8 to 12 molar SH produced a geopolymer with compressive strength of 35 to 40 MPa when cured at 85 °C for 24 h. At the same time, by the inclusion of SS (Na_2SiO_3) to the SH solution the compressive strength increases sharply up to 90 MPa. According to them, if the temperature curing time exceeds 24 h from 5 h with 85°C, the increase of strength is very minimal. The longer curing period does not affect the crystalline part of the geopolymer. It is revealed that change responsible for the difference in the strength originates within the amorphous phase of the structure [60].

Phetchuay [47] found out clay-Fly Ash geopolymers with 40 °C for a period of 7, 14, 28, and 60 days of curing exhibit higher strength than those with ambient curing when used for pavement subgrade applications. Arioz [6] investigated the compressive strengths of the geopolymer pastes for 6, 15, and 24 hours at various curing temperatures of 40°C, 80°C and 120°C. From the test results, it is concluded that the compressive strengths of samples cured for 15 hours were higher than those of the samples cured for 24 hours. On the contrary, an increase in temperature increases the strength of geopolymers. However, the strength decreased with increasing curing duration for the samples cured at 40°C after 90 days of aging. Hence to achieve a required strength temperature curing required, but high temperature or long curing period may be detrimental for strength enhancement.

3.4 Types and effects of alkali activator concentration

Alkali activator concentration is the utmost important factor for geopolymerization. Commonly used alkaline activators are potassium hydroxide (KOH), potassium silicate (K_2SiO_3), SH, SS, calcium hydroxide ($\text{Ca}(\text{OH})_2$), and combinations of the above. But the combination of SH and SS solutions is the strongest base in geopolymer synthesis. Because SH is a vital factor used for the dissolution of alumina-silicate miner-

als along with its concentration while SS is responsible for binding activities and initiating geopolymeric formation in the presence of Si [46]. The main role of adding SS is to the dissolution of an ample amount of Si ions to accelerate the formation of geopolymer precursors [62]. A clear increase in the strengths of the geopolymer pastes occurred when the SH concentration raised from 4.5 to 9.5 M [52]. They also observed that the compressive strength started to decline when the concentration of SH was as high as 16.5 M. The strength development of the geopolymers are directly proportional to an increase in alkali concentration, but at the very early stages, excess hydroxide ion concentration caused precipitation of aluminosilicate gel, as a result, the strength of geopolymers decreases [34]. The dissolution of FA was accelerated, when OH⁻ concentration was high enough, but polycondensation was hindered [63]. An increase in alkali content developed higher Unconfined Compressive strength [48]. Sukmak [53] suggested that the optimum alkali ratio (SS/SH) for FA based clay-geopolymer was 0.7.

3.5 Effects of chemical composition in geopolymer mixture

Silicate to hydroxide molar ratio

The compressive strength development depends on the molar ratio of silicate to hydroxide and especially the SS/SH ratio plays a vital role to achieve the required strength. Murmu [41] recommended using (SS/SH) ratio ≤ 1.5 because above 1.5 the compressive strength of the geopolymer stabilized Black cotton soil decreases. M_2O ($M=Na/K/metallic\ ions$)/ SiO_2 ratio shows a positive effect on the compressive strength of geopolymer. An increase in compressive strength is expected to be directly proportional to the increase in the concentration of alkali M_2O and inversely proportional to an excess amount of added silicate [23][62]. This is because excess SS hinders water evaporation and structure formation [11]. The matrix activated with K_2SiO_3/KOH achieved the greatest compressive strength as compared to SS/SH and K_2SiO_3/SH . K^+ ion allows a higher rate of solubilized polymeric ion and dissolution that leads to dense polycondensation reaction which causes an increase in the compressive strength of the matrix and overall network formation.

Silicate to aluminum molar ratio

The silicate to Aluminium molar ratio is very effective for the construction of the complete structure of the geopolymer. According to Rangan [35], the best result for strength gain was with silicate to the aluminum molar ratio between 2 to 3.5 for the construction of transportation infrastructure. For a better interparticle bonding and mechanical strength of geopolymers, a highly dissolving silicate concentration is required which synthesized alumino-silicate gel. The strength of geopolymer increases due to transformation of amorphous to semi-crystalline Polysialate ($Si/Al = 1$), Polysialate-siloxo ($Si/Al = 2$), and Polysialatediloxo ($Si/Al = 3$) [17]. The concentration of SH is contrarily proportional to the Si/Al ratio which illustrates that the leaching of silicate and aluminum was dependent on SH concentration. According to [62], the percentage of the ratio silicate to aluminum in the original raw material presents a correlation with mechanical strength. SS gels insoluble in water can be produced at

SiO₂/Na₂O molar ratios higher than 4.4. So for geopolymer, the ratio should be less than this value.

3.6 Effect of calcium hydroxide, Ca(OH)₂

The pH value of the pore water increases due to the dissociation of calcium hydroxide. Alike to the pozzolanic reaction high alkaline concentration dissolve the Si and Al from FA particles. In this geopolymer formation the aqueous Si and Al then gradually react with Na₂SiO₃. Hence Ca(OH)₂ is an important part of the geopolymerization which helps to increase the strength. According to Jaarsveld [59], FA in the presence of Ca leads to greater mechanical strength. Calcium precursors could lead to the formation of calcium silicate hydrate or (C, N)-A-S-H gels within a geopolymeric binder, improving the overall properties significantly. The presence of calcium oxides accelerates the setting procedure [60] and also improves the mechanical properties of geopolymer mixtures [34][56][30]. Phetchuay [47] used Calcium Carbide Residue (CCR) which is rich in calcium hydroxides used as a pavement material with fly ash to stabilize silty-clay soil. They suggested CCR as a sustainable alkaline activator for geopolymer stabilized subgrade materials for road construction work. However, Class F FA is preferred over Class C FA since a high amount of calcium affects the geopolymer process [13] and due to its abundant availability over high calcium FA. By the process of calcination, calcium oxide content increases. High calcium oxide content decreases the microstructural porosity and in turn, strengthens the geopolymer by forming amorphous structure Ca-Al-Si gel during geopolymerization [59].

3.7 Effect of the manufacturing process

The different manufacturing processes found from previous literature are general mixing process, separate mixing process, and pre-dry mixing process. In the “general mixing process,” the alkaline solutions are mixed previously in a container then raw material adds to the solution for better mixing [2]. In the “separate mixing process” SH solution is first mixed with raw material, then the SS solution adds to the mixture. But, in the “pre-dry mixing process” the raw materials are mixed first with the alkaline activators in its solid form then water is added to it [55]. In separate mixing processes, when NaOH added with the raw material it dissolved silica and alumina from the precursor initially, and after that SS added to the prepared paste which increases the binding activity, resulting in higher strength than that of other manufacturing processes [22]. The disadvantage of pre dry mixing process is as raw materials were previously activated the structural formation of the pre-geopolymerized geopolymer may be incomplete, causing weak bonding. In this process, the reaction is incomplete and obtains lower compressive strength. It is also due to the extra water for maintaining the dissolution property of precursor and to compensate for the water loss during mixing under an exothermic reaction of solid alkaline activators. The only advantage of the pre-dry mixing process for pavement construction is its practical feasibility along with the adequate strength in ambient curing temperature, even though the compressive strength of the dry-mixing method was slightly lower than the two aforementioned procedures.

3.8 Immobilization of toxic metals by geopolymer

More comprehensive research is required to investigate the leaching behavior of FA-based geopolymers for pavement construction applications because it causes a severe problem if leaches heavy metals and comes in contact with water bodies close to construction work. Also, geopolymerization was used as an emerging technology in the field of hazardous metals immobilization as the toxic metals were locked into the three-dimensional geopolymeric-zeolitic framework. For controlling the adsorption process the pH of the activator solution plays a significant role. The number of heavy metal adsorption capabilities of the geopolymer is directly proportional to an increase in the pH of the solution [10]. On the contrary, the adsorbent tends to select H^+ to adsorb, when the concentration of H^+ in the solution is higher. Hence, at a lower pH, the adsorption capability of heavy metals decreases. Due to less alkaline property, sodium silicate leaches out less Al and Si as compared to sodium hydroxide. The leaching of aluminum (Al^{3+}) and silicon (Si^{4+}) ions are lower with the KOH solution compared to the SH solution [54]. Increasing the concentration of water glass results in a more stable and less leachable structure. Arioz [6] studied about leaching behavior of class F FA with 12M NaOH solution and water glass in their experiments. According to them, the As and Hg immobilized in the structure, whereas some of the other trace elements like Zn, Pb, Cd, and Cr were not. Izquierdo [26] compared raw FA and FA based geopolymers by taking the solubility of elements as a parameter. They concluded that the FA based geopolymer is reasonable for the immobilization of many metal ions like Be, Nb, Ni, Pb, Sn, Cd, Th, U, Y, Bi, Co, Cr, Cu, Zr, and the rare earth elements. However, in water solution, the leached amount of elements are more in geopolymers as compared to raw fly ash. In the presence of high SH concentration, the compressive strength increases mainly through the leaching of Si and Al [12].

3.9 Effects of water addition in the geopolymer formation

Total weight of water to the total weight of solids in the mixture denoted as a water-to-solid (w/s) ratio. According to Vora and Dave [61], with the increase in water to the FA ratio, the compressive strength of geopolymer concrete decreases. The water content in the mixture plays a significant role in the hardening process. The strength of the sample decreases with an increase in a high heat curing for a longer period may cause due to heavy moisture loss through evaporation. Therefore, especially for ambient-cured processes or for the dry-mixing, the water evaporation should not happen too early, otherwise, may cause an incomplete reaction and crack formation. For fly ash-based geopolymer paste (w/s) ratio should be 0.18–0.22 [28]. Also, the overall w/s ratio was directly dependent on the liquid-to-binder ratio and (SS/SH) ratio. Increasing in additional water content increased workability, but decreased other properties of fly ash-based geopolymer concrete [5].

4 Conclusions

From the review, it can be concluded that FA geopolymers are useful Cementous material with promising potential for use in pavement construction, which could bring

economic and environmental benefits. Important conclusions from various studies are listed below:

1. The strength of a geopolymer is directly affected by the fineness of raw materials. The unconfined compressive strength increases as the fineness of precursor increases because the gel formation for the geopolymerization process started within the colloidal form with sizes varying from less than 1 μm to about 20 μm .
2. To achieve a particular strength by curing the geopolymer at ambient temperatures needs high alkaline activator concentrations, depending on the specific properties and surrounding factors of each precursor. There are many alternative methods of geopolymer heating like using a dry-mixing method, working in a hot environment, exposure to sunlight and with the addition of an appropriate dose of $\text{Ca}(\text{OH})_2$
3. With the increase in temperature the strength of geopolymers increases. However, it depends upon the curing duration of the sample. If the curing duration for the samples is too high at a particular temperature results in a decrease in strength.
4. A stronger ion-pair formation is highly dependent on a higher concentration of alkaline liquids, which provides a complete and fast polycondensation process at the particle interface. However, too high concentrations could lead to an increase in the formation of a coagulated structure.
5. The strength of geopolymer purely depends upon the factors like the chemical composition of raw material, SS/SH molar ratio, the concentration of alkaline activator, Si/Al molar ratio, and an additive used.
6. The manufacturing process of alkaline activators is one of the potential factors influencing the performance of a geopolymer, as it enhanced the degree of reaction.
7. The FA based geopolymer is capable enough for the immobilization of more than 85% of trace elements and rare earth elements. Increasing in additional water content enhances workability, but causes a decrease in other properties with the strength of FA based geopolymer.

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