SINERGI Vol. 28, No. 3, October 2024: 473-488
http://publikasi.mercubuana.ac.id/index.php/sinergi
http://doi.org/10.22441/sinergi.2024.3.004

A systematic review of geopolymer materials: innovations, prevailing constraints and resolutions

Lucia Omolayo Agashua[1],*, Chinwuba Arum[1,2], Bamitale Dorcas Oluyemi-Ayibiowu[1], Catherine Mayowa Ikumapayi[1]
[1]Department of Civil Engineering, Federal University of Technology Akure, Nigeria
[2]Department of Civil and Mining Engineering, School of Engineering and The Built Environment, University of Namibia, Namibia.

Abstract

Geopolymer is a novel eco-friendly biodegradable cementitious material for which the emergence is expected to reduce the carbon-dioxide emission caused by Portland cement manufacturing companies. Geopolymer material possesses exceptional mechanical properties and other admirable properties such as fire and corrosion resistance. Most industrial solid wastes (ISW) and waste smoldering bottom ash (WSBA) are stacked up, filling land mass, besides their harmful influence on the surroundings. Reprocessing could make them suitable for use as materials for making geopolymers. They can efficiently adsorb heavy metals, dyes or pigments, and other radioactive contaminants, which is very helpful to humanity's future development. On the other hand, due to the exceptional features of geopolymer material, its functions go further than that. Specific helpful information regarding geopolymer materials was made known in this study. The study encompassed the source of geopolymer materials, the geopolymerization process, the categories of activators, their formation techniques, and the diverse usage areas of geopolymer materials. Furthermore, the factors influencing the mechanical features of geopolymer materials were discussed. Finally, these materials' inadequacies and usage precincts were summarized, and their evolution was abridged to prepare a theoretical or hypothetical base for the lasting improvement of geopolymer materials.

This is an open access article under the CC BY-SA license

Keywords:
Activator;
Curing;
Geopolymer;
GGBS;
Polyethylene glycol;
Strength;

Article History:
Received: September 7, 2023
Revised: March 25, 2024
Accepted: March 29, 2024
Published: October 2, 2024

Corresponding Author:
Lucia Omolayo Agashua
Department of Civil Engineering, Federal University of Technology Akure Ondo State, Nigeria
Email: agashualight@gmail.com

INTRODUCTION

Geopolymer (GP), also well-known as alkali-activated material (AAM), is an inorganic polymer material that can use both waste products and natural materials as the key raw materials blended by acid activation or alkali reaction [1][2]. Popular raw (natural) materials with their acronyms are displayed in Table 1. Geopolymers are very good at resisting chemical corrosion, oxidization, and fire and possess excellent durability and high mechanical strength [3, 4, 5, 6]. Ever since the beginning of the 1980s, GP materials have been counted as stand-ins for Portland cement [1, 7, 8, 9], mostly on account of their functioning advantages and low carbon dioxide emissions. Investigators successfully formulated the geopolymer glaze with exceptional features like high strength, synthetic ageing and high temperature resistance (HTR), as well as safe processing performance (SPP), which might be utilized as glazings for light-weight polystyrene sheets (LWPS) for partitions or detachments, walls, and roofs [4, 10, 11, 12, 13]

The research work of Alrefaei *et al*. [10] on the tektite geopolymer fulfills all performance prerequisites for solar or lunar construction materials: high together with low temperature cycling, about nil water ingestion, vacuum stability, and exceptional mechanical features [2, 14, 15, 16]. Owing to its outstanding features, geo-polymer stuffs have drawn full awareness as an advanced material for structure refurbishment from the time of its discovery. For instance, geopolymers have been utilized at the airfield and in core railway sleepers in Australia. They are likewise utilized for vitiated concrete patch-up of rigid concrete (pavement) in army stations [17, 18, 19, 20]. Recently, geopolymers have also been utilized to restrain detrimental metals. Reports have revealed that the ooze actions of numerous hazardous metals through alkali-activated urban solid waste smoldering fly ash (AUSWSFA) were efficaciously obstructed, and the leaking level was within the Chinese paradigm [1, 21, 22, 23].

Hence, geopolymers not only transform waste into wealth but are also eco-friendly. In recent times, viable development has been encouraged all over the globe, which necessitates us to utilize natural and ecological resources as little as possible. With this innovation, the industrial hazardous solid wastes (IHSW) discharge, for instance; red mud (RM), fly ash (FA), effluence of dyes, heavy metals, slags, and tablets, have stirred public concern. The universal yearly production of FA is projected to range from seventy-one million to one billion tons. Lots of FA discarded in land fills, ash or slag ponds, as well as air entrainment of particles and leaching of contaminated materials into the water or soil propounds a major hazard to the environs [24][25]. Right now, there are various studies on mixed-base geopolymers.

Equally, all categories of raw materials supplement each other; on the contrary, they can efficiently lessen the ingesting of natural and ecological resources. Although some properties and usage of geo-polymers have been discussed by researchers in Nigeria and elsewhere across the globe [26, 27, 28, 29, 30], the dialogue is not broad enough presently.

This scrutiny aims to appraise the formulation and blending of geopolymer materials, the features influencing the physiognomies of geopolymer materials, and the multi-functional usage of geopolymers. From the prevailing limitations of geopolymers discovered, the resolution progress is summarized to present a theoretical and hypothetical base for long-term improvement.

MATERIAL AND METHODS

Geopolymerization

Geopolymers are blended via the geopolymerization of alumino-silicate materials that melted in the alkali-activator mixture at very high temperature, creating and materializing an amorphous stage, as well as three-dimensional (three-D) silico-aluminate net work composition [31, 32, 33, 34]. Even though investigators have different notions concerning the integration technique that happens throughout geopolymerization, there is a majority belief that geopolymerization can be split into three main phases [4, 35, 36, 37, 38, 39].

The phases include:

(1) The dissolution and suspension of alumino-silicate materials in the strong or distilled alkali solution develop the free-silica as well as the alumina tetrahedron component.

(2) The displacement, solidification, or materials gelation, as well as the concentration of alumina reaction versus silica-hydroxyl, are used to create the inorganic and inert geopolymer crystallize stage. At this phase, water is released from the system as a result of the hydrolysis system.

(3) As the crystallize stage sets, it shrinks to generate a three-dimensional (3D) set-up of silico-aluminate that creates a geopolymer. It means that activators perform a very crucial task in geopolymerization as displayed in the graphical abstract and Figures 1 (a-c).

The concentration of 10M NaOH yielded the greatest suspension rate of Si4þ plus Al3þ ions in alumino-silicate materials equated with the lesser NaOH concentration, which causes a greater rate of geopolymerization [3, 5, 40, 41, 42, 43, 44]. To boot, the curing temperature is paramount to the geopolymerization, because the suspension of raw materials is augmented with the temperature and more rapid happening of amorphous stage crest in XRD display specifies that the greater temperature is good for geopolymerization [45, 46, 47].

THE MATERIAL ORIGIN

Raw materials

Clay concept and its resources

Clay is an alumino-silicate salt with very tiny particles less than two millimeters (<2 mm). It is a broadly spread natural mineral resource, with cohesive as well as acquiescent down-to-earth rock structure. It is also a class of encrusted silicate from aluminaoctahedral layered and as well as silicon oxygen tetrahedron composition [2, 48, 49, 50, 51].

Table 1. Popular materials for construction work and their acronyms

Material	Acronyms
Clay	-
Fly ash	FA
Metakaolin	MK
Laterite	-
Red Mud	RM
Mullite	-
Silica fume	SF
Diatomite	-
Cassava pee ash	CPA
Coal gangue	CG
Volcanic ash	VA
Sewage sludge ash	SSA
Ceramic grog	CEG
Rice husk ash	RHA
Glass wool residue	GWR
Kaolin clay powder	KCP
Glass powder	GP
Kaolin	-
Iron ore tailing	IOT
Bentonite	-
Bauxite	-
Zeolite	-
Ground granulated blast furnace slag	GGBS or GGBFS
Halloysite	-
High calcium fly ash	HCFA
Drinking water treatment residual	DWTR
Palm oil fuel ash	POFA
Olive bio-mass fly ash	OBMFA
High magnesium nickel slag	HMNS
Olive bio-mass bottom ash	OBMBA
Pyroclastic flow deposit	PFD
Electrolytic manganese dioxide residue	EMDR
Red clay brick waste	RCBW
Calcium carbide residue	CCR
Urban solid waste incineration fly ash	USWIFA
Pyroclastic flow deposit	PCFD
Bauxite ore tailing	BOT

Due to its physiognomies, it has been utilized as a precursor for creating geo-polymers and widely utilized are zeolite, kaolin and so forth. Kaolin, also called dolomite, is fine, white, soft clay with fire resistance and enriched plasticity. Similarly, metakaolin (MK) is an anhydrous alumino-silicate created through kaolin clay dehydration at a standard temperature between 600°C and 900°C. Figure 2 (a) and (b), reveal the common MK that have been comprehensively utilized in the geopolymers making.

The MK-created geopolymers show thermal insulating features [5][52], very high bonding strength, as well as compressive strength [2, 7, 10], et cetera. Because of the exceptional mechanical features of MK-produced geopolymers, several investigators have blended other ingredients with the system to minimize costs and sustain its exceptional deed whereas achieving resource recycle [3, 7, 9, 24]. Likewise, the research amalgamates kaolinite-produced porous geopolymer materials (KPGM), which possess dual purposes of decreasing heat transmission and noise [8][13]. In recent times, some researchers have publicized that ninety-five percent of raw kaolin is riveted; besides, the formulation through alkali excitation has a compressive strength equal to 67.1 MPa [28][39]. Using natural or raw kaolin rather than calcined-metakaolin lessens costs and adversative ecological effects.

Lateritic Soil

Laterite is a mineral (soil) that is rich in aluminum, alumino-silicates and iron. The majority of lateritic soils are reddish-brown in colour and have been utilized for a very long period as a conventional building material, brick-making, and road construction, due to their strong resistance to oxidization. In recent years, a novel trend in geo-polymer invention has been based on laterite, which possesses high mechanical strength [6][18].

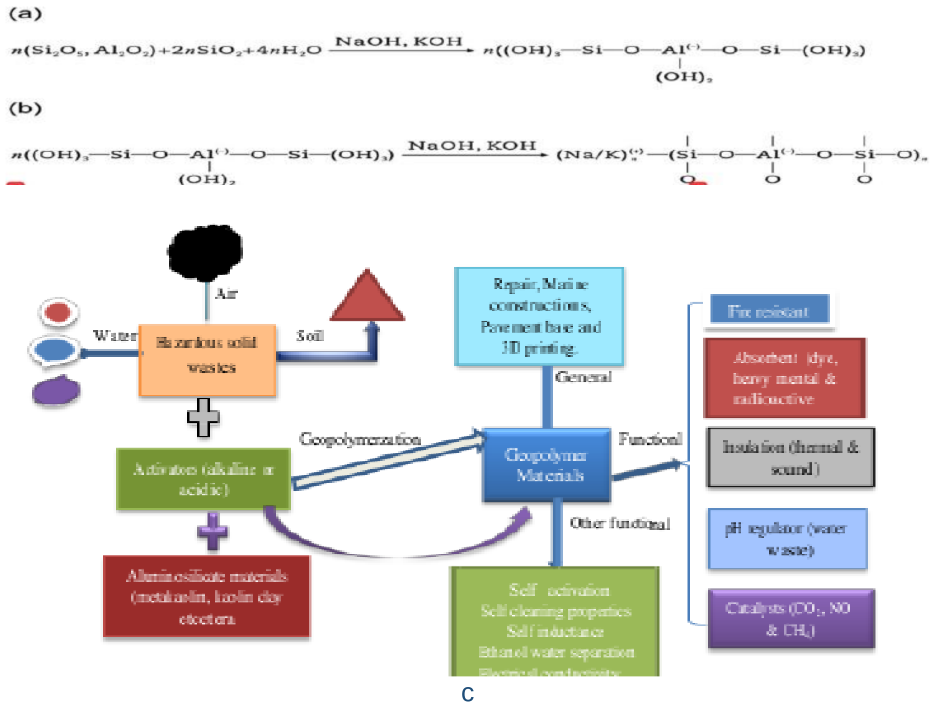


Figure 1. Graphic illustration of the creation of (a) geopolymer materials precursor, (b) backbone of geopolymer, (c) crucial task in geopolymerization [14, 17].

What is more, the chemical physiognomies of lateritic soil have excellent molar corrosion ratio (SiO_2/ or (Al_2O_3þFe_2O_3)), which is utilized as raw/ or natural material for the geo-polymer class Na-poly (sialate-siloxo) since the molar oxide proportion of silica to alumina substantially alters the microstructure as well as mechanical physiognomies of the lateritic-soil geo-polymer [1, 42, 36]. Additionally, it is preferable to mix laterite with other solid wastes to obtain high strength. Both lateritic plus mixed lateritic-slag geopolymer are good for non-load bearing building materials [4, 6, 9].

Others minerals

Raw or untreated minerals are precursors of GP, and the widely used are halloysite, bentonite, bauxite, mullite, diatomite, et cetera. Some of their features are displayed in Table 1 and are observably alumino-silicate materials. Because of the small amorphous quantities of some raw minerals, which create an unsatisfactory action, some of them must go through high temperature pre-curing as well as mechanical instigation treatment, et cetera, as presented in Figure 2.

Waste products

Blast furnace slag (BFS)

BFS, often called slag, is an iron making bi-product that can be achieved at roughly 1500^0C [8, 15, 19]. The common slag is displayed in Figures 3 (a) and (b). Based on the cooling scenario, Ground Granulated Blast-Furnace Slag (GGBFS), is the type of BFS cooled in water, which is largely utilized as a part replacement for OPC after crushing as a result of its amorphous quality, high pozzolanic as well as hardness action [20, 34, 48].

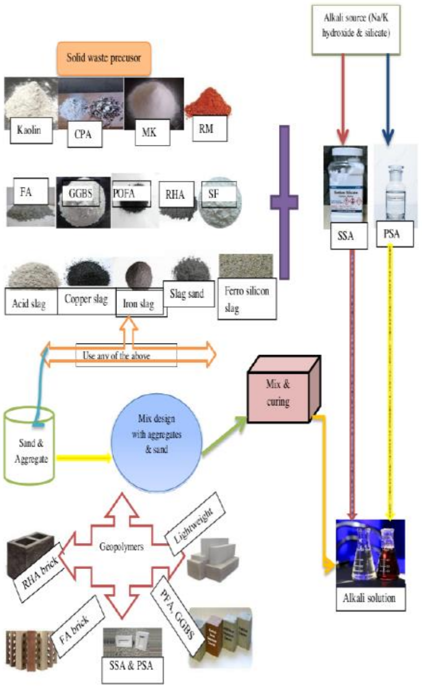


Figure 2. Geopolymer concept (materials, mix and curing)

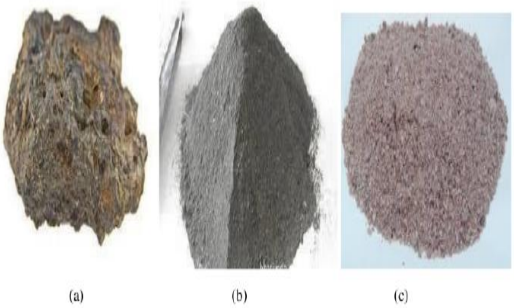


Figure 3a. Widely utilized slag raw (natural) materials; a) slag deposit; b) Powder form; c) Granulatedblast furnace slag

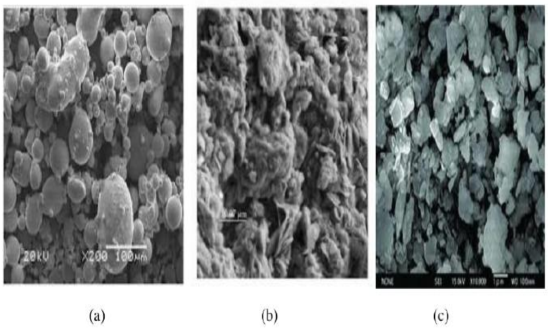


Figure 3b. SEM Images of: a) Slag; b) Steel slag and c) Granulated blast furnace slag.

GGBFS is one of the conventional raw materials for geo-polymers, with the Si/:Al ratio of 1.71-3.67. GGBFS is extremely reactive to the amalgamation of geopolymers and, it is promising at obtaining a good reaction rate at a temperature as small as 0°C [8, 45, 51]. Because when slag is utilized as a cement supernumerary, a lesser amount of heat is generated during hydration, and also decreases cracking threat [7, 43, 47]. GGBS might be utilized to enhance the long-term strength, porosity or absorbency, sulfate resistances, alkali silicate reactivity (ASR) of concrete, and lessen the water needed, permeability as well as hydration heat of the concrete [3, 8, 10, 17, 52].

Bio-Mass Ash (BMA) and Waste Blazing Bottom Ash (WBBA)

Rice fibre/ or husk ash (RHA) is derived from leftovers from burning rice husks. Agricultural or agro wastes are rich in silica, especially RHA, which is regarded as a clean substitute for enriching geopolymers' properties [8, 26, 39]. The usage of RHA additive in geo-polymer concrete can decrease the utilization of nano SiO_2 and also helps lessen the litter nuisances created by the dumping of RHA inland fills, specifically in rice producing nations [3][32]. RHA has been extensively utilized in self compacting geopolymer concrete (SCGC) owing to its great reactivity enthused via high silicon content as well as ultra high specialized surface zone [1][4].

Similarly, sugar-cane bagasse ash (SCBA) is another byproduct from industries that has been utilized by several investigators for volcanic ash materials (VAM) feed-stocking that are rich in silicates as well as alumina [6, 9, 14].Bottom ash (BA) is the principal by product of metropolitan solid waste smoldering. In heavy metals BA with a tiny particle size is very high [7][23], besides BA has lately been progressively reprocessed as building concrete and binders [7][46]. More to the point, BA from burning metropolitan sewage slurry is utilized in concrete with a ten to fifteen percent dose, which might attain greater strength than concrete without adding BA [6, 45, 49, 52].

Fly Ash (FA)

FA is a byproduct from industries created through smoldering of coal, which is in general, classified into class C, as well as class F. The incineration of bituminous coal forms a well-known class of fly ash with very little CaO contents, identified as type F fly ash (FFA) [4, 48, 50]. Both lignite as well as sub-bituminous coal are as well utilized as novel power fuels to create type C fly ash (CFA) with very high calcium content, and is displayed in Figures 4(a) and (b). FFA features are related to that of ecological volcanic ash [3, 28, 34]. FA has been a readily available by-product universally since the early 20th century, commonly introduced as a main ingredient of cement or concrete and is a widely used raw material for preparing geopolymers with microscopic shapes of fine spherical particles [6].

However, the utmost free CaO contents restrain the usage of HCFA in the OPC system, whereas, in geopolymer, the usage of HCFA is far above resourcefulness [7, 44, 47, 51]. CFA and FFA are 1.82-2.52 and 1.86-3.09, respectively. Substituting cement with FA makes the environment fine because it diminishes greenhouse gas emissions (GHGE) and lessens construction prices. FFA is advantageous at low cost, easily available, has good spherical features, and has high activity amorphous silicate and aluminate contents, et cetera. Similarly, high engineering strength geopolymers can be effortlessly manufactured in an alkali activator solution (AAS) [2, 28, 34, 43].

Red Mud (RM)

RM is obtained from Bayer process by-product utilized in industrial aluminum refinement.

Figures. 5 (a-c) display the widely used RM. Below high temperature with pressure scenario, the Bayer activities melt the soluble portion of bauxite and sodium hydroxide. Inexorably, an insignificant quantity of sodium hydroxide utilized in these activities stays in the RM, and yielded high pH value [2, 6, 7, 41].

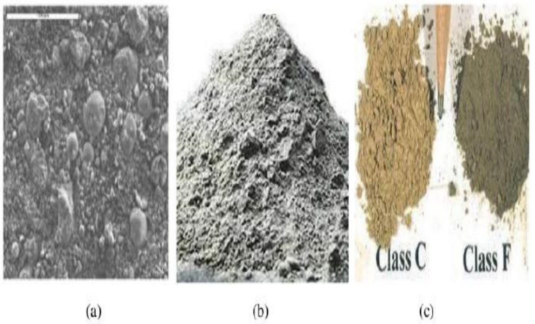


Figure 4a. Widely utilized FA raw (natural) materials; a) FA deposit; b) Powder form; c) types of FA

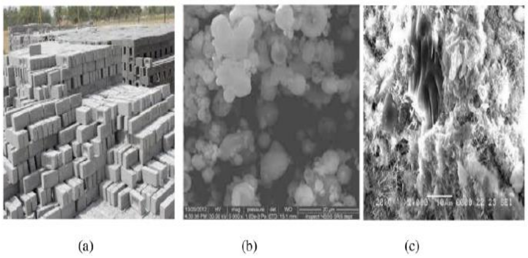


Figure 4b. Images of FA: a) Bricks; b) SEM and c) Blended composite.

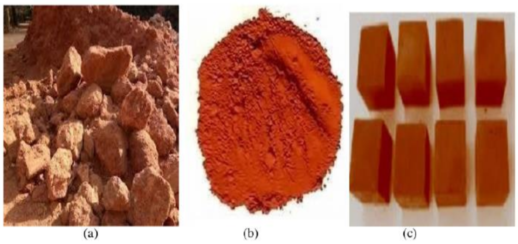


Figure 5a. Widely utilized RM raw (natural) materials; a) raw; b) Powder form; c) made with RH geopolymer

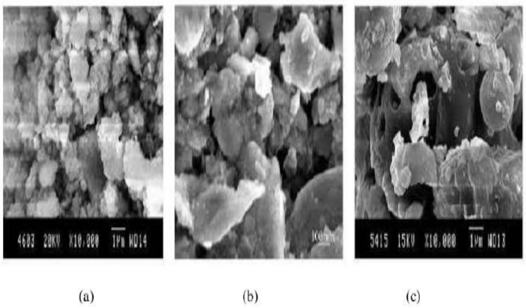


Figure 5b. SEM Images of: a) Untreated RM; b) treated RM and c) sintered RM.

Utilizing RM in this type of mud conserves the energy and time needed for mud drying; it lessens the total quantities of alkali activators through using RM at extreme alkalinity levels, hence helps reduce the cost of the GP construction [25, 37, 49]. For FA-created geo-polymers, the optimum substitution quantities of RM vary, comparative to NaOH concentration as well as curing scenarios [7][12,]. Also, research revealed that the GP blended with RM possesses greater strength plus durability [3, 43, 52].

Other raw materials

The most frequently utilized materials for geopolymer are metakaolin (MK) Figures 6 (a) and (b); steel slag (SS), coal gangue (CG), silica fume (SF), high magnesium nickel slag (HMNS), volcanic ash (VA), and waste glass (WG), et cetera. RM, FA, BFS, and materials like RHA, such as the main bio-mass ash, all indicated high silica as well as alumina content that is appropriate for add-on or gelling materials.

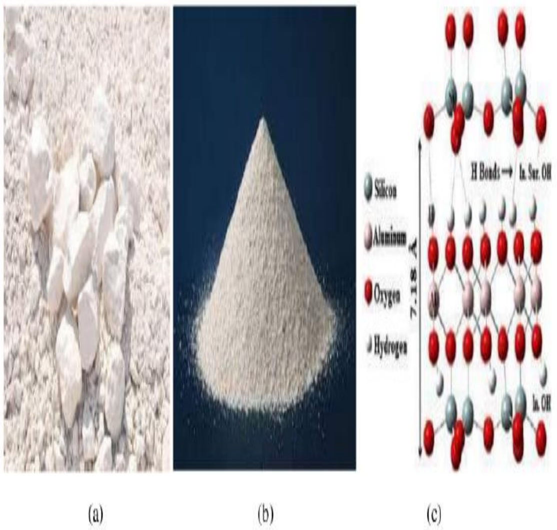


Figure 6a. Widely utilized MK raw (natural) materials; a) raw; b) Powder form; c) Bonds.

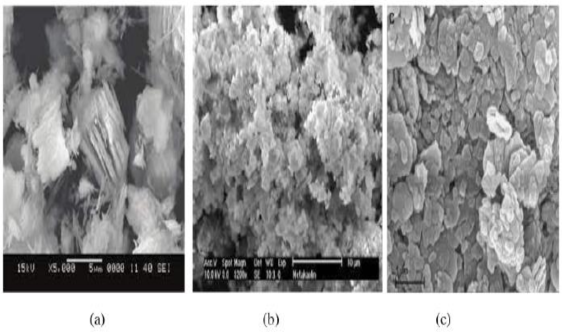


Figure 6b. Images of MK: a) SEM; b) micro-morphology and c) Reactivity in alkaline environment

The waste catalytic agent residue released from several industrial products has abundant silicon and aluminum features as well as amorphous composition, which can be utilized for synthetic geopolymers; meanwhile, its value of compressive strength ranges from 40MPa to 85 MPa [4, 32, 47].

CATEGORIES OF ACTIVATORS

Acidic activators

Some geopolymers are activated via acidic activators, while most are through alkali activators Figure 7. The MK-created geopolymer was manufactured via a phosphoric acid solution activator with an excessive compressive strength of roughly 93.8 MPa [48, 50, 52]. Additional reports also revealed that acid-created GP possesses greater temperature resistance equivalent to 1450°C and excellent mechanical features than alkali-created geo-polymers [1][7]. The scrutiny of phosphate manufactured geo-polymer samplings with various Si/ or Al and Al/or P illustrates that the impacts of P-poor, Al-enrich, and Si-enrich, features are safer [8, 32, 50].

Alkali activators

Several researchers have publicized that geopolymer materials are usually activated via alkali activators, which combine liquid and solid. Conversely, NaOH and Na_2SiO_3 have been expansively utilized as activators in prior researches, but now most of substantially corrosive alkalis are hardly utilized as activators, and are steadily substituted by diverse solid activators. For example, sodium water glass was utilized as an activator to create MK-created geo-polymer that has compressivestrength equaled to 63.82 MPa [3][28]. By using hydrated lime and solid Na_2CO_3 as activators of BFSSF-created geopolymer, the strength is between 50MPaat and 85MPaat 28 d, with curing temperatures of 25^0C and 85^0C, correspondingly [34][52].

Likewise, Na_2CO_3 and Na_2SiO_3 are activators that substantially enhanced the overall setting time, but compressive strength decreased with Na_2CO_3 quantities. Meanwhile, the synthetic activator activated geopolymer cleans above the single Na_2SiO_3 or Na_2CO_3 activated geopolymer [10]. Additionally, sodium sulfate as an activator has little influence on FA with excessive Fe_2O_3 quantities but considerably affects the early strength of FA-created geopolymer [7]. The most commonly utilized activators are potassium and sodium based activator. From prior investigations, the activation efficacy of sodium-created alkali activators is above that of potassium-created activators for FFA [3][12].

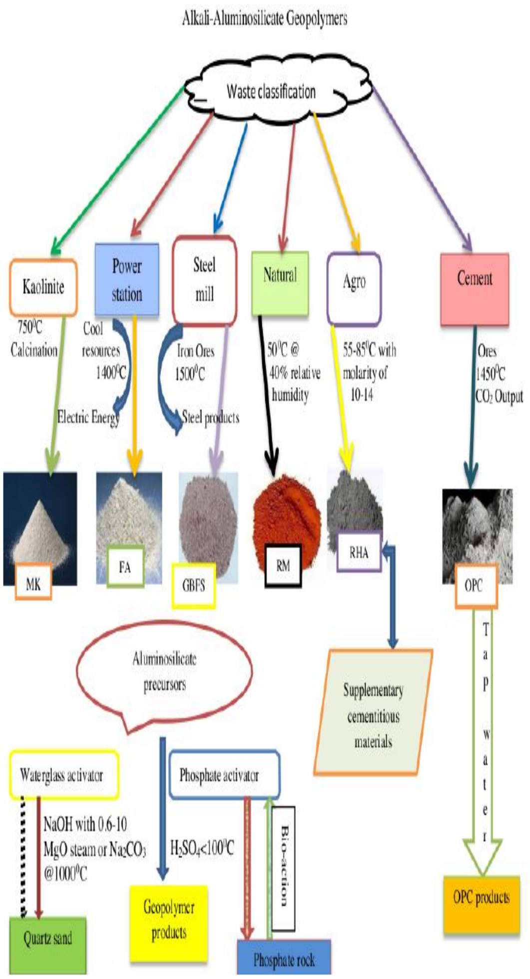


Figure 7. Creation and reinvigoration of alkali aluminosilicate geopolymers and various features [4][46]

On the other hand, Duan et al. [53] and Bouaissi et al. [50] discovered that using potassium composites in GP structures exhibited greater alkalinity than NaOH. Investigators validated the efficiency of lithium hydroxide solution as an alkali motivator that can be glazed with GP particles to lessen the suspension of active silica and the probability of liquefied active silica forming ASR gel [1][17].

FORMULATION TECHNIQUE OF GEOPOLYMERS

Based on the prior formulation techniques of geo-polymers, most of them are classified into two categories. Depending on the category of activators, the first among them is used for the formulation of one-portion, while the second is the formulation of two-portion geo-polymers. For the one-portion formulation, the handling of activators is stress-free by averting the usage of risky alkali solutions. To start with, all dry materials, comprising the precursor material and the solid activator, are dried up at steady or dawdling speed before being blended consistently. Then, the water is introduced bit by bit to the mixture while blending at a gradual rate [45][47]. For two-portion formulation geopolymers, the activator is made twenty-four hours (24h) before mixing (Figure 8). Then, the already made alkali solution is blended with more water. Next, the liquefied ingredients are introduced to the dehydrated blend and continued stirring till it is homogenous. Lastly, the freshly made blend is slowly transferred into the mould via vibration molding, covered with polyethene coat, and then discharged after twenty-four hours for curing per specification [3, 6, 10].

FEATURES OF GEO-POLYMER MATERIALS

The cement company infects the air, whereas geo-polymers are favourable to investigators due to their exceptional cleanness. Geopolymer concrete (GC) is a novel and sustainable innovation of construction materials, equating with OPC, and it has numerous merits. Understandably, the features rest on numerous physiognomies such as geo-polymer mortar (GPM) and geo-polymer concrete (GPC) novel blending deed, microstructure investigation, as well as hardening operation.

The Fresh Behaviour of Geopolymer Materials

Slump And Workability

The workability of geopolymer is essentially influenced by the particle shape of raw materials, as shown in Table 2 and Figure 9. For instance, a reduction in FA particle size enhances the fineness of FA as well as the workability of the geopolymers [6, 45, 49, 50]. On the contrary, slag created geopolymer ingredients are irregular because of their particle shape, thus producing poor machinability.

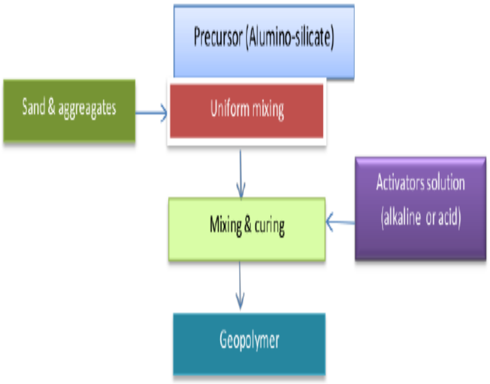


Figure 8. The formulation of bipartite geopolymers

Another investigation stated that the activator solution oxidizes with GGBFS much quicker than FA, Figure 10, and the plasticity of geo-polymer mortar (GPM) will be lessened when the proportion of GGBFS is moderately high [1][4]. The GP workability was enhanced when investigators substituted GGBS with MK [9][15]. Some findings have revealed that introducing calcium carbonate or silicon powder auxiliary materials might enhance GP workability [3][7].

Moreso, the workability of GGBFS-FA created geopolymers can be stabilized by introducing certain quantities of super-plasticizer; when the level of alkali-activator is at extreme, there is no noticeable impact on enhancing the freshness as well as hardening activities of GP mortar [2, 5, 7]. Numerous types of research on fiber-reinforced geo-polymers (FRG) reveals the impact of fiber additive on GP workability. The flow rate of GP mortar manufactured from untreated plus synthetic fibers is better than control GP mortar, which specifies that the usage of all fibers substantially lessens the flow capability of the geo-polymers [11]. Besides, the polyester fiber had a higher impact on the workability of geopolymers (GP) than those manufactured from high performance steel fiber.

Anhydrous sodiummeta-silicate (ASMS) has enhanced fluidity or plasticity than other activators [4][40]. Diverse activators have diverse viscosity that has impact onthe viscosity or glueyness of geopolymers. Similarly, the reduction in the workability of mortar is triggered by increasing the viscosity of the activator solution [1][3]. For instance, Mehta and Siddique affirm that Na_2SiO_3 act as an alkali activator and without the introduction of NaOH, causes reduction in the geopolymer concrete slump noticeably, which might be due to the extreme level of Na_2SiO_3 viscosity [5][7]. Meanwhile, another research study reveals that the slump of geopolymer concrete rises with the quantities of SiO_2/Na_2O in Na_2SiO_3 solution [53].

Setting time

Figure 11 exhibits the setting time of FA vs NaOH molarity. The workability of the slag-produced geopolymer is bad, because of the asymmetrical shape of the slag constituent part and the high slag quantity that aids the acceleration of the initial and final setting [5, 8, 12]. Using both SF and GGBS can minimize the setting time of geopolymers, though other substitute materials, like RHA, RM, HCFA, and MK, have similar effects [7, 46]. The optimum SF quantity of the FA-slag produced geo-polymer (FSPG) is four percent of the whole binder weight [1][9].

Table 2. Compressive strength (CS) of GPC

Alumino-silicate precursor& Reference	Activator	Length /Breadth ratio	Slump (mm)	Density (kg/m^3)	Curing period & T°C	Compressive strength @28days (MPA)
*FA + SF + MK [3]	PH + PS	-	-	-	25°C	80.72
*FA + GGBFS [4][5]	SH + SS		131	2433	76°C for 1 d	52.32
*GGBS [7, 9, 10]	SH	0.36	-	2248	26°C	36.02
*GGBS [12, 14]	SH + SS	0.55 (w/b)	240.02	2421	22°C	64.42
*GGBFS +RHA [7][9]	SH + SS	0.55		-	81°C for 1d	59.72 for 3d
HCFA + RHA [14][19]	SS + SH		720	-	26°C	38.21

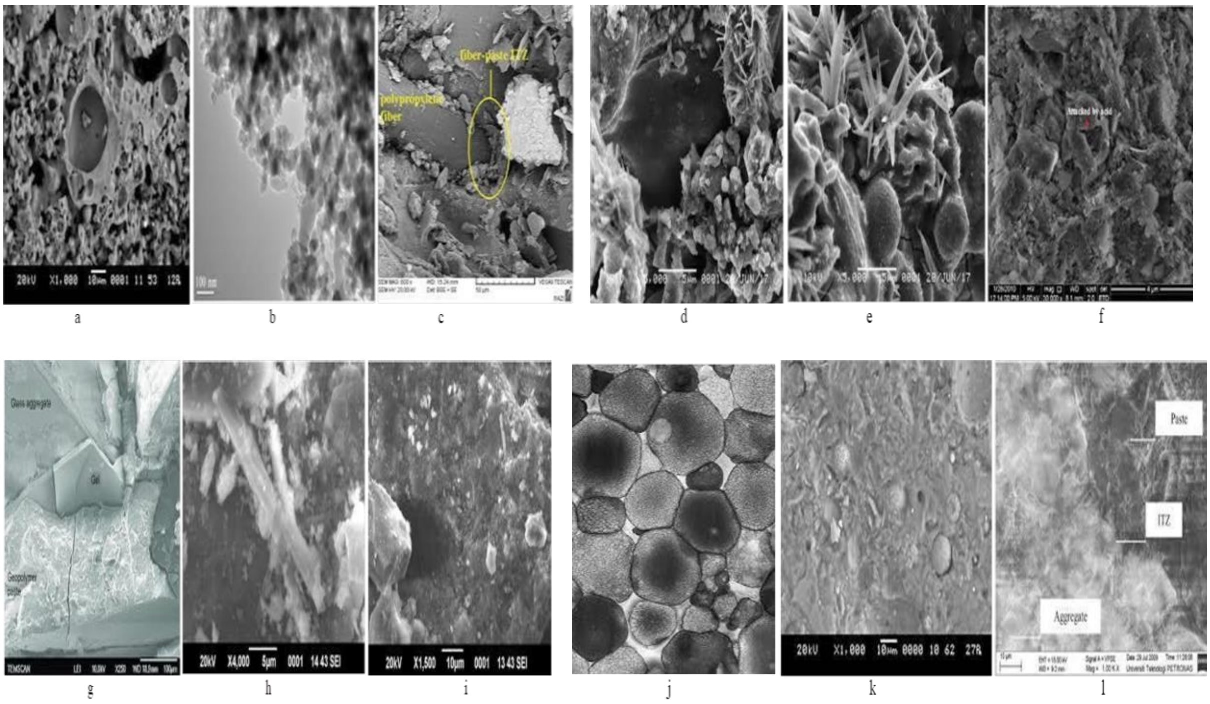


Figure 9. Illustration of various geopolymer SEM: (a) FA, (b)MK, (c)fiber, (d) Na2 \ (e) SiO3, (f) NaO2, (g) clay, (h) Alkali-Silicate gel, (i) BA, (j) GP Concrete, (k) Temperature @ 600^{0}C and (l) curing [14][29]

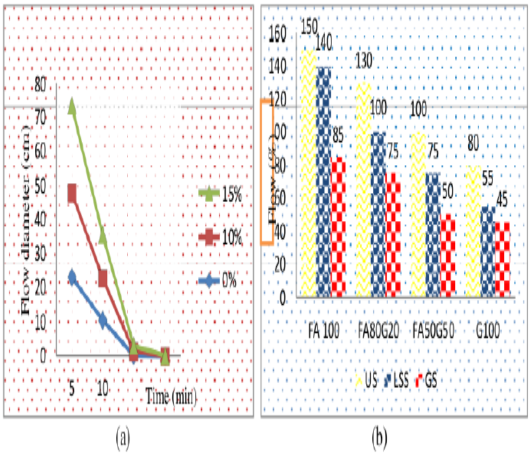


Figure 10. FA substitute with GGBS outcome showing: a) flow diameter in percentage [6,8]. b) Untreated sand (US) flow, lead smelter slag (LSS) flow, together with glass sand (GS) flow [17][19]

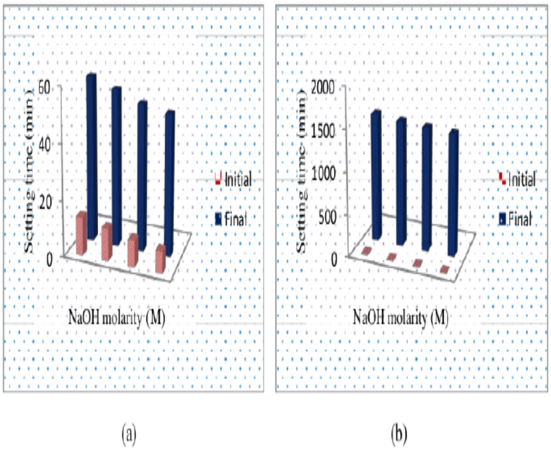


Figure 11. NaOH molarity versus setting time of FA-created GP, a) Source: [9][51], b) [4][47]

The optimum SF quantity of the FA-slag produced geo-polymer (FSPG) is 4 % of the whole binder weight [4]. Consequently, volcanic ash (VA) could be utilized to lengthen the setting time or period of slag-produced geopolymer to a satisfactory level [21][28]. Except for the morphological physiognomies, the chemical component of natural materials also triggers the setting time of GP. Upsurge in the quantities of calcium oxide proportion in the blend decreases the setting time of the GP mortar [32, 35, 51].

Curing

Curing at high temperatures might quicken the creation of concrete or mortar strength Figure 12, Figure 13, Figure 14. However, when potassium hydroxide and potassium silicate are utilized as activators, the strength of GPC manufactured at room temperature can be up to 80.71 MPa [7, 19, 39]. It was discovered from the retrospective scrutiny of the several categories of adhesive or epoxy resin and the microstructure of the study that the time of the making of the geopolymers with diverse properties, diverse molar concentration of liquid-to-binder, acid or alkali solution, and curing temperature differs.

Durability features of GP materials

Strength influences the durability of GP, besides their resistance to abrasive environments, such as chemical erosion resistance, porosity, carbonization resistance, abrasion operation, dry shrinkage, and other variables. Studies have defined this comprehensively. GP concrete is superbly more durable than ordinary Portland cement concrete (OPCC) in most scenarios [9, 13, 52]. Drying shrinkage reduction helps enhance the durability of geopolymers. Investigation into the durability of geopolymers exposes that the gel matrix of the GP is dense and impenetrable; also, integrating nano-TiO_2 can hinder the interconnection of micropores as well as successfully obstruct the nanopores in the geopolymer matrix [6, 32, 37]. Thus, the introduction of nano-materials is advantageous for GP durability improvement.

PURPOSES and advance route of GPMs

Based on geopolymers purposes, there are two classes: the orthodox physical and engineering features and the unorthodox physical, chemical and mechanical features. Efficient applications, such as fire prevention, quarantine, heat conservancy, and adsorption of detrimental ions, could be utilized for building construction in exceptional areas, such as insulation or sequestration walls and nuclear power plants.

Broad usage of geopolymer materials (GPM)

Marine constructions

Exposure of reinforced concrete for a very long time to saline soil, rainwater, or seawater will harmfully influence the structural elements' strength, stability and safety.

On the other hand, the chemical resistance capability (CRC) of geopolymer concrete, specifically sulfate resistance, makes it more appropriate for marine construction works. According to the sequel research by Phoo-ngernkham et al. [47], the FA-produced geopolymer, after being air-dried in the geotechnical laboratory for twenty-eight days (28 d), was revealed to the tidal region of the seawater (brine) environs for three years.

The infusion and oxidization of chloride ions were reduced with the molarity of sodium hydroxide. Conversely, Cong and Cheng [3] reveal that FA-based geopolymer concrete in the Salt Lake environs for six years is easier to carbonize than ordinary Portland cement concrete (OPCC) and possesses high diffusion of chlorides and sulfates.

High-temperature and fireproof materials

Destruction done to a building by fire cannot be over looked. For example, the 9/11 terrorist attacks and the Windsor Tate Fire in Shanghai caused significant loss of human properties or assets and life. Thus, selecting materials that are refractory in nature for construction works is very important. Continuous enhancement of ecosystem and sustainability must be highly focused in the formulation of high temperatures as well as fire-resistant materials today. Geopolymerization transforms company solid waste (CSW) into a non-combustible chemical durability cement binder (CDCB) with exceptional thermal strength. Farabi et al. [5] created the recalcitrant GP with GGBFS and discovered that the properties and fire-retardant ability of geopolymerization correlated to the features of the reaction products.

Similarly, Cong and Cheng [3] discovered that the GP cement produced from waste glass sodium water has a durable GP composition, which is a very nice recalcitrant material. Additionally, RHA-RM-created GPs were produced through water glass solution as an activator, then the curing of the GP samplings was at 1000^{0}C for two hours (2 h), and still displaying better fire-retardant and higher heat resistance [4, 6, 30].

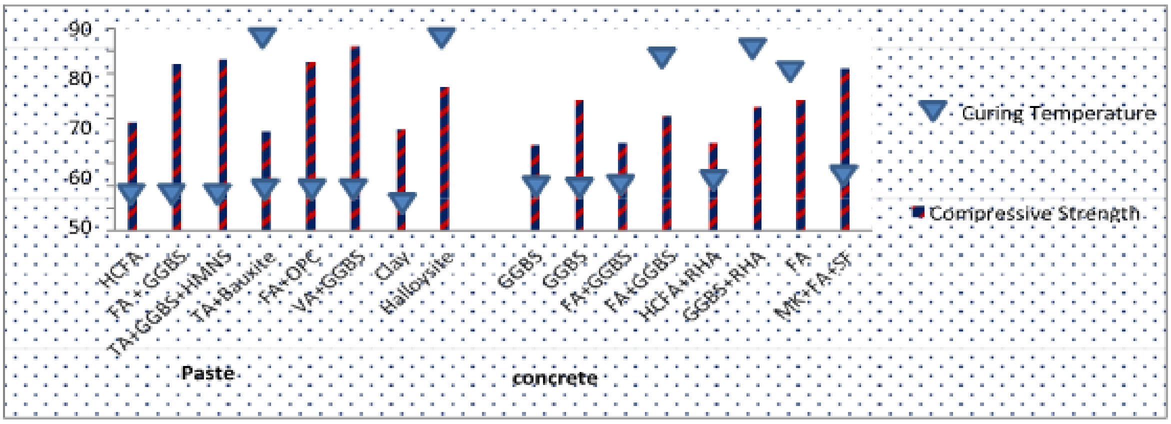


Figure 12a. Some geopolymers curing temperature plus early compressive strength for paste and concrete: Abridged from [2, 9, 50].

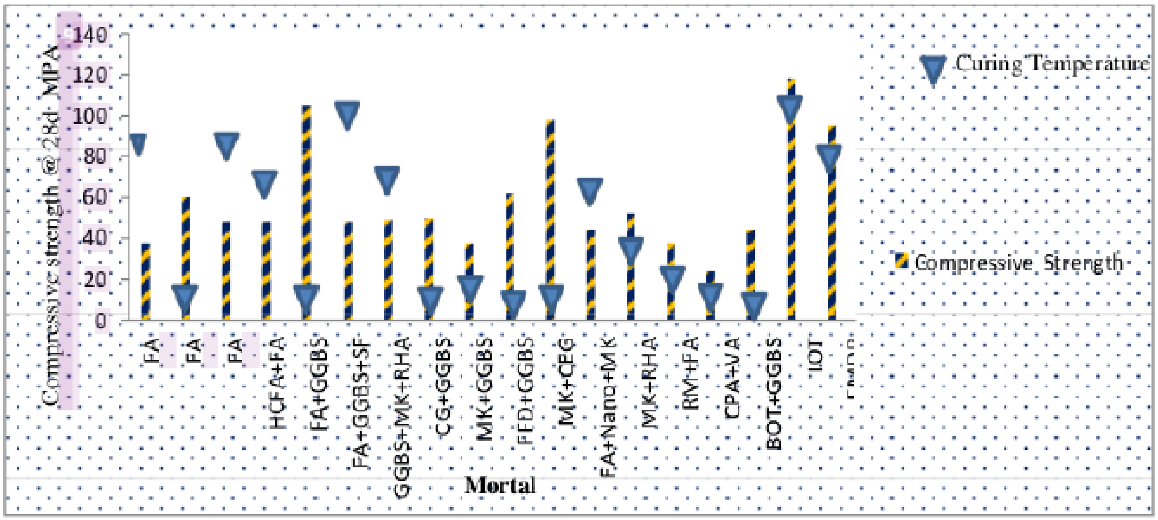
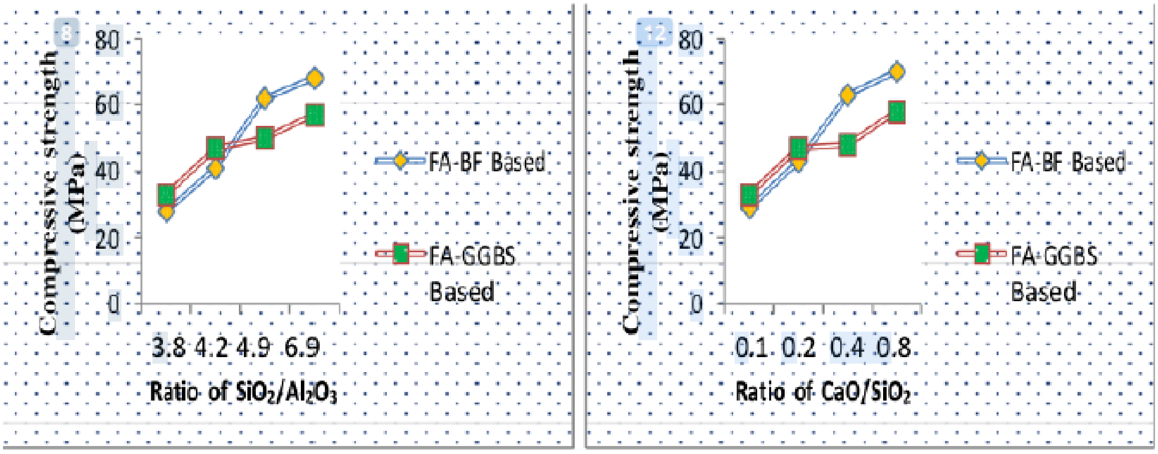


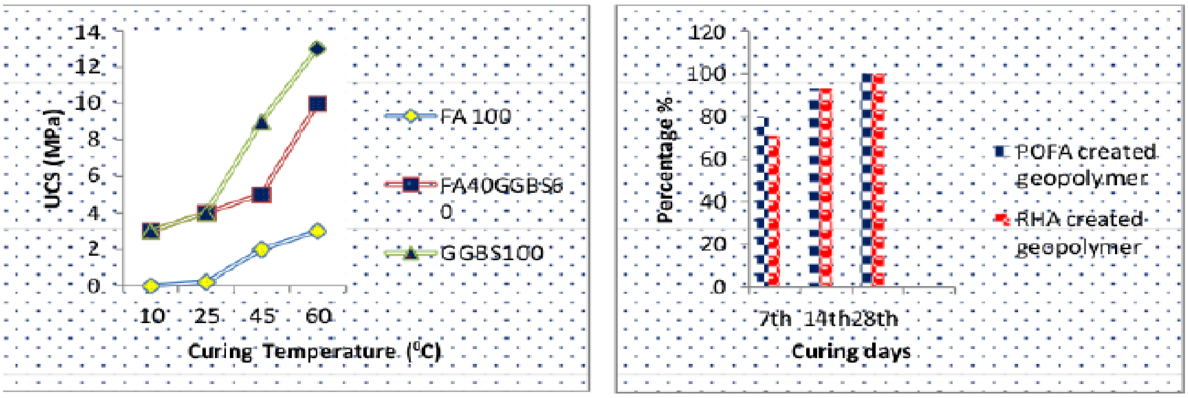
Figure 12b. Some geopolymers curing temperature plus early compressive strength for mortal: Abridged from [4, 8, 51].



a

b

Figure 13. Variation of basalt fibre compressive strength at different temperatures. (a) SiO_2/Al_2O_3. (b) CaO/SiO_2 [5, 7, 19]



a b

Figure 14. Impact of curing on the strength of blend GP
(a) one day temperature [35][50], (b) several days [2][49]

Table 3. Thermal plus acoustic features of partial geopolymer materials

Materials	Categorization	References
Geopolymer mortal	Energy-proficient (15.02%)	[3, 7, 24]
Geopolymer and stage modification materials	Energy-proficient (28.01% -30.02%)	[2, 23, 47]
Vegetal geopolymer concrete	Energy-proficient (46.02-58.01%), Thermalconductivity (0.113-0.191 $Wm^{-1}K^{-1}$).	[7, 34, 39]
Kaolin-based absorbedgeopolymer	Sound porous coefficient (0.538 @ 5000 Hz,0.808 @ 500Hz)	[11][13]
FA-based geopolymer fizzes	Sound porous coefficient (0.22@ 500Hz,0.26@2000Hz).	[8, 37, 47, 51]
SF-based geopolymerconcrete	Thermal conductivity (0.13-0.32 $Wm^{-1}K^{-1}$).	[1][14

Table 4. Adsorption impact of various geopolymers on dyes, heavy metals and etcetera

Porous material	Adsorption efficacy	Function	Citation
Ca Si-Al slags-created low alkali (AAM)	97.6% Cs^+, 99.91% Sr^{2+}	Nontoxic, sustainable	[5, 7, 13]
FA-based self-reinforced (ZFG)	>90.01% Pb^{2+}	Extreme adsorption efficacy stability	[9]
Enormity waste particulate AAM	99.41% Pb^{2+}, 100.01% Zn^{2+}	Sustainable, economical, extremely effective.	[16, 19, 28]
Multipart geopolymer based on solid wastes	99.96% - 100.01% Pb^{2+}	Stable	[2, 19, 29, 52]
FA-based geopolymer orb	94.31% MB	Reutilized for eight times (8x) keeping	[1, 13, 11, 17]
Red mud (RM-CN) composite	96.91% MB, 97.16%MG	85.01%. Reprocessed performance.	[14][19]
Permeable geopolymer composite glaze	95.01% CV	Uncomplicated regeneration	[22, 27, 29]
Geopolymer permeable duct or tube membrane	96.52%-98.72% PM 2.5, 98.02% -99.52% PM 10	Cheap and efficient	[31, 44, 50]

Renovation materials

Findings by [7][51] show that adding 10% calcium carbonate plus 14 M sodium hydroxide solution enhanced geopolymer mortars' flexural strength and shear bond. Also, Pelisser et al. [22] say that the twenty-eight days bond, tensile strength of geopolymer mortar (GPM) and commercial concrete patch-up materials are similar, and also possess the capacity to be utilized as concrete mending materials. Likewise, GP mortars possess high strength and can be utilized as a stand-in material for concrete patch-up, unlike other repair binders. Similarly, it can be utilized as high-strength geopolymer repair material (HSGRM), novel waterproof, rapid curing, and hydrophobic [33][37].

Insulation materials

Both thermal and acoustic insulators are indispensable when deliberating on building materials. A good thermal insulator can efficiently lessen energy usage and reduce greenhouse impact, as presented in Table 3. Acoustic insulators are crucial since sound-absorbing materials improve indoors. Aural comfort for inhabitants and lessening of health threats are related to acoustic contagion exposure. Geopolymer materials are good in meeting the aforementioned needs [32][50]. A brand of absorbent geopolymer from industrial waste (raw or natural) material at low T°C has the capability of stumpy thermal conductivity, price, low water assimilation, biodegradable, and decomposable, which meet the prerequisites of the departments of building for thermal insulation materials [1][19]. Prior research has publicized that GPs can lessen electricity usage to improve interior T0C, whereas amalgamating micro-encapsulated stage can considerably enhance wall thermal performance and conserve energy material made with geopolymer concrete [6][15].

Porous materials

Geopolymer serves as cleanser production materials and is frequently utilized as adsorbents and porous materials to eradicate metal ions from wastewater, immobilising and controlling heavy metal contagions. Utilizing these massive waste-produced geopolymer adsorbents that are eco-friendly, cheap and more convenient is a substitute to powder adsorbents used in the wastewater treatment scheme [21].

For example, using FA-created geopolymers from synthetic wastewater, methylene blue (MB) was produced. The permeable stuff can be utilized as the primary dye adsorbent in waste-water management. Similarly, the eco-friendly GP paste and adhesive blended from industrial plus agro waste as the porous materials might efficiently eradicate the primary dye MB from the aqueous solution [34, 42]. The quantitative classification of the porous effect of numerous GPs on dyes as well as heavy metals was briefly presented in Table 4.

PREVAILING CONSTRAINTS AND RESOLUTIONS

Scarcity of sodium silicate

From the literature review, diverse techniques for assessing the features of geopolymer materials were discovered. Though the natural material elements vary, an empirical scrutiny technique still needs to be abridged so that every researcher can learn from and enhance one another. On the other hand, the shortage of sodium silicate is one of the crucial factors obstructing the improvement of geopolymers. The geopolymer syntheses' economic benefit and ecological proficiency rest on the alkali activator's quantity.

Nevertheless, the annual global production of sodium silicate is below ten metric tons, and the processes utilized emit high carbon dioxide and energy [6, 9]. Conversely, silicon source to create industrial sodium silicate solutions like RHA can substitute sodium carbonate as well as quartz sand, which creates greenhouse gas during the production technique [7][12]. For MK-created geopolymer preparation, sodium silicate from RHA and waste glass is the best catalyst [3][29].

Efflorescence

Efflorescence, which numerous industrial applications and laboratory researches identified as salt formation in surface alkali stimulated cement, is another factor influencing the improvement of geopolymers, and its mechanism and main features ($NaHCO_3$, Na_2CO_3, and several sodium silicate components) are displayed in Figure 15. A high quantity of alkali activators of silicon rich systems, can initiate significant efflorescence. Besides, rising alumina content decreases the efflorescence level with alkali dosage [13]. Also, with the decrease in silica particle size, the increase in silica quantity, and the efflorescence inthe GP lessen [5][50].

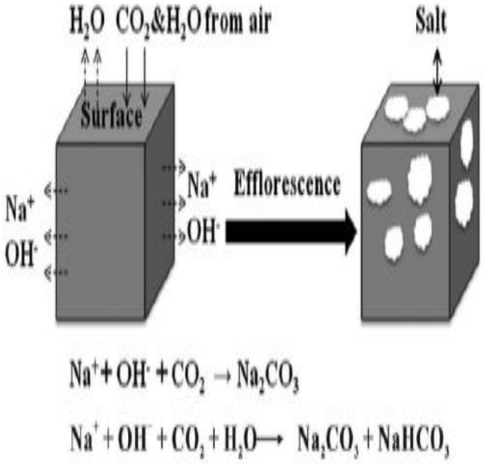


Figure 15. Geopolymer efflorescence system illustration [8, 39, 51]

CONCLUSION AND PROJECTIONS

This study presents some valuable information regarding geopolymer materials. It comprises the reaction principle, main features of geopolymer materials, source of raw materials, kinds of exciter, formulation technique and practical applications in various areas. Geopolymerization largely comprises three stages: the suspension of precursor, the creation of silicate network composition and the initial gel. Aluminum and silicon are the sources of geopolymer raw materials, which generally include RM, RHA, MK, biomass ash, FA, BFS, et cetera, also steel slag, coal gangue, SF, bauxite, waste glass, volcanic ash, diatomite, and high magnesium nickel slag. The most popular activators for geopolymer production are sodium silicate, sodium hydroxide, lithium hydroxide, sodium carbonate, calcium carbonate, phosphoric acid, and sodium sulfate.

There are several formation techniques of geopolymers. It is crucial to point out the most widely used mix to solid material, and after blended with liquid methodically. Generally, compared to ordinary Portland cement mortars as well as concretes, geopolymers have better fire resistance, are more resistant to salt erosion and acid, and have greater mechanical strength. Thus, with the advancement of technology and science, GPs are anticipated to be broadly utilized as cementing materials via intensification, and their application will be advantageous to the economyand the international environment.

REFERENCES

[1] M. Adeshokan and C. Arum, “Comparison between the Compressive Strength of Binary and Ternary Alkaline activated Pozzolanic,” *Journal of Applied Sciences and Environmental Management,* vol. 27, no 4, pp. 747-752, 2023.

[2] A. K. U Sanalkumar, and E. Yang, “Self-cleaning performance of nano-TiO_2 modified metakaolin-based geopolymers," *Cement and Concrete Composites*, vol. 115 no. 1, pp. 1-12, 2021, doi: 10.1016/j.cemconcomp.2020.103847

[3] P. Cong and Y. Cheng, “A comprehensive review”, *Journal of Traffic and Transportation Engineering (English Edition), Advances in Geopolymer Materials*, vol. 1, no. 2, pp. 1-12, 2021, doi: /10.1016/j.jtte.2021.03.004.

[4] F. Faluyi, C. Arum, C. M Ikumapayi A. Stephen, and A. Alabi, “Review of the Compressive Strength Predictor Variables of Geopolymer Concrete”, *FUOYE Journal of Engineering and Technology*, vol. 7, no, 3, pp. 1-11, 2022, doi: 10.46792/fuoyejet.v7i3.884.

[5] B. A Farabi, K. B. Rajib, A. Khan, I. Somaiya, and R. Ridwanur, “Estimation of strength properties of geopolymer concrete”, *Materials Today: Proceedings*, vol. 44, no. 1, 871-877, 2021, doi: 10.1016/j.matpr.2020.10.790

[6] A. Islam, U. J Alengaram, M. Z Jumaat and I. I Bashar, “The development of compressive strength of ground granulated blast furnace slag-palm oil fuel ash-fly ash based geopoly mer mortar,” *Materials & Design,* vol. 56, no. 2, pp. 833–841, 2014, doi: 10.1016/j.matdes.2013.11.080

[7] L. O. Agashua, C. Arum, B. D. Oluyemi-Ayibiowu and C. M Ikumapayi, “Workability and durability analysis of waste based geopolymer concrete,” *SINERGI*, vol. 28, no. 1, pp. 199-208, 2024, doi: 10.22441/sinergi.2024.1.020

[8] V. D. Cao, T. Q Bui and A. L. Kjoniksen, “Thermal analysis of multi-layer walls containing geopolymer concrete and phase change materials for building applications,” *Energy,* vol. 186, no. 3, pp. 115-124, 2019, doi: 10.1016/j.energy.2019.07.122

[9] R. Alzeebaree, A. Cevik and A. Mohammedameen, “Mechanical performance of FRP- confined geopolymer concrete under seawater attack,” *Advances in Structural Engineering,* vol. 23, no. 6, pp. 2-13, 2020, doi: 10.1177/1369433219886964

[10] Y. Alrefaei, Y. Wang and J Dai, “The effectiveness of different superplasticizers in ambient cured one-part alkali activated pastes,” *Cement and Concrete Composites*, vol. 97, no. 2, pp. 166-174, 2019, doi: 10.1016/j.cemconcomp.2018.12.027

[11] YHM Amran, R. Alyousef, H. Alabduljabbar. “Clean production and properties of geopolymer concrete: a review,” *Journal of Cleaner Production*, vol. 1, no. 1, pp. 251–263, 2020, doi: 10.1016/j.jclepro.2019.119679

[12] B. B Jindal, and R. Sharma, “The effect of nanomaterials on properties of geopolymers derived from industrial byproducts: a state-of-the-art review,” *Construction and Building Materials,* vol. 2, no. 1, pp. 252 -263, 2020.

[13] M. R. Ahmad, B. Chen, M. B Haque, “Multi property characterization of cleaner and energy-efficient vegetal concrete based on one-part geopolymer binder” *Journal of Cleaner Production*, vol. 253, no. 3, pp. 119-131, 2020, doi: 10.1016/j.conbuildmat.2020.119028

[14] J. Aliques-Granero, M. T. Tognonvi and A. Tagnit-Hamou, “Durability study of AAMs: sulfate attack resistance,” *Construction and Building Materials*, vol. 229, no. 2, pp. 117-128, 2019, doi: 10.1016/j.conbuildmat.2019.117100

[15] M. M. Alonso, C. Gasco, and M. M. Morales, “Olive biomass ash as an alternativeactivator in geopolymer formation: a study of strength, radiology and leaching behavior,” *Cement and Concrete Composites*, vol. 104, no. 1, pp. 103-114, 2019, doi: 10.1016/j.cemconcomp.2019.103384

[16] N. T Abdel-Ghani, H. A. Elsayed and S. AbdelMoied, “Geopolymer synthesis by the alkali-activation of blast furnace steel slag and its fire-resistance,” *HBRC Journal*, vol.

14, no. 2, pp. 159-164, 2019, doi: 10.1016/j.hbrcj.2016.06.001

[17] D. L Kong, and J. G Sanjayan "Effect of elevated temperatures on geopolymer paste, mortar and concrete," *Cement and Concrete Research*, vol. 40, no. 2, pp. 334–339, 2010, doi: 10.1016/j.cemconres.2009. 10.017

[18] E. Menya, P W Olupot, H. Storz, M. Lubwama, and Y. Kiros, "Characterization and alkaline pretreatment of rice husk varieties in Uganda for potential utilization as precursors in the production of activated carbon and other value-added products," *Waste Management*, vol. 81, no. 1, pp. 104-116, 2018. 10.1016/j.wasman.2018.09.050

[19] K. Mermerdaş and S. Ekmen, "Experimental assessment and optimization of mix parameters of flyash-based light weight geopolymer mortar with respect to shrinkage and strength," *Journal of Building Engineering*, vol. 31, no. 2, pp. 10-21, 2020.

[20] N. S Muhammad, I. Hadi, and P. Shelley, "Optimum mix design of geopolymer pastes and concretes cured in ambient condition based on compressive strength, setting time and workability," *Journal of Building Engineering, vol.* 23, no. 1, pp. 301-313, 2019, doi: 10.1016/j.jobe.2020.101351

[21] S. V Patankar, S. S Jamkar, and Y. M Ghugal, "Geopolymer concrete-a best solution to cement concrete in hot climate," J*. Emerg. Technol. Innov. Res.* vol. 6, no. 1, pp. 271–276, 2019.

[22] F. Pelisser, A. M Bernardin, and M. D Michel, "Compressive strength, modulus of elasticity and hardness of geopolymeric cement synthetized from non-calcined natural kaolin," *Journal of Cleaner Production vol.* 280, no. 1, pp. 124-136, 2021, doi: 10.1016/j.jclepro.2020.124293

[23] S. A Rosyidi, S. Rahmad, and N. M Yusoff, "Investigation of the chemical, strength, adhesion and morphological properties of fly ash based geopolymer modified bitumen," *Construction and Building Materials,* vol. 255, no.1, pp. 1-10, 2020, doi: 10.1016/j.conbuildmat.2020.119364

[24] S. Samantasinghar, and S. Singh, "Effects of curing environment on strength and microstructure of alkali-activated flyash-slag binder," *Construction and Building Materials* vol. 235, no. 1, pp. 1-11, 2020, doi: 10.1016/j.conbuildmat.2019.117481

[25] M. Askarian, Z. Tao and B. Samali, "Mix composition and characterisation of one-part geopolymers with different activators," *Construction and Building Materials*, vol. 225, no. 1, pp. 526-537, 2019, doi: 10.1016/j.conbuildmat.2019.07.083

[26] J. Baenla, J. B. Mbah, L. Djon, I.B. Ndjock, "Partial replacement of low reactive volcanic ash by cassava peel ash in the synthesis of volcanic ash based geopolymer," *Construction and Building Materials,* vol. 227, no. 2, pp. 116-128, 2019, doi: /10.1016/j.conbuildmat.2019.116689

[27] B. N. Bayiha, N. Billong and E. Yamb, "Effect of limestone dosages on some properties of geopolymer from thermally activated halloysite," *Construction and Building Materials*, vol. 217, no. 1, pp. 28-35, 2019, doi: 10.1016/j.conbuildmat.2019.05. 058

[28] N. B Singh and B. Middendorf, "Geopolymers as an alternative to Portland cement: An overview," *Construction and Building Materials*, vol. 237, no. 1, 2020, doi: 10.1016/j.conbuildmat.2019.117455

[29] K. Abdelli, M. Tahlaiti, M. N Oudjit "Influence of the origin of metakaolin on pozzolanic reactivity of mortars," *Energy Procedia*, vol. 139, no. 1, pp. 230-235, 2017.

[30] P. Aggarwal, P. Kumar and M. Kaur, "Effect of Chloride Ions on Compressive Strength of Concrete: A Review". *International Journal of Engineering and Technology,* vol. 7, no. 4, pp. 128-131, 2018, doi: 10.1016/j.egypro.2017.11.201

[31] C Arum, S. P Akande and S. A Alabi, "Strength Evaluation of Pozzolanic Concrete Containing Calcined Ceramic Waste And Glass Waste Powder," *Journal of Engineering and Engineering Technology,* vol. 16, no. 1, pp. 113-119, 2022, doi: 10.51459/futajeet.2022.16.1.420

[32] C618-19 ASTM, "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete", *ASTM International*, West Conshohocken, 2019.

[33] O. Babatola and C. Arum, "Determination of the Compressive Strength of Concrete from Binary Cement and Ternary Aggregates," *Open Journal of Civil Engineering,* vol. 3, no. 2, pp. 10-21, 2020, doi: 10.4236/ojce.2020.104029

[34] R. K. Chouhan, M. Mudgal, A. Bisarya and A. K. Srivastava. "Rice-husk-based superplasticizer to increase performance of fly ash geopolymer concrete," *Emerging Materials Research*, vol. 1, no. 2, pp. 6-15, 2022, doi: 10.1680/jemmr.18.00035.

[35] J. Davidovits, "Ancient and modern concretes: what is the real difference," *ConcrInt,* vol. 9, no. 1, pp.12–23, 1987.

[36] R. Dewi, H. Agusnar, Z. Alfian and T. Tamrin, “Characterization of technical kaolin using XRF, SEM, XRD, FTIR and its potentials as industrial raw materials,” *Journal of Physics Conference Series,* vol. 1116, no. 4, pp. 1-12, 2018. doi: 10.1088/1742-6596/1116/4/042010.

[37] H. Herdyana and A. Suroso. “The Impacts of 5D-Building Information Modeling on Construction's Time and Cost Performance,” *SINERGI,* vol. 27, no. 3, pp. 393-404, 2023 doi: 10.22441/sinergi.2023.3.010

[38] Mairizal, R. Alifiardi, G. A. Pratama, M. Z. Abd Majid and S. P. Ngian. “Project Managers Competency on Project Performance of Green Toll Road Development Project in Indonesia,“ *SINERGI,* vol. 27, no. 3, pp. 333-342, 2023, doi: 10.22441/sinergi.2023.3.005

[39] A. Bhutta, M. Farooq, N. Banthia, “Performance characteristics of micro fiber-reinforced geopolymer mortars for repair,” *Construction and Building Materials,* vol. 215, no. 2, pp. 605-612, 2019, doi: 10.1016/j.conbuildmat.2019.04.210

[40] L. Biondi, M. Perry and J. Mc Alorum, “Geopolymer-based moisture sensors for reinforced concrete health monitoring,” *Sensors and Actuators B: Chemical,* vol. 309, no 3, pp. 127- 137, 2020, doi: 10.1016/j.snb.2020.127775

[41] M. Z. Umar and A. F. Mustafa. “The Performance Optimization of Concrete Bricks Using a Sagu Fiber,” *SINERGI,* vol. 27, no. 1, pp. 7-14, 2023, doi: 10.22441/sinergi.2023.1.002

[42] A. Hassan, M. Arif, M. Shariq, “Effect of curing condition on the mechanical properties of fly ash-based geopolymer concrete,” *SN Applied Sciences,* vol. 1, no. 1, pp. 1-10, 2019, doi: 10.1007/s42452-019-1774-8

[43] M. D Obebe, C. M. Ikumapayi and K. K. Alaneme, “Structural performance evaluation of concrete mixes containing recycled concrete aggregate and calcined termite mound for low-cost housing,” *Alexandria Engineering Journal,* vol. 72, no. 1, pp. 237–346, 2023, doi: 10.1016/j.aej.2023.03.095

[44] O. O. Omotayo and C. Arum, “Challenges and Prospects of Widespread Adoption of Pozzolans for Building Construction: A Statistical Assessment,” *International Journal of Engineering,* vol. 1, no. 2, pp. 2-11, 2022, doi: 10.5829/ije.2022.35.10a.12

[45] P. Chindaprasirt and U. Rattanasak, “Synthesis of porous alkali activated materials for high- acidic wastewater treatment,” *Journal of Water Process Engineering,* vol. 33, no 2, 101-118, 2020, doi: 10.1016/j.jwpe.2019.101118

[46] J. Cai, X. Li, X and J. Tan, ”Thermal and compressive behaviors of fly ash and metakaolin-based geopolymer,” *Journal of Building Engineering*, vol. 30, no 4, 101-113, 2020, doi: 10.1016/j.jobe.2020.101307

[47] T. Phoo-ngernkham, S. Hanjitsuwan, N. Damrongwiriyanupap, and P. Chindaprasirt, “Effect of sodium hydroxide and sodium silicate solutions on strengths of alkali activated high calcium fly ash containing Portland cement,” *KSCE Journal of Civil Engineering*, vol. 21, no. 2, pp. 2202–2210, 2017, doi: 10.1007/s12205-016-0327-6

[48] VKJ Bohra, R. Nerella, R and S.R.C Madduru, “Material properties, processing & characterization of fly ash based geopolymer,” *Materials Today: Proceedings*, vol. 19, no. 6, pp. 2617-2621, 2019, doi: 10.1016/j.matpr.2019.10.099

[49] D. Bondar, “Method of optimisation for ambient temperature cured sustainable geopolymers for 3D printing construction applications,” *Materials,* vol. 12, no. 6, 902-914, 2019, doi: 10.3390/ma12060902

[50] A. Bouaissi, L. Li and M. M. A Abdullah, “Mechanical properties and microstructure analysis of FA-GGBS-HMNS based geopolymer concrete,” *Construction and Building Materials,* vol. 210, no. 2, pp. 198-209, 2019, doi: 10.1016/j.conbuildmat.2019. 03.202

[51] S. K. Shill, S. Al-Deen, M. Ashraf, “Resistance of fly ash based geopolymer mortar to both chemicals and high thermal cycles simultaneously,” *Construction and Building Materials,* vol. 239, no. 1, pp. 1- 13, 2020, doi: 10.1016/j.conbuildmat.2019. 117886

[52] G. Silva, S. Kim and R. Aguilar, “Natural fibers as reinforcement additives for geopolymer a review of potential eco-friendly applications to the construction industry,” *Sustainable Materials and Technologies,* vol. 23, no. 1, pp. 42-56, 2020, doi: 10.1016/j.susmat.2019.e00132

[53] P. Duan, C. J. Yan and W. J. Luo, “A novel waterproof, fast setting and high early strength repair material derived from metakaolin geopolymer,” *Construction and Building Materials*, vol. 124, no 2, 69-73, 2016, doi: 10.1016/j.conbuildmat.2016.07. 058