Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X
Volume 3, Issue 6, 2025

ADVANCED CLAY-BASED GEOPOLYMER CEMENTS: STRUCTURAL BEHAVIOR, MATERIAL PROPERTIES, PARAMETRIC INFLUENCE, AND EMERGING APPLICATIONS

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DOI: https://doi.org/10.5281/zenodo.15697361

Keywords
Clay-Based Geopolymer Cement, Structural Properties, Microstructural Analysis, Aggressive Environment Resistance, Thermo-Chemical Stability, Low-Carbon Building Materials.

Article History
Received on 11 May 2025
Accepted on 11 June 2025
Published on 19 June 2025

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Abstract

The global construction industry is undergoing a transformative shift toward sustainable and low-carbon alternatives to traditional Portland cement. Among emerging materials, clay-based geopolymer cements have gained significant attention due to their eco-friendly synthesis, utilization of naturally abundant aluminosilicate clays, and exceptional mechanical and durability performance. This study provides a comprehensive investigation into the structural characteristics, physico-chemical properties, and influential synthesis parameters of clay-based geopolymer cements. Emphasis is placed on the reactivity of various natural clays such as kaolinite, montmorillonite, and halloysite under alkali activation, along with their phase transformations, microstructural evolution, and resulting geopolymer gel formation. Key parameters, including the Si/Al ratio, curing temperature, activator concentration, type of alkaline solution, and liquid-to-solid ratio, are critically analyzed for their impact on setting time, compressive strength, porosity, and thermal stability. The influence of calcination temperature and pre-treatment methods is also examined, particularly in enhancing the amorphous phase content and facilitating dissolution kinetics. Analytical techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and thermogravimetric analysis (TGA) are employed to characterize the mineralogical, morphological, and thermal behavior of geopolymer matrices. Furthermore, this paper evaluates the long-term performance of clay-based geopolymers in aggressive environments, including acidic and sulfate-rich conditions, highlighting their superior resistance compared to conventional cements. In addition to their structural utility, the multifunctionality of these materials is explored through applications in thermal insulation, fire resistance, carbon sequestration, and hazardous waste *immobilization. By integrating original experimental findings with an extensive review of current literature, this study advances the understanding of clay-geopolymer chemistry and presents a pathway toward scalable, circular-economy-driven, and low-carbon construction materials for a sustainable future. The outcomes of this research are anticipated to significantly influence material selection in eco-construction, infrastructure resilience, and green architecture.*

INTRODUCTION

The creation, process, advancement, and use of geopolymeric materials have been extensively explored, emphasizing mostly waste material, indigenous or manufactured silico-aluminate. The composition and properties of geopolymer concrete relying on soil and clay minerals have been entirely analyzed.

Geopolymers are man-made/inorganic polymers made from Al_2SiO_5 minerals (which are composed of silicon, oxygen and aluminum) and concentrated soluble base (alkali metals cations and hydroxide anions OH^-) or a basic silicate media e.g., Na_2SiO_3 or Na_2O_3Si. After that, the drying and curing process would take place at room temperature or at a little warmer temperature in the 20–100 °C range. According to Davidovits(1, 2)geopolymerization is the interaction that outcomes in the advancement of geopolymers.

To put it another way, geopolymer creation involves strong fluid blends as shown in Figure 1sources of powdered aluminosilicate with an adequate quantity of responsive silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3). Meanwhile, the solution is an exceedingly strong basic solution.

1. Geopolymer's configuration along with nomenclature

"Geopolymer" term/name was invented by Davidovits(3). The prefix "geo" signifies an inorganic aluminosilicate got from geological components that were polycondensed with an alkaline liquid to create a material. As shown in **Error! Reference source not found.**(4), the recommended classification of geopolymer structure separates geopolymers into three essential sorts because of the silicon to aluminium proportions: Si: Al=1, Si: Al=2, and Si: Al=3.

Geopolymer is a three-layered Si-O-Al polymeric organization having an unpredictable semi-glasslike structure. All oxygen particles are divided among the SiO4 and AlO4 tetrahedra, with the Al in a precisely 4-fold connection **Error! Reference source not found.**(5, 6). The IV-overlay composed of Al currently has a contrary charge, which is killed by certain positive charged ions like (Sodium-ion, Potassium ion, calcium cation, Barium cation, Ammonium ion and Hydronium ions. etc. The existence of positively charged ions is crucial for the protection of material's lack of bias(7). In any case, it is felt that, as well as playing a charge-adjusting job, the consideration of positively charged particles is critical in deciding the eventual outcome's trustworthiness of the construction. As indicated by Saidi et al.(8), sodium cation impacts the delicacy of geopolymers. Geopolymer observational equation is as per the following:

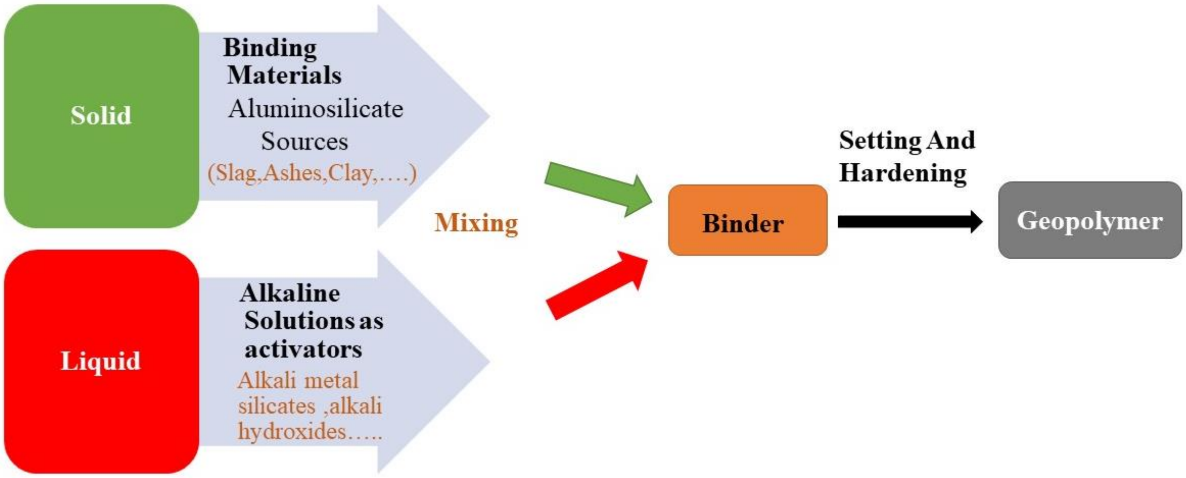
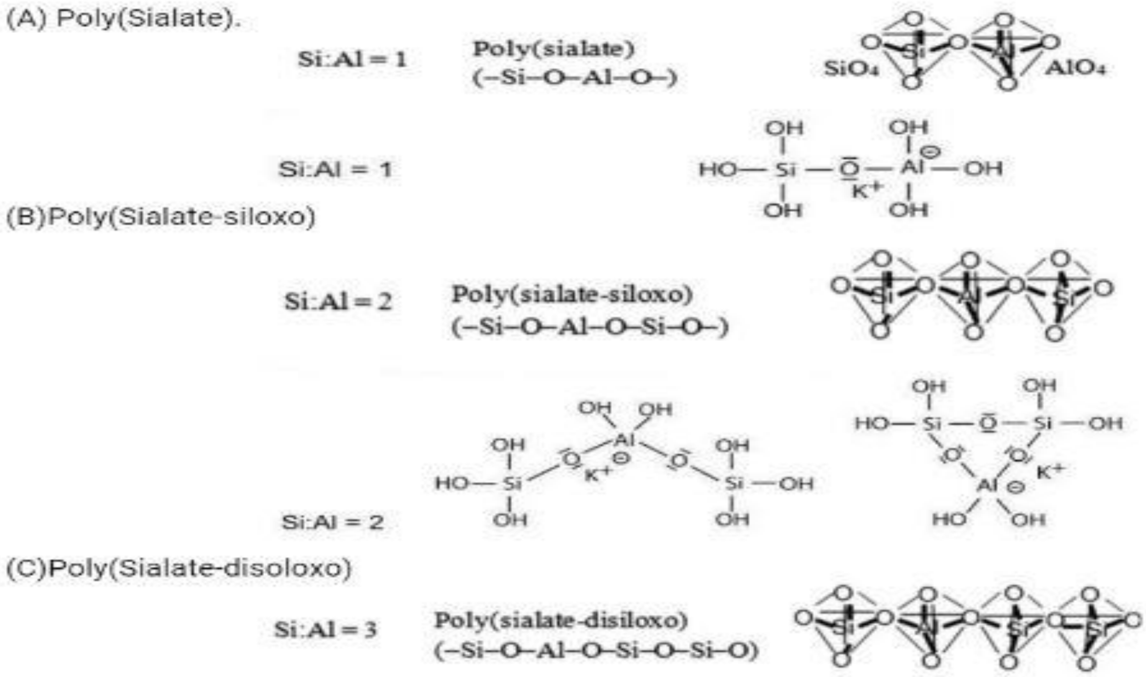


Figure 1 Geopolymer formation schematic diagram



Where M represents positive charged ions such as Ca^{2+}, Na^{+} or K^{+}; n represents measure of polymer formation or degree of Figure 2Several Geopolymer systems based on the amount of (Si:Al) ratios(5, 6) polycondensation; z represents 1,2,3… while w represents the amount of water needed for binding.

2. Aluminosilicate sources

In the development of geopolymers, an assortment of introductory unrefined substances has been utilized. Kaolinite was ordinarily utilized in geopolymer synthesis in the beginning phases of improvement(2, 4, 9, 10) . Other fundamental materials, like calcined muds, were subsequently examined(11, 12),factories throw away (e.g. ashes(13-16),slag(17, 18), rubbish glass(19), tailings from copper mines(20) etc.) also an assortment of extra regular and manufactured silicoaluminates(e.g. zeolite(21), Al_2O_3–$2SiO_2$ powder(22) in its purest form, minerals containing magnesium(23), etc.)

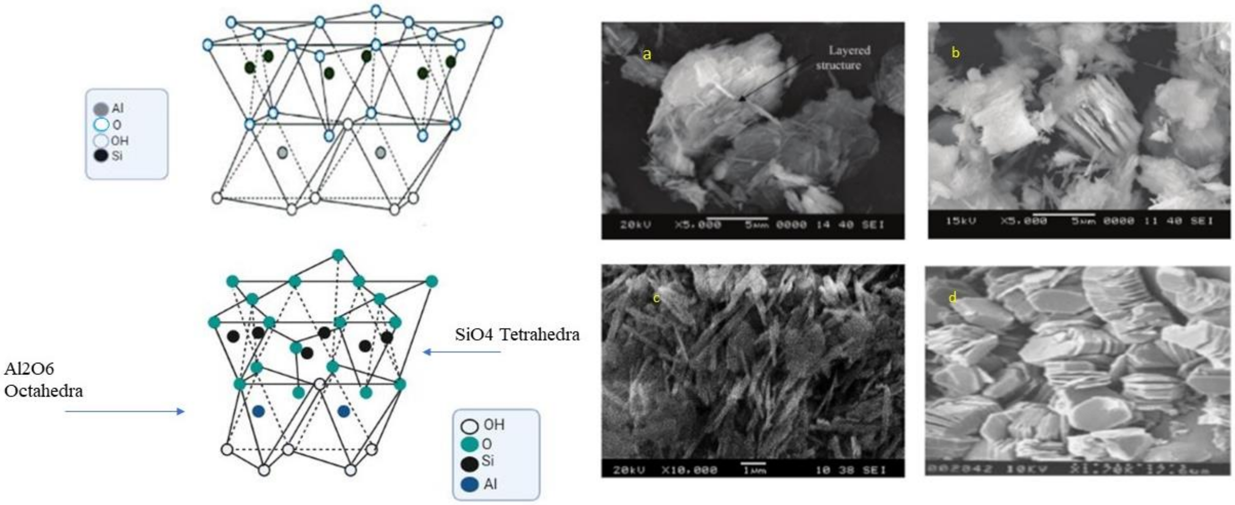
Aluminosilicates, which are high in alumina (Al_2O_3) and silica, are the fundamental material used to fabricate geopolymers (SiO_2). They can be found in enormous amounts in the world's outside layer. These source materials are significant wellsprings of Al^{3+} and Si^{4+} particles in the limiting framework, which assists with creating geopolymers. The alumina and silica compounds in the building material should ideally be in a responsive shapeless stage(5, 24)with an all-out arrangement of over 70%.

The usage of earth or dirt minerals in geopolymer development, as well as their design and attributes, are talked about in this work.

2.1 Composition Of Clay Minerals

kaolinite is a frequently used clay mineral in geopolymer creation. The design of kaolinite is comprised of 1:1 uncharged dioctahedral layers

Figure 3(a)Kaolinite Structure (b)Microstructure of Kaolinite(25)



with a substance equation of $Al_2O_3.2SiO_2.2H_2O$ as shown in a. This layer is comprised of two sheets: $(Si_2O_5)n$ and $Al(OH)_3$ (gibbsite), which are joined by oxygen molecules. As seen in b, van der Waals and hydrogen bonds(26) keep these sheets intact, delivering a sheet or layered design. Gibbsite and Si_2O_5 possess almost negligible electromagnetic charge, as well as the sheets, are arranged closely together keeping other elements from being subbed. Kaolinite possesses a small surface region for the polymerization process, in contrast, to fly ash, which has round formed particles. Due to the small surface region of kaolinite, antacid/alkali reactant disintegration is restricted, bringing about lower strength(27).

Xu and van Deventer(28) used sixteen types of aluminum silicate (Al_2O_5Si or Al_2SiO_5) materials as forerunner materials in geopolymer creation (almandite ($Fe_3Al_2Si_3O_{12}$), $Ca_3Al_2Si_3O_{12}$, fibrolite, cross-stone, cyanite, hiddenite, pyroxene augite, lithia mica, hydromica, etc). To achieve explicit characteristics, some soil minerals needed the incorporation of kaolinite as a strengthening agent. Regardless, utilizing kaolinite alone in the geopolymerization technique brought about a frail design. Stilbite had the most noteworthy compressive strength of any, at 180 bars.

Furthermore, van Jaarsveld et al.(29) found that including raised the concentration (forty-one Weight%) of kaolinite in fly ash geopolymers affected the final product's strength. This is due to the fact that not all kaolinite participates in the geopolymerization event that results in the formation of a geopolymer network. The compressive strength of kaolinite rises as it is calcined. Table 1displays the compressive strength of calcined kaolinite as determined by van Jaarsveld et al(29).

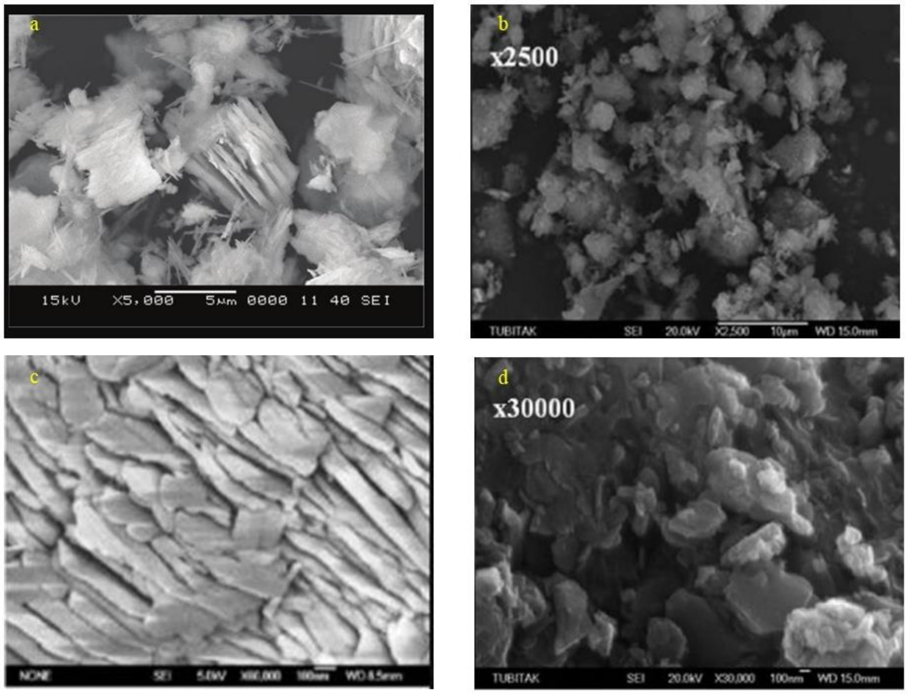
Table 1Calcination condition of metakaolinite and its effects on compressive strength of fly-ash based geopolymer with additional variables: Metakaolinite (clay) content=14% by mass, water to fly ash by mass ratio = 0.31, K_2O/SiO_2=1.14, alumina to silica ratio = 0.57(29)

Time(h)	Temperature(°C)						
	300	400	500	600	700	800	900
1	14	14	30	54	17	7	8
6	11	31	13	9	15	7	15
12	12	47	28	25	14	3	15
24	6	32	31	18	6	15	12

2.2 Clay Minerals pre-treatment

The pre-treatment of clay essentially affects the attributes of geopolymers. Geopolymers produced using heat-treated halloysite created average geopolymer attributes, as MacKenzie et al.(30) found. While using mechanochemically treated halloysite, a less complete geopolymerization process was noticed. Halloysite that had been synthetically treated in an acidic medium created inadequately set geopolymers, while halloysite that had been soluble treated for over 3 hours framed glasslike zeolites that relieved and set during geopolymer creation. Warm treatment was completed for 2 hours at 200-1000 C during the examination. Substance treatment was done by absorbing basic (0.1 Mole Sodium Hydroxide) either

Figure 4SEM micrographs of metakaolin calcined at different temperatures(31-34)



acidic (0.1 Mole Hydrochloric acid) answers for twenty hrs. and four hundred rounds per minute, while mechanical and chemical curing has been done by energetic crushing for twenty hours at four hundred rounds per minute.

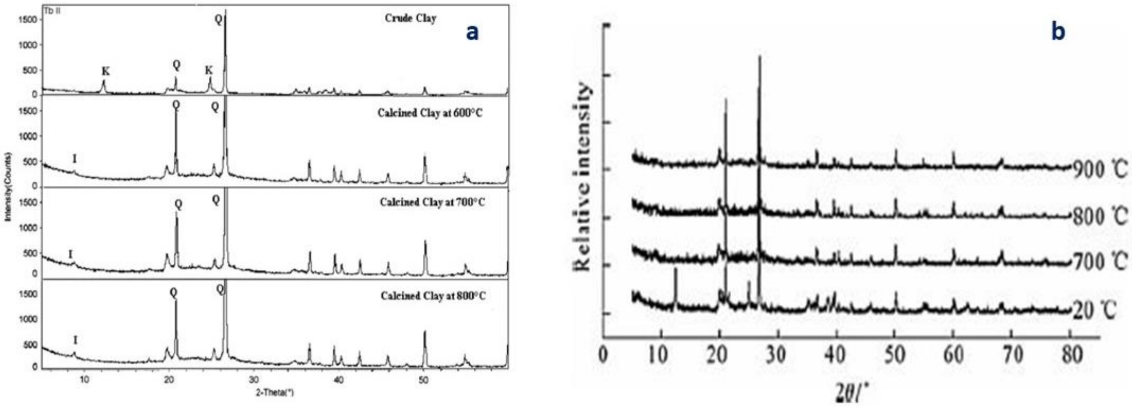
In general, geopolymers made from thermal curing raw components such as metakaolin, fly ash, and impact heater slag has improved strength(28, 35, 36). Heat treatment works on kaolinite's reactivity in the geopolymerization methodology. At the point when kaolinite is effectively calcined, it shapes incredibly pozzolanic formless stages.

Figure *4*. Metakaolin's layered construction, then again, seems to be more open than kaolinite's(31, 39). Besides, atomic changes and rearrangement over kaolinite's hexa-facilitated Al particles into penta-and

Thermal curing converts the crystalline stages to responsive amorphous stages(37). These shapeless stages without a doubt give dynamic constituents that characterize geopolymer's last strength. At 550-800 °C(38), the immovably fortified hydroxyl particles on the Aluminium built-in sheet dehydroxylate due to H_2O dehydration during thermal treatment of kaolinite. This changes kaolinite over to metakaolin's disarranged metastable stage. In spite of going through the hotness treatment method, metakaolin holds its layered construction as shown in

tetra-composed Al particles, annihilating the hexagonal layer of kaolinite(40). How much hexa-composed Al particles are changed over to Penta-and tetra-facilitated Al particles uncover metakaolin's reactivity. When the Hexa-composed Al particle is at its least(39), metakaolin has the most reactivity.

Figure 5 (a)XRD of Calcined clay at different temperatures (b)XRD of kaolinite and its calcined product at 20°C,700°C,800°C and 900°C(26, 41)



The thermal curing range of kaolinite is typically between 599 and 899 degrees Celsius. Rowles and his coworkers(42)showed that receptive metakaolin is made by warming kaolinite at 749.5°C in the atmosphere for twenty-four hours. The MAS NMR examination uncovered an exceptionally cluttered organization of metakaolin with wide vibrations of (-104.8 parts per million) and Q^4 (-111.5 parts per million). Singh et al.(43), employed the same calcination temperature, but for a brief duration of 10 hours. Wenying et al.(44), on the other hand, found that calcining kaolin at 800 °C for 2 hours was the best. The metakaolin made low-strength geopolymer items when warmed more than 900 degrees Celsius. This was in all probability inferable from over calcination, which drove in the difference in responsive nebulous stages into dead consumed and non-receptive mullite crystalline phases. Then again, ideal calcination at 900 °C has been recorded. Zuhua et al.(26) acquired an XRD diffractogram, which is displayed underneath in **Error! Reference source not found.**b. The translucent pinnacles of kaolinite get more fragile as the temperature increments. This suggests that the glasslike design of kaolin has been obliterated. The calcination temperature of kaolin in the scope of 649-849°C, then again, has no basic impact on the mechanical properties of geopolymers, as per Kong et al.(45). As the Si/Al proportion developed from 1.40 to 1.54, the impact of calcination temperature turned out to be more perceptible. With a-Si/Al proportion of 1.54, the most elevated strength of 45 megapascals was reached at a calcination thermal reading of 750 degrees Celsius. The surface area of unrefined components is expanded by heat treatment. Ferone et al(46). seen that calcining supplies clay sediment at 400 and 750 degrees Celsius for 2 hours before alkalination expanded how much disintegration of the clay sediments. The compressive strength of clay samples treated at 750 °C was more noteworthy (between 6-12 MPa) than those cured at400 °C (between 1-4 MPa). It has shown that treated unrefined components had an enormous surface region for alkali/basic reactant disintegration and ensuing geopolymer process response.

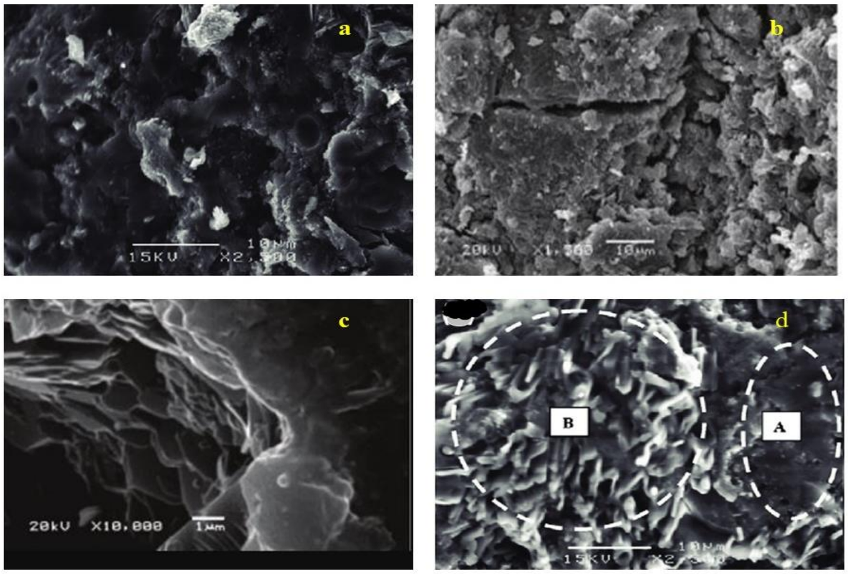
Calcination in the air or a heater is utilized for the warm treatment expressed previously. Kolousek et al(46). and partners utilized an alternate calcination strategy. For their situation, inferior class of kaolin was used for calcination with a blend of sodium hydroxide and potassium hydroxide. After calcination interaction, the substance was pounded & blended straightforwardly with $H_2O(I)$ (instead of a salt reactant) for the production of geopolymer. This geopolymer was named a one-part geopolymer. The completed item, notwithstanding, just had a strength of 1 MPa.

Feng et al. (47)created geopolymers with adequate compressive strength of 40 MPa following 4 weeks, rather than Kolousek et al.(48). The final sample was created in their examination by calcination of albite with soda ash (Na_2CO_3) or caustic soda (NaOH). Ke and his co-researchers(49), Peng with his friends(50), andNematollahi with his co-researchers(51), explored comparative test work, however with different unrefined components like bauxite residue, coal ash, slag, and calcium hydroxide. The interest in this field of examination is critical on the grounds that it can expand the reasonability and monetary capability of geopolymers.

1.1 Geopolymers made of Clay (Clay-Based geopolymers)

Clay is oftentimes utilized as the beginning material for geopolymers since it accommodates straightforward translation of the outcomes and disposes of the requirement for modern understanding. Due to the presence of debasements and impurities, the use of confounded unrefined components, for example, fly ash and slag might affect the outcome result.

Figure 6SEM pictures of (a), (b), (c) pure metakaolin and (d) Metakaolin geopolymer with Slag where ("A" shows geopolymer matrix and "B" shows CSH gel)(52)



Clay is high in Al_2O_3 and SiO_2, with an all-out piece of 70-90 percent of both

. Clay structure changes generally relying upon its source as well as the geography of the area. The impact of changing variables like silicon to aluminium as well as sodium to aluminium molar proportions, explicit surface and synthesis of clay, soluble base centralization of alkali reactant arrangement, modulus of alkali silicate arrangement, heat treatment and circumstances, etc. have been concentrated widely in metakaolin geopolymers for quite a long time(53-55). A few analysts make blended geopolymers as opposed to utilizing metakaolin alone in geopolymer amalgamation. Metakaolin is combined with other initial fixes such as $Ca(OH)_2$, ash, and cinders. In the geopolymer network, these unrefined components fill in as both a fastener/binder and a filler. Alonso and Palomo(56, 57), for instance, acquainted $Ca(OH)_2$ with metakaolin & he discovered that$Ca(OH)_2$ did not affect on the results. Moreover, Yunsheng et al(57). showed that adding 30% slag to metakaolin geopolymersfurther developed strength improvement. If more than half of the slag i.e., 50% was applied, the strength was reduced. The mechanical characteristics of the result were upgraded by filling huge grains of slag(40).

CaH_2O_4Si (CSH) stages create in blend with the geopolymer matrix because both $Ca(OH)_2$, as well as slag, have abundant "Ca" concentration. Yunsheng et al. (52) made microstructure geopolymers, as displayed in **Error! Reference source not found.**. Pure metakaolin geopolymer has only one homogenous stage, though slag-metakaolin geopolymer has two unmistakable stages (CSH and geopolymer framework). Buchwald et al(58), have also made a similar observation.

Table 2 Various clays of different composition from different areas

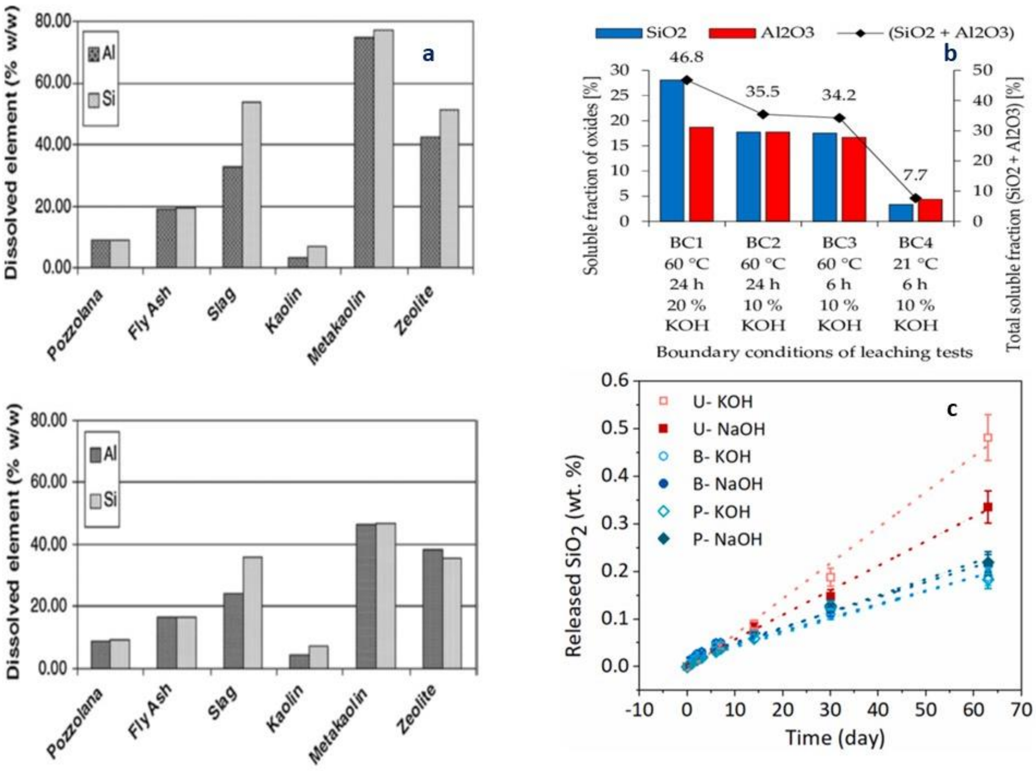
Clay Mineral	SiO_2	Al_2O_3	Cao	K_2O	Na_2O	Fe_2O_3	TiO_2	MgO	P_2O_5	LOI	SO_3	MnO	References
Metakaolin	51.35	44.24	0.13	0.08	0.16	0.98	0.90	0.48	0.45	0.72	-	0.01	(59)
Metakaolin	52.1	43.0		2.5	0.12	0.7	-	0.3	-	1.0	-	-	(58)
Metakaolin	59.7	34.1	0.1		0.2	0.9	-		-	1.2	0.12	-	(60)
Occhito pond, clay, Italy	47.5	15.6	10.2	1.9	0.3	6.7	-	2.4	-	15.4	-	-	(46)
Sabetta pond, clay, Italy	50.0	15.9	6.9	1.7	0.3	5.7	-	1.9	-	17.5	-	-	(46)

Kaolinite from Jordan	48.92	25.16	0.68	1.4	0.21	7.52	0.86	0.21	0.16	11.93	2.94	0.01	(61)
Kaolinite	49.35	36.03	0.02	2.29	0.04	0.20	0.02	0.02	-	11.94	-	-	(62)
Kaolinite	40.86	39.87	0.12	0.17	0.01	0.39	0.46	0.12	-	17.91	-	-	(62)
Kaolinite	42.66	40.92	0.14	0.09	0.14	1.12	0.45	0.04	-	14.13	-	-	(62)
Halloysite	48.12	36.33	0.04	0.03	0.04	0.33	0.16	-	-	14.8	-	-	(62)

Alkali Reactant

A solvent alkali metal because of sodium or potassium is utilized as a salt reactant. Alkali silicates, hydroxides, carbonates, and extra added substances like sodium aluminates or concrete oven dust are among them. The aluminosilicates quickly disintegrate in a solid basic media, delivering silicon-oxygen tetrahedron and AlO_4 tetrahedral units and advancing the broke up species for polycondensation(63, 64). A solution of hydroxides (sodium hydroxide and potassium hydroxide) and silicates is the most well-known alkali reactant solution (Sodium silicate and potassium silicate)(10, 37, 68).

Figure 7. (a)Aluminium (Al) and silicon (Si) dissolved in 10% in 10M of NaOH and KOH solution respectively. (b)Soluble friction of oxides and total soluble friction of oxides of metakaolin. (c) Released SiO_2 of differentaggregates in 0.4M of NaOH and KOH solutions as a function of time at 38°C(65-67)



1.2 Sodium or Potassium-based alkaline solution

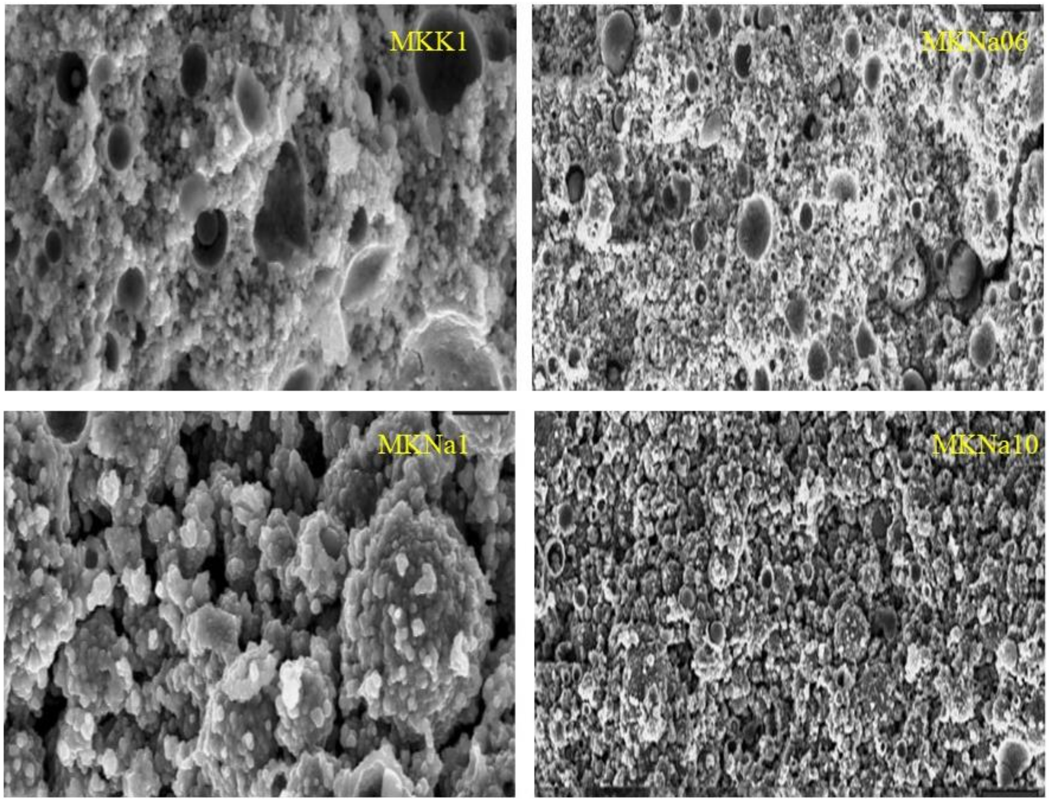
Alkalinity is accomplished utilizing NaOH or KOH arrangements. The limit of different aluminosilicate sources to filter in NaOH and KOH arrangements has been all around explored. The disintegration of aluminosilicate sources regularly increments as the centralization of alkali solution rises. The limit of a geopolymer to disintegrate is as often as possible connected to its last strength(28). Nonetheless, the majority of analysts concurred that Al_2SiO_5 materials disintegrate better in sodium hydroxide rather than in potassium hydroxide. The geopolymers produced using Al_2SiO_5 material possess greater compressive strength in potassium hydroxide than in sodium hydroxide solution, despite higher dissolution in NaOH solution.

Figure 7a. More modest Na+ particles are easier to consolidate with silicate anion to make little

Panagiotopoulou et al(65). explored the limit of Al_2SiO_5 to leach in 10 molar sodium hydroxide and potassium hydroxide solutions, individually. The aluminosilicates break down more promptly in NaOH than in KOH, true to form. The ability to leach was decreased in the accompanying request: kaolin > metakaolin > zeolite > slag >fly debris > pozzolana

oligomers, as per Xu and van Deventer(28). All in all, when more K+ particles are joined with silicate anion, bigger oligomers result. Therefore, the compressive strength of K-based geopolymers is 42% greater than that of Na-based geopolymers. For kaolinitic build-up, a comparable example has been seen(24). Also, greater K+ particles help in the setting of geopolymers(70).

Figure 8.Metakaolin geopolymers of the same composition made with different activating cations (MKK1- shows geopolymers prepared with k-based activating alkali solution while MKNa1- shows geopolymer prepared with Na-based alkali solution while "06" and "10" shows different molarity of Sodium alkali solution(69).

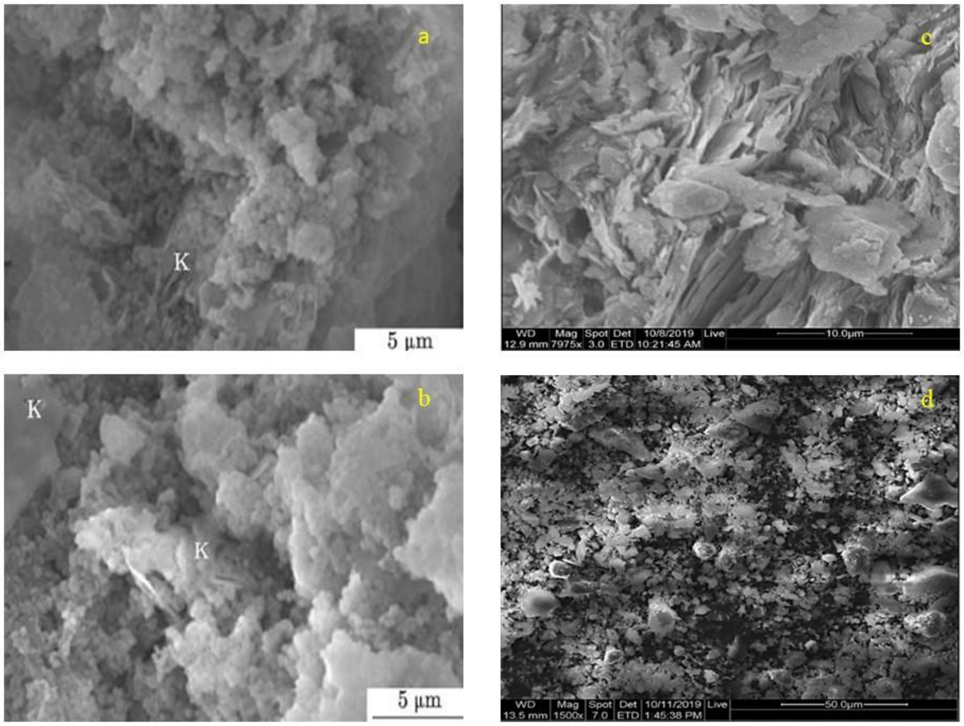


Steveson and Sagoe-Crentsil(69) have detailed a captivating outcome. The microstructure of geopolymers made with K and Na antacid arrangements is displayed in

Figure *8*. geopolymer had a more unmistakable geopolymer grid showed by globular units and less unreacted metakaolin particles in light of morphology (layered design). K-based geopolymers, then again, have a better surface and a denser design. Na-based geopolymers would do well with compressive strength than other geopolymers, which was amazing in view of the SEM picture. More modest Na+ particles are believed to be more dynamic insoluble base responses, bringing about superior disintegration and adjustment of silicate monomers and dimmers in arrangements. Rahier et al.(71) utilized DSC analysis to affirm the outcome.

Lizcano et al(72). tracked down the comparable example of microstructures. In any case, the compressive strength estimation varied from that of Steveson and Sagoe-Crentsil(69). despite the way that the Na-based soluble base reactant is thicker and responds speedier, it forestalls the creation of a homogenous design, bringing about a permeable construction and lower strength.

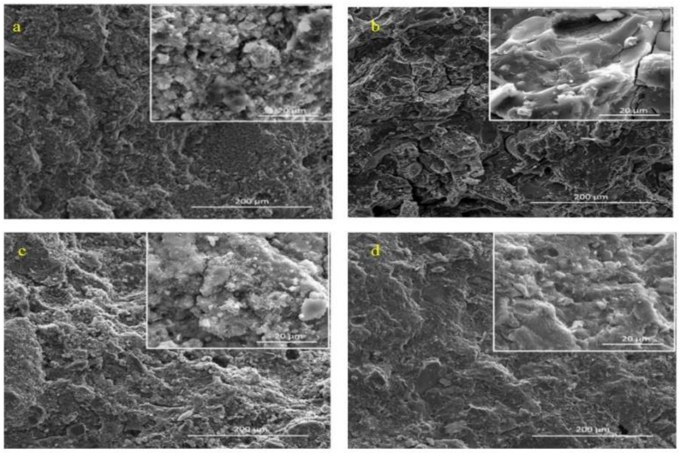
Regardless, the Na-based alkali reactant arrangement is liked for geopolymer alkalinization since this method is more practical.



1.1 Mixture of alkali silicate solution and alkali hydroxide

While alkali hydroxide is fundamental for aluminosilicate disintegration, soluble base silicate capacities as a fastener, alkali reactant, dispersant, or plasticizer(73). Silica fume, notwithstanding Na_2SiO_3/K_2SiO_3 solution may be utilized as another option or additive to metal silicate. They were now and then used to change Figure 9SEM of (a) and (b) shows kaolin made with NaOH solution while (c)and (d) are the SEM images of kaolin made with alkaline sodium silicate solution. (74, 75) the silica content of the combination and improve silicate gelation and precipitation.

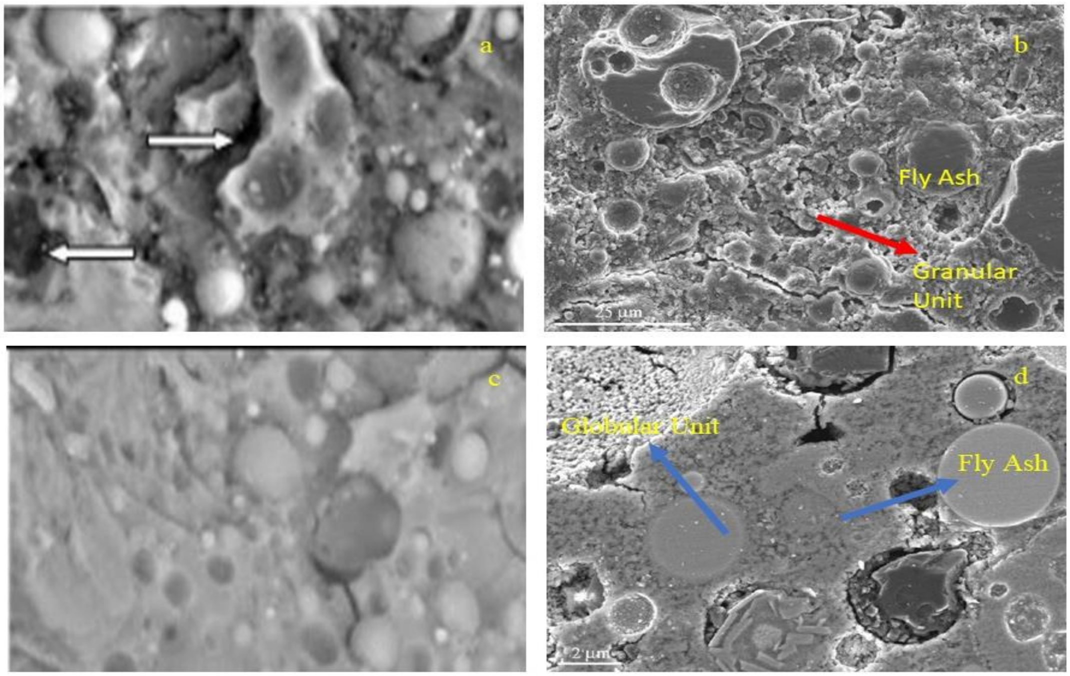
Figure 10 SEM micrographs of geopolymers made using (a) NaOH solution and (b)(c)&(d) a combination of NaOH and Na_2SiO_3/Sodium silicate solutions using clay particles from the Occhito reservoir. Blast furnace slag was used as a supplement/additive after the clay sediments were subjected to heat at 750 °C(46)



An examination of geopolymer created with soluble base hydroxide alone versus a mix of basic hydroxide and metal silicate arrangements was done. The presence of alkali silicate arrangement in alkali reactant arrangement is vital, as per most examinations, and prompts improved microstructure and strength characteristics. A particular extent of solvent SiO2 structures monomers, dimmers, and oligomers in the alkali silicate solution(43).

NaOH-responded kaolin geopolymers had a compressive strength of 20 MPa, as per Mohsen and Mostafa(74), while soluble sodium silicate-responded kaolin geopolymers had a compressive strength of 60 MPa. Pinto found a comparative strength design. Kaolin geopolymers made with Na_2SiO_3 arrangement have fine texture and a high-density construction, as seen in microstructures inFigure 9. This suggests that the sodium silicate geopolymerization response has advanced.

Figure 11 SEM of Fly Ash based geopolymer made with (a)(b and (c) NaOH Solution while (d) shows the SEM of fly ashy geopolymer made with alkaline silicate solution (76, 77)



Ferone et al.(46) mentioned a comparative observable fact, which is found in Figure 10. Albeit the compressive strength of NaOH-responded and NaOH-Na_2SiO_3-responded geopolymers is comparable, their microstructures are tremendously unique. The minimal construction was created when responded with NaOH-Na_2SiO_3 arrangement, showing more viable alkalization of Al and Si. Because of its dissolvable silicate content, which will in general modify the speed of geopolymerization reaction(71), fluid metal silicate is inclined toward alkali silicate solution in geopolymer creation.

Moreover, alklinization of Al_2SiO_5 with strong antacid/alkali without a solution of alkali silicates yields items that fluctuate from geopolymers, as indicated by Davidovits(78). zeolite A translucent or hydroxy sodalite as opposed to fly based geopolymers, thealkali silicate-responded fly ash-based geopolymer framework had globular units as geopolymer stages.Translucent/Crystalline and granular designs were found in the NaOH-responded fly debris geopolymer silicate-responded kaolin geopolymers had a compressive strength of 60 MPa. Pinto found a comparative strength design. Kaolin geopolymers made with Na2SiO3 arrangement have fine texture and a high-density construction, as seen in microstructures inFigure 9. This suggests that the sodium silicate geopolymerization response has advanced.

Figure *11*(77).In addition, geopolymers have been formed using a mixture of alkali reactant solutions of potassium silicate/sodium hydroxide, sodium silicate/sodium hydroxide, and potassium silicate/potassium hydroxide. Alkali reactant solutions of the same alkali elements (sodium silicate/sodium hydroxide and potassium silicate/potassium hydroxide) usually outperform different alkali metal reactant solutions in terms of strength. this was felt that potassium silicate has a quicker polycondensation rate than sodium silicate, bringing about more salt elements being occupied with the polycondensation interaction instead of aluminosilicate disintegration(70). Geopolymers containing sodium silicate set faster than those containing potassium silicate, according to Kong et al.(45).

O'Connor and Mackenzie(79) utilized a lithium-based salt reactant to make halloysite geopolymers notwithstanding Na and K-based antacid/alkali reactants. Because of the reactantimpact on gel development and stage division, the end results didn't show the common nebulous element/ final product of geopolymers, but instead lithium zeolites. Na_2CO_3, K_2CO_3, and K_2SO_4 may be utilized as salt reactant arrangements notwithstanding the previously mentioned normal alkali reactant solution(7, 17, 80). clay based geopolymers, then again, definitely stand out enough to be noticed with the above alkali reactants.

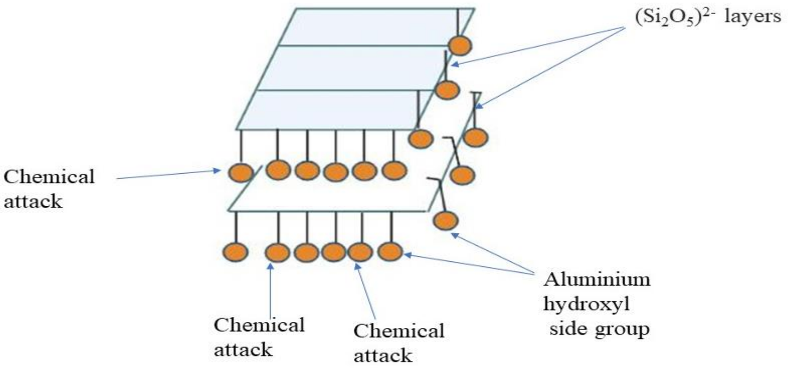


Figure 12Attack of chemical on kaolinite layers (orange circles represents Aluminium hydroxyl side group)(81)

3. Reactions that occur during the formation of Geopolymer (Geopolymerization Process)

The reaction happening during the geopolymer formation process is a synthetic reaction in which aluminosilicate (Al_2SiO_5) materials change over to some extent or completely from the amorphous phase into 3D polymer organizations rapidly. Alkali reactant as well as the type of (Al_2SiO_5) material used, decides the science of alkinization.

No matter what the underlying fixings are used, the geopolymer combination follows a comparable system. Understanding the response that prompts the making of geopolymers is vital. The particular geopolymerization reaction has not been understood. Most investigations concur, in any case, that geopolymer creation involves dissolving Al and Si species from aluminosilicate surfaces, cross-linking (polymer formation process) of dynamic planes gatherings and solvent atoms and ions making a gel, afterward solidifying to shape gives an unbending strong known as geopolymer.

3.1 Reaction that occurs during creation of geopolymer formation (Geopolymerization process)

Aforementioned that, kaolinite-based geopolymers have overlay construction, as well as ionic charges are negligible which prevents ion interchange after interaction with soluble base reactants. As a result, kaolinite layer chemical assault begins at the outward area and borders & gradually perforates the structure sheet by sheet **Error! Reference source not found.**(81) illustrates this. This becomes the primary reason of poor strength performance of almost every geopolymer made with clay or soil.

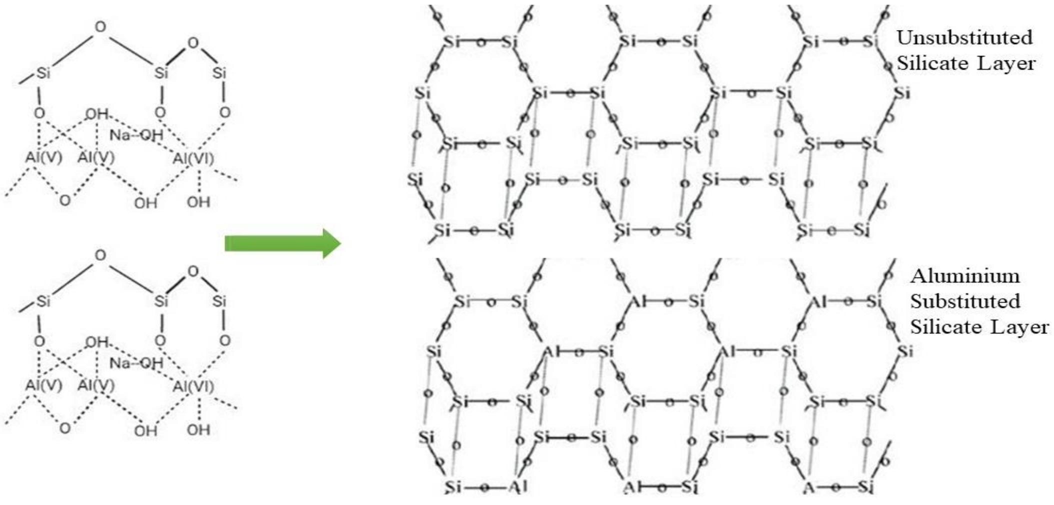


Figure 13: Schematic diagram showing the unsubstituted silicate layer and substituted aluminium silicate layer after interaction of meta kaolin with NaOH solution(82).

Meanwhile, the production of aluminium-substituted silicate layers after assault by sodium hydroxide solution is depicted in a schematic model given in

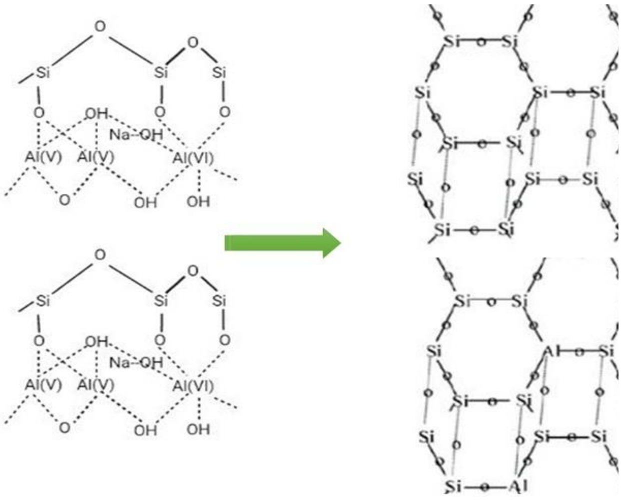


Figure *13*(82). Structure damaged aluminium sites were produced & changed into tetra-organized aluminium sites after the chemical attack.

3.2 Mechanism of Reaction

Geopolymerization is an exothermic reaction that is thought to be carried out by oligomers (dimer, trimer) that supply the real unit structures of three-dimensional macromolecular edifices. The equations for geopolymer production proposed by Davidovits(1, 83) are shown in Figure 14**Error! Reference source not found.** (Si_2O_5, Al_2O_2) refers to Al's IV-fold coordination, whereas SiO_2 comes from a silicate solution. The backbone of the final product is Si-O-Al.

The existence of OH^- in the soluble base reactant starts the breakdown of Al_2SiO_5 in alkaline media, releasing ($Si_2O_5^{2-}$)n and (AlO_3^{1-})ions to aid in the geopolymer formation process(73, 84). The amount of disintegration is determined by fine grains, the capability of ion interchange, alkaline solution concentration, and the structure of the precursor materials. The geopolymerization reaction is thought to take place in many steps that occur simultaneously(29, 57, 85)

- Aluminosilicates disintegrate in an unequivocally alkaline reactant;
- Strong state change and solidifying/hardening to create hard strong/solid;
- Depolymerization to create Al_2SiO_5 gel stages; and
- Strong state change & solidifying to frame strong geopolymer.

Also, Xu and van Deventer(86) introduced a response system for the union of geopolymers, as displayed in Eqs. (2)- (4). The creation of geopolymers occurs in Eq (4). The time expected for Si-Al material to make a continuous gel is determined by raw material processing(73).

Al-Si material (s) +MOH (aq) + Na_2SiO_3 (s or aq) (1)

Al-Si material (s) + [M_z $(AlO_2)_x$ $(SiO_2)_y$. nMOH . mH_2O] gel (2)

Al-Si material (s) [$M_a(AlO_2)_a$ $(SiO_2)_b$. nMOH . mH_2O] (3)

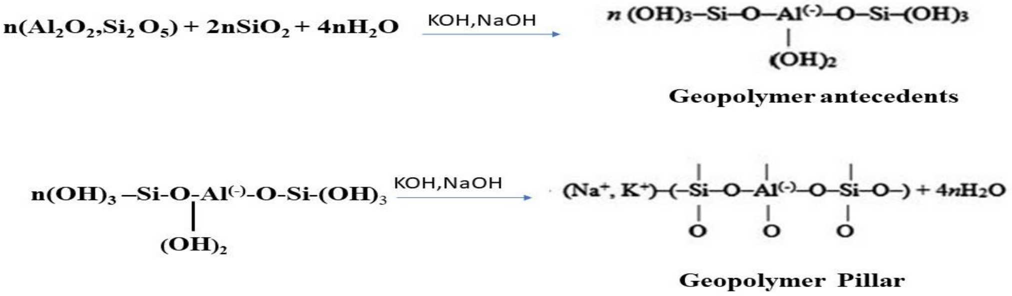


Figure 14Diagram showing geopolymerization process(1, 83)

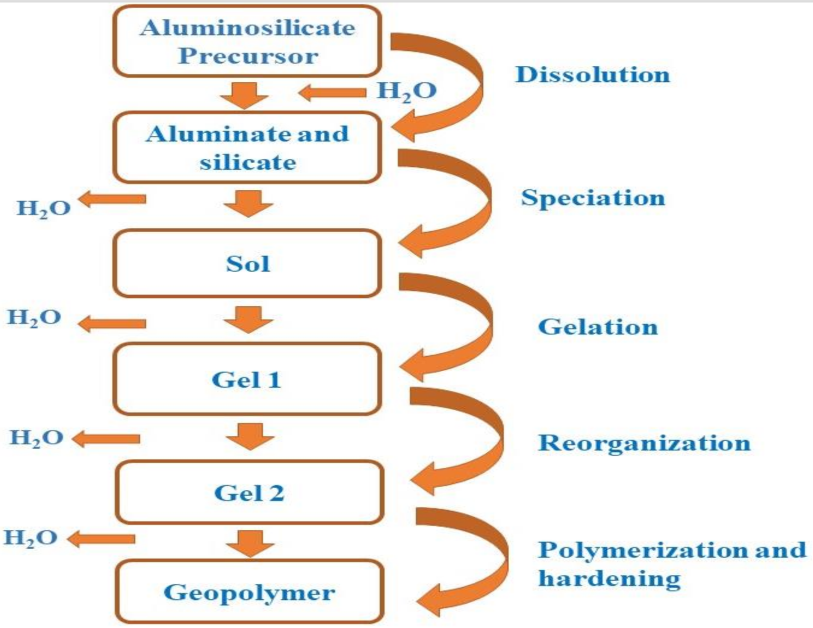


Figure 15Processes that happen during geopolymer formation(87)

The initial geopolymer gel phase is distinct from final gel stage after broadened heat treatment and curing, as indicated by the Provis and his co-researchers (87, 88) as shown in**Error! Reference source not found.**. During curing and treatment, the gel phase goes through a steady adjustment toward more prominent crosslinking, with unbound water being launched out and the creation of some zeolitic crystallites. In their model, the beginning and last gel stages are addressed by the 'hardening and solidifying" and 'ongoing gel reworking and crystallization", separately. More arranged phases were shaped in the end product.

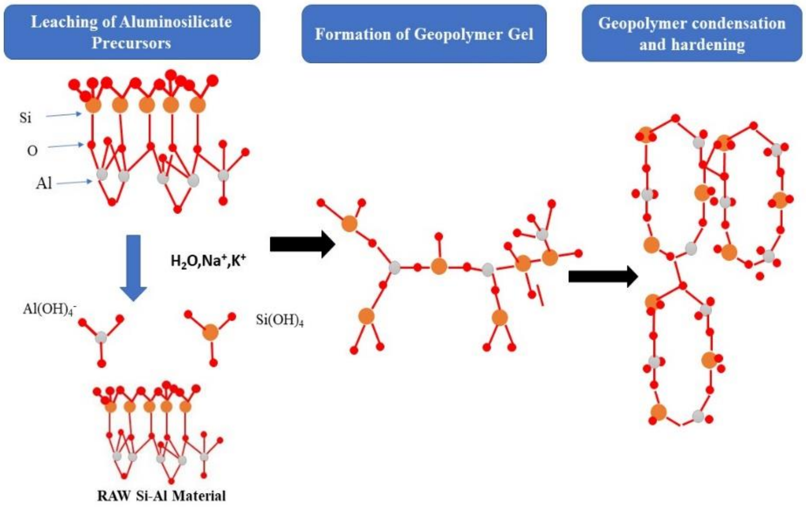


Figure 16: Graphical model of geopolymerization process (orange circle represents Si, red circles represent "O" and grey colour circles represents "Al"(89)

When Si-O-Si and Si-O-Al covalent bonds come in touch with just an alkaline solution during geopolymerization, they dissociate into a colloidal phase. Most analysts(89) accept that the disintegrated items interact and produce a coagulated design. As the response creates, the middle of the road item (Gel 1), having a strong measure of Aluminium, the recoganize into Gel 2, Gel 2 contains a higher measure of Si as shown in **Error! Reference source not found.**. At long last, the gel creates and delivers three-layered designs. The paradigm that followed was very similar to that given by Provis et al.(87), in which the reaction entails the continuous orchestration of gel into three-dimensional geopolymer structures.

Geopolymer structures at an incredibly quick rate. The previously mentioned conjectured process happens for all intents and purposes at the same time. Response energy or reaction kinetics are interconnected. Thus, it's almost difficult to detach the reaction steps in tests.

3.3 Formation of Geopolymer

The best blending results in a homogeneous geopolymer combination with amazing strength subsequently. Direct blending of aluminosilicates with a soluble base reactant is the most widely recognized method for creating geopolymers. The geopolymer glue is restored at room temperature or somewhat higher temperature subsequent to projecting and embellishment. To limit extreme dampness/moisture misfortune, the uncovered surface is covered with a slender plastic layer.

Different blending successions have likewise been utilized. To produce kaolin/white dirt slag mixed geopolymers, one of the manners which utilizes the standard blending process as expressed previously. The aluminosilicates are joined with fluid/liquid sodium silicate in the subsequent method, and the NaOH solution/arrangement is added following 3 minutes(40). Neither one of the methodologies was fruitful in decreasing the degree of geopolymerization. Nonetheless, on the grounds that the combination acquired excess water, the last methodology is unfavorable to mechanical strength. Rattanasak and Chindaprasirt(90) uncovered incongruous discoveries in the example of fly debris geopolymers. When contrasted with the primary methodology, the subsequent technique delivered more grounded geopolymers since additional time accommodated for the filtering of aluminosilicates, which works on the response.

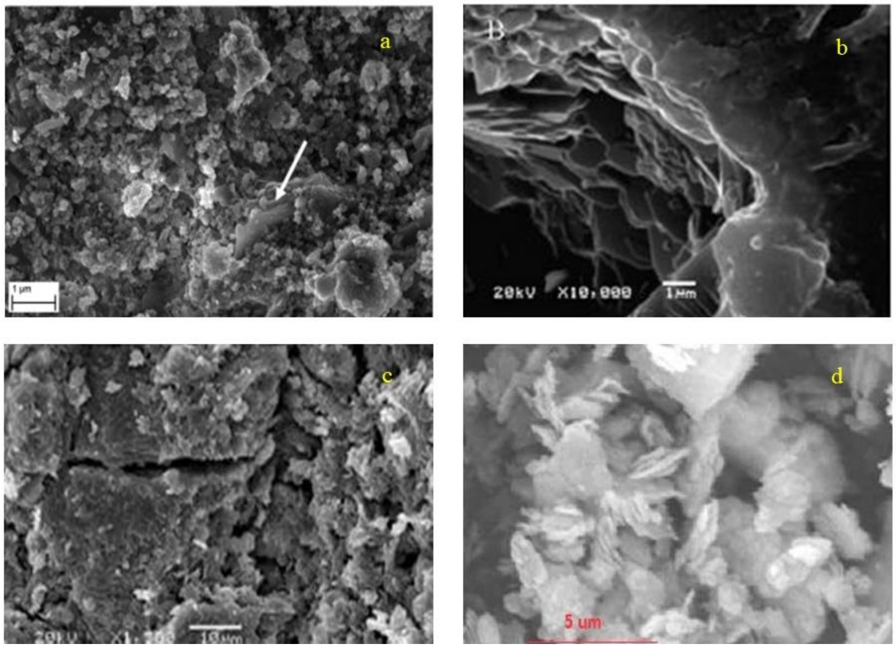


Figure 17: SEM pictures obtained for metakaolin geopolymers(91-93)

The sort of the underlying materials utilized, as well as the blending/mixing proportions, decide if an adjusted blending arrangement could further develop the geopolymerization reaction. Overabundance of water was expected all through the blending work in the clay examination to deliver satisfactory consistency. clay-based combinations are frequently gooier and tackier than fly ash-based mixtures(94). This is because clay-based geopolymer has layer-like construction, which diminishes the blend's functionality for basic dealing . Fly ash, then again, contains circular formed particles that cause diminished molecule erosion or inter-particle friction while additionally increasing the usefulness of the geopolymer mixture. This could clarify why fly ash-based geopolymers have better mechanical attributes. During the planning of geopolymers, functionality is a significant variable to consider. A genuine functionality issue will make compaction troublesome and bring about a permeable/porous and delicate last design(27, 31).

4. Characterization and structure of Clay-based geopolymers

4.1 Morphology of Clay-Based Geopolymer

Microstructural investigation might be utilized to follow the development of geopolymers through time. The thickness and porosity of a geopolymer structure are firmly associated with its strength. Low porosity, high thickness, and fine-grained microstructure are altogether factors that add to high strength geopolymers overall(69).

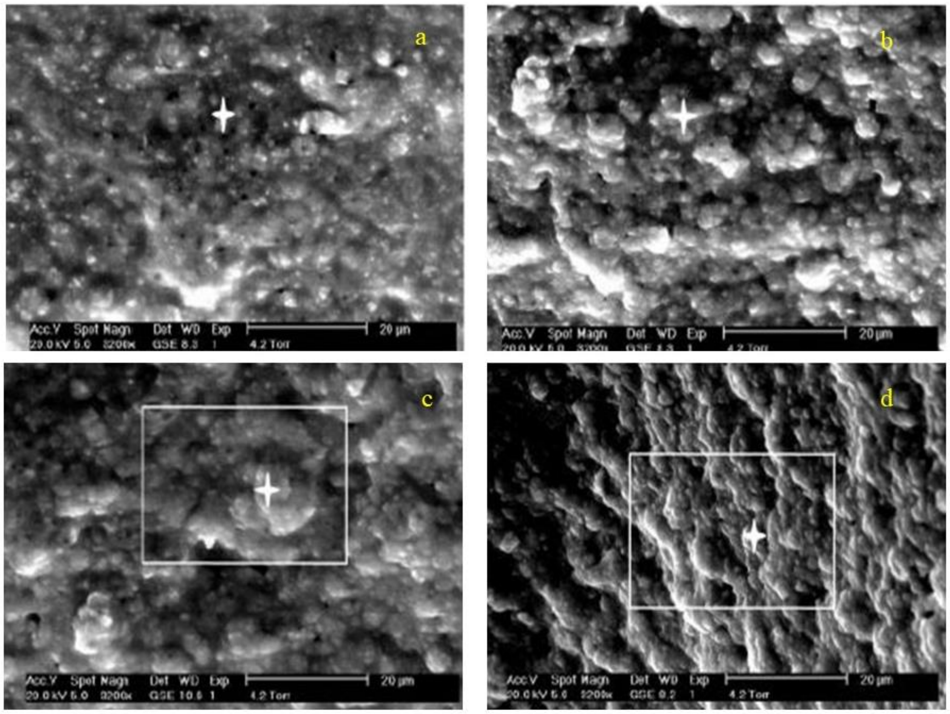


Figure 18 : ESEM micrographs obtained for the same area at different mixing times (a)10 min(b)3 hr.(c)6hr and (d) 9hr respectively.(95)

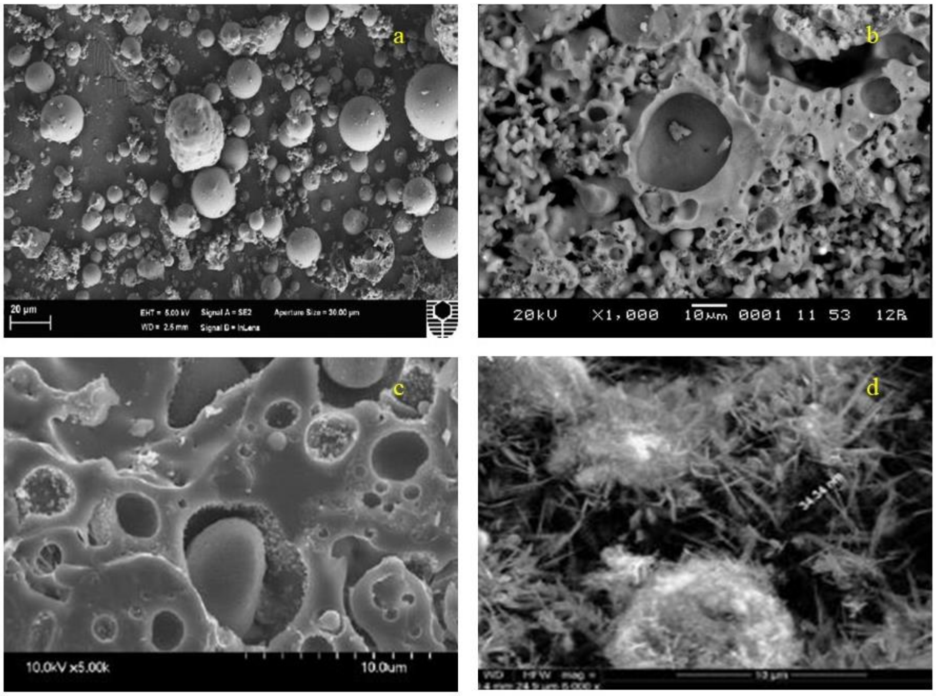


Figure 19: (a)SEM of Fly ash-based geopolymer(b)SEM micrograph of Fly ash-based geopolymer after calcination at 400,6000 and 800°C(c) SEM micrographs of fly ash-based geopolymer calcined and cured at room temperature for 24 hours and at 80°C for another 24 hours(d)SEM of Fly ash Geopolymer mixed at 80°C(96-98)

The SEM pictures procured by different researchers(91) are displayed inFigure 17. The layered design of metakaolin geopolymers was protected during the geopolymerization occasion.

upholds and approves Davidovits'(78) guarantee that the response happens on the outer layer of geopolymers.

The precipitation of sponge-like geopolymer globular units on the outer layer of approximately paced metakaolin particles, densification, and ceaseless arrangement of thick geopolymer grid inside and outside voids was seen as the microstructure of metakaolin geopolymers advanced over the long run, as displayed in**Error! Reference source not found.**(95, 99).

Zhang et al.(95) noted that the potassium(k) to aluminium (Al) and Silicon (Si) to Aluminium (Al) molar ratios were high early in the mixing process due to the release of Si from liquid Na_2SiO_3. At this point, Al dissolution is minimal. As additional dissolved Al entered the system, these molar ratios decreased with time. According to Song et al.(100), lower Si/Al and Si/Na ratios weakened the strength of geopolymers.

The existence of residual particles in bulk geopolymer structures, according to Rowles et al.(42), constitutes a stress concentration site that generates cracks and fractures. Furthermore, leftover particles may modify the nominal composition of the geopolymer, preventing the entire growth of the geopolymer network.

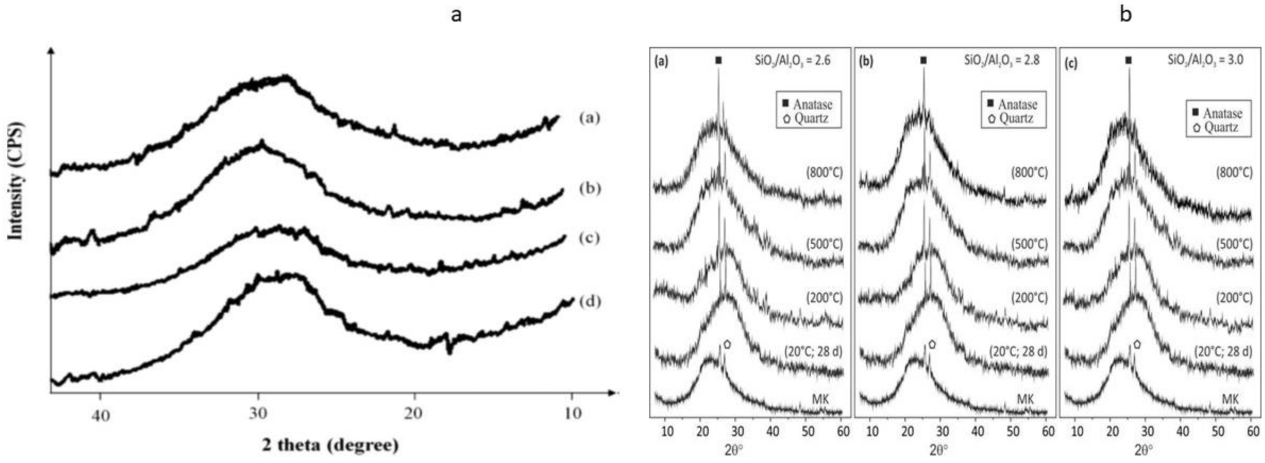


Figure 20: (a)XRD diffractograms for poly(sialate-siloxo) geopolymers with molar ratios of SiO2/Al2O3 of (a) 4.02; (b) 3.98; (c) 3.39; and (d) 4.11 (b) XRD of Geopolymer at different SiO_2/Al_2O_3 ratios while cured at different temperatures(1, 101, 102)

Fly ash geopolymers contrast with metakaolin geopolymers in that they unveil heterogeneous materials, for example, non-responsive fly ash particles in the empty spaces left by to some extent dissolve fly ash particles as shown in**Error! Reference source not found.**. Non-responsive particles serve as a filling particles & help to reinforce the composite. Instead of globular units of geopolymer matrix in metakaolin geopolymers, smooth and connected geopolymer matrix was discovered in fly-ash geopolymers.

4.2 Geopolymer Phases

As per X-ray diffraction (XRD), geopolymers are completely nebulous. As outlined in **Error! Reference source not found.**, they frequently have a diffuse hollow peak around 27-30° 2ɵ(1, 40, 72, 95, 101). The shapeless aluminosilicates, which include the significant cover deliberately ease in geopolymer framework and add to geopolymer strength, correspond to the wide diffuse hump. The Si/Al proportion decides the slant of this diffuse halo. The level of the mound is decreased when the Si/Al proportion rises(72). Wang et al.(91) likewise found response items with halo diffuse qualities somewhere in the range of 18° and 25° for metakaolin geopolymers.

The quartz stage has been demonstrated to be by and large inert after alkalination. In any case, because of inadequate calcination, the impurities in kaolin decline in intensity **Error! Reference source not found.**(53).

Related to the indistinct period of geopolymers, the development of glasslike stages, eminently zeolites, can be identified in the x-ray diffraction example of geopolymers **Error! Reference source not found.Error! Reference source not found.**(78, 103). Geopolymer has a substance cosmetic that is equivalent to zeolitic materials. Geopolymers are in some cases remembered to be a zeolitic forerunner. Geopolymers and zeolites change in that Zeolites are very much perceived for their permeable nature and poor mechanical qualities. It was once imagined that the amount of glasslike stage that the lattice could support was restricted 100% of the time. A few specialists(48, 107) noticed that zeolite crystals strengthen the geopolymer matrix and increase its toughness, however that the drawn-out strength is altogether diminished. Fly ash geopolymers have shown a comparable strength development design(108).

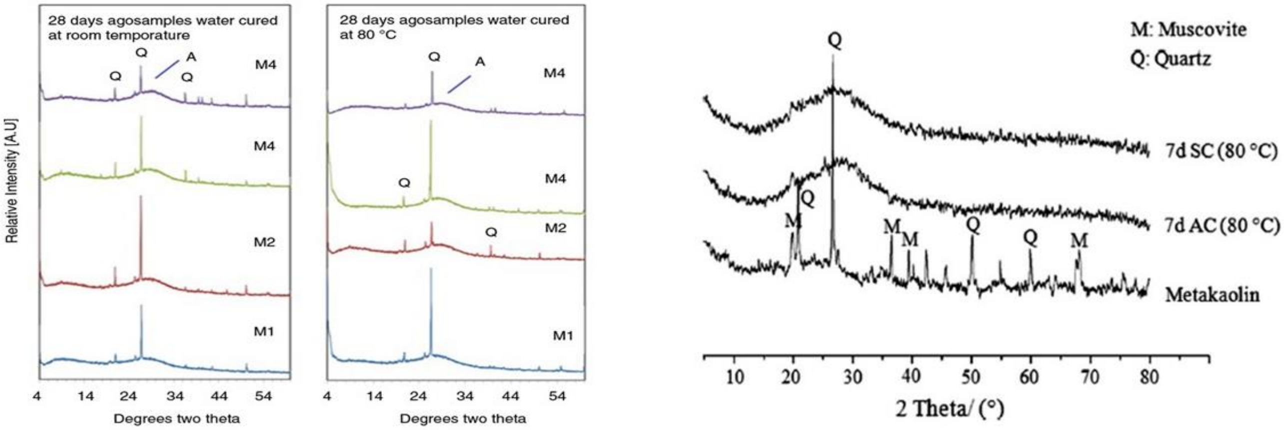
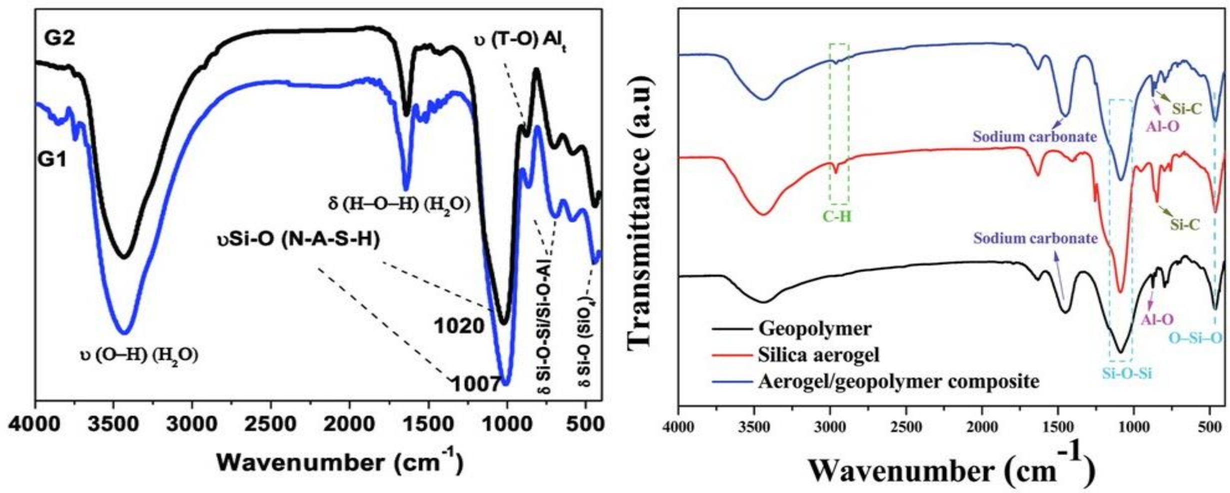


Figure 21(a) (a)XRD of geopolymers of different composition cured at room temperature and at 80°C for 28 days (A=Amorphous phase=Quartz) (b)XRD of geopolymers at different calcined/curing temperatures (AC=Air Curing, SC=Steam Curing)(53, 104)

4.3 Identification of Functional group

FTIR spectroscopy might be utilized to offer data on the progress of vibrations inferable from little underlying changes, as well as aiding the investigation of functional groups of geopolymers. The essential ingestion/primary band of clay-based geopolymers is around 990 cm^{-1}, which relates to the deviated extending/asymmetric stretching of silicon and oxygen bonds and aluminium oxygen links(57, 109). As the polycondensation cycle advances, this band concentration increases which means (an increase in Al_2SiO_5 lattice/matrix). Moreover, because of the more prominent relieving temperature, it moved to a higher wavenumber. This is on the grounds that the swap of aluminium for silicon causes atomic primary adjustments(110). The progress of Gel 1 to Gel 2 proposed by Duxson et al(89). is shown the spectrum changes from lower to upper wavenumbers. On account flyash geopolymers, this was as per Criado et al(112). as shown in**Error! Reference source not found.**. Besides, geopolymers display a peak at 720 cm^{-1}, which is inferable from Si-O-Si/Si-O-Al extending/stretching. Other ingestion groups or absorption bands might be seen at 560 cm^{-1} and 690-440 cm^{-1}, showing tetrahedral aluminium extending/stretching groups and Si-O-Si/Si-O-Al(56, 57, 94) twisting vibrations, individually. Expanded silica focus in geopolymer structures improves geopolymer strength. This is because of the way that Si-O-Si bonds are more impressive and stronger than Si-O-Al bonds(113).

Figure 22(a)FTIR spectrum of (G1=Gel 1) and (G2=Gel2) (b)FTIR spectrum of Geopolymer, aerogel/geopolymer composite and aerogel(111, 112)



5. Properties of Clay-Based Geopolymers

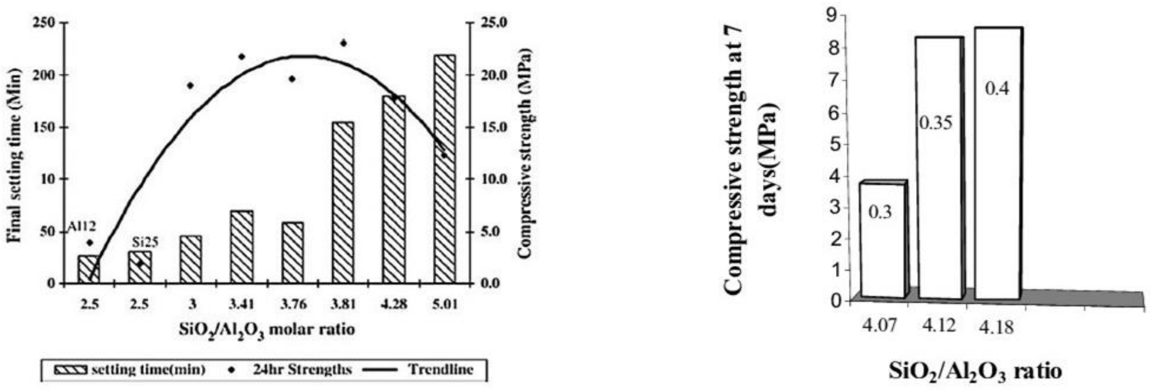
Geopolymers have outstanding physical and mechanical characteristics, including extraordinary mechanical strength, low thickness, and chemical, fire, and hotness opposition/heat resistance, in addition to other things. Therefore, they are broadly utilized in an assortment of disciplines, including novel pottery, fireproof materials, and innovative materials.

The bulk density of metakaolin geopolymers has been viewed as somewhere in the range of 1.20 and 1.80 g/cm^3. Geopolymers can along these lines are utilized to make lightweight things. The expressed bulk density is lower than OPC concrete and practically as low as geopolymers produced using fly ash and slag. Customary Portland concrete glue/cement, for instance, has a density of >1.80g/cm^3(31), though coal fly ash geopolymers have a bulk density ranging from 1.40 g/cm3 to 1.80 g/cm3(114, 115).

The curing condition, as well as other combination factors including the sort of geopolymers, alkali concentration, and the nature of soluble base metal silica (SiO$_2$), altogether affect bulk density. As the curing temperature rises, the bulk density decreases(109). The compressive strength of a material is corresponding to its mass thickness. Potassium based metakaolin geopolymers (1.38 to 1.82 g/cm3) and sodium based metakaolin geopolymers (1.24 to 1.71 g/cm^3) had almost indistinguishable density values. Geopolymers in view of Na are generally lighter than those in light of K. This is on the grounds that potassium based geopolymers have high density and fewer openings, as recently expressed(72).

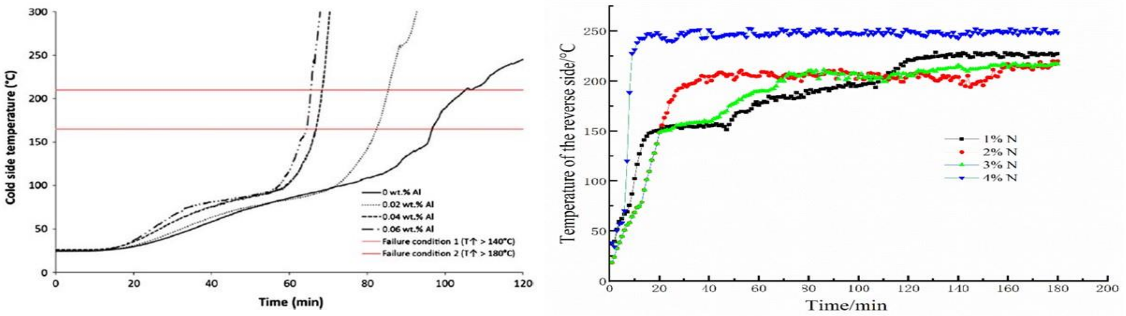
Geopolymers rush to set. Metakaolin geopolymers set and solidify in around 24 hours. De Silva et al(116). announced a short set season of 4 h at a restoring or curing temperature of 40 °C. Rather than metakaolin geopolymers, fly ash geopolymer glue sets and solidifies all the more rapidly. As indicated by Hardjito et al.(117), they can be dealt with for as long as 2 hours when restored at 65 °C and 80 °C. Indeed, even yet, the restoring temperature significantly affects the setting time. The geopolymer sets quicker at higher temperatures.

Figure 23 (a)Compressive strength of geopolymer at different SiO$_2$/Al$_2$O$_3$ ratios after 24 hr(b)Compressive strength relation of geopolymer with different SIO$_2$/Al$_2$O$_3$ ratios(116, 118)



The geopolymerization strategy required 4 hours at 50 degrees Celsius. Besides, at 85 °C and 95 °C, the geopolymerization cycle required 1.5 and 0.5 hours, separately(2). It might require over one day for the geopolymer glue to set in the event that it is restored at temperatures beneath encompassing/below ambient. Rovnanik (109)observed that the strength of geopolymers didn't debase following 28 days, in any event, when they were invested for a more extended time of energy.

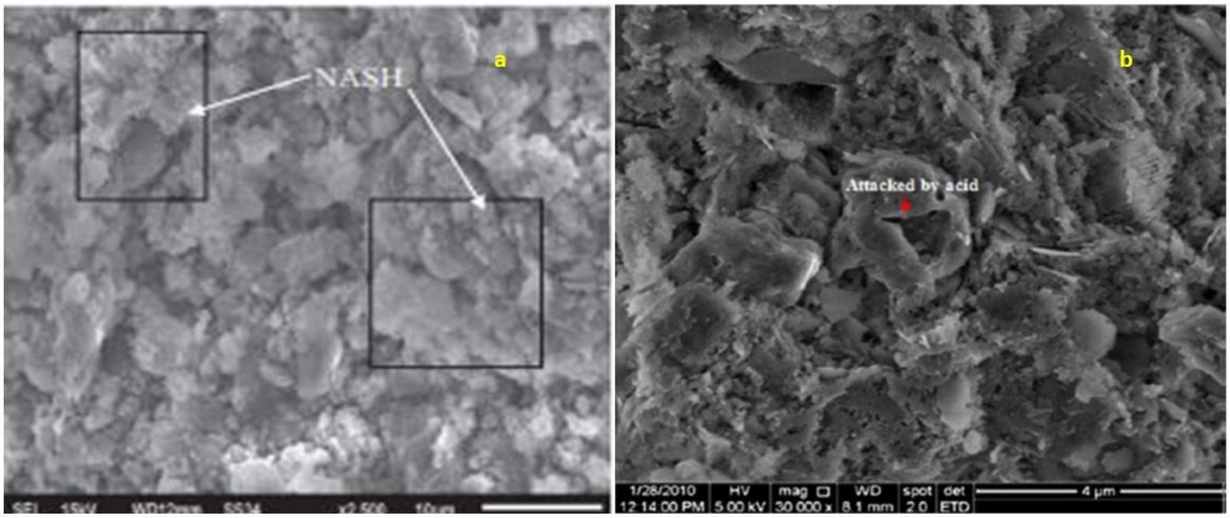
Figure 24(a)Fire testing of different 4 mixes of metakaolin geopolymer(b)Fire resistance test of metakaolin geopolymer activated with Na_2O_2 while “N shows Percentage of Na_2O_2(119, 120).



De Silva et al(116). tracked down that a high SiO_2/Al_2O_3 proportion in the underlying synthesis prompts delayed setting and solidifying terms **Error! Reference source not found.**a.Despite the fact that the setting time was longer, metakaolin geopolymers with a silica to alumina ratio of 3.8 gained higher and more stable strength a later period, for fly ash-based geopolymer the highest compressive strength after 7 days was obtained at SiO2/Al2O3 ratio of 4.18 as shown in **Error! Reference source not found.**b. Setting time is speedy on the off chance that the Al2O3 fixation is high; notwithstanding, assuming the SiO_2 content is low, the strength will endure. Moreover, the “Ca” percentage of the forerunner material has a huge impact on the setting time. This is on the grounds that the presence of calcium offers more nucleation locales for the precipitation of broken up species, coming about in a speedier pace of setting and solidifying.

After just 4 hours at 20 degrees Celsius, geopolymers procure compressive strength of 20 MPa. Geopolymers' 28-day compressive strength may be pretty much as high as 70 to 100 MPa(1). An increase in strength shows that source materials break down more effectively or all the more rapidly, bringing about more aluminosilicate species, which are the main components in the geopolymerization interaction. The compressive qualities of made geopolymers can straightforwardly assess the response degree of source materials. Geopolymer is not entirely set in stone by the gel stage strength, how much gel stage is created,& the amorphous nature of the reaction products(89).

Figure 25 (a)SEM of fly ash based geopolymer exposed to acid attack for 365 days(b)SEM of Kaolinite geopolymer exposed to acid attack for 90 days(61, 121)



Geopolymers, then again, offer extraordinary hotness dependability with simply 2% shrinkage. Geopolymers have a ceramic-like design and are steady up to 1000-1200 °C(4, 63, 122, 123). Geopolymers are correspondingly steady in the functioning reaching somewhere in the range of 250 and 800 degrees Celsius, as per Subaru and van Riessen(124). Filler (for example SiO_2 or rock) and foaming agents (for example grind aluminium, H_2O_2) were added to geopolymers during blending to build their thermal characteristics. The expansion of quartz or rock to the blend diminished shrinkage to 1%(124).

Besides, as per researchers(120), foamed geopolymers supported with $(C_3H_6)n$ strands have a flame resistance of something like 60 minutes **Error! Reference source not found.**. Foamed geopolymers have a great deal of guarantee for use as a warm protector/thermal insulator in the climate in view of their low thickness and compressive strength. To accomplish a comparative fire rating, materials should have exceptionally low thermal conductivity and thermal damage opposition. Elim et al.(125) tracked down that when metakaolin geopolymers were given heat somewhere in the range of 300 and 900 degrees Celsius, their solidarity/strength dropped. It was portrayed because of the geopolymer framework's slow progress into translucent stages. At 1000 degrees Celsius, the metakaolin geopolymers extended and broke.

In acidic and alkaline circumstances, geopolymers have a high tirelessness/ preseverance (107, 126). In the examination, they are steadier in an antacid climate. Whenever lowered in ocean water having (potential of hydrogen=8) and Na_2SO_4 arrangement (5% sodium sulfate) for a full year, mechanical properties didn't fall apart. Geopolymers, then again, were fundamentally harmed when lowered in HCl answer for a drawn-out timeframe. While test mass misfortune expanded, pressure strength diminished. This was undoubtedly brought about by the de-aluminization of the geopolymer structure in an exceptionally acidic climate. Because of the breakage of Si-O-Al bonds, de-aluminum causes a mass loss of geopolymer structure, bringing about more silicic corrosive particles in the corrosive media. The subsequent geopolymers' microstructure developed more permeable or porous **Error! Reference source not found.**(61).

Drying shrinkage happens when unbounded water is lost during the relieving, causing the geopolymer grid to contract. As recently expressed, adding filler to geopolymer tests lessens shrinkage. As a general rule, materials with a higher convergence of better components/finer components will quite often contract more than those with a high substance of coarser materials(120). The drying shrinkage of geopolymers with sand filler, for instance, was 0.01 percent following 180 days. The drying shrinkage of geopolymers without sand filler, then again, changed somewhere in the range of 0.03 and 0.04 percent(61).

6. Variables Influencing characteristics of Clay-Based Geopolymers

Geopolymer development is affected by different variables, for example, introductory solid or fluid substance, molecule size, how many reactive stages, substance organization/ chemical composition and kinds of Al_2SiO_5, sorts of metal silicate, alkali concentration, restoring systems (curing regimes), fillers or added substance content as well as the water content.

6.1 Concentration of alkali

The physical and mechanical qualities of geopolymers are extraordinarily impacted by alkali substances. Soluble alkali expands the dissolvability and disintegration of aluminosilicates, as well as the pace of geopolymerization(53). How many particles are expected for the dissolving are still up in the air by the soluble alkali focus, which is pH subordinate. As a rule, expanding the convergence of NaOH in the scope of 4-12 M fortifies metakaolin geopolymers. XRD examination uncovered that the number of shapeless stages rose in couple with the grouping of NaOH as shown in **Error! Reference source not found.**(91). The pace of heat evolution in the response increments as the alkali/antacid fixation rises. The ideal alkalinity for the disintegration of source materials is recommended by a higher heat evolution rate(53, 127).

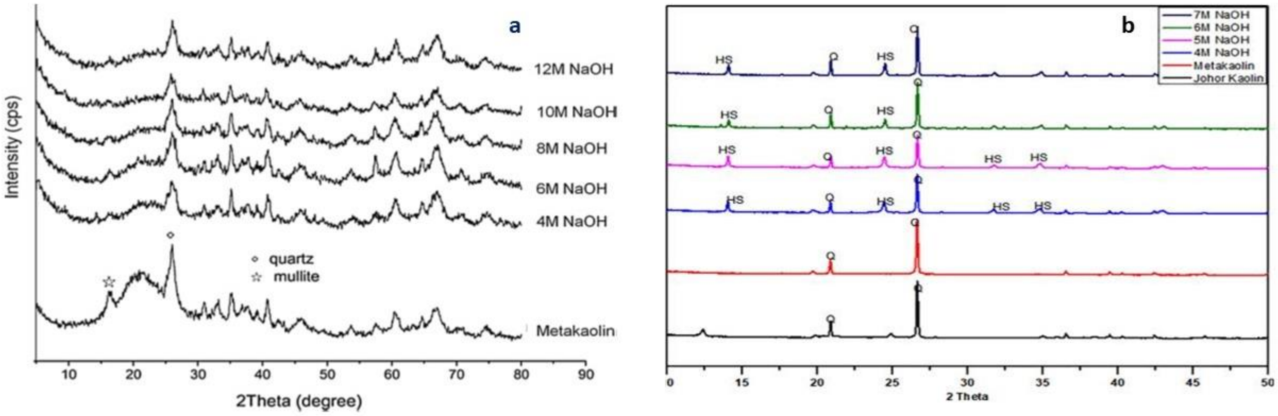
The Na+ particle and the OH will be connected during the cycle. There will be lacking OH to break down Si4+ and Al3+ from the aluminosilicates in examples with low sodium concentration, as well as inadequate Na+ to take into account total geopolymerization. Thus, geopolymer has a poor compressive strength(54).

In spite of the prior finding, various researchers concurred that over-the-top alkalinity diminishes geopolymer strength. Geopolymer strength increments with expanding/increasing NaOH focus/solutionand diminishes once it reaches ideal/optimum value. As indicated by Zuhua et al.(127), the best NaOH fixation for the creation of metakaolin geopolymers is 9 M. Polymerization response is undesired over this ideal value. Since a high convergence of sodium hydroxide arrangement is sticky, it might impede the leaching of silicon and aluminium from Al_2SiO_5 sources, the untimelyprecipitation of geopolymer gels, and the deficiency of finished resultmechanical attributes, attributable to leftover precursor material(128).

As opposed to what Alonso and Palomo(56) found, expanding NaOHcontent dials back the polycondensation interaction as shown in **Error! Reference source not found.**. The scope of NaOH focuses utilized (10-18 M) is marginally higher than others. concentration increase was remembered to defer polymerization because countless broken down particles in an emphatically basic arrangement produce immersion/saturation, which confines/restricts communication between polymerized species and the formation of coagulateddesigns(7, 56). Singh et al(82). concurred, expressing that a high alkaline climate with more than 30 mol% of complete Na_2O increase isn't suggested.

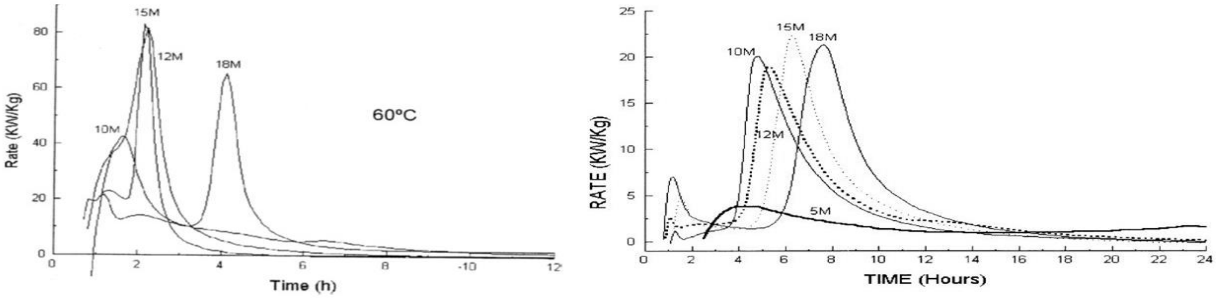
The speed of geopolymerization is likewise supposed to be connected to the pace of geopolymer setting. Metakaolin geopolymers don't set in 6 M of NaOH arrangement, as per Steveson and Sagoe-Crentsil(69), yet flash set in 13 M of NaOH arrangement. With expanding alkali substance (7-12 M), geopolymers become denser and have a smoother surface. The expansion in strength goes connected at the hip with this. The quick setting is helped by a high alkali concentration, which brings about deficient time for disintegration and a lot of unreacted material in the result. Expanding the concentration of NaOH, then again, has been connected to a more drawn-out setting time. Blast furnace slag and potassium hydroxide arrangement have been used in that situation, with the clarification that potassium hydroxide diminishes the viscous behavior of the geopolymer framework and thus leads to a lower setting(18).

Figure 26.(a)XRD of metakaolin geopolymer made with different NaOH concentrations and cured with temperature (20°C) for 1hr and then cured for 10hr at temperature of 65°C (b)XRD of (a) Johor kaolin(b)metakaolin and hydrosodalite at 4M,5M,6M & 7M respectively(91, 129)



Likewise, the functionality of geopolymer changes relying upon the alkali concentration used. As recently expressed, an increment in alkali concentration causes to geopolymers to set at faster rate, which is associated with paste usefulness. At the end of the day, expanding the alkali substance lessens the geopolymer pastes' functionality. The impact of soluble base fixation on the usefulness of metakaolin geopolymers, then again, has gotten little consideration. Expanding the concentration of fly ash geopolymers decreased their functionality(131, 132).

Figure 27 (a)calorimetric curves of calcium hydroxide used with metakaolin geopolymer(b)Curve showing heat evolution of geopolymer activated with NaOH solution(56, 130)



Both low and high antacid/alkali concentrations/fixations have been connected to low compressive strength. This may likewise be found in a geopolymer framework made of fly ash and slag(18, 133). It's memorable essential that the soluble alkali concentration should be sufficiently high to charge-balance the geopolymer networks, however not too high to even think about causing the creation of (Na_2CO_3) through carbonation(134).

6.2 Solid/Liquid ratios

The solids content addresses (Al_2SiO_5) during geopolymer creation, while the fluid substance addresses the alkali reactant. The solid to liquid proportion is critical in light of the fact that it controls how much solids and fluid utilized in homogeneous blending, which straightforwardly affects functionality, disintegration, geopolymerization response, and, at last, the completed item's solidarity/strength. All in all, for clay geopolymers, especially metakaolin geopolymers, the ideal S/L proportion is 0.80(98, 127, 135).

The S/L proportion fundamentally affects geopolymer paste usefulness. Usefulness was diminished when the S/L proportion expanded/increased. S/L proportions more prominent than 2.0 brought about the restricated usefulness of metakaolin geopolymers, as indicated by Xiao etal.(53). Low S/L proportion, then again, dials back/slows down the geopolymerization response.

With expanding S/L proportions, Fernandez-Jimenez and Palomo(136) observed a comparative usefulness pattern for fly ash geopolymers. Fly ash geopolymers, then again, can endure a more noteworthy S/L proportion. As a result of the wide between molecule distance and lesser molecule impedance/interference, a medium that has a high liquid proportion (low solid to liquid proportion) limits molecule to-molecule contact of precursor materials, working on the functionality of geopolymer paste(27).

Because of usefulness requirements/workability constraints, an indistinguishable S/L (solid to liquid) proportion for both fly ash and metakaolin geopolymers would never be acquired. It’s critical to remember that fine raw materials have an impact on water utilization. Metakaolin, indeed, has a bigger fluid need than fly ash. This is inferable from the distinction in molecule structure among metakaolin and fly ash; metakaolin has a layered design, whereas fly ash form/structure is circular. The multilayer construction limits molecule versatility during blending, making it less serviceable. To acquire uniform blending, metakaolin geopolymer requires lower solid to liquid proportions than fly ash geopolymers. In the synthesis of metakaolin and fly ash geopolymers, for instance, Kong and his friends(98) proposed solid to liquid proportions between 0.8 and 3, individually. The void volume and porosity in geopolymer, and consequently the strength of the end result, are straightforwardly impacted by the functionality of the glue/paste(45).

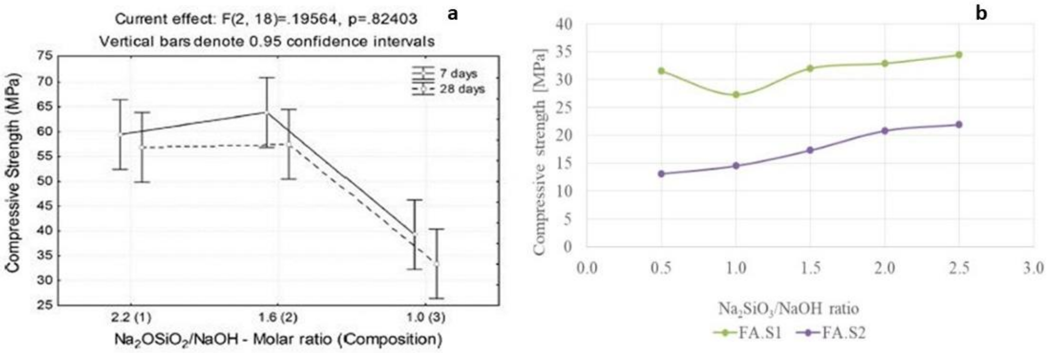
As per Zuhua et al.(127), a lower S/L proportion advances quick aluminosilicate disintegration. Despite the fact that expanding the Concentration of sodium hydroxide expanded aluminosilicate draining/leaching, it was restricted by diminishing the polycondensation cycle at a really high fixation, as depicted previously. Regardless, more noteworthy S/L proportions of 3 (91) have been seen previously, and some have contended that the S/L proportion should be in the scope of 1 to 5(111).

6.3 Alkali Reactant ratios

The ratio of sodium hydroxide solution and liquid Sodium silicate solution is essential for creating geopolymers. This is on the grounds that in the geopolymerization response, NaOH fills in as a dissolvent and Na_2SiO_3 capacities as a fastener/binder.

In light of prior research, a wide scope of Na_2SiO_3/NaOH proportions is still up in the air, going from 0.24 to 2.2. For metakaolin geopolymers with an extreme compressive strength of 59 N/mm^2, Wang et al.(91) prompted a Na_2SiO_3/NaOH proportion of 0.24. Pelisser et al.(137), then again, made metakaolin geopolymers utilizing a bigger scope of Na_2SiO_3/NaOH proportions (1.0, 1.6, and 2.2). At 1.6, the most elevated strength (64 MPa following 7 days) was accomplished. The least strength was accomplished with a proportion of 1 and apermeable geopolymer grid as shown in **Error! Reference source not found.**. The above result was supported by Poowancum and his co-researcher(138),for geopolymer made with calcined clay particles. In any case, while utilizing sedimentary clay, the best proportion was viewed as 0.50, with a strength of 27 N/mm^2 as shown in **Error! Reference source not found.**. The strength of clay sediment geopolymers is weaker than metakaolin geopolymers, which is likely due to clay sediment's weak reactivity when contrasted to metakaolin. It was anticipated that at 1.0, there would be deficient NaOH and Na_2SiO_3 for full disintegration and binder formation/folio development, separately.

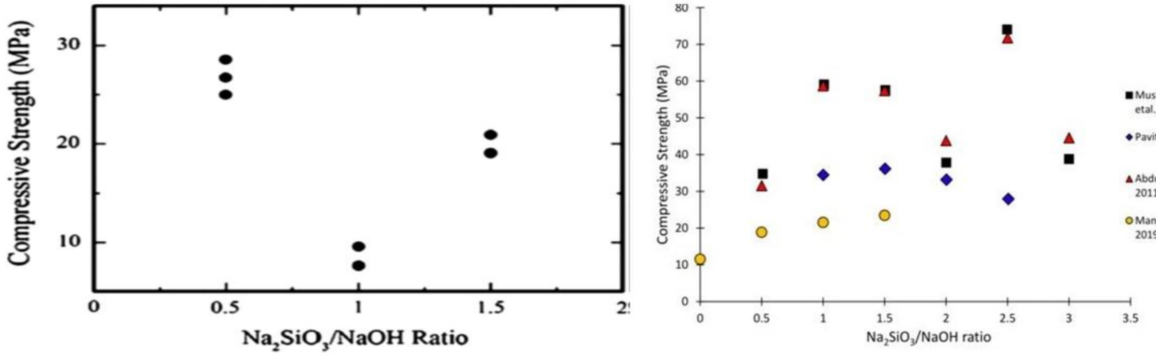
Figure 28(a) Graph showing the relationship between molar ratios of alkali reactants and compressive strength(b)Graph showing the relationship between compressive strength and ratio of alkali reactant while in this case NaOH concentration is 10M(139, 140)



The strength of geopolymers is expanded when the alkali reactant proportion is expanded. The polymerization cycle is leaned toward expanding Na_2SiO_3 concentration, which brings about a final product with expanded mechanical strength(35). The degree and speed of the geopolymerizationis decided by the soluble alkali reactant proportions(71). Nonetheless, at a specific high proportion, the glue's usefulness is restricted, bringing about a decrease in strength.

Pinto claims that metakaolin geopolymers couldn't be joined at a proportion under 0.85. This is most likely owing to the viscosity of liquid Na_2SiO_3, which results in a tacky geopolymer glue(27). The strength development of zeolite geopolymers is helped by expanding the Na_2SiO_3/NaOH proportion to 1.5(22). It is basic to recall that the antacid/alkali reactant proportion is not set in stone by the usefulness of the geopolymer combination clay geopolymers regularly utilize a more modest and lower soluble alkali reactant proportion range. Alkali reactant proportions of 0.05-3.00 and 0.40-2.50 have been utilized(136, 146, 147) for fly ash geopolymers. This is attributable to the way that circular structure particles decrease particle friction(148) and diminish surface-to-volume(149), expanding the functionality of blends.

Figure 29(a)Relationship between ratios of alkali reactant and compressive strength of sedimentary clay geopolymers(b)Relationship between alkali reactant ratios and compressive strength by different researchers in different investigation(138, 141-145)

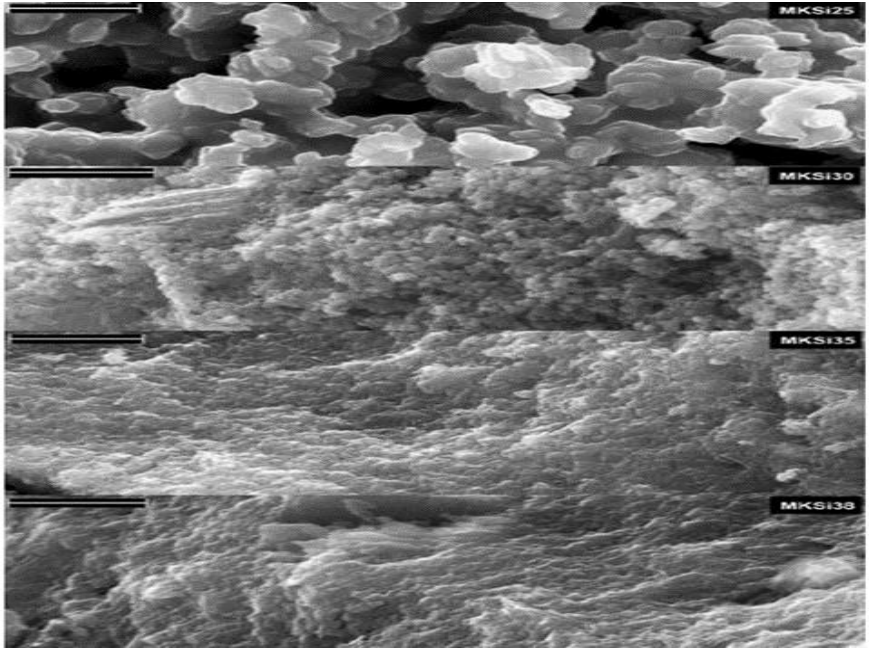


The alkali reactant proportion, then again, might be expressed as a molar proportion of SiO2/Na2O. Expanding the SiO_2/Na_2O proportion eases back the cycle/slows the process and makes the glue set later. The response pace of a framework with a Na-silicate solution is slower than that of a framework with K-silicate solution(71). To achieve further developed strength and sturdiness, Davidovits(68) suggested a SiO_2/Na_2O proportion of 1.85 for basic reactants.

Higher alkali reactant proportions brought about geopolymers with more unreacted particles, as indicated by Duxson et al.(113), while lower alkali reactant proportions brought about a gel microstructure. Huge quantities of little labile species like $(Si_2O_5^{2-})_n$, AlO_3^{1-} monomer, and Al_2SiO_5 dimer were anticipated to be available in metakaolin geopolymers created utilizing arrangements with a low SiO_2/M_2O molar proportion of 0.50 all through the absolute framework. For a higher SiO_2/M_2O molar proportion of “1”, a larger percentage of the aluminium released after disintegration was projected to be consolidated in the geopolymer network.

NaOH pellets are, regardless, more affordable than liquid sodium silicate. Accordingly, it is empowering to utilize a low alkali reactant proportion in the geopolymer union without compromising the finished result's usefulness and strength.

Figure 30High resolution SEM micrograph of metakaolin with different silica content (MK=Metakaolin, MKSi25-SiO_2/Al_2O_3=2.5, MKSi30-SiO_2/Al_2O_3=3.0, MKSi35-SiO_2/Al_2O_3=3.5, MKSi38-SiO_2/Al_2O_3=3.8)(69)



6.4 Molar ratios (Sodium, Aluminium, Silicon and water contents)

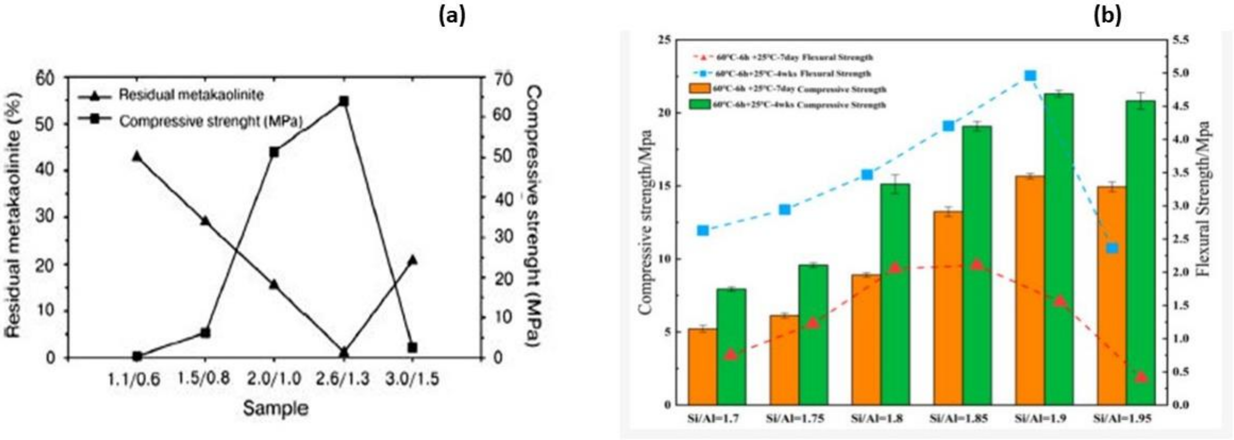
The Na content of a geopolymer framework is resolved to utilize fluid Na_2SiO_3 and NaOH arrangement. Aluminosilicates and fluid Na_2SiO_3add to the Si content, while aluminosilicates alone add to the Al content. The NaOH arrangement, fluid Na_2SiO_3, and free water presented during the mixing system all add to the H_2O concentration. In the geopolymer framework, changing mixing parameters (like NaOH focus, S/L proportion, and Na_2SiO_3/NaOH proportion) result in different nuclear or oxide molar proportions. Regardless, the reactivity or receptive phases of the aluminosilicates, the time available, and how well they are consolidated to form a rigid organization/stiff network influence the amount of every element present in the geopolymerization reaction.

Table 2Recommended molar ratios of oxides by Dividovits

Molar proportion of different oxides	Limitations
H_2O/Na_2O	15-17.50
Na_2O/SiO_2	0.20-0.28
Na_2O/Al_2O_3	0.80-1.20
SiO_2/Al2O_3	3.50-4.50

The amorphous-crystalline phase change is constrained by the underlying substance of Si, Al, and Na(116, 150, 151) . The Si/Al and Na/Al proportions are the most fundamental of all. To accomplish high strength and toughness, Davidovits(2) recommended that the structure of geopolymers ought to be inside the reach introduced in**Error! Reference source not found.**. Notwithstanding this, he reached the resolution that the ideal Na_2O/Al_2O_3 and SiO_2/Al_2O_3 proportions are 1.00 and 4.00, individually.

Figure 31(a)Compressive strength and residual metakaolin concentration in geopolymer at different Si:Al/Na:Al ratios as calculated by MAS spectra(b)Flexural strength and compressive strength of geopolymer at various Si/Al ratios(42, 152)



The Si/Al proportion altogether affects geopolymer disintegration, hydrolysis, and buildup responses. Most examinations announced ideal SiO2/Al2O3 proportions of 3-3.8 in light of prior research, which is rather lower than the reach depicted by Davidovits(2) as shown in**Error! Reference source not found.**.

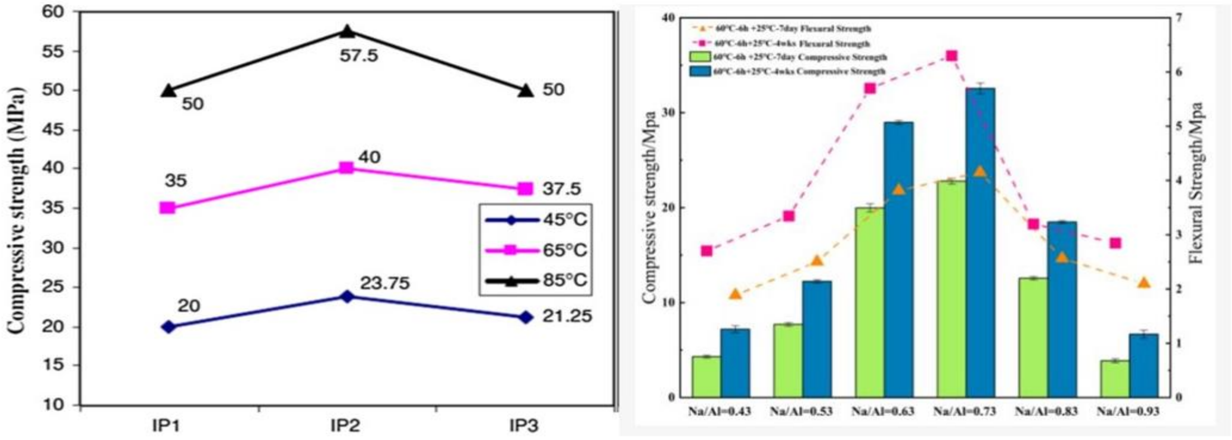
Mechanical characteristics are improved by expanding the SiO2/Al2O3 proportions(78, 153). The mechanical strength of geopolymers is affected predominantly by silica content, while the setting of geopolymers is constrained by alumina focus/concentration. This might be ascribed to the expanded disintegration of aluminosilicates toward geopolymerization responses when Si concentration rises(37, 53, 54, 85). Expanded silicon to aluminium and sodium to aluminium proportions increment the mechanical strength of geopolymers while additionally changing them into a more homogenous design(54).

According to analysts(116), increasing the (silica (SiO_2)/ alumina (Al_2O_3)) ratios from 2.5 to 3.80 enhanced the initial strength of metakaolin geopolymers with defined (water (H_2O)/sodium oxide (Na_2O)) ratio of 13. With a (silica (SiO_2)/ alumina (Al_2O_3)) ratio of 3 to3.80 and a (sodium oxide (Na_2O)/alumina (Al_2O_3) ratio of around “1.00”, good strength (22 MPa) was attained. Duxson et al.(113) agreed on these ideal ratios, with a maximum strength of around 80 MPa. In contrast, Provis and van Deventer (88, 154) found that raising the (silica (SiO_2)/ alumina (Al_2O_3)) ratio from 2 to 3.5 slowed the early reaction speed of geopolymerization owing to binder solidification. The focus of their research was reaction kinetics, with no mention of strength.

Besides, De Silva et al. (116)exhibited that the buildup cycle of geopolymer frameworks with low Si/Al proportions happens principally among aluminate and silicate species, coming about in poly(sialate) structures. Poly(sialate-siloxo) and poly(sialate-disiloxo) geopolymer structures delivered in geopolymer frameworks with high Si/Al proportions as an outcome of ruling buildup communication between silicate species, producing oligomeric silicates that respond with Al(OH4)4. Poly(sialate) has less siloxo Si-O units than poly(sialate-siloxo) and poly(sialate-siloxo), as exhibited in **Error! Reference source not found.**. Strength was improved by expanding/increasing how much siloxo units.

Steveson and Sagoe-Crentsil(69) utilized a comparable scope of SiO_2/Al_2O_3 proportions. The most extreme strength (47 MPa) was accomplished with a silica/alumina proportion of 3 to 3.89, that's almost twofold that revealed by De Silva et al.(116). The compressive strength increased in consistency as the structure improved to become a better, denser, and mediating geopolymer matrix. The distinction in their examination was a little lower water to sodium peroxide proportion of 12 and a somewhat high sodium peroxide to alumina proportion of 1.2 in their trials. This demonstrates that the test by Steveson and Sagoe-Crentsil(69) contains more Na_2O(sodium peroxide), bringing about more disintegration of source materials and length of geopolymer creation/production.

Figure 32a)compressive strength of pozzolan geopolymer at different Na/Al ratios and cured at different temperatures under hydrothermal treatment (IP1-Na/Al=0.92, IP2-Na/Al=1.08, IP3-Na/Al=1.23) (b)Flexural and compressive strength of geopolymer at different value of Na/Al ratio.(110, 152)



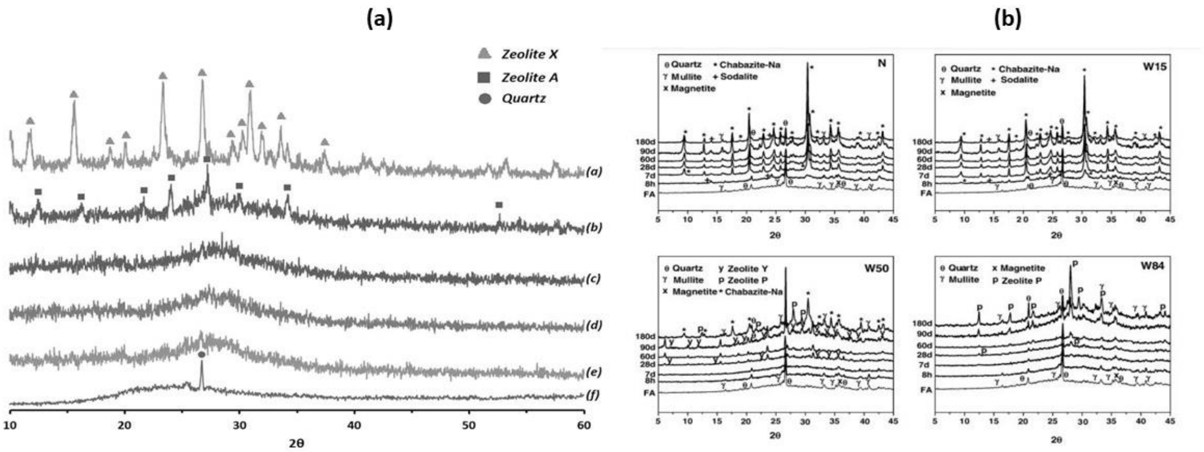
Lizcano et al. (72) developed geopolymers with a strength of 34 MPa with a silica to alumina ratio of 3.00, at fixed water to sodium peroxide and sodium peroxide to alumina proportions of 1 and 10 respectively., utilizing a potassium-based alkali reactant arrangement. The size and dissemination of breaks, voids, and incorporations will decide the eventual outcome's strength. At high Si/Al proportions, lingering/residual metakaolin particles in the lattice act as defects, bringing down the strength(69, 113). Rowles and O'Connor (42) result demonstrate this as well as shown in**Error! Reference source not found.**. Geopolymer density and pores are unaffected by the silicon/aluminium proportion(155).

As indicated by Kong et al.(45), the ideal strength of 44 MPa was moreover accomplished with a SiO_2/Al_2O_3 proportion of 3.08. Then again, Strength dropped when the proportions were expanded up to 4.6. The result varies based on what was previously published.The decay was believed to be the aftereffect of the increment in strength and was attributable to the way that the silica fume provided to the response toward the beginning didn't react all through the geopolymerization reaction.

To make metakaolin geopolymers, scientists utilized uncommonly high SiO_2/Al_2O_3 proportions in a few analyses. The molar proportion of SiO_2/Al_2O_3 was found by Fletcher et al.(156). The best-pulverizing strength (10.9 MPa), is accomplished when the proportion is 16:1. At a proportion more noteworthy than 24, the mechanical strength couldn't be laid out/established. Shockingly, tests with $SiO_2/Al_2O_3<2$ didn't display the common attributes/characteristics of geopolymers, however, tests with silica to alumina ratio higher than 24 were run on typical geopolymers, showing elastic rather than brittle behavior.

Soluble alkali positive ions have to be present in geopolymer networks to adjust the Aluminium anion in IV-overlay – coordination. For electrical neutrality, one mole of IV-overlap facilitated Al^{3+} requires 0.5 moles of sodium peroxide (Na_2O)(5, 101, 150). As per most review articles, the reasoning for ideal strength when Na/Al = 1 is a result of this. The highest Si/Al proportion that might be accomplished for geopolymers with sodium to aluminium proportion = 1 is "4"(2, 113, 124). Subaer and van Riessen(124), dissimilar to past specialists, found that residual metakaolin of geopolymer network expanded the density and subsequently the strength of geopolymers. The strength result got by Kani and Allahverdi(110) is displayed in **Error! Reference source not found.**a. Geopolymers with lower or more prominent sodium to aluminium proportions than 1 have restricted strengths are shown in **Error! Reference source not found.** b.

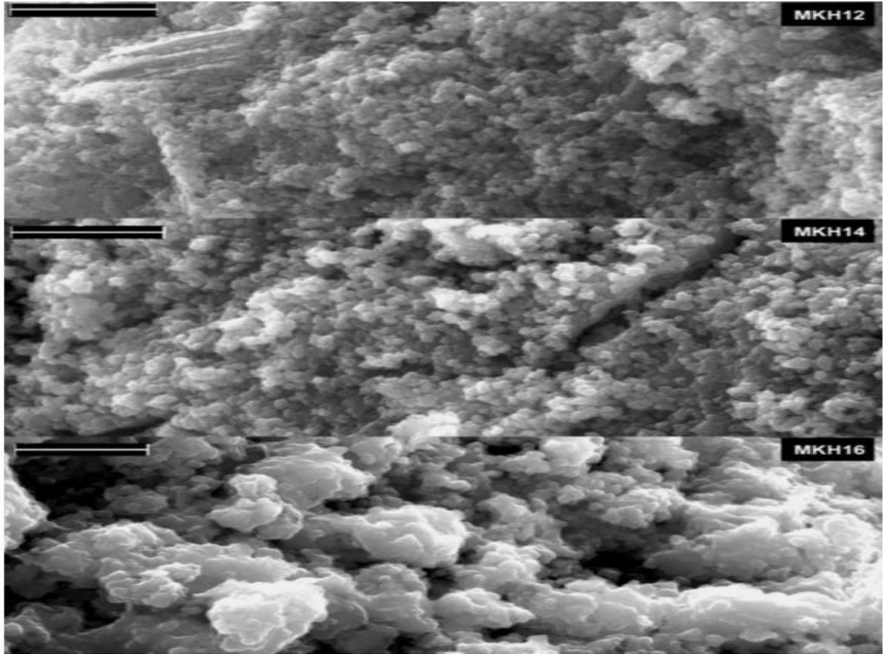
Figure 33(a)XRD of metakaolin geopolymer made with different SiO_2/Na_2O ratios as (a)2.25(b)2.50(c)3.00(d)3.50and (e)4.00 and (f)shows the XRD of metakaolin(b)XRD of fly ash geopolymer with different SiO_2/Na_2O ratios, for N,W15,W50 and W84 the SiO2/Na2O values are 0,0.19,0.69,1.17(157, 158)



As recently expressed, it is due to the overabundance of sodium in geopolymer networks, which is bad for geopolymer strength. The level of geopolymerization of dissolved species is constrained by the SiO_2/Na_2O molar proportion. Expanded K_2O or Na_2O fixation came about at a speedier setting rate, improved geopolymer strength development(159), and decreased the event of cracking(37). As per Nasab et al.(157) 's XRD diffractogram in **Error! Reference source not found.**high silicate to sodium peroxide proportion (high silicate species)proportions brought about a bigger combination of indistinct/amorphous geopolymer items, while lower silicate to sodium peroxide proportions of brought high crystalline zeolite materials. With a proportion of 2.5 to 3, the geopolymer matrix becomes better grained and denser. On account of fly ash geopolymers, Provis et al. (160)back this up.

The amount of reaction products generated is controlled by the alkalinity of the alkali reactant solution in the form of the Na_2O/H_2O ratio, which has no effect on the type of the end products(159). In most cases, raising the Na_2O/H_2O ratio improves clay-based geopolymer dissolution and mechanical strength development(28). This contradicts the findings of Latella et al.(161), who found tha tlow water (water to sodium proportion <5.5) in geopolymer resulted in fractures after 10 days, whereas water to sodium proportion =6resulted in a larger quantity of porosities. Steveson and Sagoe-Crentsil(69) found that raising the H_2O/Al_2O ratio from 12 to 16 improved roughness, pores, and intervening geopolymer matrix **Error! Reference source not found.**.Anyways, some H_2O must be there in the geopolymer for internal structure, and the H_2O that was evacuated due to hardening formed holes in the finished geopolymer product.

Figure 34SEM of metakaolin geopolymer at different H_2O/Al_2O_3 while MKH represents H_2O/Al_2O_3 (a)12(b)14(c)16(69)



Through gradation analysis, Yunsheng et al.(150) found that (sodium oxide to alumina) and (water to sodium oxide) molar proportions greatly affected geopolymer strength than (silica to alumina) molar proportions. (Silica to alumina ratio) = 5.5, (sodium oxide to aluminaratio) = 1.0, and (water to sodium oxide) ratio = 7.0 had the greatest strength (34.9 MPa). With noticed (Silica to alumina) ratio= 6.3 and (sodium oxide to alumina) ratio= 1.1, the detailing was considered a responded geopolymer, that was close to the hypothetical values of a polymer (sialate-disiloxo). Barbosa et al.(10) additionally tracked down an ideal creation of (sodium peroxide to silica) ratio = 0.25, (water to sodium oxide) ratio = 10, and (Silica to alumina) ratio = 3.3. The molar proportion of H_2O/Na_2O of 25 was found to shape geopolymers with low and immense strength. The geopolymerization response was demonstrated to be reliant upon the first structure of blends, eminently the water content.Heah et al.(27) found that the best molar ratios of (Silica to aluminaratio), Na_2O/SiO_3, water to sodium oxide, and sodium oxide to alumina for undehydrated kaolin geopolymers were 3.28, 0.28, 14.61, and 0.92, respectively. Even though that the observed molar oxide ratios are within Davidovits'(2) range, he achieved strength was weak and not completely reactive, as evidenced by the huge number of un reacted molecules(162).Based on Kamalloo et al's(163) filled contours**Error! Reference source not found.**. Geopolymers with (potassium oxide to sodium oxide), H_2O/M_2O (M = alkali metal), M_2O/Al_2O_3, and (Silica to alumina) ratios of 0.6 to 1, 10 to 11, 1 to 1.2, and 3.6 to 3.8, respectively, had the highest compressive strength (80 MPa). Due to the mixed alkali effect, they discovered that K+ cations were better charge balancers in geopolymer structures than Na+ cations.

To close, the measures of Si, Al, and Na in geopolymers considerably affect their definitive qualities. When aluminosilicates other than clay based were used, the substance shifted/contents varied. Regardless of whether a large portion of the scientists changed the combination's unique organization, the degree of response will conclude the last characteristics since various raw materials have shifting receptive stages and every part's ability to tie-in the situation to make a rigid network. Analysts found the best oxide molar proportions inTable 3. Regardless, most of the examination concentrates on reasoned that the combination of geopolymers is restricted to a particular scope of Si, Al, and Na substance.

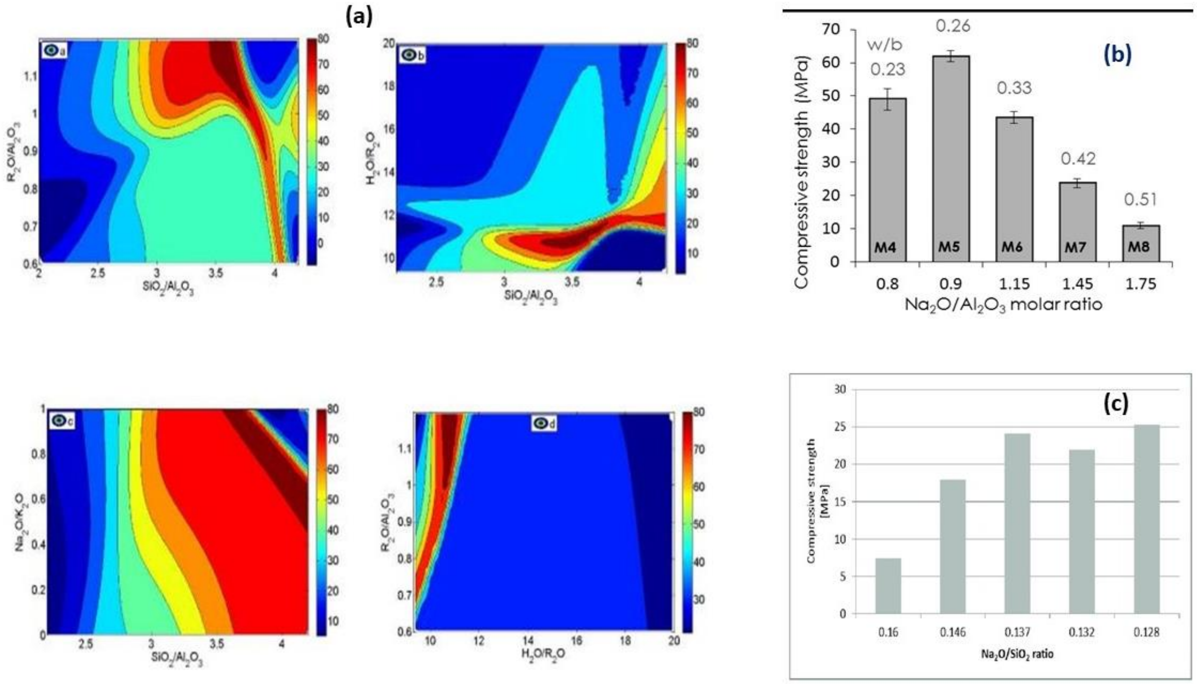


Figure 35The effect of various molar ratios (R_2O/Al_2O_3, SiO_2/Al_2O_3, Na_2O/K_2O and H_2O/R_2O) where (R=Na or K) on the compressive strength of metakaolin geopolymers is shown in contour plot. The units of contour are in MPa(b)Graph showing the effect of Na_2O/Al_2O_3 molar ratios on compressive strength of geopolymer(c)Graph showing the effect of Na_2O/SiO_2 molar ratios on compressive strength of geopolymer(163-165)

6.5 Content of Water

Water affects geopolymer development, design, and attributes. It is a fundamental part of geopolymer. Water fills in as a mechanism for oligomer disintegration, particle transport, and oligomer hydrolysis and polycondensation. Zuhua et al.(127) acquiredError! Reference source not found., which portrays the elements of water during geopolymer arrangement/formation.

Water additionally works on the flowability of the geopolymer blend. An adequate measure of water helps with blending and offers a path for ion transport(150). The incorporation of extra water during geopolymer creation is dependably a cause of stress. Overabundance of water was remembered to weaken the framework's alkalinity and move particles/ions from the reaction zone(10, 53) . Since geopolymerization is water releasing reaction(78), abundance water could hinder its turn of events.

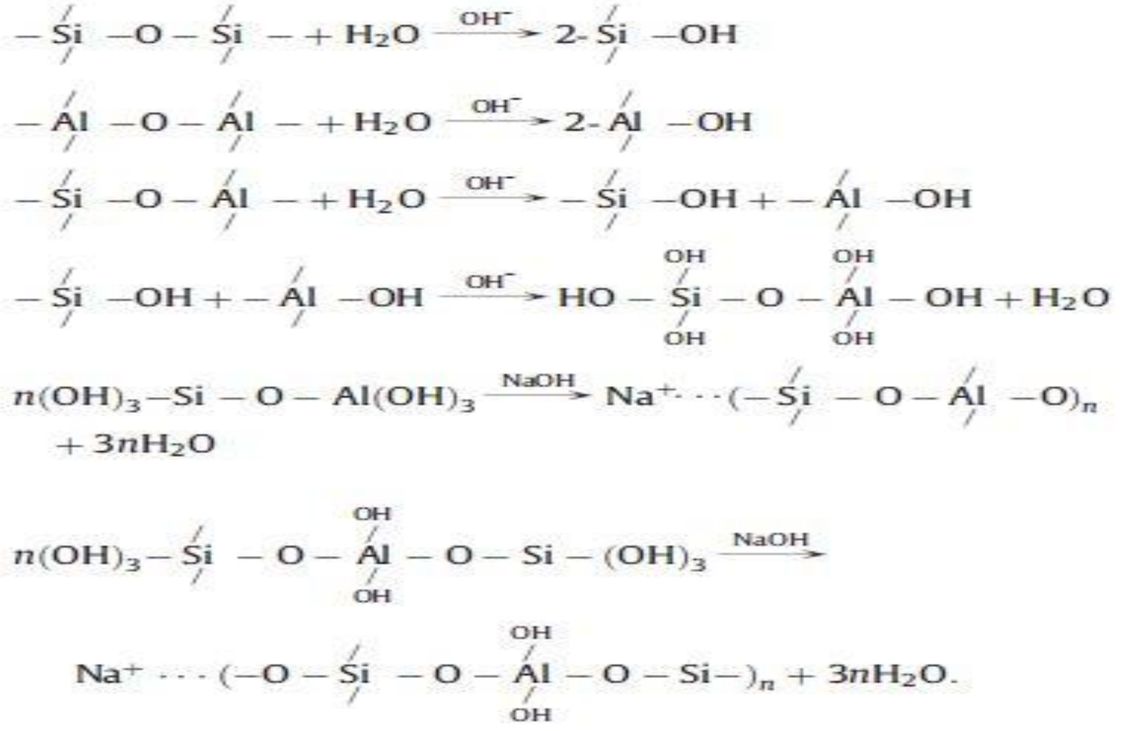
The response rate is eased back by high and low water content, as indicated by Rahier et al.(71) . This is believed to be connected with a drop in hydroxyl ions concentration where there is a lot of water in the system. Interestingly, even while the OH^- concentration ascends at low water content, the receptive species (monodeprotonated monomer H_3SiO_4) for connection between silicate oligomers drops, dialing back the geopolymerization action.

The water demand is usually setup/determined by the framework's makeup. By and large, a low Na/Al ratio requires the utilization of more water. This raises the risk of breaking during the curing stage(166). Moreover, how much water in the geopolymer framework affects the thickness/density and open porosity of the results. Open porosity is expanded when there is a lot of water(155, 161).

Table 3 Outline of ideal molar ratios by researchers

Source material	Molar ratios			Compressive strength	References
	H_2O/Al_2O_3	Na_2O/Al_2O_3	SiO_2/Al_2O_3		
Metakaolin	13.6	1	3-3.81	22MPa@3 days	(116)
Metakaolin	54	5	16	10.9 MPa@1 day (crushing strength)	(156)
Metakaolin	12	1.2	3.9	47 MPa@2 h	(69)
Metakaolin	10	1	3	34 MPa@1 day (K-based alkali reactant)	(72)
Metakaolin	-	0.42	3.08	45 MPa@3 days (K-based alkali reactant)	(45)
Metakaolin	18.01	1.29	5	64 MPa@1 Week	(42)
Metakaolin	10	0.6	3	86 MPa@1 Week	(124)
Natural Pozzolan	8.5	0.92	6	45 MPa@1 Month	(110)
Metakaolin	7.2	1	4	70 MPa@10 days (addition of 60% sand)	(161)
Metakaolin	7	1	5.5	34.9 MPa@1 Month	(150)
Metakaolin	10	0.83	3.3	49 MPa@3 days	(10)
Kaolin	14.61	0.92	3.28	6 MPa@6 Months	(27)
Metakaolin	10-11	1-1.2	3.6-3.8	80 MPa@1 Week	(163)
Metakaolin	11	1	3-3.8	80 MPa (No testing days were mentioned)	(113)

Figure 36Function of water in geopolymer formation(127)



$$-\mathrm{Si}-\mathrm{O}-\mathrm{Si}- + \mathrm{H_2O} \xrightarrow{\mathrm{OH^-}} 2\text{-}\mathrm{Si}-\mathrm{OH}$$

$$-\mathrm{Al}-\mathrm{O}-\mathrm{Al}- + \mathrm{H_2O} \xrightarrow{\mathrm{OH^-}} 2\text{-}\mathrm{Al}-\mathrm{OH}$$

$$-\mathrm{Si}-\mathrm{O}-\mathrm{Al}- + \mathrm{H_2O} \xrightarrow{\mathrm{OH^-}} -\mathrm{Si}-\mathrm{OH} + -\mathrm{Al}-\mathrm{OH}$$

$$-\mathrm{Si}-\mathrm{OH} + -\mathrm{Al}-\mathrm{OH} \xrightarrow{\mathrm{OH^-}} \mathrm{HO}-\overset{\mathrm{OH}}{\underset{\mathrm{OH}}{\mathrm{Si}}}-\mathrm{O}-\overset{\mathrm{OH}}{\underset{\mathrm{OH}}{\mathrm{Al}}}-\mathrm{OH} + \mathrm{H_2O}$$

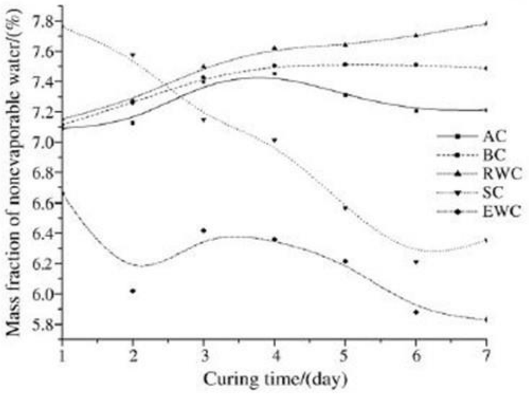
$$n(\mathrm{OH})_3-\mathrm{Si}-\mathrm{O}-\mathrm{Al}(\mathrm{OH})_3 \xrightarrow{\mathrm{NaOH}} \mathrm{Na^+}\cdots(-\mathrm{Si}-\mathrm{O}-\mathrm{Al}-\mathrm{O})_n + 3n\mathrm{H_2O}$$

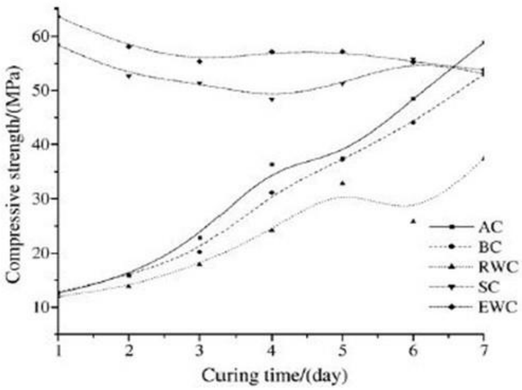
$$n(\mathrm{OH})_3-\mathrm{Si}-\mathrm{O}-\overset{\mathrm{OH}}{\underset{\mathrm{OH}}{\mathrm{Al}}}-\mathrm{O}-\mathrm{Si}-(\mathrm{OH})_3 \xrightarrow{\mathrm{NaOH}}$$

$$\mathrm{Na^+}\cdots(-\mathrm{O}-\mathrm{Si}-\mathrm{O}-\overset{\mathrm{OH}}{\underset{\mathrm{OH}}{\mathrm{Al}}}-\mathrm{O}-\mathrm{Si}-)_n + 3n\mathrm{H_2O}.$$

The water that was lost before drying shrinkage is known as free water. They are caught in pores rather than chemically reinforced. Structural water is characterized as an element of theshrinkage brought about by the geopolymer framework structure. To stay away from shrinkage, a high starting water content is essential, which takes into consideration extra water to be launched out before shrinkage starts(167). To keep up with the strength consistent, non-evaporable water must be available in the geopolymer structure **Error! Reference source not found.**. Shrinkage and a deficiency of strength happen because of the deficiency of water during the restoring/curing process

Figure 37Under varied curing conditions, variations in (a) non-evaporable water by weight fraction of metakaolin geopolymers and (b) non-evaporable water by weight fraction of metakaolin geopolymers. [AC = in air (22 degrees Celsius), BC = in sealed bag (22 degrees Celsius), RWC = room temperature water (22 degrees Celsius), SC = in steam (80 degrees Celsius), and EWC = in raised temperature water (80 degrees Celsius)](127)





Be that as it may, how much water not set in stone by the properties of the unrefined components/raw materials used. Moreover, extra blending variables like soluble base focus, S/L proportion, and alkali reactant should be considered related to the water content in the geopolymer system/framework.

6.6 Curing Regime

Subsequent to blending, geopolymers are ordinarily relieved/cured at room temperature or somewhat higher. Generally speaking, a temperature of under 100 C is liked for curing/restoring. Most of scientists agree on this. Davidovits(2) suggested a restoring temperature scope of 60 to 95 degrees Celsius. Following 4 hours of curing at 75°C, the geopolymer arrangement is almost finished, and the compressive strength of 39.8 MPa is accomplished with no further treatment(7). To acquire prevalent mechanical and durability execution, adequate curing is generally required(73). Heat helps the polycondensation cycle and solidifying of the geopolymer matrix by accelerating the disintegration of SiO_2 and Al_2O_3 species from Al_2SiO_5 and advancing the disintegration of silica and alumina species from aluminosilicates(45, 56, 128, 166). To put it another way, heat is expected to conquer the heat activation of the cycle and start the geopolymerization reaction. Regardless of how increasing the relieving temperature increases strength, if the temperature is elevated or the temperature exposure duration is too long, the strength may be reduced. Although a high restoring temperature advances early strength, it may compromise long term strength(60). Thermal treatment from 20 to 50 degrees Celsius increased the geopolymerization cycle's reaction time., as indicated by an examination by researchers(53) as shown in **Error! Reference source not found.**. Curing at room temperature consumes a large chunk of the day, however curing at 50 degrees Celsius doesn't advance strength development. This is no doubt attributable to the fast making of a ageopolymer structure on the molecule surface, which forestalls further aluminosilicate disintegration(127). At a temperature of 35 degrees Celsius, the ideal is reached.

As per Rovnanik(109), higher relieving temperatures bring about the development of enormous/big openings/holes, which diminishes the strength of geopolymers. Rovnanik (109) created the discoveries displayed inError! Reference source not found.. High-strength goods are obtained by treating at 60 and 80 degrees Celsius, however, the strength is lost after 28 days. Geopolymers cured at 20 or 40 degrees Celsius showed an improvement in strength after being tested for 1 to 28 days. Zuhua et al.(127) supported this case. At the point when the geopolymers were treated in water at 20 to 22 degrees Celsius, nonetheless, the strength was poor. It's believed to be brought about by broke down species spilling from geopolymer surfaces(127). Moreover, high-temperature treatment would certainly improve the breaking capability of geopolymer products. This is because of quick water loss, which reduces open porosity(166). The fast vaporization of blending water prevents the fundamental strength from developing(74). Thus, sealing the geopolymer samples at uncovered surfaces during the relieving system are proposed all the time. To limit breaking and keep up with structural integrity, a little amount of underlying water should be kept in the construction(29, 170). Indeed, even in a fixed climate, water shipped and liberated to the outer layer of the geopolymer by narrow activity will prompt a decrease in primary water, as per Zuhua et al.(127). Crack-free metakaolin geopolymers were provided at ambient and regulate dmoisture content after light heat treatment of 40 to 60 degrees Celsius,as per Perera et al.(166).

Figure 38a)Curing temperature effect on geopolymer reaction (S17=20°C, S18=35°C, S19=50°C)(b)Effect of temperature on geopolymer reaction and setting time(53, 168)

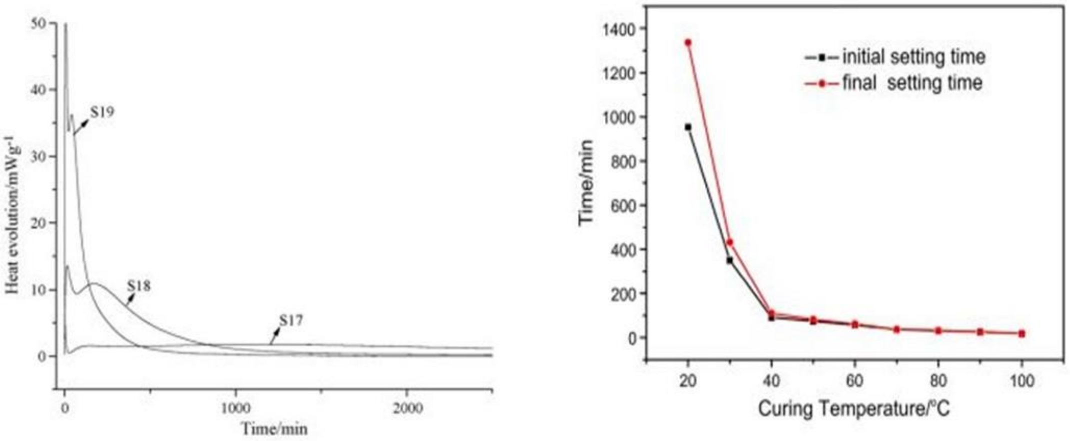


Figure 39(a)Data showing effect of curing temperature and time on (a)flexural strength &(b)compressive strength of metakaolin geopolymer(b) Flexural and compressive strength of metakaolin geopolymer after

different curing temperatures(109, 169)

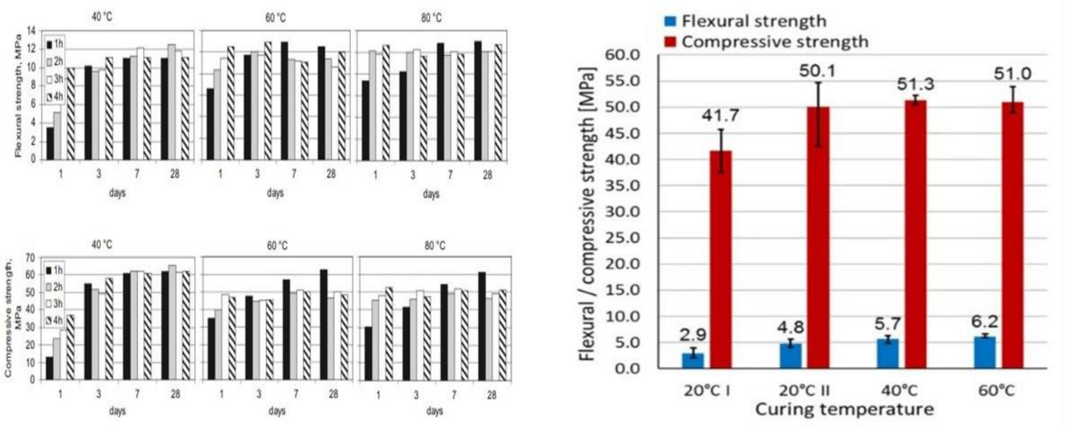


Figure 40SEM micrographs of geopolymers made of vitreous calcium aluminosilicate that were treated at 65°C for 60 minutes, 4 hours, 2 days, & 3 days respectively(b)SEM micrograph of Fly ash based geopolymer cement with (a)calcium aluminate=0%(b) calcium aluminate=2.5%(c) calcium aluminate=5%(d) calcium aluminate=7.5%(171, 172)

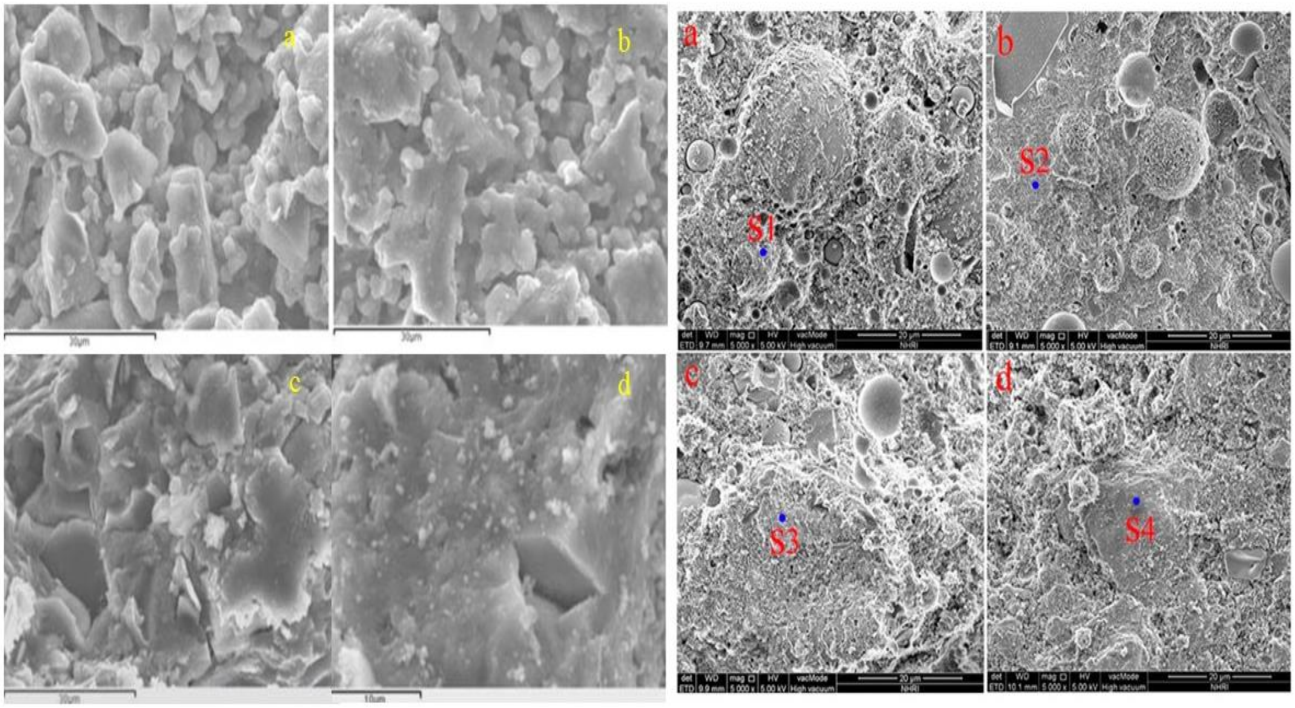
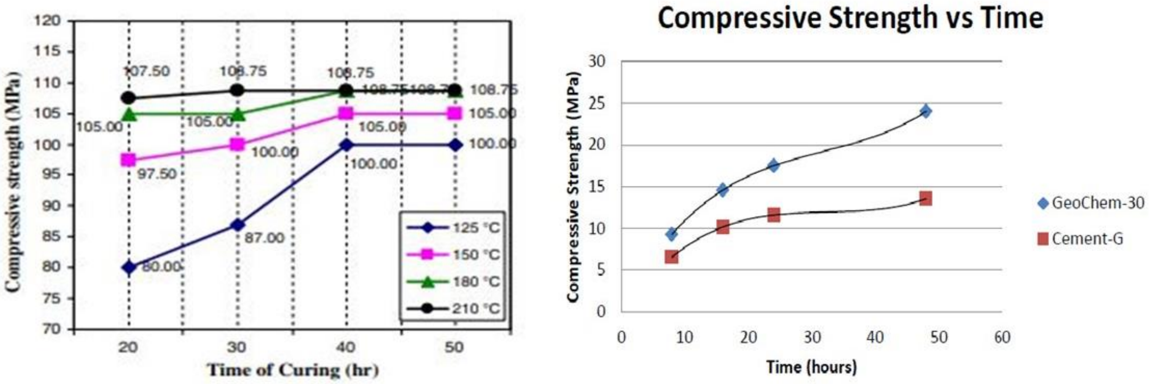
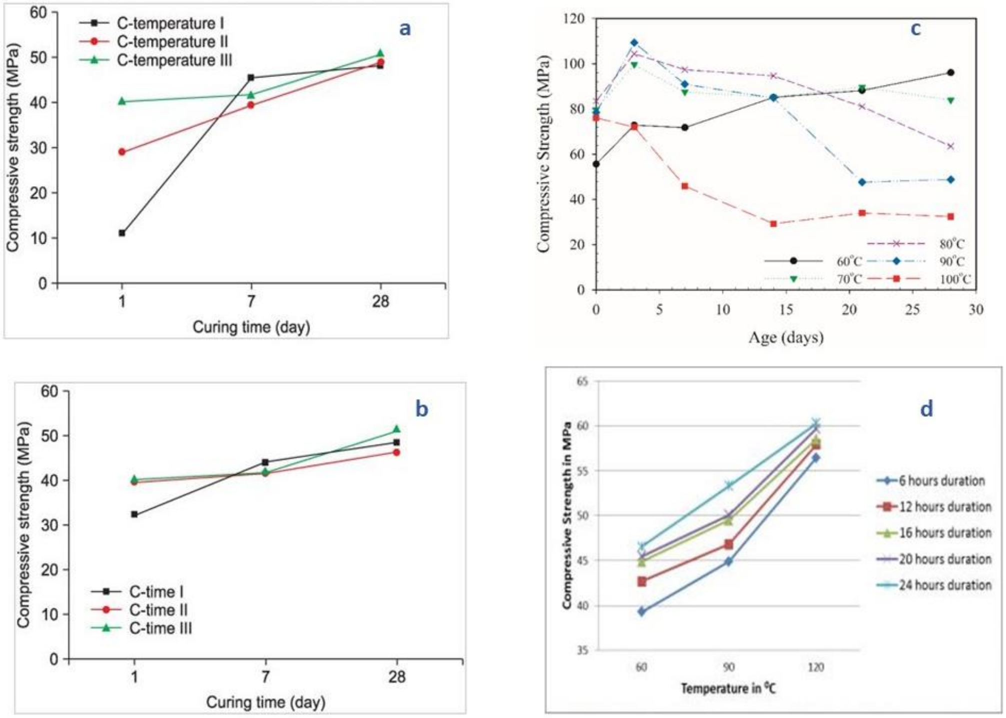


Figure 41 a)Compressive strength development of geopolymer for curing of 7 days at different temperature(b)Compressive strength development of geopolymer at time(110, 173)



With relieving time, the development of geopolymer design or organizations shifts. Geopolymer structural properties alleviated at 60 minutes, 4 hours, 2 days, and 3 days at 65 degrees Celsius are displayed in**Error! Reference source not found.**. The microstructures uncover the production of an indistinct stage/amorphous phase and grid/matrix densification as the fix/cure time frame advances. At 65 degrees Celsius, the best restoring/curing period was 72 hours(171). At the point when geopolymers in light of red mud and rice husk ash are matured 35 days(128), the compressive strength is almost consistent (11.7 MPa). This meant that the geopolymers would only finish

Figure 42The impact of (a) pre-relieving temperature and (b) pre-restoring/curing time on metakaolin geopolymer compressive strength (C-temperature I - room temperature; C-temperature II - 50 C and C-temperature III - 75 C;C-time I - 3 hr.; C-time II - 6 hr.; C-time III - 24 hr.)(c)Effect of curing time on compressive strength of geopolymer(d))Effect of curing time on compressive strength of geopolymer (174-176)



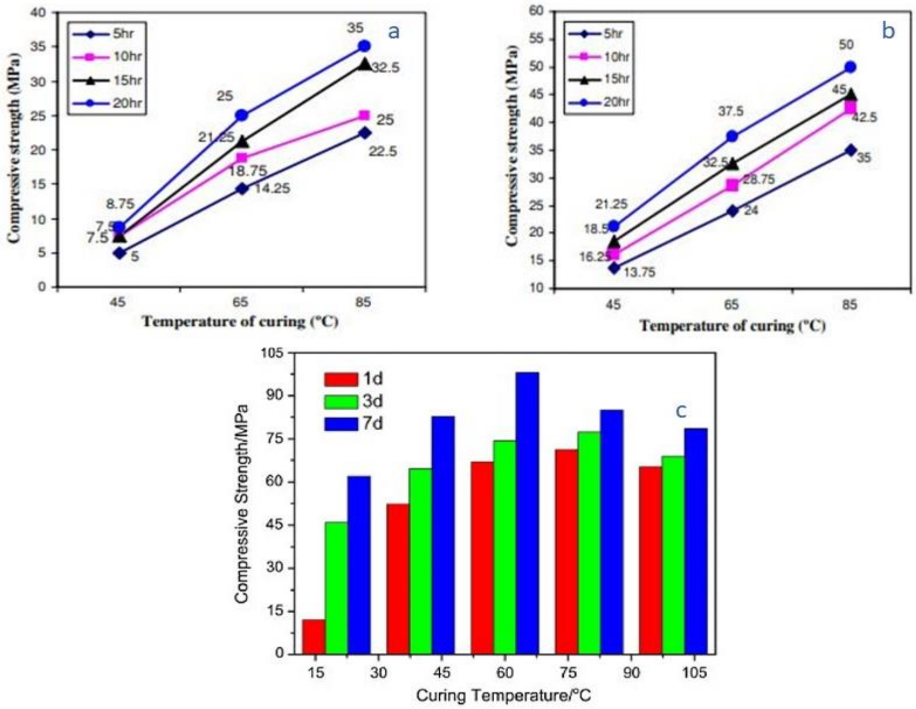
Kani and Allahverdi(110) concentrated on a few curing procedures, including steam-saturated aqueous curing & autoclave treatment. The aqueous treatment takes less time and is done at a lower temperature than autoclave relieving/curing. Autoclave curing at 210 degrees Celsius for 30 hours after 7 days of pre-curing (25 °C, 95 percent RH) improves the strength enhancement (109 MPa) of geopolymers with no primary small cracks as shown in**Error! Reference source not found.**. Restoring by electric helps with relieving temperature directed by electricity supply, flow, & potential difference, then again, has shown no distinction in eventual outcome strength when contrasted with conventional curing(177). This could possibly be an alternate approach to restoring.

It has been shown that procuring geopolymer before typical curing works on the strength of geopolymers(110, 166, 174). The strength result acquired by Kim and Kim(174) is displayed in**Error! Reference source not found.**. To make high-strength metakaolin geopolymers, pre-treatment at 75 degrees Celsius for three hours and afterward treatment at ambient temperature for 28 days is encouraged (51.06 MPa).

Pre-treatment is expected for the consistent growth of strength during the thermal treatment process, and great strength can be accomplished at the beginning phase. Apart that, pre-curing diminishes the pores in geopolymer's lattice, taking into consideration all the freer water to stay in the structure(166). Pre-curing in a humid condition for quite a while prior to thermal treatment is gainful to strength growth **Error! Reference source not found.**(110).

Synthesis of geopolymers in view of extra aluminosilicate sources, for example, fly ash (136) and regular zeolites(21), additionally shows a detrimental influence on mechanical strength at delayed expanded relieving temperature. clay-based geopolymers, in contrast with fly ash-based geopolymers, for the most part require a high temperature thermal treatment and a more extended relieving time to accomplish more noteworthy strength geopolymers. Nonetheless, it's reliant on the aluminosilicate materials' reactivity as well as the natural substance/raw materials blending proportions.

Figure 43a)(b) Following 1 day and 7 days of pre-relieving, the compressive strength of Taftan pozzolan geopolymers restored under different hydrothermal treatments(c)Effect on curing temperature on geopolymer compressive strength(110, 178)



For ideal disintegration and build-up of silica and alumina species, a proper relieving system should be utilized. Unacceptable restoring conditions (exceptionally low or high temperature) may adversely affect the mechanical properties of geopolymers. (128) In impacting the strength improvement of geopolymers, relieving temperatures are connected to the sort and centralization of alkaline reactant solution. During the amalgamation of geopolymers, the relieving temperature and duration should be coordinated with the soluble base reactant arrangement and source material.

7. Geopolymers development and applications: Past and future

Geopolymers offers a wide scope of potential employment. A few applications, for example, GEOPOLYMITE binders and PYRAMENT mixed concrete, have been effectively evolved and sold. PYRAMENT mixed concrete has been taken on in structural designing for the assembling of precast and pre-focused concrete(179) , while GEOPOLYMITE binders have been utilized in an assortment of disciplines including building warm/heat protection, heater protection, shaping, tooling, and foundry work.

Geopolymers have likewise been used to make excellent clay tiles and blocks(4). Beforehand, kaolinite geopolymers were made utilizing a low-temperature geopolymer setting (L.T.G.S.) and super quick fire at 1000-1200 C to deliver tiles and blocks. A few specialists have been looking towards a similar methodology recently(180). Geopolymer ceramics are non-ignitable and flame resistant. Besides, a clever way for creating fired materials is to pack geopolymer powder utilizing powder metallurgy and afterward sinter at 1000-1200 °C(181).

Flame resistant geopolymer fibre-supported composites were first used in aeronautics in 1994 as plane composites and lodge insides (roof, floor boards, parcels, and sidewalls) to forestall lodge fires following plane accidents. The idea emerged from the issue of current plastic materials being flammable and radiating risky vapor when consumed. Geopolymers have likewise been utilized in vehicle working by Formula One groups in light of the fact that to their destructive, fire, and hotness obstruction(4).

In structural designing, lightweight substantial materials made of geopolymers have been created because of the requirement for lightweight materials that are simpler to move and consume less energy(182). Besides, the lightweight concrete capacities as a heat protector and helps loading bearing(183). There have likewise been examinations on foamed geopolymers in warm protection materials for home structures (184). Zhang et al.(185) utilized geopolymers to make an intelligent and hotness protecting covering. The covering created has 90% reflectivity and warm protection capacity up to 24 °C, on account of the utilization of shades and fillers, (for example, titanium dioxide, empty glass microspheres, and powder), as well as a scattering specialist, wetting specialist, and water-holding specialist.

Moreover, as per Temuujin et al.(186), geopolymers have anti-ultraviolet and anti-aging properties, making them ideal for use as a covering on outside walls to save energy. Geopolymer warm and fire execution examinations have likewise been published somewhere else(59, 125, 187-190).

Geopolymers, as recently expressed, have atomic models that are like zeolitic materials. Because of their capacity to ingest and harden unsafe synthetic waste, they can immobilize harmful material or weighty metals. This is favorable to the strategy of immobilization(191, 192).

Extensive research has been done over the years to see if geopolymers can be used in more applications. Okada et al.(193) developed porous geopolymers for application in cooling systems. Geopolymers with strong water retention capabilities or slow water release properties inspired this notion. This makes geopolymers appropriate for moisture evaporation-based surface cooling, which aids in reducing global warming resulting from human activities and national growth.

Pacheco-Torgal et al.(194) expressed that geopolymer may be utilized in infrastructure repair. In fiber-reinforced polymer retrofitting, geopolymer glue can be utilized as a sealant for developments and can supplant epoxy cement. Geraldes et al.(195) led an almost indistinguishable review in which geopolymers were used as tile fix materials.

Hung et al.(196) depicted the amalgamation of geopolymer for acoustic protection notwithstanding warm insulative abilities. Geopolymers can be utilized as sound protecting materials in development and structures and can do as such. The sound decrease coefficient is impacted by the thickness of the geopolymer framework.

Scientists(49, 50, 197) have concentrated on a one-section geopolymer framework in which a geopolymer blend might be shaped simply by adding water, to work on the utilization of geopolymers in structural designing. The requirement of geopolymer innovation for in-situ application, which restricts its financial worth, provokes the consideration of this review.

Geopolymer research has advanced as of late, determined to involve them as biomaterials. Pang Daeng et al.(60) showed that geopolymer has high bioactivity, which is improved by the expansion of white Portland concrete. Jams torp et al.(198) and Cai et al.(199), then again, examined geopolymer as a medication conveyance procedure. Geopolymers with differing pore structures for drug discharge at target cells based on them.

Conclusion

This study reviews geopolymers and their construction, as well as raw components, alkali reactant arrangement, reaction process, characterization, qualities/characteristics, and applications, with an accentuation on clay-based geopolymers. It very well might be derived from the audit that, no matter what the primary material used, the geopolymerization cycle follows a similar component. The response items might be impacted by contrasts in prime material characteristics, for example, chemical composition, molecule shape and size, surface region, and impurities. The layered-like design of clay-based antecedents/precursors is the basic limitation, bringing about low reactivity and, subsequently, low strength geopolymers. This is, be that as it may, a notable issue. Changes in the design of clay materials should be sought after with more enthusiasm. Also, alkali focus/concentration, blending/mixing proportions and extents, restoring/curing regimes/systems, water content, and the inclusion of added substances/fillers all sway the qualities of geopolymers. The ideal exhibition of the geopolymer is not entirely settled by a blend of a few blending and handling factors. Primary attributes (soluble alkali substance, blending proportions and combination extents, and relieving systems/ curing regimes, among others) are remembered to fundamentally affect geopolymers. Geopolymers have been successfully utilized in an assortment of disciplines because of their prevalent characteristics, and extra uses will be found later on.

Author Contributions

We strongly encourage authors to include author contributions and recommend using CRediTfor standardised contribution descriptions. Please refer to our general author guidelines for more information about authorship.

Conflicts of interest

In accordance with our policy on Conflicts of interest please ensure that a conflicts of interest statement is included in your manuscript here. Please note that this statement is required for all submitted manuscripts. If no conflicts exist, please state that “There are no conflicts to declare”.

Acknowledgements

The acknowledgements come at the end of an article after the conclusions and before the notes and references.

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