Review Article

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Studies on Alkaline Activator, Manufacturing Methods and Mechanical Properties of Geopolymer Concrete - A Review

M. Nanthini*, R. Ganesan and V. Jaganathan
Department of Civil Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, TN, India
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*nandhupriya.md.10@gmail.com

ABSTRACT

Continuous production of cement products, a new environmentally responsible geopolymer material, can reduce CO_2 emissions from increased cement production. Compared to ordinary Portland cement (O.P.C.) geopolymer concrete, it has better mechanical strength and corrosion and fire resistance. Most industrial solid wastes and bottom ash from waste incineration are disposed of unevenly, which consumes land resources and negatively affects the ecosystem. The best alternative resource for the synthesis of geopolymer composites is recycling. Metals, pesticides, and other radioactive pollutants are successfully absorbed by geopolymer composites, which is very favorable for the ultimate development of civilization. Therefore, this review has examined essential material parameters, including new properties, compressive strength, flexural strength, elastic Modulus, compressive strength, and split-tensile strength applications. According to the previous experimental results, G.P.C. offered better fresh properties than conventional composites. This review revealed the geopolymerization process, the types of alkaline/alkali activators, synthesis techniques, sources of natural raw materials, and applications of geopolymer concrete. The present work discussed the conceptual framework for the sustainable production of geopolymer materials by evaluating the drawbacks, applications, and restrictions of geopolymer materials and their potential development.

Keywords: Fresh properties; Geopolymer concretes; Flexural and shear behavior; Ordinary Portland Cement.

1. INTRODUCTION

Concrete based on Ordinary Portland Cement (O.P.C.) is frequently used for structural construction worldwide due to the quantity of abundant raw materials for producing O.P.C. and its high mechanical strength (Wongpa *et al.* 2010; Zhang and Zong, 2014). In order to fabricate O.P.C., marble must be heated to high temperatures using coal combustion. This process releases significant amounts of CO_2 into the atmosphere, resulting in oxygen depletion, decomposition, and the greenhouse effect (Tho-in *et al.* 2012). Cement is a primary structural material used in architecture that is expanding rapidly worldwide, driving the demand for O.P.C. in the future. It is essential to use different concrete mixes to reduce environmental impact. New and eco-friendly building material was first developed in 1990 due to raw materials availability and admirable properties (Bernal *et al.* 2011) and is considered a potential alternative to aggregate concrete. G.P.C. offers two benefits to the atmosphere: it reduces emissions of gases that contribute to climate change and uses waste materials to make concrete (Gunasekara *et al.* 2016). Koushkbaghi *et al.* (2019) investigated using G.P.C. to reduce the probability of global temperature increases by 61%. Nkwaju *et al.* (2019) showed that using geopolymers reduces CO_2 emissions by 80-90% compared to Portland concrete, significantly contributing to industrial waste control. In addition, G.P.C. uses only water as a primary compound, requiring less water (Vaičiukynienė *et al.* 2018).

Creative cement-based polymers called G.P.s can completely replace O.P.C. hybrids while producing less CO_2 than ordinary Portland cement (Ahmed *et al.* 2021). "Geopolymer" is an alkaline solution capable of forming the interaction with Si and Al in an original material or waste material. During treatment with aqueous liquid media, alumina-silicate substances such as lime powder, rice husk ash, and powder granular blast furnace debris can be converted to G.P.C. (Ahmed *et al.* 2020). The type of resource materials and most widely used form of alkali solutions are potassium hydroxide (K.O.H.), sodium silicate (Na_2SO_3), mixed proportions of potassium silicate (K_2SiO_3), and sodium hydroxide (NaOH), and used to predict the performance of G.P.C. (Duxson *et al.* 2007). Geopolymer resin has become an alternative to traditional cement materials in recent decades. The alkaline solutions lead to polymerizing the binder material such as wood ash, husk ash, red mud copper mine, waste glass, and metakaolin (Hassan *et al.* 2019; Assaedi *et al.* 2019). Geological or agricultural materials such as blast furnace slag and silica are referred to as "body," while "polymer" refers to the sequence of atoms from a standard unit (Khaleel *et al.* 2020).

Liquid Al_2O_3 and SiO_2 undergo a polymerization process throughout the electrochemical process to form 3D crystalline alumina–silicate with comparable or greater strength to O.P.C. cementitious materials. Figure 1 shows the synthesis of Geopolymer fabricated techniques. This synthesis process is followed by three phases: With highly alkaline conditions, oxide particles from the starting materials often dissolve silica and alumina during the initial phase. The second phase involves haling or acclimatization of the liquid oxide material, followed by agglomeration. The last phase is polycondensation, which creates a three-dimensional parent material of silica-aluminate structures (Part *et al.* 2015; Cui *et al.* 2020). As demand for products such as fly ash and GGBS has increased dramatically in recent years, research is also being conducted to develop alternative binder materials. In order to reduce the greenhouse gas emissions associated with cement production, various industrial by-products are often used as full or partial substitutes for cement products. In an empirical investigation, Arunkumar *et al.* (2021) investigated the feasibility of using low-calcium wood ash as a substitute for fly ash in geopolymers. Experimental observations indicated that 30% of the reinforcement material was the best wood ash to achieve high flexural and compressive strength. (Yousefi *et al.* 2019) reported that the same results were achieved using biomedical waste-reinforced GGBS geopolymer concretes. The investigation was conducted using up to 10% proximate composition. According to the results, adding more biowaste medical ash increased the compressive strength. Scrap rubber is used as a fiber, and waste wood chips are used as reinforcement material for developing G.P.C. rather than F.A. The results suggested that Geopolymer with improved mechanical properties could be provided using a residue of wood ash and 1% discarded waste fiber.

Arunkumar *et al.* (2021) experimented with developing sustainable geopolymers using wood chip ash and scrap tires as fibers as a substitute for rice husk ash to improve properties such as energy absorption, stiffness, and impact strength. Scientific progress in various fields has produced abundant and homogeneous organic by-products through industrial, agricultural, mining, and domestic endeavors. Some of these by-products can be achieved from effective reuse, including improved durability and strength properties, reduced construction costs by using less concrete and aggregates, and potential benefits include decreased CO_2 emission and simple removal of unwanted pollutants (Xie *et al.* 2019). Fly ash recycling has emerged as a significant problem in previous decades due to its enormous production, increasing disposal costs, decreasing transport to landfills, and increasing disposal regulations. Flyash-based construction or preparation of Geopolymer during geopolymerization, dissolving Si and Al without an alkaline activator with polycondensation to form a cemented solid with geopolymer concrete, is the most efficient use of fly ash. According to prior research, Class F fly ash-based geopolymers work better thermophysical and physically at levels lower than 500°C. Researchers also showed that Class C fly ash-based cementitious materials perform well thermally and retain stiffness at heating temperatures above 800 °C. However, including glass waste particles in fly ash-based cementitious materials improved its compaction performance, shortened the curing process, and strengthened the integrity of the gel, all of which improved the fire resistance of the Geopolymer.

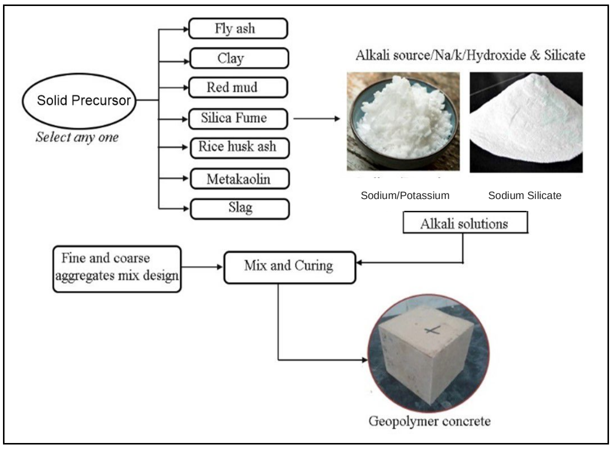

Fig. 1: Steps Involved in the Geopolymer Synthesis

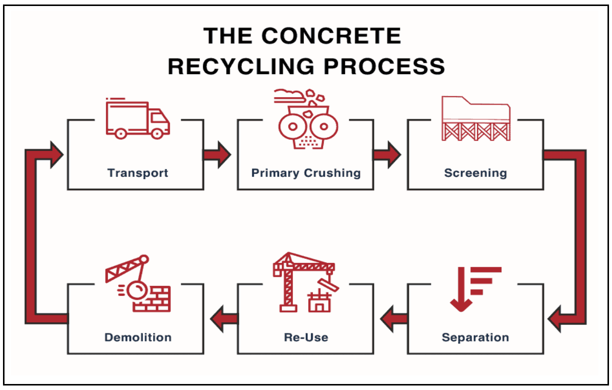

Fig. 2: Recycled aggregate plant

The most commonly used products are copper slag (Youssf *et al.* 2022), blast furnace slag (Zawrah *et al.* 2016), and waste aggregates (Gupta *et al.* 2017). Coconut shells, fibers (Alyousef et al., 2020), and tobacco waste are the best alternatives for cement and coarse aggregates (Siddika *et al.* 2018). Due to the flammability of significant aggregates, concrete blocks are one of the most significant non-static artificial structures. Portland cement is currently handled at a production capacity of 30 million metric tons per annum. With this increase in total consumption expenditure, demand for new products is expected to increase over the next ten to fifteen years. As a result, cement production is highly resource-intensive, leading to significant environmental, electricity, and financial exploitation because it produces 50% primary material, 40% total energy, and about 50% waste aggregates (Behera *et al.* 2014).

Recycling and demolition waste (C&D waste), primarily generated by the construction industry as a significant source of recycled materials, is now a primary concern for governments and construction companies (Ferronato *et al.* 2019). Recycled aggregates (R.A.) from construction and trash disposal have been the subject of extensive investigation over the years to understand their unique qualities better. The procedure for developing the R.A. process is shown in Figure 2. The different types of coarse aggregates are shown in Figure 3. According to past research studies, R.A. can be advantageous in replacing concrete with new aggregates while still achieving the same high quality as traditional concrete structures (Tan *et al.* 2020). Recycled Aggregate Concrete (R.A.C.) is mainly employed for construction and non-structural uses. It has previously been proven economically and scientifically feasible (Mukesh *et al.* 2012). Figure 4 shows the standard XRD pattern of fine sand C & D waste powder, verifying the presence of calcite ($CaCO_3$) and quartz (SiO_2) in addition to different aluminosilicates and silicates.

Fig. 3: Classification of aggregates

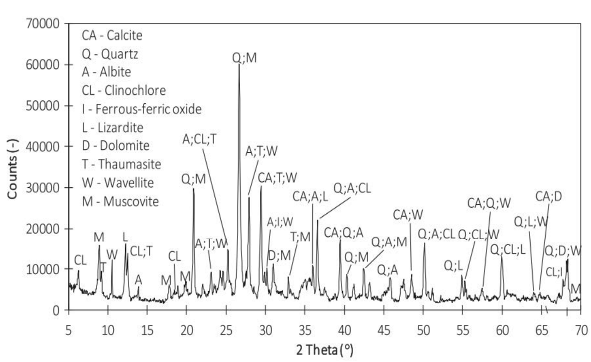

Fig. 4: XRD pattern from Recycling and demolition waste (Bassani *et al.* 2019)

The present investigation comprehensively examines recent advancements in geopolymer material cementitious materials employing recovered concrete and waste from C&D as a partial or complete replacement for aggregates. They also revealed the different states of fresh properties and mechanical characteristics of various mixed designs using different types of binding material. This assessment will help close the gap between experimental research and the building sector. Figure 5 shows the investigation flow chart of Geopolymer concretes.

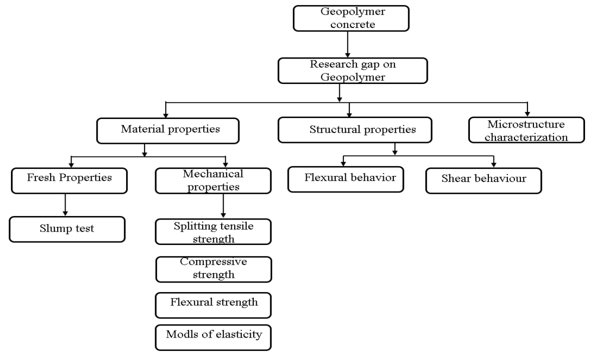

Fig. 5: Review process flow chart

1.1 Research Gap

1. Studies on the serviceability of structures made of geopolymer concrete.
2. The examination into the fragile behavior of dense microstructure geopolymer concrete.
3. More studies need to be done on the life cycle evaluation and commercial feasibility of employing geopolymer concrete in this field.
4. Mathematical Modeling of rheological properties in geopolymer concrete.
5. Influence of nanocomposites in Geopolymer.
6. Finite element analysis of structural elements limited research only uses the geopolymer concrete.

2. GEOPOLYMERIZATION PROCESS

During the setting and hardening (polymerization) of adsorbed aluminosilicate materials in alkaline activators at ambient temperature, the crystalline phase and the 3D silicoaluminate structure are formed (Ren *et al.* 2017). Although there are many theories regarding the chemical reactions that occur during polymerization, most researchers agree that the process could be classified into three phases (Prud'homme *et al.* 2011).

1. As the aluminosilicate minerals dissolve, concentrated alkaline treatments free form the silica and aluminosilicate tetrahedron unit.

2. The gel phase inorganic geopolymer is formed by silica and alumina hydroxide due to condensation reaction during the solidification. The hydrolysis causes the water to pull out the structure at this stage.
3. As the gel phase solidifies, it aggregates to create sub-cementitious materials of the three-dimensional structure of silicoaluminate.

The 10 M NaOH concentrations produced a higher Si_4 and Al_3 ion solubility ratio in aluminosilicates than in lesser NaOH concentrations, contributing to a sophisticated degree of geopolymerization. Geopolymerization highly depends on crystallization temperature (Prasanphan *et al.* 2019). Temperature increases the rate at which natural resources dissolve, and the rapid appearance of an amorphous phase peak in an X-ray diffractometer indicates that rising temperatures are better for geopolymerization. (Zang et al., 2020). Figure 6 shows the Geopolymerization process.

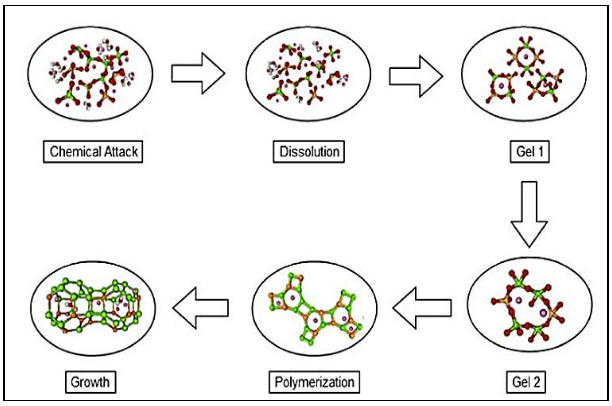

Fig. 6: Geopolymerization process (Castillo *et al.* 2021)

3. ACTIVATORS

3.1 Alkaline Activators

Several studies have revealed that alkali activators, Solid and liquid forms, are commonly used in high-strength concrete materials, especially geopolymer materials. However, the use of highly destructive alkalis as transcription factors is declining and eventually being replaced by various solid catalysts. NaOH and Na_2SiO_3 are among the most widely used activators in previous research. The mechanical strength of MK-GPC is obtained at 63.8 MPa due to the sodium water glass activator (Tchakouté and Rüscher, 2017). At 25 C and 85 C hardening conditions, stiffnesses of about 50 and 85 MPa were achieved at 28 days using solid Na_2CO_3 and hydrated lime as catalysts for BFSSF-based cementitious materials (Kearsley *et al.* 2015). The geopolymerization alkalis are Aluminosilicates, M_2O*nAl_2O_3, weak acid $M_3PO_4.M_2SO_3$, and M.O.H. The vital acid salt is M_2SO_4. Alkaline solutions dissolve the pozzolanic material during polymerization, forming silicon and aluminum as solutions. The compressive strength of mortar is much higher when using a $Na_2SiO_3.5H_2O$ solid accelerator than when using a liquid activator because it lowers the water-binder ratio by combining insoluble sodium metasilicate pentahydrate nanoparticles with some water (Dong *et al.* 2020). The Na_2SO_3 and Na_2CO_3 catalysts dramatically extended the static stability periods of geopolymers and reduced their compressive strength. The composite activator-activated Geopolymer is lighter than individual Na_2SiO_3 or Na_2CO_3-driven interfacial bonding (Ma *et al.* 2019). Properties and initial strength in F.A. are greatly affected by sodium sulfate as an accelerator, but it has a different effect on F.A. with significant Fe_2O_3 concentration (Velandia *et al.* 2016).

Alkali activators that rely on sodium and potassium are the most widely used.

Previous literature surveys have shown that sodium-alkaline activators can bind the F.F.A. more than potassium-based activators (Helmy, 2016). Compared to NaOH, using potassium ions in cementitious materials showed greater alkalinity. Potassium carbonate solid form in steady state acts as a reliable solid activator (Askarian *et al.* 2019). Researchers have shown that the Li hydroxyl compound works well as an alkaline activator and that the probability of A.S.R. gel formation by dissolving activated silica can be reduced by coating lithium using cementitious materials particles (Chen *et al.* 2012). The formation of FA-slag-based composites using a variety of activators, including LiOH and other catalysts (such as CaO, $NaAlO_2$, $CaAl_2O_4$, and Li_2CO_3) has been researched, as the strength of the resulting Geopolymer reaches 38 MPa in 28 days (Askarian *et al.* 2019b). Furthermore, $NaAlO_2$ is a significant key source because it provides additional functional aluminum-based geopolymers.

Consequently, it is essential to progress in selecting activators, depending on the qualities of natural resources. Activators include biodegradable combustion ash and solid waste. The main components of Calcium silicate hydrate and C-A-S-H gel are low calcium precursors and recycled waste activators, in contrast to Calcium silicate hydrate and C-A-S-H gel, made from alkali-activated Ca material and ceramic recycling accelerator (Liu *et al.* 2020).

3.2 Acidic Activators

Although many geopolymers require acidic activators, alkali activators stimulate most of them. The activation of phosphorous, alkaline solutions produces MK-based geopolymers, which have a remarkable compression strength of up to 93.8 MPa. Further research demonstrates that acid-base cementitious materials have improved mechanical properties and more robust heat tolerance than alkali-based cementitious materials. Al-rich, Si-rich, and P-poor elements exhibit the most potent synergistic effects, according to a combination examination of phosphate-based cementitious materials specimens with different Si/Al and Al/P ratios. According to a combined study of samples of phosphate-based cementitious materials with different Si/Al and Al/P ratios, Al-rich, Si-rich, and P-poor components exhibit synergistic solid activity.

4. RAW MATERIALS SOURCE FOR GEOPOLYMER

Several resources may be employed to produce geopolymers because any substance rich in silicon and aluminum can be a raw material (see Figure 7). Kaolinite was the component that was utilized most frequently in the production of geopolymers. Based on the successful application of this new material, researchers began to develop new raw materials, including industrial wastes such as Slag (El-Wafa and Fukuzawa, 2021), calcined clay particles (Tuyan *et al.* 2018), fly ash (Constâncio *et al.* 2022), and aluminum mine tailings (Burduhos *et al.* 2018), waste glass (Tuyan *et al.* 2018), and, etc. and naturally occurring silicoaluminate.

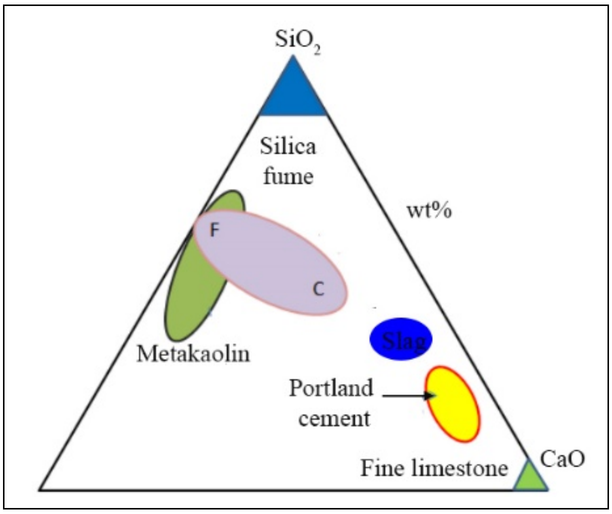

Fig. 7: Geopolymer ternary diagram (CaO-Al_2O_3-SiO_2) (Khatib, 2016)

4.1 Waste Material Resources

4.1.1 Red Mud

The Bayer process produced red mud mixtures for aluminum refinement in aluminum industries. The solubility portion of bauxite is exposed to NaOH using the Bayer method at a high temperature and pressure. Similarly, the finite volume of NaOH utilized in these techniques continues in the red mud, resulting in a higher pH level (Nie *et al.* 2019). By exploiting the high alkalinity of R.M., using it as a slurry reduces the overall rate of alkaline activators, reducing time and energy while also decreasing the rate of geopolymer Engineering (Yang *et al.* 2019). The suitable residual value of R.M. for FA-derived concrete mixture differs based on the quantity of NaOH and the solution mixes (Yeddula and Karthiyaini, 2020). In addition, research demonstrates that nanocomposites and R.M. composites have higher endurance and strength (Liu *et al.* 2020). Figure 8 and 9 shows the chemical composition of red mud and raw materials respectively.

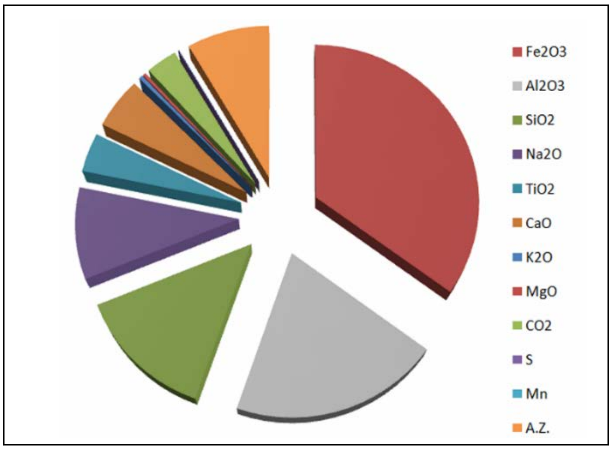

Fig. 8: Chemical compositions of red mud (Burduhos *et al.* 2018)

Fig. 9: Raw materials

4.1.2 Slag

Iron can be produced by products called blast furnace slag (B.F.S.) at temperatures of approximately 1500 (Amran *et al.* 2020). Also, B.F.S. is repeatedly referred to as sludge. Figures 9(b) and 10(b) show the typical blasted furnace slag sludge. Due to its amorphous state, wear resistance, and pozzolanic reaction, GGBS, freshwater-reduced B.F.S., is primarily used as an alternative to O.P.C. after processing (Silva *et al.* 2020). The formation of geopolymers using GGBS is highly reactive, and it is possible to achieve high reaction rates at temperatures below 0^0 C. As an alternate concrete resource, blast furnace slag uses less heat during the presence of moisture and reduces the risk of cracking. GGBS is used to lower concrete's water consumption, transparency, and heat of hydration while enhancing its resistance, long-term strength, and permeability to sulfate and alkali silicate responses (Li and Yi, 2020).

4.1.3 Fly Ash

Burning coal produces ash, classified as Class F and Class C commercial waste. Class F fly ash is a typical type that results after burning coal combustion and has a shallow CaO content (F.F.A.). Class C fly ash (C.F.A.) has a more excellent calcium content and is produced using alternative energy sources such as sub-bituminous coal and lignite (Guo *et al.* 2017). Fly ash, an acceptable form of small circular nanoparticles is a widely accessible by-product frequently used as a source material for synthesizing cementitious materials (Rashad, 2015). The use of HCFA in O.P.C. methods is limited by its relatively high concentration, and its use in preparing geopolymers has exceeded all assumptions (Wongsa *et al.* 2020). F.A. has been used since the first decade of the twentieth century and is frequently used as a key ingredient in concrete and cement (Scrivener *et al.* 2018). F.A. reduces construction costs while reducing emissions of environmental gases, making it an excellent alternative to concrete. F.F.A. has the advantages of being affordable, easily accessible, having excellent surface morphology, increased activity, and abundant in aluminosilicates with crystalline silicates. High-strength geopolymers are easily made in an alkaline activator mixture (Gupta *et al.* 2017).

4.1.4 Biomass Ash

Combustion of rice husk produces a by-product called rice husk ash (R.H.A.). Agricultural waste with high silica content, or R.H.A., is regarded as a safe substitute for strengthening the characteristics of geopolymers (Tosti *et al.* 2018). R.H.A. is utilized in geopolymers to lower the concentration of nano-SiO_2 and to lessen environmental issues brought on by R.H.A. landfilling, particularly in nations that produce rice. (Nuaklong *et al.* 2020). Due to R.H.A.'s high catalytic activity and significant effective surface area, influenced by its high calcium concentration, it has recently been frequently used in self-compacting pozzolanic cementitious materials (Molaei *et al.* 2018). Many researchers have also used bagasse from sugar cane ash, an industrial by-product, as a substrate for generating volcanic ash products that are silicate and alumina-rich. (Yadav *et al.* 2020). Insufficient wastewater is produced by incineration of municipal organic waste to ash. The concentration of heavy metals with fine particles is significant in the bottom ash. Bottom ash has recently been used more in construction and masonry products (Nagrockienė and Daugėla, 2018). Also, 10% to 15% of bottom ash from sewage sludge incineration from municipalities is added to the mix, making concrete stronger than conventional concrete or improved without bottom ash (Rutkowska *et al.* 2018).

4.2 Natural Resources

4.2.1 Clay Minerals

Clay is an essential mineral that is extracted from renewables. It is an aluminosilicate solution with microscale particles (2 mm). This flexible and resilient rock has a brown hue. An octahedral layer of aluminum and a tetrahedral layer of silicon-oxygen make up clay, a multilayered silicate. Due to their compositional characteristics, clay minerals such as zeolite, kaolin, and others are often used as precursors for cementitious materials. Often called kaolin, limestone is a white, granular, soft clay with good drainage and fire protection. Dehydration of metakaolin yields anhydrous aluminum hydroxide, or metakaolin (M.K.), at the proper temperature.

Figure 10(e) depicts a typical M.K. widely used to manufacture cementitious materials. MK-based geopolymers exhibit excellent thermal properties (Prud'homme *et al.* 2011). and mechanical solid and adhesive strengths (Duan *et al.* 2016). While MK-based nanocomposites give outstanding structural strength, numerous studies have coupled other materials with the technique to minimize costs, maintain better performance, and accomplish resource regeneration. (Istuque *et al.* 2019). In addition, research is developing porous geopolymers built on kaolinite that have the combined benefits of thermal performance and reduced disturbance. Rietveld makes up 95% of organic kaolin, and modern studies have demonstrated that cementitious materials produced by alkali induction have compressive strengths of up to 67 MPa. Using organic kaolin instead of calcined metakaolin reduces costs and negative ecological impacts. An example of an alumino-silicate material is zeolite, which has excellent absorbency, electrochemical treatment, catalysis, chemical resistance, and temperature resistance, among other properties. An example of an alumino-silicate material is zeolite, which has excellent absorbency, electrochemical treatment, catalytic, chemical resistance, and thermal resistance, among other properties. In addition to having the compressive performance of the hydrogel matrix, the composite material formed by the alkaline activation of the synthetic zeolite also retains the high porosity properties of the zeolite (Rożek *et al.* 2019).

4.2.2 Laterite Soil

Aluminosilicates, iron, and aluminum are abundant in hydrated lime. Due to its excellent corrosion resistance, hydrated lime is reddish-brown and has long been used as a regular brick for roads and buildings. A new development has emerged in preparing lateriticbased geopolymers with superior mechanical strength (Subaer *et al.* 2019). In addition, Na-poly, the raw material for laterite cement products, has a high molecular oxidation rate. The proportion of silica molecular oxides to alumina significantly impacts laterite geopolymer's shape and structural performance (Subaer *et al.* 2016). Furthermore, high-strength cementitious materials combine laterite with other solid wastes. Laterite and mixed laterite-slag composite materials offer feasible economic opportunities in non-load-bearing construction components (Lemougna *et al.* 2017).

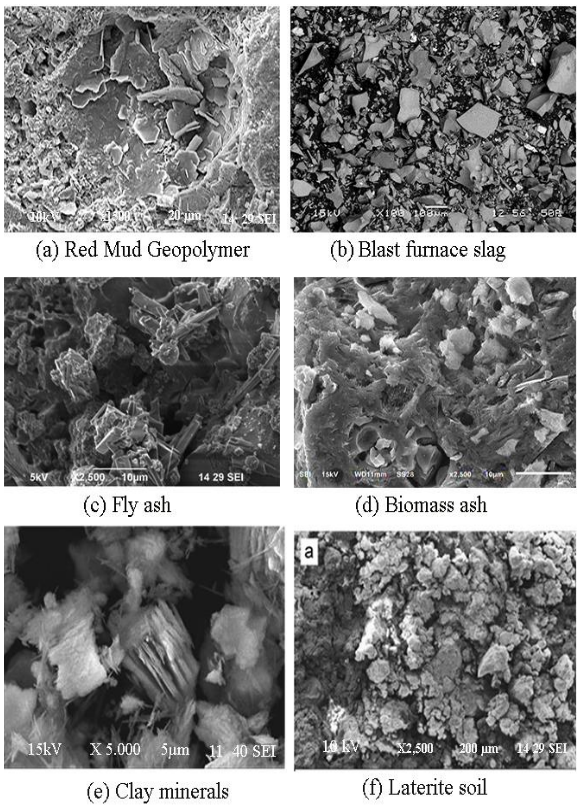

Fig. 10: Scanning Electron Microscope (S.E.M.) of microstructure morphology (Li *et al.* 2023)

5. GEOPOLYMER CONCRETE MATERIALS PROPERTIES

5.1 Fresh Properties (Workability)

The fresh properties are characterized by the term "workability" in the applications of existing technology. Concrete shrinkage is significant for internal works. The workability of G.P.C. concrete is derived from small factors such as flow table, slump cone, and slump flow. Also, water content and the amount of superplasticizers and activators can lead to the varying workability of G.P.C. (Hardjito *et al.* 2004). Farhan *et al.* (2019) investigated the new properties of conventional concretes and the effect of increased fly ash and GGBS in geopolymer mixtures. Fixed strength F.A.- and GGBFS-based G.P.C. and Portland cement were found to have adequate workability to be produced, mixed, compacted, and manufactured. Also, the durability of GGBFS geopolymer fly ash and conventional mixes was reduced due to a reduction in the bonding ratio. This improved the bonding strength in high-strength concrete.

Additionally, as NaOH's molar concentration expanded, the alkaline solution's viscosity increased significantly, resulting in an incredibly viscous mixture. As a result, G.P.C. works more effectively in combination with F.A. and GGBFS. In addition, increasing the alkaline solution to F.A. ratio increases G.P.C. viability, as Ghafoor *et al.* (2021) reported. Whereas an increase in the molar concentration of NaOH was observed to decrease the workability of G.P.C. composites (Ghafoor *et al.* 2021). Similarly, adding water content and superplasticizer enhanced the excellent workability of G.P.C. concretes.

Similarly, Aliabdo *et al.* (2016) found that adding plasticizer percentage, additional water content, and aqueous activator ratio improved the workability of the G.P.C. mixture while decreasing the molar concentration of NaOH and SS/SH ratio had a negative effect. Moreover, as the molar concentration of salt bicarbonate and the water-cement content increased, the machinability of G.P.C. reduced (Chithambaram *et al.* 2018).

It was observed that the chemical properties of G.P.C. composite were decreased by Nuaklong *et al.* (2020) reinforcement of nano-silica, especially at high percentage conversion. The 3.0% nano-silica concentration was 17% higher than the conventional G.P.C. mixture in the G.P.C. slump test. Additionally, adding 2.0% nano-silica increased the slump value from 660 mm to 670 mm in the G.P.C. composite. The novel properties of G.C. are generally influenced by the high concentration of nanomaterials, regardless of the types of nanostructures, and this is associated with a high demand for both water and aqueous activator. Furthermore, previous researchers have identified that the performance of G.C. improved as the number of nanomaterials increased due to the ball-milling effect created by the sphere-shaped particle structure of the nanomaterials.

The main product's primary particulate form significantly influences geopolymers' performance. As the F.A. particle diameter is reduced, the quality of the F.A. and the processability of nano-components are enhanced. However, due to the uneven shape of the particles, ground-granulated blast geopolymer materials need better processing. In addition, the N-C-A-S-H gel dominates the reactions of the by-products of the FA-based Geopolymer (Askarian *et al.* 2019). The Geopolymer based on FA-slag contains a significant amount of aluminum C-S-H gel. FA-sludge-based composites have much lower workability than FA-based cementitious materials because the sludge-based geopolymer structure is more compact and contains less non-reactive particulates, as shown in Figure 11 (Yousefi *et al.* 2019).

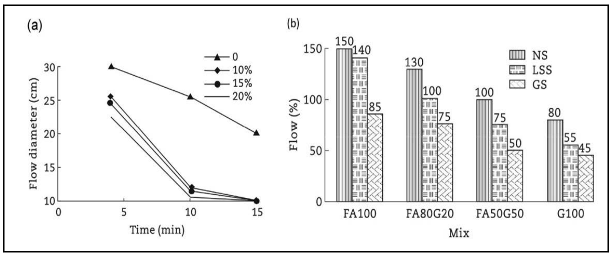

Fig. 11: Fresh properties of fly ash with GGBS (a) based on the flow diameter (Yousefi *et al.* 2019) (b) based on the different types of sand (Gholampour *et al.* 2019)

Further research shows that when the ratio of GGBS is vast, the flexibility of cementitious materials is reduced, as the activation solutions with GGBS work significantly faster and more efficiently than Huseien *et al.* (2018) revealed that the workability of geopolymers has been improved by adding GGBS with M.K. Additionally, several studies have demonstrated that using admixtures such as calcium carbonate or silicon powder can increase the strength and durability of cementitious materials (Laskar and Talukdar, 2018). When the number of alkaline activators is high, there is no obvious development in the properties of stiffness and freshness of cementitious materials. However, the workability of achieving GGBS-FA components can be improved by using deficient levels of superplasticizer (Laskar and Talukdar, 2018).

Some researchers have investigated the effect of fiber reinforcement in geopolymers and improved their workability. The porosity values of geopolymer materials paste comprising both natural and synthetic fibers demonstrate that using all fibers significantly reduces the flow properties of geopolymers compared to standard geopolymer mortars (Gülşan *et al.* 2019). The observations demonstrated that high-strength steel fibers have less impact on the performance of geopolymers than synthetic fibers (Bhutta *et al.* 2019).

Table 1. Compressive strength of Geopolymer concretes

Aluminosilicate precursor	Activator	Curing temperature	Compressive Strength MPa				References
			Three days	Seven days	14 days	28 days	
Cement +GGBS +Silica fume	SS/SH	90^{0}C	85	100	-	130	(Mayhoub *et al.* 2021a)
FA(F)+FA(HPA)+GGBS	SS/SH	20-25^{0}C	-	-	-	49.32	(Mesgari *et al.* 2020)
Fly ash + OPC+ Crumb rubber	SH/SS	60^{0}C	-	-	-	49.02	(Charkhtab *et al.* 2021)
LM+SF+FA	SH/SS	15-30^{0}C	-	35.46	58.24	64.4	(Das *et al.* 2020)
HCF +LCF + recycled aggregates	SH/SS	60^{0}C	-	-	-	58.21	(Nuaklong *et al.* 2021)
Fly ash + GGBS	SS/SH	25^{0}C	-	-	-	63.4	(Chowdhury *et al.* 2021)
Fly ash + GGBS	NAp	25^{0}C	-	-	-	50	(Alrefaei *et al.* 2019)
MK+GGBS	SS/SH	27^{0}C	-	-	-	47.84	(Huseien *et al.* 2018)
FA	SS/SH	25^{0}C	-	67.0	-	-	(Hadi *et al.* 2018)
FA+HCFA	SS/SH	60^{0}C	-	52.5	-	-	(Nuaklong *et al.* 2019)
FA + GGBS + SF	SS/SH	90^{0}C	-	47.5	-	-	(Elyamany *et al.* 2018)
FA + Nano-MK	SS/SH	70^{0}C	-	45	-	-	(Kaur *et al.* 2018)
GGBS	SH	25^{0}C	-	-	-	36	(Gholampour *et al.* 2019)
GGBS+RHA	SS/SH	80^{0}C	-	-	-	59.7	(Mehta and Siddique, 2018)
HCFA+ RHA	SS/SH	25^{0}C	-	-	-	38.1	(Kanagaraj *et al.* 2022)
MK + FA + SF	SS/SH	25^{0}C	-	-	-	80.7	(Zhang *et al.* 2020)
PFD + GGBS	SS/SH	20^{0}C	-	-	-	69.77	(Katpady *et al.* 2020)
Clay	SS/SH	24^{0}C	-	-	-	47.77	(Bayiha *et al.* 2019)
HCFA	NAp	25^{0}C	-	-	-	50	(Mohammed *et al.* 2019)
FA+ Bauxite	SS/SH	80^{0}C	-	-	-	45	(Wang *et al.* 2020)
Fly ash + GGBS+HMNS	SS/SH	25^{0}C	-	-	-	76.57	(Bouaissi *et al.* 2019)

5.2 Mechanical Properties

5.2.1 Compressive Strength

Compressive strength is among the most crucial variables when assessing the impact of reinforcements on cementitious materials concretes, particularly GCP. It has been accessing the total performances of proposed concretes (Ahmed *et al.* 2020). At the same time, the compressive strength of concrete at 28-D is essential for architectural engineering and construction techniques. The study thoroughly studied the C.S. characteristics for a few G.C. types with different ratios, curing ages, and setting temperatures.

Furthermore, they detail the effects of mixing ratios, curing temperature, and duration on the mechanical properties of G.P.C. The experimental and systematic analysis of geopolymer concrete is characterized based on critical factors such as compression strength according to curing ages, temperature, types of alkaline used, various mixtures and water content, and specimen ages.

Aliabdo *et al.* (2016) conducted the experiment by using Na_2SiO_3/NaOH ratio (0.4); the addition of chemical mixtures (10.5 kg/m^3) and water content (35 kg/m^3) and molarity (16) enhanced the G.P.C. with increasing alkaline solution ratio for 0.40 and then reversed. The same trend was found by Joseph and Mathew (2012), as geopolymers with C.S. enhanced the ratio of activator solution by 0.55. The C.S. of G.P.C. after 7 and 28 days was improved by continuously increasing the alkali solution/binder ratio, as reported by Shehab *et al.* (2016).

Researchers have also done in-depth research on the molar concentration of NaOH. Several studies indicate that a molar concentration value of 12 M provides the most excellent C.S. for G.P.C., while others show that 13 M and 14 M are the best molar concentration values (Chithambaram *et al.* 2018). The results of some other studies stated that a molar concentration of 16 M produced G.P.C. with a higher C.S., but the results do not apply to all of these investigations. In comparison, Joseph and Mathew (2012) recommended using a molar concentration of 10M to achieve higher compressive strength. The dissolution of Si and Al particles during the polymerization process improves the C.S. of polymer blends due to the increasing molarity of NaOH (Ahmed *et al.* 2020). Al and Si particles are completely softened throughout the polymerization process; Si and Al's nanoparticles suddenly dissolve when the concentration of NaOH is high. A mixture of NaOH with a sizeable molar concentration generally increases the C.S. of G.P.C. polymer matrix materials. Figure 12,13 and 14 shows the compressive strength SEM images of Geopolymer concretes.

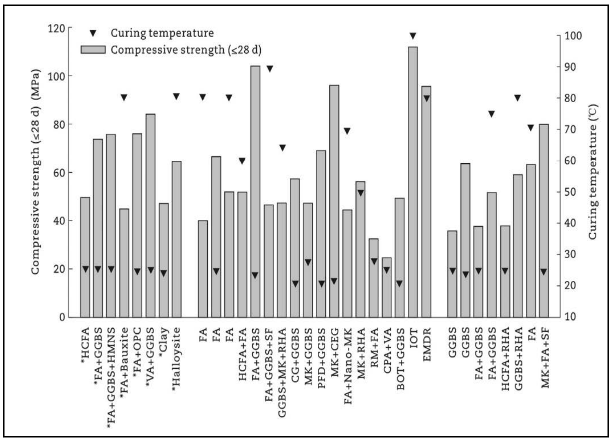

Fig. 12: Geopolymer Compressive strength (Cong and Cheng, 2021)

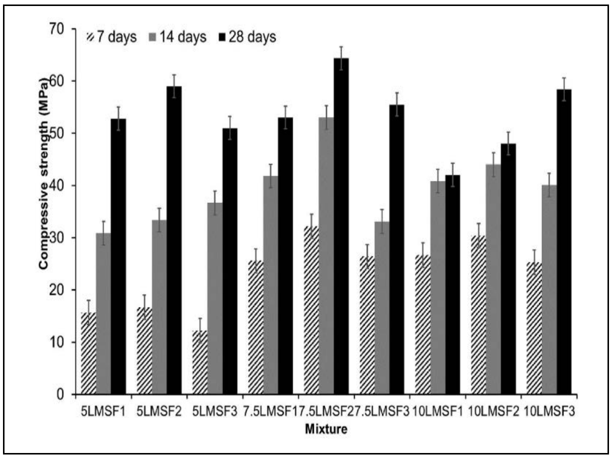

Fig. 13: Geopolymer Compressive strength (FA+SF) (Das *et al.* 2020)

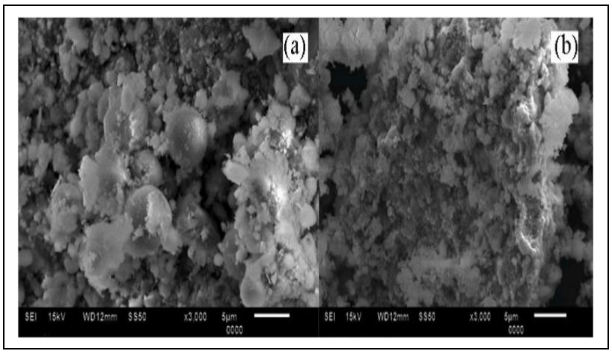

Fig. 14: S.E.M. images of FA+SF (a) 7 days (b) 28 days (Das *et al.* 2020)

According to Hardjito *et al.* (2004), applying superplasticizer to G.P.C. up to 2% binders improved the fresh characteristics and C.S., while the application above was detrimental to the C.S. of G.P.C. by adding fly ash. Additionally, they realized that a fly ash G.P.C. with more water lowered C.S. significantly. However, the research has established that C.S. strength decreases when more water is added to the G.P.C. formulation (Al-

Azzawi *et al.* 2018). Regarding curing regimes, G.P.C. aggregates are generally cured under atmospheric, furnace, and boiler curing conditions. Variations in curing methods (Fig. 16) depend on the nature and chemical composition of the raw materials used for the binders. For example, compared to all other curing factors, most studies used furnace and air-drying temperatures and steam curing parameters to cure fly ash, added G.P.C.

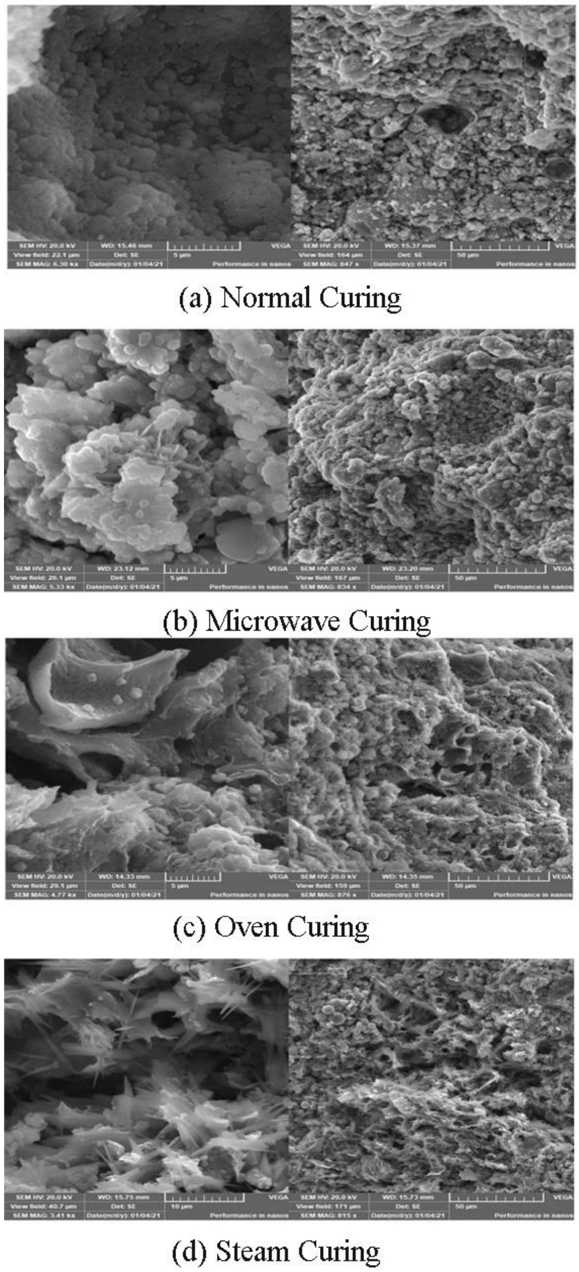

Fig. 15: Different types of Curing (Mayhoub *et al.* 2021a)

The C.S. of many cementitious materials is related to different geopolymer compositions, curing temperatures, and sample ages. To modify the tensile and compressive properties of composite FA/GGBFS with Sodium Silicate (S.S.), respectively. They created M5P-tree models, regression analysis, multivariate regression, artificial neural networks, etc. As they examined the suggested alternatives, they used various analytical techniques. Their results revealed that the artificial neural networks model is more accurate than other models in predicting the robustness properties of G.P.C.s. Conversely, the variables that significantly affected the C.S. of G.P.C. were alkali solution to binder ratio, NaOH concentration, molar ratio, aging, and curing conditions.

The flexural and compressive properties of cementitious materials constructed either with or without steel fibers were investigated by Alsaif and Abdulrahman (2022). Geopolymer composites using an adhesive made from metakaolin and fly ash. Instead of 20% of traditional aggregates, waste tire rubber (W.T.R.) is used. Also, a combination of industrial steel fibers (ISF) and internal reinforcement is provided by waste tire steel fibers (WTSF). This shows that the interfacial bonding between the W.T.R. and G.P.C. developed a moderate cementitious mixture with sufficient strength and improved ductility (Alsaif and Abdulrahman, 2022).

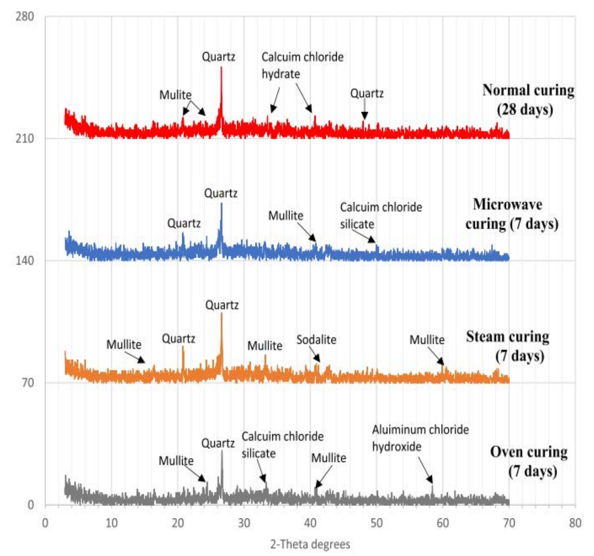

Fig. 16: XRD analysis of Geopolymer for different curing conditions (Mayhoub *et al.* 2021b)

5.2.2 Split Tensile Strength

Split-tensile strength (S.T.S.) is another significant mechanical property of G.C. as determined hypothetically using AS EN 12390-6/ASTM C-496 standardized experimental techniques. Among the important indicators for assessing the tensile strength of Geopolymer concretes, such as R.C. slabs, frameworks, and columns, is the elasticity of fracture, also known as strength properties. Standard-recognized test methods such as ASTM C-293, ASTM C-78, and BS EN 12390-5 evaluate the F.S. of ordinary P.C.C. composites (Mohammed *et al.* 2021).

The percentage of S.T.S. enhancement is lower than the CSS progress reported by Ryu *et al.* (2013). Switching from F.A. to GGBS in the same context had a more minor effect on S.T.S. and F.S. than C.S. (Ryu *et al.* 2013). Testing these modifications improved the C.S. of the GGBS composite and revealed a reduction in F.S., increasing from 15% to 20% when replacing FS/CS (Yousefi *et al.* 2019). (Hassan *et al.* 2019) demonstrated that curing G.P.C. at 75 °C for 26 h substantially increased total C.S. and F.S. compared to the stiffness of flexibility of G.P.C. The S.T.S. and Flexural strength of G.P.C. were established by Rabiaa *et al.* (2020), who incorporated nano-MK and nano-silica into an existing G.P.C. composite. They are found to be 4%, which represents the ideal concentration for these two nanostructures. The development of F.S. and S.T.S. of G.P.C. with the addition of nano-silica, even though various concentrations of nano-silica were used. C.F. was used as an additive by adding fly ash to the mixture at weight-based ratios of 0, 0.1, 0.2, and 0.3% (Çevik *et al.* 2018).

Table 2. Split-Tensile strength of Geopolymer concretes

Aluminosilicate precursor	Activator	Curing temperature	Spilt -Tensile strength (MPa)	References
Fly ash + OPC+ Crumb rubber	SH/SS	60 ^{0}C	4.7	(Charkhtab *et al.* 2021)
Fly ashes: high calcium fly ash (H.C.F.) and low calcium fly ash (L.C.F.).	SH/SS	60 ^{0}C	3.5	(Nuaklong *et al.* 2021)
Fly ash+ GGBS	SH/SS	20 ^{0}C	3.6	(Poloju and Srinivasu, 2021)
Flyash based Geopolymer	PH/SS	20 ^{0}C-30 ^{0}C	4.4	(Ramujee and PothaRaju, 2017)
GGBS	SH/SS	20 ^{0}C	4.9	(Chithambar *et al.* 2021)

Nuaklong *et al.* (2021) examined the fly ash geopolymer concretes of mechanical properties with Recycled Concrete Aggregate (R.C.A.) by singing carbon fiber (C.F.). The outcomes showed how C.F. enhanced the mechanical characteristics of cementitious materials integrating R.C.A. thanks to increased aggregate and fiber bonding effects for polymerization procedures. Adding 0.2% C.F. combined with 100% R.C.A. produced cementitious products with high compressive and splitting tensile strength. Using 50% R.C.A. resulted in better flexural strength and external wear resistance performance, significantly improving these two properties. Therefore, instead of using organic natural aggregates, C.F. improves by using microaggregate. Figure 17 shows the splitting tensile strength of RCA geopolymer concrete.

5.2.3 Modulus of Elasticity

When determining the stiffness of Geopolymer concretes during the elastic phase, one crucial material property is their Modulus of elasticity. ASTM C-469 standards were used to carry out the test, providing improved deformation resistance. According to Hartzidow's (2005) measurements, the M.E. of G.P.C. rises as C.S. rises and exhibits the same trends as C.S. of G.P.C. Nath and Sarker (2017) stated that the curing process does not significantly affect the M.E. of geopolymers. However, Saravanan *et al.* (2019) found that when 50% of F.A. was replaced with GGBFS, I significantly increased against C.S. In addition, the Mechanical properties of stabilized concrete with stabilized, high-strength F.A. and concrete with unique features were compared by Farhan *et al.* (2019). Although these results differ, the researchers found that the values at 28 days with conventional concrete and average strength (35 MPa) G.P.C. were 16.59, 16.13, and 17.98 GPa, respectively. For structural applications (65 MPa), F.A. and GGBFS-oriented G.P.C. and static concrete improved to 19.46, 19.36, and 20.95, respectively.

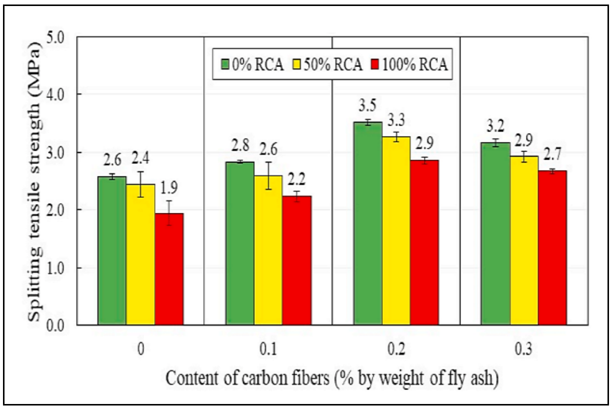

Fig. 17: Split tensile strength (Nuaklong *et al.* 2021)

Table 3. Modulus of elasticity of Geopolymer concretes

Aluminosilicate Precursor	Activator	Curing Temperature	Modulus of Elasticity	References
Ordinary Portland cement (O.P.C.) +GGBFS+ Silica Fume	SS/SH	20^{0}C	58GPa	Charkhtab *et al.* (2021)
Natural coarse aggregate+ Low-calcium fly ash	SS/SH	40^{0}C	34GPa	(Nuaklong *et al.* 2021)
GPC	SS/SH	20^{0}C	25GPa	(Poloju and Srinivasu, 2021)
Coarse R.G.A. + P.C.C. + Low calcium F.A. (class F)	SH/SS	40^{0}C	33GPa	(Ramujee and PothaRaju, 2017)
GGBS	SH/SS	20^{0}C	42GPa	(Chithambar *et al.* 2021)

Table 4. Flexural and shear strength of Geopolymer concrete

Aluminosilicate precursor	Activator	Curing temperature	Flexural strength MPa	References
HCF +LCF + recycled aggregates	SH/SS	20^{0}C	5.2	(Nuaklong *et al.* 2021)
Natural coarse aggregate+ Low-calcium fly ash	SS/SH	40^{0}C	6	(Mesgari *et al.* 2020)
Fly ashes: high calcium fly ash (H.C.F.) and low calcium fly ash (L.C.F.)	SS/SH	60^{0}C	5.1	(Hardjito *et al.* 2004)
Coarse R.G.A. + P.C.C. + Low calcium F.A. (class F)	SH/SS	40^{0}C	6	(Ramujee and PothaRaju, 2017)
GGBS	SH/SS	20^{0}C	6.8	(Chithambar *et al.* 2021)
Fly ash + GGBS	SH/SS	30^{0}C	2.81-6.11	(Rathinam *et al.* 2022)

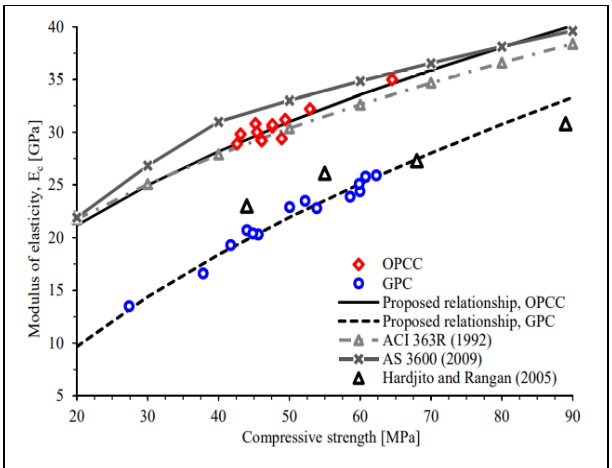

Fig. 18: Modulus of elasticity (Noushini *et al.* 2016)

Similarly, Ghafoor *et al.* (2021) maintained that FA-based G.P.C. curing at ambient temperature was maintained by increasing sodium hydroxide molarity up to 14 M and then decreasing it. As the NaOH concentration increased, the M.E. of G.P.C. increased to 78.9%, 41.1%, and 96.4% from 8 to 10 M, 10 to 12 M, and 12 to 14 M, respectively. However, small changes were observed using Na_2SiO_3/NaOH and alkaline activator/F.A. ratios. Several studies have identified aggregate properties as an essential factor in determining the ductility of concrete. Along with fine aggregates and strength characteristics, other essential factors to consider when determining the Modulus of elasticity for G.P.C. and OPCC include the curing time, conditions, and test age. According to A.C.I. and AS design guidelines, figure 18 depicts the link between G.P. and O.P.C. cementitious materials' elastic Modulus and strength properties. Assumptions that can be made include: For atmospheric and high-temperature O.P.C. concrete, the postulated and A.C.I. 363R (1992) models suggest a reasonably acceptable modulus of elasticity For ambient and high-temperature fly ash-based cementitious materials concrete, AS3600 (2009) and A.C.I. 363R (1992) models are unsuitable (Noushini *et al.* 2016).

5.2.4 Flexural and Shear behavior of Geopolymer Concretes

Several Investigations on Deformation Behavior Patterns of R.C. Concrete Geopolymer-Made Trusses. Many researchers have used conventional concrete beams strengthened under similar conditions to test G.P.C. performance on horizontal structures in the components of fracture moment, endurance, maximum bending strength, and deflection at diverse loading phases. Related work on the behavior of R-GPC beams during flexural analysis is summarized. The performance and functions of the newly developed GGBFS are subject to G.P.C.'s experimental and theoretical investigation framework components. G.P.C. beams with L and uniform regular sections were investigated. The outcomes showed that the strength-to-weight ratio of G.P.C. in identical examples is greater than that of regular concrete beams. The analytical results demonstrated that the empirical observations and output of the ANSYS program were broadly comparable.

Essential variables include dowel action, shearing time frame depth ratio, the ratio of reinforcing elements, and C.S. of concrete and material interlocking. The strength of concrete plays a significant role in determining the shear load-bearing capabilities of a building.

Thick beams are cementitious composites of T-shaped structures with a shearing effective height ratio of 1.90, which Madheswaran and Philip (2014) studied for their shear behavior. G.P.C. beams performed adequately as components of construction. All beams are shear tested and compared to traditional beams made of concrete of the same strength under two-point pressures. Cracks were visible in the soffit of the beams. All beams developed flexural cracks in the early stages of loading. A shear crack is detected in the shear plane as the load rises. The breaking loads for each beam were observed to range from 30 to 90 kN. The shear performance of tall columns with F.A. and Portland cement was studied by (Mourougane *et al.* 2012). The G.P. beams have lateral spacings of 150 mm, 200 mm, and 230 mm and are cast in two tension-strengthening situations. The bending effectiveness of F.A. and Slag steel-reinforced-strengthened with cement composite columns was examined by Ali and Khalid (2023). The results showed that, on average, the slag-based G.P.C. beams had higher strength capacities than conventional concrete beams. Fracture diameter, fracture width, and crack number of tensile stresses in slag-based G.B.C. and conventional beams were all developed in the same sequence (Alsaif and Abdulrahman, 2022). Figure 19 shows the shear behviour of geopolymer concretes.

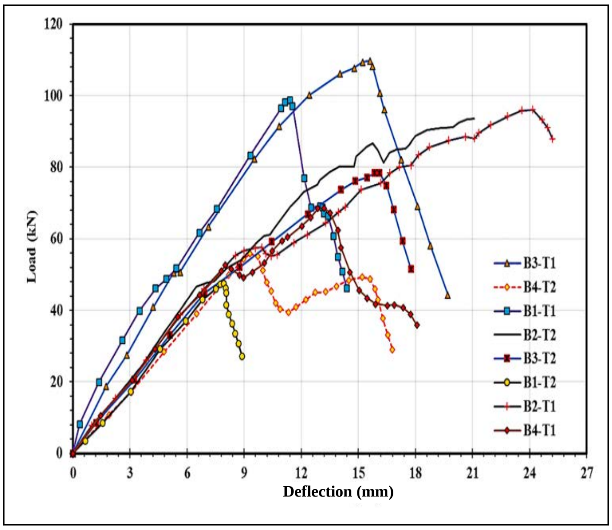

Fig. 19: Shear behaviour (Aldemir *et al.* 2022)

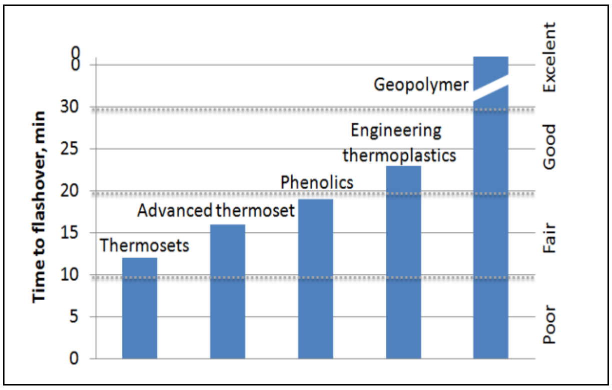

Fig. 20: Time to flash over for various organic resources

7. APPLICATIONS OF GEOPOLYMER CONCRETES

The literature studies based on their uses of geopolymers are classified into two different aspects. One with conventional mechanical and physical assets and another method of primary materials with other chemical and physical properties combinations. Applications are isolation, fire resistance, adsorptions of harmful irons, thermal shock refractories, nuclear power plants, and their insulated walls.

7.1 Marine

The durability and stability of the construction will be affected if the reinforced concrete is subjected to rain, sea, or salty soil for long periods. Geopolymer concrete is also well suited for construction materials because of its chemical inertness, which mainly works as sulfate resistance. Geopolymer concrete has more crystalline features, less permeability, and more mesopores than concrete mixtures. The rigid microstructure of geopolymers makes it difficult for saltwater to penetrate. Geopolymer concrete is a promising implementation aim in the marine ecosystem as an anti-corrosion coating because it provides superior stiffness to corrosion by chlorine ions and a prolonged, extremely corrosive crack propagation period relative to O.P.C. concrete. Cementitious composite constructs were predicted based on deionized water-induced voltage and low calcium F.A. A follow-up study by Chindaprasirt and Chalee (2014) demonstrated reduced absorption and corrosion of FA-based geopolymer chloride ions with a molar concentration of sodium hydroxide when air-dried for 28 days and exposed to a splash area in the marine environment for three years.

Furthermore, FA-based geopolymer material has been more readily carbonized than O.P.C. concrete mixtures, and chloride ions and sulfates diffuse more easily into the atmosphere of saltwater lakes after six years. Alzeebaree *et al.* (2020) state that cementitious materials fabrics bonded with carbon and basalt fibers can be modified to oppose chloride ion corrosion. Fiber-reinforced concrete can be used as a structural substitute for conventional cementitious materials because it has fracture properties similar to those of conventional cement. The solubility of chlorinated ions can be improved by adding M.K. and nano-SiO_2, but this can be reduced by introducing O.P.C. to F.A.

7.2 3D printing Materials

Consumers have voiced widely about 3D printing. Additionally, the advancement of print media is essential. Geopolymers are used in the coating of materials for 3-D printing. The researchers designed cementitious composites using commercially available granular 3D printing technology. The fundamental geometric accuracy and structural performance of 3D printing technology mainly depend on the load-carrying direction due to the anisotropic printing technique. The position of the adjacent elements is represented by the strength properties, primarily influenced by the 3D-printed variables and the rate at which the material strength increases. As the complete structure is built through layers of Geopolymer, adequate fracture toughness will ensure the durability and reliability of the design. SiO/Na_2O alkaline activator ratio 3.22 improved the prepared geopolymer concrete's workability, strength, and retention capacity.

Similarly, activator/binder and water/solid mixing ratios of 0.35 and 0.30 with 5% clay added achieved the best results. 3D-prepared geopolymer concrete with 50% slag and 50% F.A. has a compressive strength of 25 MPa, which is sufficient for many structures. The cementitious materials' thixotropic characteristics as alkali-activated Slag were considerably improved by adding 0.4% bentonite. The physical agglomeration rate and moisture needed for large-scale 3D printing are increased by adding 2% water magnetite seedlings to this hybrid development.

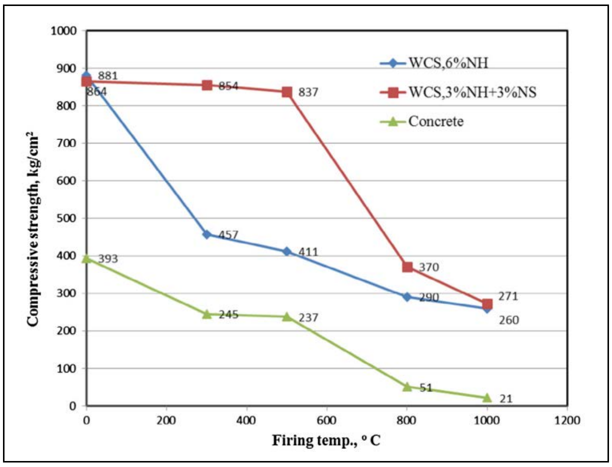

Fig. 21: Geopolymers heat exposure using 6% WCS + 3% NH + 3% N.S. (maintain the concrete strength (Abdel-Ghani *et al.* 2018)

7.3 High-temperature and Fire-resistant Materials

One of the critical elements in the process of creating geopolymers is fire protection. Increasing the resilience and sustainability of resistance to fire and high-temperature materials is a top concern today. Geopolymerization converts commercial waste material into a cementitious matrix with exceptional mechanical stability, thermal properties, and non-flammability. (Cheng and Chiu, 2003) revealed that GGBS was involved in geopolymerization and worked as an excellent fire-resistance material, thus combining it with reaction products. A mixture of M.K., hydrogen peroxide (2%-3.5%), and phosphoric acid geopolymer foams (PAGEs) achieves high fire resistance for 2 hours, and a reverse temperature of about 220 ^{0}C. Sodium aqueous glass waste-derived geopolymer cement has a robust cementitious material structure and is an excellent refractory material. An aqueous glass mixture was used as the catalyst to create RM-RHA-based nanocomposites. In addition, cementitious materials exhibit improved heat and fire resistance with a 2-hour curing requirement at 1000^0 C. During the first 30 minutes of the fire test, R.H.A. and nano-SiO_2 helped reduce the strength reduction of the polymers. After exposure to high temperatures, basalt fiber helps increase the torsional capacity of composite structures and provides some survivability. The geopolymer coating is replaced by a layer of silicate minerals, which inhibits the transfer of mass and temperature. As a result, the heat release rate and fire growth factor decreased while the fire performance measurement improved. Figure 21 shows the geopolymer concrete to heat exposure condition.

8. SCOPE OF RESEARCH

Based on the recent mechanistic and thorough analysis of the composition and structure of G.P.C. used in this investigation, the following are considered and emphasized regarding possibilities and limitations for further research:

1. G.P. adhesives require moderate pH and curing process parameters. To achieve broader environmental acceptance, initiatives are needed to improve the atmospheric temperature-cured G.P. technique that utilizes solid activators instead of alkaline solutions.
2. Additionally, conflicting results in comparison of the environmental impact and operational efficiency of G.P.s with O.P.C. demands have been noticed.
3. The correct directions should influence the combination of fine and coarse aggregates in the G.P.C. Developing design procedures for each significant precursor is essential for developing geopolymer composites.

4. Investigation of the process of ensuring G.P.C. from a social, environmental, and economic sustainability perspective needs to be more comprehensive. This indicates that more research is required to adequately assess the sustainable development of G.P.C. and that a life cycle assessment process is required.
5. To better understand the structural behavior of G.P.C., researchers need to investigate the workability of concrete, especially fracture development studies.
6. Additional in-depth studies on the shear strength of cementitious materials are necessary to confirm the precision of the flexural resistance of geopolymer engineering structures.
7. As G.P.C. produced by industry may deviate from test reports, long creep and compressibility should be investigated.
8. Studies on additional engineering structures such as walls, slabs, foundations, connections between columns and beams, and columns still need to be included. Consequently, extensive research is needed in these areas.

9. CONCLUSION

In this research, critical, relevant details about geopolymer materials are presented. It covers the mechanism of reactions in alkaline solutions, raw material sources, preparation techniques, fundamental characteristics of geopolymer materials, and potential application in a wide range of industries. After a thorough analysis of the relevant material, the following conclusions can be drawn:

1. Cement-free concrete, known as G.P.C., uses commercial and organic materials. O.P.C. converted waste charcoal as the primary binder material, giving an eco-friendly and effective construction material. G.P.C. decreases. Reduces construction costs, helps conserve, eliminates waste, and reduces the impact of CO_2 emissions.

2. The carbon emissions caused by conventional concrete with Portland cement affect the environment. Geopolymer concrete is among the most environmentally acceptable options for developing the construction industry.

3. The dissolution of the precursors, the production of the first gel, and the development of the silicate network construction are the three main processes in polymerization.

4. Natural resources of geopolymers are abundant in aluminum and activated silicon. In addition, among the raw materials for geopolymers, Steel slag, S.F., waste glass, diatomite, volcanic ash, coal slag, bauxite, high-magnesium nickel slag, etc., are commonly used.

5. Many variables are cement material, including sodium hydroxide concentration, sodium silicate/sodium hydroxide ratio, water/solid ratio, curing age and curing method, chemical admixtures, acid environment solution/binder ratio, mixing period, and strength period of G.B. mix, raw material, binder material.

6. The presence, bulk composition, and additional water content affected G.P.C's fresh and mechanical properties.

7. The compressive strength of geopolymers containing GGBS increases up to 110%. It was found that the Modulus of elasticity was 5%-10% higher than that of O.P.C. concrete.

8. Compared to O.P.C. concrete, G.P.C. has 8%–12% maximum tensile strength and 1.4 times higher flexural strength.

9. Compared to OPCC, which has comparable mechanical properties, G.P.C., which has a fly ash and slag mixture, has 10% stronger binding strength with reinforcing steel. Geopolymer provides more excellent durability, fatigue, and high acid resistance than conventional concrete with Portland cement.

10. The state of cementitious materials is influenced by their liquid and solid states, structure, and concentration of catalysts. The Geopolymer formed is very strong when the curing temperature is between 60^0 C and 100^0 C. Geopolymers are affected by aggregate particle shape and material.

11. There are countless conceptual design formulas for G.P.C. structures that have been implemented. Therefore, there are still opportunities for R-GPC members to examine the structural behavior of G.P.C. to develop a standardized design process that is less expensive and more reliable.

DATA AVAILABILITY

The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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All authors contributed to the study's conception and design. The first draft of the manuscript was written by [M. Nanthini] and all authors provided language help, writing assistance, and manuscript proofreading. All

authors read and approved the final manuscript. Dr. R. Ganesan - Supervise and Execute the investigation outline.

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