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Geopolymers as Supplementary Cementitious Materials to Reduce Carbon Dioxide Emissions

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ABSTRACT

Geopolymers are an alternative and sustainable substitute for ordinary Portland cement (OPC) Geopolymers are being investigated as supplementary cementitious materials to lower carbon dioxide emissions in the building sector. To lower emissions, geopolymer concrete also improves the environment by substituting OPC with supplementary cementitious materials. In addition to keeping waste out of landfills, it produces lightweight, environmentally friendly building materials that fit the circular economy model. Geopolymer concrete reduces global warming as compared to traditional OPC concrete, offering sustainable solutions for construction applications and mitigating carbon dioxide emissions, thereby promoting sustainable development in the construction sector. In the building sector, geopolymer materials provide environmentally friendly substitutes for OPC materials by enhancing water absorption, lowering carbon dioxide emissions, and fostering environmental sustainability. In terms of mechanical qualities, robustness, and environmental sustainability, geopolymers have demonstrated encouraging outcomes.

INTRODUCTION

In the construction industry, the use of cement as a binding building material has enormous and serious impacts on the environment. Its preparation in the kiln takes place when the raw materials are heated for clinker production. However, firstly, these raw materials, because of their extraction from the environment, become reduced, and secondly, during the process of cement manufacturing, the large amount of energy usage produces a large amount of carbon dioxide, which causes an increase in temperature around the world, leading to global warming and influencing drastic effects on the environment, climate change, rising sea levels, pollution, severe health issues, and other global issues. The cement industry emits 8 percent of greenhouse gases; however, to keep global warming to 1.5°C and safeguard public health and welfare, immediate action is required. To ensure a sustainable future, carbon dioxide emissions must be reduced. So, to prevent these issues, there is a need to use industrial waste, such as fly ash or slag, because of their harmful nature. It is better to reuse them, so they react with alkaline solutions and generate the binding gel. However, supplementary cementitious materials, which are solid wastes that include aluminosilicate, can effectively substitute cement. They improve the properties of hardened concrete such as geopolymer (alkali activated) materials (de Oliveira et al. 2022), i.e., they are healthier, and more durable in both acidic and alkaline solutions, and because of their ability to absorb water, they can resist changes in temperature as well as freeze-thraw cycles (Alahmari et al. 2023) high mechanical strength, sustainable for the environment, lesser carbon dioxide emissions from these gases, and lower energy use (Chen et al. 2010, Mohamad et al. 2022, Sbahieh et al. 2023) with lower permeability, improving strength, and making concrete mixtures more cost-effective. It had been suggested that artificial binders, rather than natural stones, were used in the construction of the pyramids. Rather than being organized in layers like calcium remains, the blocks were arranged like an artificial binder (Davidovits & Cordi 1979). Geopolymers are long-range, covalently bonded, non-crystalline networks made of inorganic ceramic and aluminosilicate; certain blends of geopolymers contain octahedral fragments. Their network structure is three-dimensional, and they are inorganic polymers consisting of Al-O and Si-O in tetrahedral form linked with an oxygen bridge (Wan et al. 2017). To generate geopolymers based on the chemical nature of these polymers, Davidovits proposed the term poly (sialate) as shown in Table 1. Sialate, which stands for silicon-oxo-aluminate, is made up of tetrahedra of SiO_4 and AlO_4 joined by oxygen atoms.

RAW MATERIALS FOR GEOPOLYMERS PRODUCTION

Clay minerals and other raw materials with high silica and alumina contents are used in the production of geopolymers. Because of its cohesive and pliable earthy structure, clay, an aluminosilicate salt with small particles, is an appropriate precursor for the synthesis of geopolymers.

Metakaolin, as shown in Table 2, a mineral, is a popular starting material for geopolymerization due to its predictable properties and chemical makeup. The natural minerals in which silica and alumina are present are more than 65% in the earth's crust. MK is essentially a pozzolanic substance made from kaolin clay employing high-temperature calcination. When compared to OPC, metakaolin geopolymers improve mechanical properties, workability, and resistance to heat, corrosion, and water. When compared to alternative binding materials, they offered improved compressive and flexural strength. Even though metakaolin is a key product, its production is unable to keep up with the world's demand for pozzolanic ingredients used in the manufacturing of cement and concrete. The geopolymerization of Al-Si minerals and clays, such as metakaolin and kaolinite, takes place (Xu & Van Deventer 2000). Metakaolin is the starting material for geopolymerization, but it is too soft and has too many water requirements. The thermal and mechanical processing of kaolin can increase its reactivity and surface energy while decreasing its crystallinity. This method can decrease gases and pollution i.e. released in heat treatment.

Despite their benefits, metakaolin-based geopolymers have restrictions in the areas in which they can be used due to their low mechanical strength and high water requirements. Much work has been done in the last few decades on the geopolymerization of Al-Si minerals and clays, especially metakaolin and kaolinite. However, these raw materials are naturally occurring and are primary sources. So, the usage of secondary raw materials such as fly ash, GGBS, etc.

Table 1: Classification of geopolymers based on sialate composition and Si:Al ratios.

Polymer Type	Chemical Composition	Si:Al Ratio
Poly (sialate)	Silicon-oxo-aluminate	1
Poly (sialate-siloxo)	Silicon-oxo-aluminate with siloxo	2
Poly (sialate-disiloxo)	Silicon-oxo-aluminate with disiloxo	3

Table 2: Primary raw materials.

	Aluminosilicate source material	Uses
Metakaolin ($2SiO_2 \cdot Al_2O_3$)	The thermal treatment of kaolinite at 600–800°C leads to the collapse of the original clay structure and the formation of metakaolin.	In ceramics production, but is used as cement in concrete replacement.

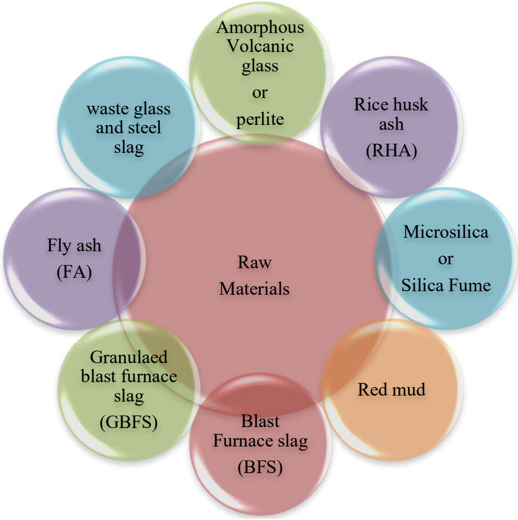

Fig. 1: Raw materials for Geopolymer production.

Their nature is harmful, so it is better if we use and recycle them. And use them as a replacement for cement for construction purposes in buildings. However, these raw materials from aluminosilicate sources were created artificially, and although any silicate or hydroxide can be used, sodium hydroxide and sodium silicate are the main alkaline activators. Fly ash and blast furnace slag are examples of industrial wastes and products that can be used as raw materials to produce geopolymers in a more for geopolymer ecologically responsible way. On the other hand, the final product's strength, setting times, slump, and shrinkage can all change if contaminants are included.

Fly ash, as shown in Fig. 1, an anthropogenic element obtained by industrial waste from coal-fired power plants, is a valuable material for geopolymer synthesis due to its low water demand, high workability, and easy availability. The primary constituents of fly ash (FA) are SiO_2 and Al_2O_3 as shown in Table 3. It poses environmental issues. It is separated into two classes: Class F fly ash and Class C fly ash. Class F fly ash is a low-calcium fly ash derived from bituminous coal or anthracite, which is pozzolanic. Class C fly ash is a high-calcium fly ash derived from lignite or sub-bituminous coal. It possesses self-cementing and pozzolanic qualities. FA's special qualities, like its mix of silicate and alumina, can be utilized in the synthesis of geopolymers (Guo et al. 2017), and its uses in construction, road replacement, brick production, and soil stabilization. So, to protect the environment, it is better to reuse it. Despite its availability worldwide, its utilization is limited. Geopolymerization can be an effective method to use fly ash, considering its heterogeneous nature and low reactivity. Mechanical activation and metakaolin addition can make fly ash an appropriate base material for geopolymers with high mechanical strength and enhanced durability (Duxson et al. 2007, Rangan 2008).

Granulated blast furnace slag (GBFS) as shown in Fig. 1, is an iron-making byproduct that is glassy and granular and contains SiO_2, CaO, Al_2O_3, and MgO as shown in Table 3. For more than 75 years, it has been utilized as a substitute material for the manufacturing of cement and geopolymeric systems (Duxson et al. 2007). At 0°C, it can still attain ideal reaction rates. Mix reactivity, strength, resistance to sulfate, and mineral structure are all enhanced by GBFS. (Katarzyna et al. 2020) Clinker requirements were decreased by using blast furnace slag in place of cement. Because of its high alumina and silica concentrations, it may also be used to produce geopolymers, providing a greener method of building.

Blast-furnace slag (BFS) as shown in Fig. 1, is produced by blast furnaces using iron ore, coke, and limestone to produce iron. Slag is removed, iron is transformed, and cooling occurs. The clinker requirements decreased with it.

Red mud (RD) as shown in Fig. 1, is a by-product of the Bayer process, which uses sodium hydroxide to dissolve bauxite into alumina. It is composed of both metallic and solid oxides, with iron oxides making up more than 60% of its mass (Singh 2018). It is also an industrial waste generated during alumina extraction. Red mud leaching can be reduced by using geopolymers. It is appropriate for the manufacturing of geopolymers because of its high alkalinity and alumina content. Red mud geopolymers can also be utilized to make high-quality paving blocks when employed as cementitious materials in the construction of roads. Red mud (RM) is produced over 1 to 2.5 tons for every tonne of alumina extracted from bauxite. Its iron oxide content, which ranges from 20% to 60%, gives it its red color. Researchers investigated the use of RM in alkali-activated binder formulations and OPC production. It has been demonstrated that adding a tiny amount of RM to cement could improve its mechanical qualities.

Microsilica, or silica fume, as shown in Fig. 1, is a valuable by-product of ferrosilicon and silicon alloy production. Its compact size reduces permeability and increases strength, durability, and density by filling voids in the microstructure. Both natural and artificial sources could yield SF, a highly reactive pozzolan with chemical, mineralogical, and physical characteristics. It is a useful additional material for geopolymers in concrete applications due to its nano-porous formation. The addition of silica fume improved the properties of geopolymers and offered sustainable substitutes.

A filler known as rice husk ash (RHA)**,** as shown in Fig. 1, is a byproduct of processing and growing rice that has special pozzolanic qualities and a high silica concentration. It is made by calcining rice husks, which poses a risk to the environment. When RHA is burned in a boiler, 100 kg of husks give 25 kg. The chemical composition is sensitive to the conditions of combustion; unburned carbon results in a grayish-black color and small, fine particles ranging in size from 3 to 75 μm (Singh 2018). In concrete, it could be applied to increase workability, decrease permeability, and lengthen the setting time. The potential of geopolymers to improve mechanical properties, durability, sustainability, and lower production costs when compared to regular polyethylene (OPC) intrigued RHA.

Amorphous volcanic glass, or perlite, as shown in Fig. 1, is a raw material used in the manufacturing of geopolymers. In agriculture, perlite, which is high in SiO_2 and Al_2O_3 as shown in Table 3, is utilized as a water absorbent. But it's waste because of its porosity or tiny particle size. Waste geopolymerized perlite can be utilized alone as a thermal insulator or in combination with fly ash to create building materials and immobilize hazardous waste (Vance et al. 2009).

Waste glass, silica fume, and steel slag as shown in Fig. 1, are the materials that include amorphous structures and a large amount of silicate and aluminum components. Metakaolin and other waste materials can be added to geopolymer-based constructions to make them better. Particle fineness, oxide concentration, and composition of the amorphous phase all affect the microstructure of geopolymer materials (Helmy 2016). To generate a three-dimensional network of silico-aluminate, the geopolymer binding process involves dissolving aluminosilicate precursors to form reactive particles, restructuring and altering structures, releasing water, and polymerization/polycondensation. Aluminosilicate powder and an alkali solution are combined to create a geopolymer, which is a gel-like material with remarkable qualities like low density, high strength, thermal stability, fire resistance, and chemical resistance. These non-polluting materials can have their excellent adhesive qualities enhanced by adding carbon fiber reinforcement.

In the geopolymerization reaction, as shown in Fig. 2, the waste products containing aluminosilicate mix with alkaline activators like sodium hydroxide or KOH and sodium silicate or potassium silicate. However, when Si-O-Si bonds break aluminum atoms penetrate them to form aluminosilicate gel. With more alkali, these gels harden into a geopolymer cement. This cement is mixed with aggregate and water to form geopolymer concrete. In geopolymerization, activator solutions play a critical role in promoting reactions and establishing the structure of the material. Strongly alkaline activators promote stable hydrates with limited solubility by accelerating the dissolution of aluminosilicate. Their chemical and physical characteristics have a big impact on the way the activated material performs. Alkali activators play a crucial role in the activation process of geopolymer materials, influencing their alkalinity, durability, resistance to

Table 3: Raw materials and their composition.

Raw Material	Composition	The cement replacement percentage of these raw materials
Fly ash	SiO_2, Al_2O_3, $Fe_2O_3$and CaO	15-30%
GBFS	CaO, SiO, $Al_2O_{3,}$ MgO	Normal conditions 40-50% and for marine conditions 50-60%
BFS	CaO, SiO_2, $Al_2O_{3,}$ small quantity of Fe, Ti, Mg and Mn (Li *et al*., 2022)	50-85% Gruyaert et al. 2013)
Red mud	$Fe_2O_{3,}Al_2O_{3,}TiO_2$	20% (Viyasun et al. 2021)
Microsilica	SiO_2 main impurities C, SiC, and oxides of alkaline (earth) metals	5% and 15% (Tak et al. 2023)
Rice husk ash (RHA)	90% Si, 5% C, 2% K_2O	5% partial replacement of cement with RHA for structural concrete 15% for non-structural construction (Singh 2013)

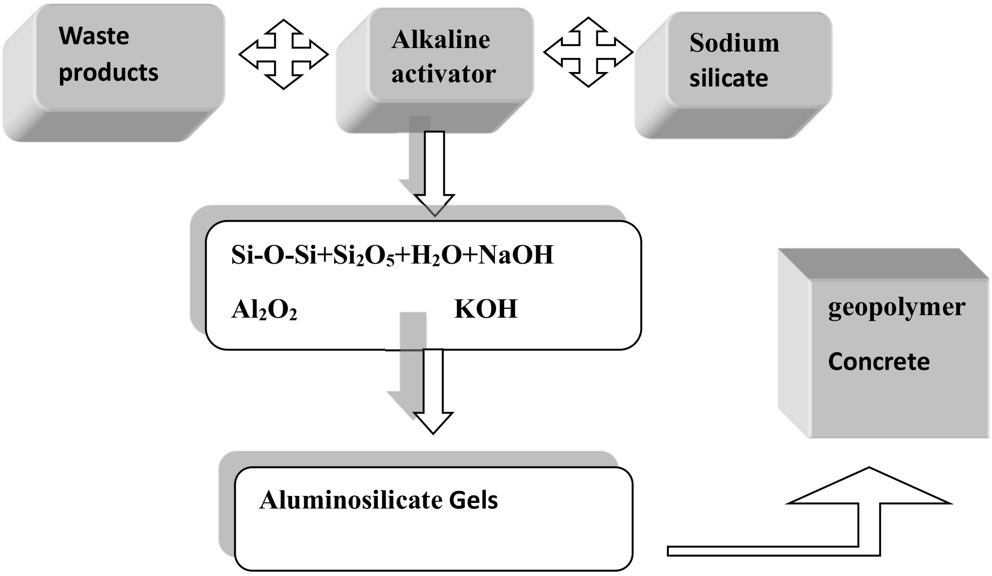

Fig. 2: Mechanism of Geopolymer Concrete.

Fig. 3: Geopolymer cement.

chemical attacks, and strength growth. Aluminosilicates are polymerized by it, resulting in GPC. The Si and Al atoms dissolved in alkaline solutions and were then reassembled into the geopolymeric network. The microstructure, mechanical characteristics, and activation efficiency of the material were all influenced by the type of activator used; sodium-based activators exhibit higher levels of efficiency. Research indicated that potassium compounds, as opposed to NaOH, can raise alkalinity in geopolymer systems. While acidic activators are sometimes used to activate geopolymers, alkali activators are typically used to do so. It was preferable to use acid-based activators rather than alkaline ones, which are formed from phosphate or humic acids. Phosphoric acid and aluminum phosphate-based activators were two common phosphate-based activators. Silicate solutions, carbonates, and activators based on sodium or potassium are frequently utilized because they are readily available and reasonably priced. Sodium waterglass, ash from solid waste, and organic material can also be employed as activators; however, sodium-based activators exhibit higher activation efficiency in the formation of FA. In geopolymers, alkali activators are frequently utilized, while acidic activators are also used in some compositions. The MK-based geopolymer exhibits better mechanical properties, increased temperature resistance, and compressive strength of up to 93.8 MPa. Geopolymers with phosphoric acid as a base could act as heat- or fire-retardants (Tchakouté & Rüscher 2017).

PROPERTIES OF GEOPOLYMERS

An eco-friendly as shown in Fig. 3, cementless binder geopolymer with superior strength, strong mechanical characteristics, and resistance to chemical attacks Waste products such as silica fume, fly ash, and blast furnace slag can be used to make them. Recent investigations concentrate on improving qualities and broadening usage, providing a useful and sustainable substitute for conventional concrete (Xu et al. 2022). Geopolymers are being investigated as sustainable substitutes for conventional concrete because of their superior mechanical qualities and tolerance to high temperatures. They use waste materials as binders and lower carbon dioxide emissions. Geopolymer composites have promising qualities, are long-lasting, and have many beneficial applications. They are cost-effective, satisfy specification standards, and show resistance to acid, carbonation, and high temperatures (Noviks 2023). In this study, the research approach to geopolymers-alumino-silicon gels manufactured from natural and artificial mineral components from Latvia-such as sand, clay, wood ash, and brick waste examined. Using sodium silicate and sodium alkali solutions, the study sought to ascertain that the content of the interacting components affected the geopolymer formation process at constant exposure factors. They concluded that geopolymers are inexpensive, green materials with superior mechanical, thermal, and chemical characteristics. Because composite geopolymer materials perform better, researchers are now concentrating on them. Because of their high specific surface area, porous structure, ion exchange capabilities, and compressive strength, geopolymers perform exceptionally well in adsorption. They are perfect for industrial uses in wastewater treatment, waste gas treatment, purification, separation, and pigment removal because of their high porosity, which enables pollutant interception and increased surface area.

Geopolymers can have their surface charge and pore size changed to accommodate different purposes. Nevertheless, this characteristic necessitates high levels of alkali activator usage, high environmental conditions, and great experimental precision. This results in higher expenses and emissions, which makes the practical use of geopolymers difficult. New materials are being developed to address these challenges. The components of geopolymers have a considerable impact on material qualities, necessitating continued research and development. To create a thorough theoretical system, variables such as the ratio of raw materials and coupling agents should be investigated. Similar in structure to zeolite, geopolymers can be made from pure chemicals or naturally occurring minerals. Flat membranes, tubular membranes, multi-channel membranes, and single or multiple geopolymer membranes are only a few of the industrial uses for them. To apply geopolymer innovation to real-world uses, more study is required in the areas of performance, cost, emissions, and practical application (Noviks 2023). Recent studies have demonstrated the potential uses of metakaolin-based geopolymers as environmentally friendly building materials because of their quick coagulation, superior resilience, and compact structure which can be further increased by the appropriate use of cement. Applications include materials for pavement repair, heavy metal curing, silt solidification, and soil stability (Dai et al. 2023). With room temperature curing, the metakaolin-based geopolymer was created as a quick repair material. Improvements in bulk density, flowability, mechanical qualities, and consistency were achieved by adding Portland cement. The geopolymer's strength was shown to be enhanced by a 40% cement component. Cement exhibited its promise in on-site geopolymer construction as the modified geopolymer created a compact skeleton structure (Wei et al. 2023).

COMPRESSIVE STRENGTH OF GEOPOLYMERS

Geopolymers the composite materials known for their exceptional mechanical strength, endurance, stability in acidic and alkaline conditions, and heat resistance. A few examples of the variables that affect their compressive strength are the water content, contaminants, alkaline activator concentration, activator weight ratio, and curing temperature. Higher curing temperatures and periods are preferred for high-strength geopolymers with Si/Al ratios. On the other hand, contaminants and greater water content may weaken its compressive strength (Castillo et al. 2021, Teo et al. 2023). The advancement of geopolymers with high compressive strength will help the building, geotechnical, and architectural industries. The weight ratios of the activator to the binder and the sodium silicate to the NaOH determine the compressive strength of geopolymers. The goal of this work is to predict the qumax by utilizing the chemical compositions of binders that combine SiO_2, Al_2O_3, and CaO (Teo et al. 2023). The compressive strength of zeolite-based geopolymer which is made with different alkali to zeolite ratios and curing temperatures investigated in this work. The findings indicate that A/Z and curing temperature have a major impact on strength values, with 60°C being the optimal temperature for strength (Djamaluddin et al. 2022). An alternative to concrete manufacturing that produces less pollution is geopolymers, which are made by combining aluminosilicates with an alkaline solution. Tailings from copper flotation can be utilized as a starting material to make geopolymers, which have both financial and environmental advantages. The alkaline activator impact determined on the compressive strength of geopolymers based on copper flotation tailings was investigated at the Sustainable Mining Research Center (CIMS) of Engineering Consulting Company JRI. The highest compressive strength was found in 100% sodium silicate (SS) geopolymers, which reached 36.46 MPa after 7 days of curing at 90°C. The two geopolymers were impermeable and non-toxic. (Castillo et al. 2022). The impact of sodium silicate (Na_2SiO_3) on fly ash type F (low calcium) geopolymerization is examined in this work. Three sources of fly ash from power plants were characterized using varying quantities of Na_2SiO3. The 32% Na_2SiO_3 produced the best geopolymer, with a compressive strength of 21.62 MPa and a setting time of 30 hours (Hidayati et al. 2021). In comparison to Portland cement concrete, geopolymer concrete has many benefits, such as increased fracture energy, corrosion resistance, superior bond strength, and stability at high temperatures, because of its polymer formwork. Based on compressive strength, research utilizing the finite element method and the 3D ATENA program determines ductility values. The highest ductility value was found in specimens at 25 MPa, with a value of 5.33, and in specimens at 45 MPa, with a value of 3.39 (Aziz et al. 2022). Geopolymer concrete, which employs industrial or agricultural by-product ashes as binder materials instead of Portland cement, is one way that the concrete industry is trying to become more environmentally friendly. The compressive strength of geopolymer concrete is affected by many factors, including an alkaline solution to binder ratio, binder type, chemical composition, aggregate, alkaline solutions, curing regime, and specimen age. A systematic assessment was carried out to determine the effect of these parameters on fly ash-based geopolymer concrete (FA-GPC), and multi-scale models, such as artificial neural networks, were developed to predict the compressive strength of FA-GPC composites (Ahmed et al. 2023). A prediction model for the compressive strength of geopolymer concrete is provided in this study, emphasizing the significance of different components and curing times. Variables including hydroxide concentration, the ratio of alkaline liquid to geopolymer solids, the ratio of sodium hydroxide to sodium silicate, temperature, curing time, water/geopolymer solids ratio, age, binder fineness, rest duration, admixtures, and aggregates are identified in the study (Faluyi et al. 2022). The composition and strength of the geopolymer paste and mortar specimens are the primary fields of investigation in this work. According to the investigation, the maximum compressive strength of 12.59 MPa and 21.75 MPa at 28 days was obtained at 12M NaOH molarity and an alkaline ratio of 2.5. The study also discovered that longer setting times are caused by higher alkaline ratios and NaOH molarity. Green materials geopolymers have the potential to take the place of conventional cementitious materials (Chairunnisa & Nurwidayati 2023). For concrete, a building material, to perform as intended, a mixed design is needed. An alkaline solution is needed for the polymerization process in geopolymer concrete, an environmentally acceptable substitute for Portland cement that uses fly ash instead. Although there are no regulations governing mix design for geopolymer concrete, modeling can be done using the data already available. Concrete compressive strength is negatively impacted by water and NaOH, according to a regression model with a standard error of 9,60179 that was created using SPSS multiple linear regression (Karongkong et al. 2022). Because of its lower carbon dioxide emissions than Portland cement, geopolymer has gained popularity as a substitute. Because of its low cost and potential, fly ash (FA) is the most widely utilized binder material for geopolymer concrete. Using 247 experimental datasets, this study created multiscale models to forecast the compressive strength (CS) of fly-ash-based geopolymer mortar. The models were assessed using R2, RMSE, SI, OBJ, and other statistical measures. The alkaline liquid-to-binder ratio and the SiO_2% of FA were the most useful characteristics in the NLR model, which outperformed the LR and MLR models (Ahmed et al. 2022).

ADVANTAGES OF GEOPOLYMERS OVER TRADITIONAL CEMENT

Because of their improved mechanical and physical qualities, geopolymers are a sustainable substitute for conventional cement. They offer good mechanical and thermal qualities, are safe for the environment, and can be used as building materials (Kočí & Černý 2022). Waste binders used in geopolymer composites provide excellent mechanical strength and resistance to corrosion. In addition, they are inexpensive and emit less CO_2. To reinforce and fill gaps and cracks, grouting technology entails pumping a slurry made of cement into these areas. Although cement-based materials have many applications, high strength, and low cost, they also have high water separation rates, poor stability, and lengthy setting times. Made from industrial waste leftovers and volcanic ash, geopolymer materials have drawn interest due to their environmentally friendly qualities. Geopolymer materials are environmentally friendly, use little energy, and are efficient in recovering and reusing industrial waste residue. The characteristics of geopolymer grouting cementitious materials are significantly influenced by temperature. The impact of these variables on the characteristics of geopolymer grouting cementitious materials is thoroughly investigated (Yang 2022). Threats to current and future construction come from rising sea levels and erratic weather. Due to its lightweight, corrosion resistance, and magnetic neutrality, geopolymer concrete has drawn interest from researchers. Owing to the lower pH of alkali-activated materials compared to regular Portland cement, future projects requiring environmental proofing may find it feasible to use a dual system of suitable concrete and reinforcing bars (Pradhan et al. 2022). Compared to regular concrete, geopolymer concrete has greater strength, flexibility, and durability. In this work, ground granulated blast furnace slag and sugar cane bagasse ash are combined with alkaline liquids for reactivity to substitute ordinary Portland cement. Using the Taguchi method, the binder content, molarity, and alkaline activator-to-inder content ratios were the main areas of attention for geopolymer concrete optimization (Hadi et al. 2017). A dependable and long-lasting building material, concrete accounts for 5-7% of global CO_2 emissions. A recent innovation is geopolymer concrete (GPC), which is made from fly ash, powdered granulated blast furnace slag, and silica fume. When compared to traditional concrete, GPC is less expensive and provides superior resistance to chemical attacks as well as strong early strength. The environment, human health, and land scarcity can all benefit from the reuse of industrial waste materials in GPC manufacture (Kakasor et al. 2022). When used as a binder, geopolymer concrete (GPC), which uses marginal materials like fly ash and ground-granulated blast furnace slag (GGBS), is a sustainable alternative to conventional concrete. According to the study, GGBS enhanced strength rapidly, peaking at 81.43 MPa after 28 days. GPC was a high-resistance substitute for traditional concrete since it was resistant to water and chemicals and had a higher molarity. This environmentally friendly substitute for cement composites is essential for cutting carbon emissions (Bhikshma et al. 2012).

COMPARISON OF GEOPOLYMERS AND ORDINARY PORTLAND CEMENT IN TERMS OF CARBON DIOXIDE EMISSIONS

Concrete, a widely used construction material, has become less environmentally friendly due to its high CO_2 content in the Portland cement manufacturing process. To replace OPC, fly ash is being used as a substitute. Geopolymer concrete, with 0% cement content, can reduce carbon emissions by up to 56.02% compared to normal concrete, which contains 552.22 kg. This innovative approach is based on the A1-A_3 carbon factor value (Setiawan et al. 2023). Although Portland cement (PC) is a commonly used material in civil infrastructure engineering, 8% of global emissions are attributed to its manufacture. The utilization of agro-industrial waste (AIW) in cement-based products is examined. Geopolymers (GPs) have the potential to replace PC in the building industry entirely or in part, while also lowering carbon dioxide emissions. AIW and an alumina-silicate phase are combined in GP technology to create GP-cement, which has exceptional mechanical and durability properties. The mechanical qualities, longevity, and environmental sustainability of AIW-based geopolymer composites are encouraging, indicating that they have great potential as building materials in the future (Alawi et al. 2023). To evaluate sustainability and identify environmental practices, this study examines the last seven years of research on geopolymer concrete. For SO_x and NO_x, the study indicated that emissions ranged from 1,865 g-SO_x/m^3 to 1,161 g-NO_x/m^3, respectively. Nominal CO_2-e equivalent emissions were observed to vary from 56 to 661 kg-CO_2/m^3. For upcoming geopolymer research, the report suggests a straightforward way of determining the nominal carbon dioxide emissions value (Talaat et al. 2023). Climate change is seriously threatened by the carbon-intensive process used in the production of Portland cement (OPC), which produces large amounts of CO_2 emissions. Carbon footprints may be decreased by using geopolymer, a binding material derived from industrial by-products like fly ash and GGBS. However, because of the risks associated with handling and mixing, it has not been extensively used. One-part geopolymer concrete emits about 65% less CO_2 and 23% less than OPC concrete, according to research comparing it with OPC and other forms of concrete (Neupane 2022). The emission of carbon dioxide from Portland cement, the world's most popular product, leads to pollution and climate change. A greener substitute is geopolymer cement, which is made from industrial waste that is high in silicon and aluminum. This study examines the mechanical characteristics, performance, and features of geopolymer concrete and concludes that it is on par with or superior to Portland cement in certain areas. Geopolymer exhibits great potential as a material of choice in the future (Ahmed et al. 2022). The carbon dioxide emissions from Portland cement, a common building ingredient, contribute to global warming. Alternative binders are required for the manufacturing of concrete to prevent this. A study employed an alkaline solution and a thermal power plant to make a low-calcium fly ash-based geopolymer. An alkaline solution to fly ash ratio enhanced the strength of the geopolymer concrete, indicating the possibility of using different binders while making concrete (Ryu et al. 2013). Ten percent of global warming is caused by the extremely energy-intensive building ingredient known as Portland cement (PC). Researchers are researching environmentally friendly and sustainable concrete substitutes, such as geopolymer concrete (GPC), which is stronger and more durable than regular concrete. Because of its workability and comparable strength, GPC is a green building material that lowers CO_2 emissions and has shown effectiveness in structural applications. The mechanical qualities of GPC concrete are on par with or even superior to those of PC concrete, although many variables can impact its microstructure (Saeed et al. 2022). For fifty years now, concrete material that is widely used because of its affordability, adaptability, and water resistance has been crucial to the development of the world. Nonetheless, the process of making cement, which mostly entails burning fossil fuels and decarbonizing limestone, increases carbon dioxide emissions. Reduced use of Portland cement is made in preference to geopolymer concrete and fly ash, two lower-temperature alternatives, to protect the environment. This creative invention provides a low-cost, greener substitute for traditional concrete. According to the study, geopolymer concrete has the potential to be a sustainable substitute for regular Portland cement concrete because it may be utilized in similar circumstances (Farooq et al. 2021). In comparison to traditional OPC concrete, sustainable geopolymer concrete combinations have lower thermal energy and CO_2 emissions, according to a life cycle analysis. The mixtures with fly ash binder and sodium silicate had the lowest CO_2 emissions and thermal energy consumption. Alternatives to sodium hydroxide, a major source of energy and CO_2 emissions, are being investigated by researchers (Saidjon & Bakhrom 2021). Because of its significant CO_2 emissions, Portland cement is one of the main greenhouse gas emissions and is being reduced. A well-liked substitute, geopolymer, gained attention for its qualities of fire resistance, low permeability, chemical resistance, and compressive strength. It investigates the microstructure and strength of fly ash and metakaolin-based geopolymers (Barbhuiya & Pang 2022). The fire resistance of geopolymer concrete, an environmentally friendly building material, has been investigated because of its special three-dimensional mesh structure. This study examines the inorganic geopolymer concrete's static characteristics at high temperatures, emphasizing the necessity for more investigation into the material and structural design requirements before the material's use in engineering construction (Zhu & Zha 2023). The study investigates the application of geopolymer concrete, a fly ash-based substitute for traditional concrete, to strengthen it and address environmental issues. Comparing geopolymer concrete to ordinary concrete, the study discovered that it had a slightly lower Poisson's ratio but a greater modulus of elasticity, splitting tensile strength, and compressive strength. This creative method provides a sustainable substitute for conventional concrete (Indriyantho et al. 2023). Because of its better mechanical qualities, geopolymer concrete low-carbon and environmentally friendly substitute for cementitious composites drew attention. The potential of fibers to increase compressive strength, splitting tensile strength, flexural strength, and fracture toughness lies in the analysis of the types and characteristics of fibers employed to increase the toughness of geopolymer concrete. The kind of fiber determines the ideal fiber volume rate, and aspect ratio and hybrid fiber combinations have a big influence on the geopolymer concrete's characteristics (Wang et al. 2023). This study investigates the use of fly ash, silica fume, manufactured sand, and ground granulated blast furnace slag as fine aggregate and binder in high-strength geopolymer concrete (HSGPC). The mix design methodology produced a maximum compressive strength of 104 MPa at 28 days, and all concrete grades showed promising mechanical properties. Microstructural analysis revealed a dense microstructure of various gel formations, and the environmental impact assessment of HSGPC revealed a 90% lower carbon emission than conventional concrete (Jagad et al. 2023). Fly ash, aggregates, and an alkaline activator are the three components of geopolymers, which were developed in response to environmental concerns. Fiber reinforcements made of carbon, basalt, glass, cotton, and PVA fibers are examples of recent innovations that concentrate on mechanical qualities and appropriate substitutes (Jat et al. 2022). A green substance, geopolymer recycled aggregate concrete (GPRAC), uses recycled aggregates in place of Portland cement. By altering the curing temperature, utilizing various precursor materials, including fibers and nanoparticles, and establishing ideal mix ratios, it is possible to enhance the material's mechanical qualities, durability, and microscopic features. GPRAC can help modern society move toward low-carbon and green development by lowering carbon emissions, energy loss, and environmental degradation. In order to offer recommendations for the implementation of GPRAC in geopolymer concrete, the research examines variables including curing temperature and the amount of recycled aggregate included (Zhang et al. 2023).

New substitute materials, such as Alccofine-1203(A), Metakaolin (MK), and Ground Granulated Blast-furnace Slag (GGBS), have been developed as a result of recent research in concrete technology. To create a geopolymer concrete mix, this study examined the interactions between the microstructure and the chemistry of the materials. Finer particles decrease voids and boost concrete strength, according to the study. SEM and EDAX were used to examine the microstructure of the mix, and the results showed good interlocking qualities that have a direct effect on the mechanical properties of the concrete (Karthikadevi & Saraswathi 2023). The mechanical characteristics of geopolymer concrete with a somewhat low alkali activator are examined in this study, with particular attention paid to the following: bond strength, shear strength, flexural strength, elastic modulus, compressive strength, and split tensile strength. The fly ash and alkaline activator ratios were changed during the experiment. The outcomes demonstrated that higher than 19 MPa could still be produced using geopolymer concrete with a 4% alkaline activator (Romadhon 2022). This study investigates the use of fly ash geopolymer concrete (GPC) instead of ordinary Portland cement (OPC) in the building sector, emphasizing the material's durability and mechanical qualities as well as its capacity to lower CO_2 emissions (Shebli et al. 2023).

As a result of aggregate quarrying and Portland cement production's energy inefficiency, the building industry is moving toward environmentally friendly materials. Geopolymer concretes can be made using construction and demolition waste (CDW), which eliminates the requirement for PC and natural aggregates. Using recycled aggregates and precursors such as bricks, tile, concrete, and glass, this study examined the durability of geopolymer concretes based on CDW. As compared to PC-based concrete, the results indicated no discernible loss of weight or compressive strength, and there was similar chloride penetration (Ozcelikci et al. 2023). Because ordinary Portland cement (OPC) emits hazardous amounts of carbon dioxide, it is not a good choice for concrete used in green infrastructure development. Despite being a superior material with sustainable qualities, geopolymer concrete (GPC) is not yet widely adopted because there is little knowledge regarding its long-term qualities. Twelve traits and twenty elements were found in a study on the durability of GPC over the previous thirty years, which also identified major and secondary affecting factors. The study also emphasized the gaps in the field's understanding of global acceptance and the need for more GPC research (Pradhan et al. 2022). A sustainable substitute for ordinary Portland cement (OPC), geopolymer concrete is made using the geopolymerization process. With this environmentally friendly method, aluminosilicate materials such as fly ash and metakaolin may be converted into a geopolymer binder with just an alkaline activator. Promising findings have been found in studies on the durability of geopolymer concrete, particularly with regard to its resistance to heat and chemical attack. It is a possible substitute due to its high compressive strength, resistance to acid attack, and low to medium chloride ion penetrability (Wong 2022).

The longevity of metakaolin-based geopolymer concrete (MGPC) in harsh settings is examined in this work. The study examined four experimental factors: the duration of exposure to the hostile environment, the type of aggressive environment, the weight ratio of sand to metakaolin, and the curing temperature. The outcomes demonstrated that the performance of the MGPC was greatly impacted by each of the four parameters. It was discovered that the most effective weight ratios for harsh conditions were those that validated the tolerable durability of MGPC. The study emphasizes how crucial it is to take these things into account when designing geopolymer concrete (Forouzandeh Jounaghani et al. 2023). This study assesses the durability of fly ash (FA) and ground-granulated blast furnace slag (GGBS) geopolymer concrete (GPC) that has been activated with sodium silicate and hydroxide. The mixes were put to the test for depth of water penetration, resistance to sulfate and acid attacks, and strength. In tests of water penetration, all GPC mixtures showed moderate permeability and good performance in both acidic and alkaline environments. The findings imply that GPC mixes can successfully take the place of concrete made with ordinary Portland cement (OPC) in the building sector (Srividya & Kannan Rajkumar 2022). Concrete and geopolymeric cement are being used more frequently in the construction industry as substitutes for conventional OPC. Four variables that impact the characteristics of metakaolin-geopolymeric cement specimens are identified in this investigation. The findings demonstrate that the activator and metakaolin contents greatly increase the specimen's durability. The optimal durability is obtained when the ratio of metakaolin to cement is 1.5 and the ratio of activator to cementitious material is 0.3, according to microscopic tests such as SEM and FT-IR (Feng & Liu 2022). A dependable and long-lasting building material, concrete accounts for 5-7% of global CO_2 emissions. A recent innovation is geopolymer concrete (GPC), which is made from fly ash, powdered granulated blast furnace slag, and silica fume. When compared to traditional concrete, GPC is less expensive and provides superior resistance to chemical attacks as well as strong early strength. The environment, human health, and land scarcity can all benefit from the reuse of industrial waste materials in GPC manufacture (Kakasor et al. 2022). Waste materials like GGBS, fly ash, and slag are increasingly being utilized to make geopolymer concrete, which is made by reacting silicate and aluminate minerals with a caustic activator. New materials, such as Alcofine, have been added recently by research, increasing its endurance even at room temperature. The higher strength, durability, and environmental sustainability of geopolymer concrete are attributed to its enhanced polymerization processes and improved resistance to chemical assault. (Niveditha & Koniki 2020)

CARBON DIOXIDE EMISSION REDUCTION POTENTIAL

The development of strategies to lower carbon dioxide emissions is essential in light of the seriousness of climate change. Waste material streams appropriate for the disposal of carbon-negative concrete were mapped by a study. 1.9 Mt/a of total carbon dioxide uptake potential was revealed in the study, which is sufficient for the production of cement and concrete in Finland from secondary raw materials. Finland's carbon dioxide emissions might be decreased from 1.9% to a negative 1.3% if carbon-negative concrete were utilized (Mäkikouri et al. 2021). With its significant role in the world's CO_2 emissions, the cement industry needs a sustainable future. This study investigates the decrease of CO_2 emissions in the Macedonian cement sector, which is a prospective member of the EU. The steps include removing CO_2 from flue emissions, using additives to lower the ratio of clinker to cement, increasing energy efficiency, and switching from fossil fuels to alternative fuels. By 2020, these actions can enhance local environmental effects, cut emissions by 65-70%, and help Macedonia produce cement more sustainably (Mikulčić et al. 2012). The study investigates how CDM initiatives might improve energy efficiency in South Africa, Brazil, Indonesia, China, and India's heavy industrial sectors. Promising project types are suggested, such as cement blending, ammonia manufacturing process integration, and near net shape casting. On the other hand, estimating the whole potential is challenging (Hayashi & Krey 2005). The population, urbanization, GDP per capita, energy intensity, and industrial structure of East and South Coastal China are among the elements analyzed in this research that have an impact on carbon emissions between 2000 and 2015. The findings indicate that while energy intensity lowers emissions, GDP raises them. Slightly over the national objective, carbon intensity was lowered by 48.5% in 2020 and 59.7% in 2030. It was higher in the advanced scenario, though. Mitigation strategies for carbon intensity include restructuring the industrial organization, optimizing energy structure, and increasing energy efficiency (Wang et al. 2018). India lags in technical management even though modern aircraft and engine technology may attain fuel efficiency of 3.5 liters per 100 passenger kilometers. The sixth busiest air route in the world, from Delhi to Mumbai, produces 5.62 million tonnes of CO_2, 3.03 million tonnes of NO_x, 0.57 million tonnes of N_2O, and 0.15 million tonnes of CH_4 emissions every liter of fuel used. Three strategies-installing dryers, installing air units, and installing blended winglets-are how the lower CO_2 emissions. The report focuses on the significant cost of flight delays between Delhi and Mumbai, as well as India's technology management lag (Komalirani & Rutool 2012). The environment and society may suffer from excessive CO_2 emissions. Though its steady linear structure presents obstacles, reducing CO_2 is one possible way to mitigate its effects. With distributed atomic catalysts exhibiting great efficiency, Cu/TiO_2 has demonstrated potential for CO_2 photocatalytic reduction. In supported single atom catalysts for CO_2 reduction, surface oxygen vacancies and photoexcited electrons are important. Even at ambient temperature, the bending, anionic CO_2 production that is facilitated by Cu atoms with O_v allows for a rapid reduction of CO_2 (Chen et al. 2018). The necessity of cutting-edge technologies to lower CO_2 emissions in the connection between automobile transportation and climate change. It examines possible fuel-efficiency-boosting technologies as well as the effects of LPG, CNG, and battery-electric cars as well as their compatibility and maturity (Krail & Schade 2011). The study calculates potential reductions by examining China's energy and CO_2 emissions intensity from 2000 to 2013. The findings point to decreasing emissions, a less pronounced north-south distribution, and a slower trend in energy demand that will peak before 2030. China has enormous potential to reduce its carbon emissions; the most promising regions are Shanxi, Inner Mongolia, and Hebei (Chen et al. 2019).

CONCLUSIONS

In conclusion, when used in place of regular Portland cement in concrete, geopolymer cement has demonstrated the ability to cut carbon dioxide emissions by up to 80%, hence lowering the environmental effect of construction materials. Utilizing fly ash and other supplementary cementitious materials, geopolymer types of cement address environmental issues associated with standard cement production techniques and provide a sustainable way to lower carbon dioxide emissions in the construction industry. Through the reduction of CO_2 emissions and improvement of sustainability in construction operations, geopolymer technology presents an environmentally benign substitute for traditional cement manufacture. This shift is in line with international initiatives to mitigate climate change and lower carbon emissions. In addition to being a more affordable option to traditional cement concrete, geopolymer concrete has several advantages over cement concrete in terms of the environment, strength, durability, and greenhouse gas emissions. This highlights the need of sustainable construction methods. In order to combat climate change and encourage greener building techniques, geopolymer cements provide a viable way to lower carbon dioxide emissions throughout the cement-making process. They improve sustainability in the building sector by providing a viable substitute for conventional cement production.

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