

Geopolymer Concrete Composites and its Properties- A Clean and Sustainable Development

Jotesh Gupta^{1*}, Vanita Aggarwal²

Abstract

Production of geopolymer composites, an inventive and environmentally friendly substitute for regular Portland cement concrete, involves the polymerization of several industrial waste materials, including fly ash, powdered granulated blast furnace slag, silica fume, and rice husk ash, using solutions that are very alkaline. Because this technique removes the requirement for calcination, which is a significant contributor of CO₂ emissions during the manufacturing of OPC, GPC is more ecologically friendly. Alkaline activator solutions and alumino-silicate source materials are the essential components that start the geo-polymerization process and provide a binder that can bind aggregates. GPC offers advantages like higher compressive strength, improved durability, and resistance to chemical attacks compared to OPC concrete. The compressive strength results showed that for M40 grade under normal curing, the nominal OPC mix achieved 48.94 MPa at 28 days, while 100% replacements with GGBS, silica fume, fly ash, and rice husk ash achieved lower strengths of 18.11, 16.86, 10.23, and 8.03 MPa, respectively. Under heat curing, these values increased, with GGBS exhibiting 21.01 MPa. For M50 grade, the nominal OPC mix attained 54.14 MPa under normal curing and 59.27 MPa under heat curing. The 100% GGBS, silica fume, fly ash, and rice husk ash mixes achieved lower strengths under both curing regimes. The maximum 28-day strength of 41.3 MPa under normal curing and 45.54 MPa under heat curing was reached by the GGBS mix when 40% additional materials were added to 60% OPC for M40. This was followed by mixes including silica fume, fly ash, and rice husk ash. Comparable patterns for M50 grade were noted. Ultimately, geopolymer concrete is a viable, environmentally friendly substitute that has exceptional mechanical qualities like as resilience to chemicals, strength, and durability, which enable it to be used in a variety of settings.

Keywords: Geopolymer Composites; Supplementary Cementitious Ingredients; Geopolymer Properties, Alkaline Activation Solution; CO₂ emission.

INTRODUCTION

Concrete is a very significant and extensively used building material worldwide because of its affordability, adaptability, robustness, longevity, and the abundance of its constituent elements. Cementitious materials play a crucial role in the construction sector as they serve as necessary binding

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agents for both plain and reinforced concrete applications. Historically, Ordinary Portland Cement (OPC) has been the primary binding ingredient used in the manufacturing of concrete. But OPC manufacturing contributes significantly to the world's carbon dioxide (CO₂) emissions, which raises environmental issues and necessitates the development of sustainable substitutes. The calcinations process used in the manufacturing of OPC, which requires heating limestone and the accompanying release of CO₂, is the primary cause of the cement industry's 9% annual worldwide CO₂ emissions. Researchers in

the construction industry are investigating substitute binders for OPC that may either fully or partly replace it while preserving or improving the intended characteristics of concrete due to the significant environmental effect of OPC. Geo-polymer concrete composites (GPC), a viable substitute, are created from a combination of waste materials and industrial byproducts. GPC not only tackles environmental concerns by decreasing the use of natural resources and mitigating waste disposal problems, but it also provides exceptional durability and strength characteristics in comparison to traditional OPC concrete. By reacting alumino-silicate materials with very alkaline solutions chemically, a three-dimensional network of alumino-silicate polymers is created, which is the idea behind geo-polymerization. This approach eliminates the need for calcination of limestone, resulting in a considerable reduction in the carbon footprint connected with the manufacturing of OPC. Mostly aluminum-silicate raw materials and alkaline activator solutions make up GPC and geopolymer composites. Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF), Rice Husk Ash (RHA), and other industrial byproducts or waste materials rich in silica and alumina are common alumino-silicate source sources. Activating these materials and starting geo-polymerization requires alkaline solutions like potassium silicate (K_2SiO_3), potassium hydroxide (KOH), sodium silicate (Na_2SiO_3), or sodium hydroxide (NaOH). The mechanical properties, durability, and chemical resistance of GPC are superior to OPC concrete. The compressive strength of GPC may exhibit significant variations depending on parameters like as the kind and quantities of the source material. The key factors to consider are the materials used for activators, curing conditions, and mix design. Nevertheless, GPC demonstrates rapid initial strength growth and may attain compressive strengths that are equivalent to or above those of traditional OPC concrete. Combination of areca fiber (AF) and glass fibers (GF) with alkali treatment improved tensile, flexural, and impact properties, as well as wear resistance, compared to untreated fibers [1]. Fully biodegradable "green" composites by combining natural fibers with biodegradable resins can be used in various applications, including consumer products with short life cycles or products intended for one-time or short-term use [2]. Extracted cellulose exhibited unique physicochemical properties, making it a potential alternative source for reinforcing filler material in polymer composites [3]. High-quality wood Plastic Composites (WPCs) can be used as the natural fiber in the polymer matrices [4]. Aerial root fiber of *Ficus retusa* L. (FRL) can be used as an alternative to synthetic fibers in polymer composites reinforcement for its potential as a sustainable [5].

Moreover, GPC is recognized for its low permeability, resistance to acid and sulfate attacks, and ability to withstand extreme temperatures without degradation. These characteristics make GPC a suitable choice for various applications, including structural elements, precast components, pavements, and infrastructure projects, particularly in aggressive environments such as marine structures and nuclear power plants. The production of GPC involves several steps, including mixing the alumino-silicate source materials with alkaline activator solutions, along with fine and coarse aggregates. The mixing process is followed by casting and curing regimes, which can involve ambient, steam, or oven curing, depending on the desired properties and applications. The curing method plays a crucial role in the strength development and overall performance of GPC, as it facilitates the geo-polymerization process and the formation of the alumino silicate polymer network. As the construction industry continues to prioritize sustainability and environmental responsibility, the adoption of GPC as an alternative to conventional OPC concrete has gained significant attention. By utilizing industrial by-products and waste materials as source materials, GPC not only contributes to sustainable development by reducing the consumption of natural resources and minimizing waste disposal issues but also offers superior mechanical properties and durability, making it a promising material for a wide range of construction applications. Furthermore, the production of GPC does not involve the calcination process associated with OPC production, significantly reducing CO₂ emissions and contributing to the mitigation of greenhouse gas emissions. This environmental benefit, coupled with the exceptional performance characteristics of GPC, has driven extensive research and development efforts to optimize the production processes, explore alternative source materials, and expand the potential applications of this innovative concrete technology. As societies strive towards a more sustainable future, the construction industry plays pivotal role in reducing its environmental impact and embracing eco-

friendly practices. GPC represents a significant step in this direction, offering a viable solution that combines superior performance with environmental responsibility, paving the way for a cleaner and more sustainable construction industry.

Table 1. GPC vs OPC [6].

GPC	OPC
• High resistivity to chemicals	• Accountable to freeze and thawing cycling
• Suitable resistance to freezing and thawing	• Restricted methods to quicken strength gains
• It can with stand extreme temperature Without degrading.	• Capable of being attacked by low pH materials
• Modulus properties that the designer choose in a dynamic way.	• Extreme age degradation and carbonation when heated
• Set timings that are faster or slower	• Modulus traits that are difficult to modify but are classic
• Adapt able remedying methods for ultimate potency and timing	• Restricted to specific hours
• Provide insulation with an R-value equal to cellular material.	• Certain control on penetrability
• It has quite extensive air and water porosity.	• Restricted qualities

CONSTITUENT MATERIALS OF GPC

GPC is a composite material composed of two main constituents: alumino-silicate source materials and alkaline activator solutions. The careful selection and combination of these constituents play a crucial role in determining the properties and performance of the resulting GPC[7].

Alumino-Silicate Source Materials: The alumino-silicate source materials serve as the primary precursors for the geo-polymerization reaction and contribute to the formation of the binder in GPC. These materials are typically industrial by-products or waste materials rich in silica and alumina. Some commonly used alumino-silicate source materials include:

- FA is a substance that is produced when coal is burned in power plants. It is often utilized as a source material for GPC because it contains a high amount of silica and alumina.
- GGBS is widely used source material enhances the mechanical qualities of GPC and supplies calcium oxide. It is derived from the iron and steel sector.
- SF is a highly reactive pozzolanic substance; silica fume is a by-product of the manufacturing of silicon metal and may be added to GPC mixes to improve their strength and endurance.
- RHA is a by-product of burning rice husks. It is a pozzolanic substance that may enhance the mechanical and durability characteristics of GPC.
- Metakaolin is an additional cementitious material may be employed in GPC combinations as a source of alumina. It is made by calcining natural kaolin clay.

Alkaline activator solutions are essential for beginning and enhancing the geo-polymerization process. Typically, these solutions consist of chemicals derived from alkaline metals, such as sodium or potassium-based compounds. Typical alkaline activator solutions used in GPC manufacturing comprise:

- Na_2SiO_3 is a chemical that is created by mixing sodium oxide with silica. It is often employed as an activator in GPC because it has the capability to provide both alkali and silica components.
- NaOH, sometimes referred to as caustic soda, is a strong alkaline solution that efficiently activates alumino-silicate source materials.
- K_2SiO_3 is comparable to sodium silicate in that it has both alkali and silica components. This makes it a suitable activator for GPC synthesis.
- KOH is a chemical compound. Alumino-silicate compounds in GPC mixes may be activated by potassium hydroxide, another strong alkaline solution.

The alumino-silicate source materials and alkaline activator solutions are meticulously optimized in terms of selection and quantities to get the specific qualities and performance characteristics necessary for GPC. The reactivity, fineness, and particle size distribution of the source materials, along with the concentration and modulus of the activator solutions, are some of the key factors that affect the mechanical characteristics, workability, and durability of the final GPC. In addition, the use of added cementitious materials, such as lime stone powder or calcium-rich substances, may increase the characteristics and effectiveness of GPC by facilitating further chemical reactions and altering the microstructure of the geo-polymer binder. By meticulously choosing and blending the suitable alumino-silicate source materials and alkaline activator solutions, while also optimizing the mix design and curing conditions, one can customize the characteristics of GPC to meet specific application needs. This makes GPC a versatile and flexible material for different construction purposes.

By-Products Materials Source

According to Davidov its Geo-polymer is a result of Geo-polymerization process under which patchy silicate- alumino cementing material under goes the poly-condensation reaction with alkaline solution at mild temperature. In this process valuable product called GPC is produced by converting silicate-alumino into inorganic polymers. Figure 1 shows the particle size and specific surface area of the binder materials. In the subsequent sections various by-products with their chemical compositions and physical characteristics are discussed.

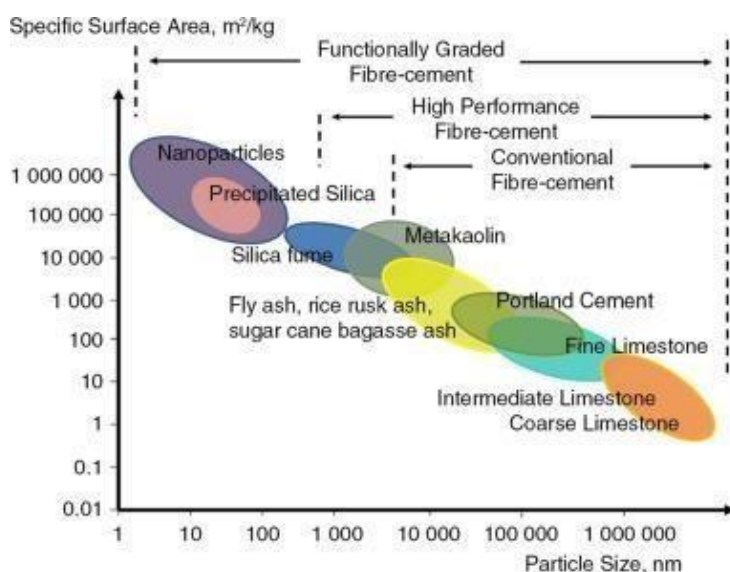


Figure 1. Particle Size and Specific Surface Area of Various Binder Materials [8].

Fly Ash

Coal industries produce FA as a by-product that is obtained by the combustion of coal at binder stations. It is a bituminous or anthracite by-product. During the coal combustion, fine particles that are blown out from boiler along with flue gases those results into the FA a “pulverized fuel ash”. In the construction of concrete, it is reliable to be used as a substitute of OPC. FA possesses high strength and durability properties, having less permeability, resistance to alkali- silica reaction and more service life and low cost as compared to OPC. Moreover, it can be poured readily. There is about 10%-20% content of iron oxide and lower than 5% content of calcium oxide by weight in FA. The particle size of FA is less than 50 μ m. FA is cheaper than OPC by the price variation of double cost. Its cost increases when it has to be shipped over long distances. It rarely affects the environment and is a sustainable by-product in place of OPC [9]. Due to having very small particle size, it increases the durability and frost resistance of GPC and lessens the permeability [17]. Table 2 presents the chemical composition of OPC and FA. Chemical composition of FA and OPC is represented in table 2 and Physical properties of FA are depicted in table 3.

Table 2. OPC and FA Chemical Compositions [11].

Material	Specific Surface	LOI (%)	IR (%)	Na ₂ O (%)	Fe ₂ O ₃ (%)	MgO (%)	SiO ₂ (%)	Al ₂ O ₃ (%)	CaO (%)	So ₃ (%)
Cement	4.51m ² /kg	1.65	0.76	0.14	2.66	0.36	19.33	5.66	63.07	3.38
FA	3.60m ² /kg	2.88	0.30	0.73	6.62	2.82	54.92	23.04	3.84	0.76

Table3. Physical Properties of FA [14].

Characteristic	Value
PH	8.40
Liquid Limit	32
Colour	Grey
Specific Gravity	2.15
Plasticity	Non-Plastic
Fineness Modulus	2.85

Silica Fume

The SF Association was founded in 1998 with the goal of encouraging SF manufacturers to increase their output levels so that it may be utilized in applications and endorsing SF for use in concrete. SF is a by-product of silicon metal or ferrosilicon alloy that is highly reactive to pozzolan. It is a basic substance that may be utilized to create high- performance concrete. Due to its physical, chemical, and mineralogical characteristics, including its stronger activity to pozzolan that may be created from natural or artificial resources, Silica Fume Ash (SFA) was also employed in concrete to replace 10–40% of OPC [9]. If the pozzolanic reactivity and chemical composition is accounted it is observed that amorphous silica is more reactive than crystalline silica. SFA contaminated concrete has high durability and strength properties. SF is basically non-crystalline i.e., amorphous silicon dioxide (SiO₂) and Particle size of SF is 1/100 of cement particle. SFA shows high pozzolanic reactivity due to having large surface area and presence of high SiO₂ content and fine particles. The standards for SFA quality are ASTM C 1240 (ASTM, 2012) and AASHTOM 307. When creating concrete, it can be applied either dryly or wetly. It is employed in the transportation sector in projects like the building of bridges and there orientation of existing buildings. [20][22]. Table 4 presents the chemical composition of silica fume and its physical properties are depicted in Table 5.

Table 4. SF Chemical Composition [15].

Constituent	Weight (%)
Na ₂ O	0.1
Fe ₂ O ₃	0.1-0.5
MgO	0.1-0.2
SiO ₂	92-94
CaO	0.1-0.15
K ₂ O	0.1
Carbon	3-5
MnO	0.008
Al ₂ O ₃	0.2-0.3

Table 5. Physical Properties of SF [16]

Characteristic	Value
Colour	Dark Grey
Specific Gravity	2.2
Fineness Modulus m ² /kg	20000
Bulk Density mg/m ³	2.247

Rice Husk Ash

RHA is produced by processing rice paddy within the volume of 20% to 25% and is used for power generation. It is a green by-product when used as GPC due to presence of sodium silicate particles when activated with alkaline solution produces new crystalline phase having high thermal stability and pozzolanic properties. It is used in nuclear power plants, marine environments and bridges due to having high strength and performance, low permeability. India export RHA by price of \$500 per ton to US which is far greater than selling prices of China [10]. RHA based GPC improves the workability of blended concrete and reduce the porosity by adjusting its pore configuration and has low permeability. It has high long-term compressive strength and mechanical properties. It has less water diffusion and less activated to sulphate attack [16]. The chemical composition and specifications of RHA are presented in table 6 and 7 respectively.

Table 6. RHA Chemical Composition [18]

Constituent	Weight (%)
Na ₂ O	0.1
Fe ₂ O ₃	0.21
MgO	0.53
SiO ₂	90.23
CaO	1.58
K ₂ O	0.39
Carbon	1.23
Al ₂ O ₃	3.54

Table 7. Technical Specifications of RHA [22].

Technical specifications	Percentage/Size/ Value
Colour	Grey
pH value	8
P	75 %minimum
Loss on ignition at 800°C	4 %maximum
Humidity	2 %maximum
Particle size	25microns(d50)

Ground Granulated Blast Furnace Slag

GGBS is obtained from the iron ore, coke and limestone mixture when fed under approximately 1500°C temperature under controlled conditions. The melted by-product contains about 30-40% of silicon dioxide (SiO₂) and calcium oxide (CaO) that is very similar to OPC. This mixture can be located easily in large volumes to produce GGBS. It can replace OPC to 35-70% and possess fine properties when combined with other materials forming GPC. Q 0 type glass particles have nano-silicates; present in GGBS make it dissolvable in any medium likewise OPC. This content also increases its volume by 85% of total volume having density in between 1200kg/m³ and 1300kg/m³ and specific gravity varies in between 2.7 to 2.9 that is lower than of OPC [11]. Table 8 represents the chemical composition of GGBS and physical properties of GGBS are represented in Table 9. GGBS has long term strength and capability to refine the pores. It also resists the alkali and sulphate effect and reduces the demand of water. It also lowers the effect of hydration like permeability and heat generation. GGBS influence the GPC characteristics matrix and can be added 5-50% of volume and activated at 27°C. When the aluminum and silicon particles of GGBS get activated by alkaline solution results into the GPC mixture and bind the aggregates. Upon increasing the percentage of GGBS results into the increase in resistance to acid, ultrasonic velocity and compressive strength of GPC mixture [18].

Table 8. Chemistry of GGBS [19].

Oxides	Quantities specified by ASTM, %	Quantities specified Practically, %
Iron Oxide, Fe ₂ O ₃	1.8	8-10
Silicon Dioxide, SiO ₂	40.0	30-35
sulfur, S	1.0-1.9	-
LOI	0.0	-
Manganese Oxide, MgO	3.6	7-9
Aluminum Oxide, Al ₂ O ₃	13.5	8-22
Sulfur ion, SO ₃	4	3-7

Table 9. Physical Properties of GGBS [19]

Characteristic	Value
pH	10.03
Liquid Limit	40
Colour	Whitish
Specific Gravity	2.84
Plasticity	Non-Plastic
Fineness modulus	4
Bulk Density (loose) kg/m ³	1480
Bulk Density (Compacted) kg/m ³	1695
Grading Zone	II
Consistency	31%

Fine Aggregates

Fine aggregates are obtained from the foundry sand and contribute in the production of GP Composites. It contributes 25% in the GPC mixture along with coarse aggregates. In the GPC mixture; it and coarse aggregates both contribute 25%. By using Bayer's production technology, the set in aggregates may be extracted from red mud sand quarries. It has high density sand, even fine particle size and highly responsive silica content. Table 10 shows the characteristics of fine aggregates [6].

Table 10. Properties of Fine Aggregates [19].

Characteristic Name	Value (Approximated)
Water adsorption (%)	1.02
Specific gravity	2.68
Fineness modulus	2.50
Grading zone	II
Type	Uncrushed (shape)

Coarse Aggregates

Sandstone, asphalt, tile, and other similar materials can all be used to make recycled coarse aggregates. It can substitute the natural coarse aggregates in the mixture of GPC by 15-50%. Extraction of natural coarse aggregates results in to the greenhouse effect. These coarse aggregates are also obtained from the construction and demolition wastes and upon recycling such wastes reduce the need of natural aggregates and minerals [13]. RCA shows 10% more compressive strength at 7 to 28 days when added to GPC with high molarity alkaline solution is mined from wastepaper slush instead of FA and slag. Upon examining the mechanical properties of RCA, it can replace 50-100% NCA. Table 11 shows the physical properties of coarse aggregates influenced by particle size distribution [20].

Table 11. Physical Properties of Coarse Aggregates [10]

Characteristic Name	Value (Approximated)
Compaction Factor	0.85-0.95

Absorption of the aggregates	~1%
Specific Gravity	2.5-2.80
Elongation Index	~28.72%
Bulk density	1550-1570kg/m ³

Alkaline Liquids System (ALS)

ALS for GPC serves as an activator solution that may be used in either a liquid or solid condition. Na_2CO_3 , NaOH , Na_2SO_4 and $\text{Na}_2\text{O} \cdot \text{Na}_2\text{Si}_2$ etc as presented in table 12 are some Alkaline activator solutions. These liquids work as a binder for GPC solution and enhance the durability properties and also resist the external effects. ALS contains mixture of alkaline metals like potassium or sodium to balance the alumina's negative charge. These alkaline liquids extract Al and Si atoms from them enrich by-product materials that behave like binder for GPC [10].

Table 12. Alkaline Liquids and pH Scale [21].

Typical alkaline liquids	H ⁺ concentration w.r.t. pure water	pH
Ammonia solution	0.0001	11
Liquid drain cleaner	0.0000001	14
Soapy water	0.00001	12
Bleach, oven cleaner	0.0001	13

CLEAN PRODUCTION OF GPC

One of the key advantages of GPC is its clean and environmentally friendly production process compared to traditional OPC concrete. GPC's manufacturing process adheres to the tenets of sustainable development by diminishing the use of natural resources, minimizing waste creation, and substantially cutting greenhouse gas emissions. The primary constituents of GPC are aluminosilicates materials, which are typically industrial by-products or waste materials rich in silica and alumina. Common source materials include FA from coal-fired power plants, GGBS from the iron and steel industry, SF from silicon metal production, and RHA from agricultural waste. By utilizing these by-products, GPC production effectively diverts waste materials from landfills, contributing to a circular economy and reducing the waste and demand for virgin raw materials. The production process of GPC begins with the mixing of the aluminosilicate source materials with highly alkaline activator solutions. These activator solutions, typically composed of compounds like Na_2SiO_3 , NaOH , K_2SiO_3 , KOH , initiate the Geo-polymerization process by dissolving the aluminosilicate materials and forming a binder capable of binding aggregates. Unlike OPC production, which involves the calcinations of limestone at high temperatures, releasing significant amounts of CO_2 , the production of GPC does not require this energy-intensive and emissions-intensive process. The Geo-polymerization reaction occurs at relatively low temperatures, significantly reducing the energy consumption and associated CO_2 emissions. Furthermore, the curing process for GPC can be carried out at ambient or moderately elevated temperatures, depending on the desired properties and applications. This flexibility in curing regimes allows for energy-efficient production and further contributes to the clean and sustainable nature of GPC. In addition to the environmental benefits, the clean production of GPC also offers economic advantages. By utilizing industrial by-products and waste materials as source materials, the production costs of GPC can be lower compared to OPC, which relies on the extraction and processing of virgin raw materials. The clean production of GPC is not limited to the raw materials and manufacturing process but also extends to the construction phase. GPC demonstrates exceptional longevity and resilience against chemical assaults, resulting in reduced requirements for regular upkeep and restoration. Consequently, this reduces the utilization of extra resources and the creation of building waste throughout the life span of structures. To further enhance the sustainability credentials of GPC, ongoing research efforts focus on exploring alternative and locally available source materials, optimizing mix designs, and developing advanced curing techniques. In conclusion, the clean production of geo-polymer concrete represents a significant step towards sustainable construction practices. Clean production of GPC is presented in Figure 2.

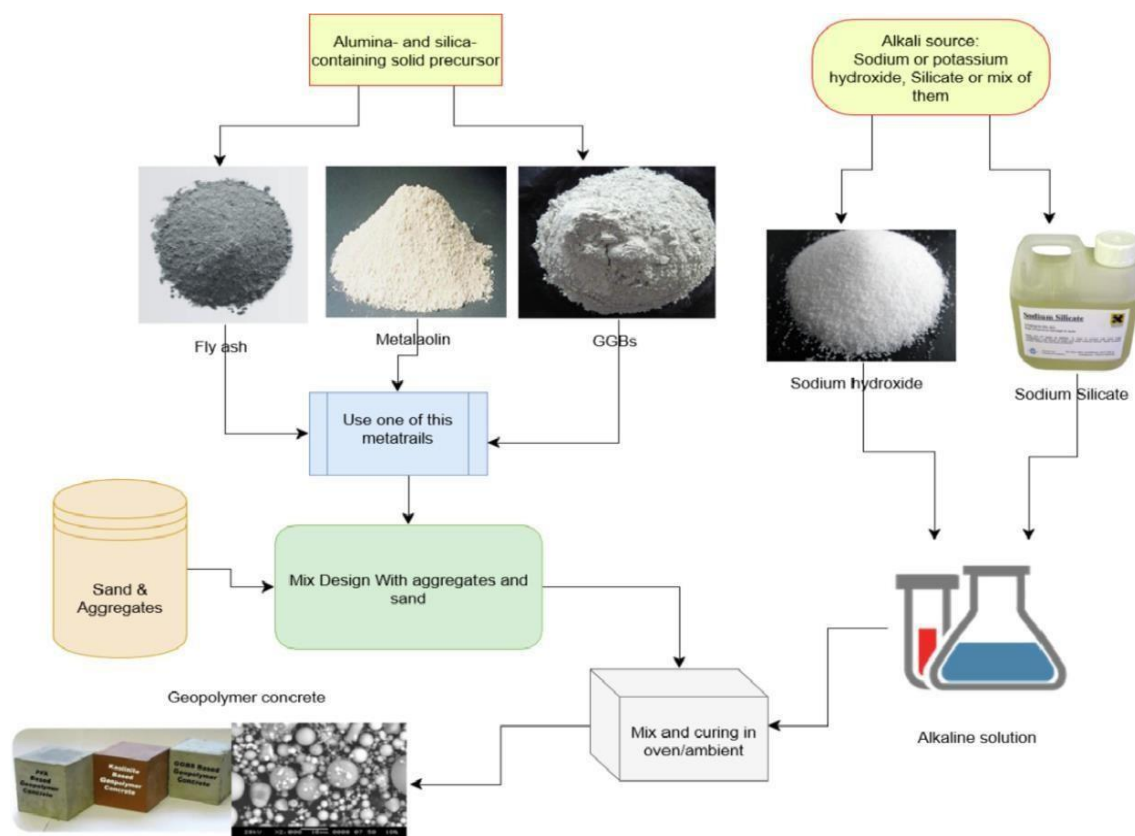


Figure 2. Components Employed in the Creation of GPC [14]

Composition of GPC

Geopolymer cement, which requires Al-Si precursor material for its manufacture, is needed to support the OPC. Al-Si precursor material mostly consists of Na or K soluble silicates with a molar ratio (MR) of 1.65 SiO₂ to M₂O. Blast furnace slag, which are largely a resource of calcium cations, are employed for materials that harden at room temperature. First alkali-activated FA-based GPC has to harden between 60 and 80 °C. The head hardened of FA-Based geopolymer would then be carried out at room temperature in the subsequent slag. The FA granules are then embedded inside this aqueous silicate solution [12][20].

Curing regimes of GPC

Furthermore, casting of specimens is performed and ambient curing is done. Then, it is kept aside for a day at room temperature of 20±3°C. Then slag is added to FA-based mixture to enhance the compressive strength. Then steam curing is performed in autoclaves with a temperature ranging from 160 °C to 190 °C and pressures of 0.55 to 1.70 MPa to make a concrete better in parametric substances, majorly, less shrinkage, no efflorescence, sulphate resistance etc. [15]. The technique of oven curing is applied in a hot air oven where the temperature lies between 40°C and 120⁰ C Cover 24 hours. Then the cubes are extracted from oven to get cooled at room temperature and the samples scattered in oven are collected for testing for improving the compressive strength of FA- based GPC. Besides, the curing has a critical role in development of strength of GPC [9] [10].

Fresh properties of GPC

It is also imperative to get know-how on fresh GPC properties that primarily includes, setting time, deformability, stability, workability and compatibility. As per the guidelines issued by EFNARC, the limited values of fresh GPC tests have been calculated and these tested values are presented in table 13 [17].

Table13. Limited Results of Recent GPC Testing in Accordance with the EFNARC Recommendation [23]

Typical tests	Units	Maximum Value	Minimum Value
V-funnel	Second	12	8
J-ring	Mm	10	0
Slump flow	Mm	800	650
U-box	H2/H1	30	0
L-box	H2/H1	1.0	0.8
T50 cm slump flow	Second	5	2

The term stability refers to capability that a material possesses to maintain its structure and original formation while various influences are impacting it such as environmental impacts. The word "compatible" refers to how different mix design elements interact with chemical admixtures. Setting time is a crucial factor, as the start and ultimate setting durations of various materials vary. For instance, the beginning setting time for geo-polymer mortar is 35 minutes, while the ultimate setting time is 600 minutes. Alkali activated FA samples have a 5–7 minute initial setting time, which can increase to 20–40 minutes. Workability, as stated by, is a measurement of the additional water in GPC. For the calculation of stresses and strains, structural deflections, and the creation of constitutive models for simulations, deformability is a crucial metric. Like-wise, there are some mechanical properties that primarily include the terms splitting tensile and flexural strengths, compressive, stress–strain behavior, rate of strength development and Modulus of Elasticity (Moe). The compressive strength of a material inculcates several parameters like curing time, particles size, curing temperature, wet-mixing time, and some additives are added such as $Al(OH)_3$ etc. The splitting tensile strength is brittle and is a characteristic of concrete and cannot withstand tension. The self-compacting concrete has an STS of approximately 30% more in comparison to normal concrete. The term Modulus of elasticity being interrelated with the term compressive strength, dictates that high degree of geo-polymerization can result in higher. Stress-Strain behavior is an important mechanical property that carries the capability of categorizing the performance of GPC material and is dependent upon type of concrete and confinement used. The mechanical property strength development rate depends upon parameters such as the alkaline activators, the curing conditions, chemical composition of source materials etc. [22].

COMPRESSIVE STRENGTH OF GPC

The compressive strength of geopolymer Concretes Composites can vary widely depending on factors such as the type of binder materials, activators used, curing conditions, mix proportions, and curing time. However, geo-polymer Concrete Composites generally exhibits high early-age strength development and can achieve compressive strengths comparable to or even higher than conventional Portland cement concrete. Table 14 to 17 shows the results of compressive strength of OPC and GPC using various admixture under simple and heat curing for M40 and M50 grades.

Table 14. Compressive Strength Findings of M40 paver blocks with 100% Replacement of OPC.

Sr. No.	Mix	28 Days Compressive Strength (Normal Curing) (N/mm ²)	28 Days Compressive Strength (Heat Curing) (N/mm ²)
M1	NOMINAL MIX	48.94	47.5
M2	GBS-100%	18.11	21.01
M3	SF-100%	16.85	19.84
M4	FA-100%	10.22	12.27
M5	RHA-100%	8.02	10.47

Table 14 presents data on the compressive strength after 28 days of different concrete mixes for M40 grade concrete under normal curing and heat curing conditions. M1 mix represents the reference mix, likely consisting of OPC fine aggregate, coarse aggregate, and water. Under normal curing conditions,

this mix achieved a 28-day compressive strength of 48.94 MPa, while under heat curing conditions; it achieved a slightly lower strength of 47.5 MPa. M2 mix is composed of 100% GGBS. Under normal curing conditions, this mix achieved a compressive strength of 18.11 MPa after 28 days, while under heat curing conditions; it exhibited a higher strength of 21.01 MPa. M3 mix is composed of 100% SF and achieved a compressive strength of 16.8567 MPa under normal curing conditions where as a higher strength of 19.8467 MPa under heat curing conditions after 28 days. M4 mix is composed of 100% FA and had a compressive strength of 10.2267 MPa under normal curing conditions whereas a higher strength of 12.27 MPa under heat curing conditions after 28 days. M5 mix consists of 100% RHA. This mix exhibited the lowest compressive strength among the mixes, with 8.0267 MPa under normal curing conditions and a higher strength of 10.47 MPa under heat curing conditions after 28 days. Figure 4 shows its graphical illustration.

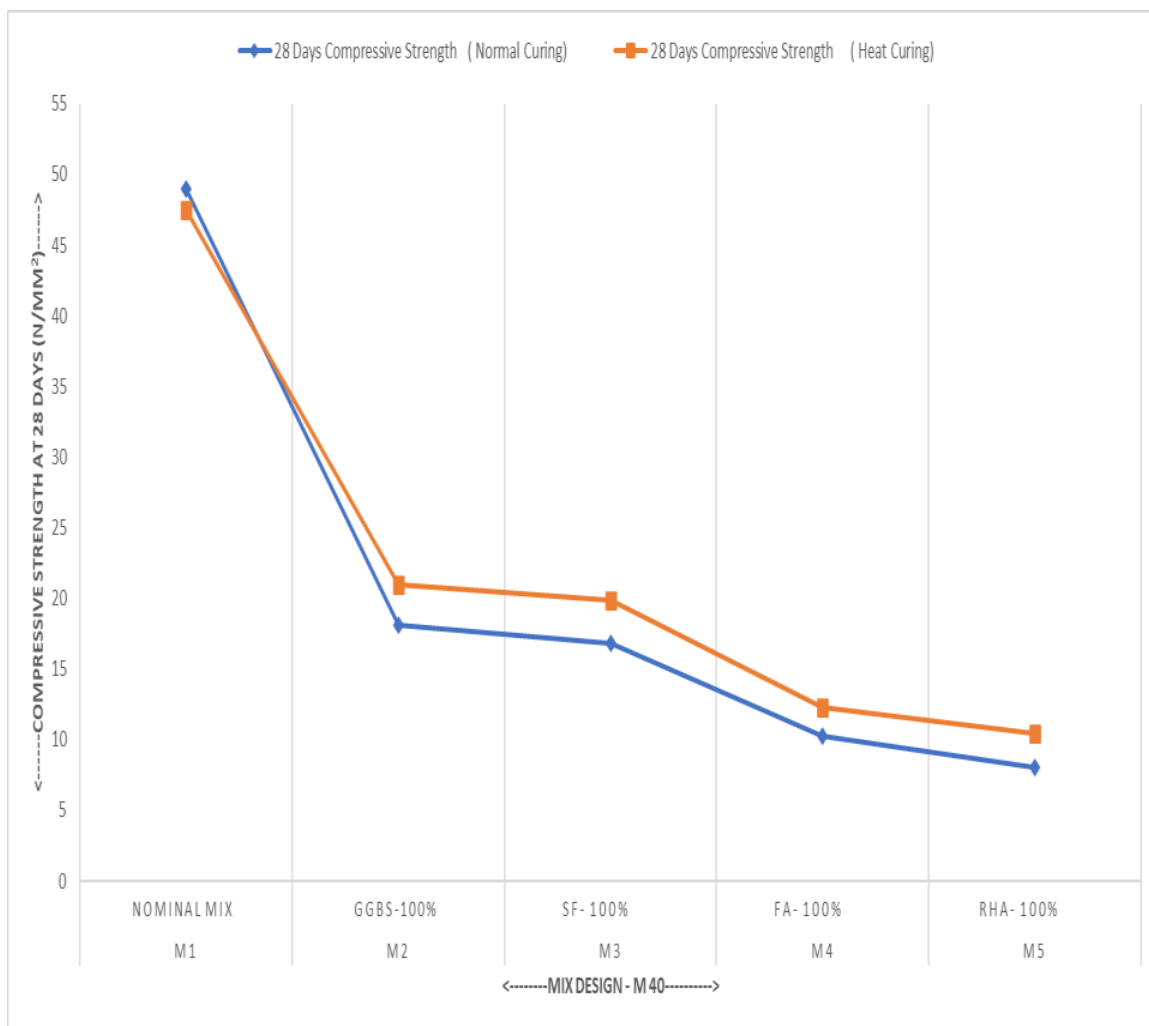


Figure 3. Compressive Strength Findings of M50 paver blocks with 100% Replacement of OPC

Figure 3 illustrates the influence of various extra cementitious ingredients on the compressive strength of concrete mixtures. It is evident that the nominal mix (M1) achieved the highest compressive strength under normal curing conditions, while the mixes containing supplementary materials (M2 to M5) exhibited lower strengths. However, under heat curing conditions, the compressive strengths of the supplementary material mixes generally increased, with GGBS (M2) showing the most significant improvement. It is important to take in to account other variables, including as mix proportions, curing conditions, and testing methodologies, when interpreting these findings, since these might affect the compressive strength of concrete.

Table 15. Compressive Strength Finding so fM50 paver blocks with 100% Replacement of OPC.

S. N.	MIX	28 Days Compressive Strength (Normal Curing) (N/mm ²)	28 Days Compressive Strength (Heat Curing) (N/mm ²)
M6	NOMINAL MIX	54.14	59.27
M7	GGBS-100%	23.01	28.22
M8	SF-100%	21.7633	24.3233
M9	FA-100%	11.5267	11.62
M10	RHA-100%	9.3267	9.82

Table 15 presents data on the compressive strength of several concrete mixes for M50 grade concrete under normal curing and heat curing conditions after 28 days. M 6 represents the reference mix for M 50 grade concrete, likely consisting of OPC, fine aggregate, coarse aggregate, and water. Under normal curing conditions, this mix achieved a compressive strength of 54.14 MPa, while under heat curing conditions; it achieved a higher strength of 59.27 Mpa after 28 days. M 7 mix is composed of 100% GGBS where under normal curing conditions, the GGBS mix achieved a compressive strength of 23.01 MPa, while under heat curing conditions, it exhibited a higher strength of 28.22 Mpa after 28 days. M 8 mix consisted of 100% SF and achieved a 28-day compressive strength of 21.7633 MPa under normal curing conditions whereas a higher strength of 24.3233 MPa under heat curing conditions. M 9 mix consists of 100% FA and had a compressive strength of 11.5267 MPa under normal curing conditions whereas a slightly higher strength of 11.62 MPa under heat curing conditions after 28 days. M 10 mix composed of 100% RHA. This mix exhibited the lowest compressive strength among the mixes, with 9.3267 MPa under normal curing conditions and a slightly higher strength of 9.82 MPa under heat curing conditions after 28 days. Figure 4 depicts its graphical presentation.

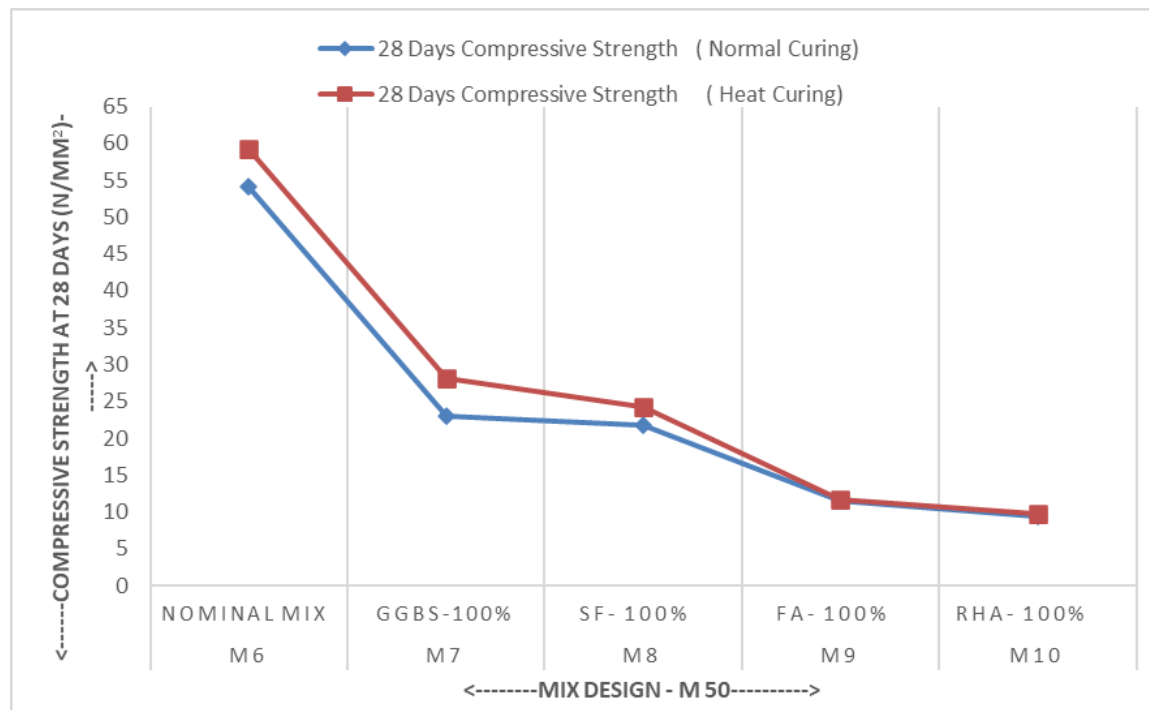
**Figure 4. Compressive Strength Findings of M 50 paver blocks with 100% Replacement of OPC**

Figure 4 illustrates the influence of various extra cementitious ingredients on the compressive strength of M50 grade concrete mixtures. The nominal mix (M6) demonstrated greater compressive strength under both normal and heat curing conditions, while the mixes containing supplementary

materials (M 7 to M 10) exhibited lower strengths. It is noteworthy that the M 50 grade mixes compressive strength is generally higher than those reported in the previous graph, which is expected due to the higher grade of concrete. Other variables, such as mix proportions, curing conditions, and testing procedures, which may affect the compressive strength of concrete, should be taken in to account when interpreting these findings.

Table 16. 40% GP Composites and 60% OPC M40 paver blocks Compressive Strength.

SR.NO.	MIX	28 Days Compressive Strength (Normal Curing) (N/mm ²)	28 Days Compressive Strength (Heat Curing) (N/mm ²)
M11	GGBS-40%, CEMENT 60%	41.3	45.54
M12	SF-40%, CEMENT 60%	33.4	39.3
M13	FA-40%, CEMENT 60%	27.7	33.3
M14	RHA-40%, CEMENT 60%	19.3	25.4

Table 16 presents data on compressive strength of several concrete mixes for M 40 grade concrete under normal curing and heat curing conditions after 28 days. M 11 mix is a combination of 40% GGBS and 60% OPC. Under normal curing conditions, this mix achieved a 28-day compressive strength of 41.3 MPa, while under heat curing conditions; it achieved a higher strength of 45.54 MPa. M 12 mix consists of 40% SF and 60% OPC. This mix achieved a compressive strength of 33.4 MPa under normal curing conditions and a higher strength of 39.3 MPa under heat curing conditions after 28 days. M13 mix is a combination of 40% FA and 60% OPC. The mix had compressive strength of 27.7 MPa under normal curing conditions and a higher strength of 33.3 MPa under heat curing conditions after 28 day. M14 mix consists of 40% RHA and 60% OPC. This mix exhibited the lowest compressive strength among the mixes, with 19.3 MPa under normal curing conditions and a higher strength of 25.4 MPa under heat curing conditions after 28 days. Graphical presentation is shown in Figure 5.

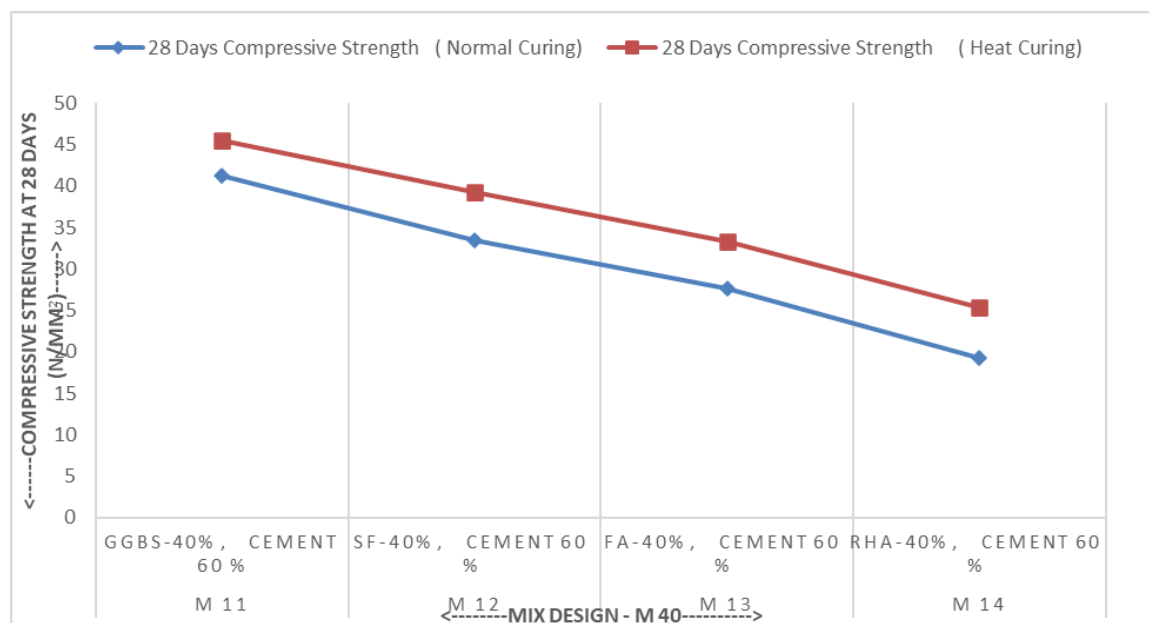


Figure 5. 40% GP Composites and 60% OPC M40 paver blocks Compressive Strength.

Figure 5 illustrates the influence of integrating various extra cementitious materials with OPC on the compressive strength of M40 grade concrete mixtures. The GGBS (M11) mixture had the maximum

compressive strength when subjected to both normal and heat curing conditions. It was followed by the mixtures including SF (M12), FA (M13), and RHA (M14), in that order. The use of supplemental cementitious materials consistently led to reduced compressive strengths. Never the less, the heat curing conditions resulted in arise in compressive strength for all mixtures. Other variables, such as mix proportions, curing conditions, and testing procedures, which may affect the compressive strength of concrete, should be taken into account when interpreting these findings.

Table 17. 40% GP composites and 60% OPC M50 paver blocks Compressive Strength.

SR NO.	MIX	28 Days Compressive Strength (Normal Curing) (N/mm ²)	28 Days Compressive Strength (Heat Curing) (N/mm ²)
M15	GGBS-40%, CEMENT 60%	52.8	57.67
M16	SF-40%, CEMENT 60%	41.4	45.2
M17	FA-40%, CEMENT 60%	33.3	42.5
M18	RHA-40%, CEMENT 60%	25.1	34.3

Table 17 displays data on the compressive strength of several concrete mixes for M50 grade concrete, comparing normal curing and heat curing conditions after 28 days. M 15 concrete mixture consists of 40% GGB Sand 60% cement. Under typical curing circumstances, this mixture attained a compressive strength of 52.8 MPa after 28 days. However, when subjected to heat curing conditions, it exhibited a greater strength of 57.67 MPa. M16 is a mixture consisting of 40% SF and 60% OPC and exhibits compressive strength of 41.4 under normal curing conditions and a greater strength of 45.2 MPa with heat curing. M17 mixture consists of 40% FA and 60% cement. The FA mixture exhibited compressive strength of 33.3 MPa after 28 days of curing under normal circumstances, and notably higher strength of 42.5 MPa when subjected to heat curing. M18 mixture consists of 40% RHA and 60% cement. The RHA mix exhibited the lowest compressive strength among the mixes, with 25.1 MPa under normal curing conditions and a higher strength of 34.3 MPa under heat curing conditions after 28 days. Figure 6 presents its graphical illustrations.

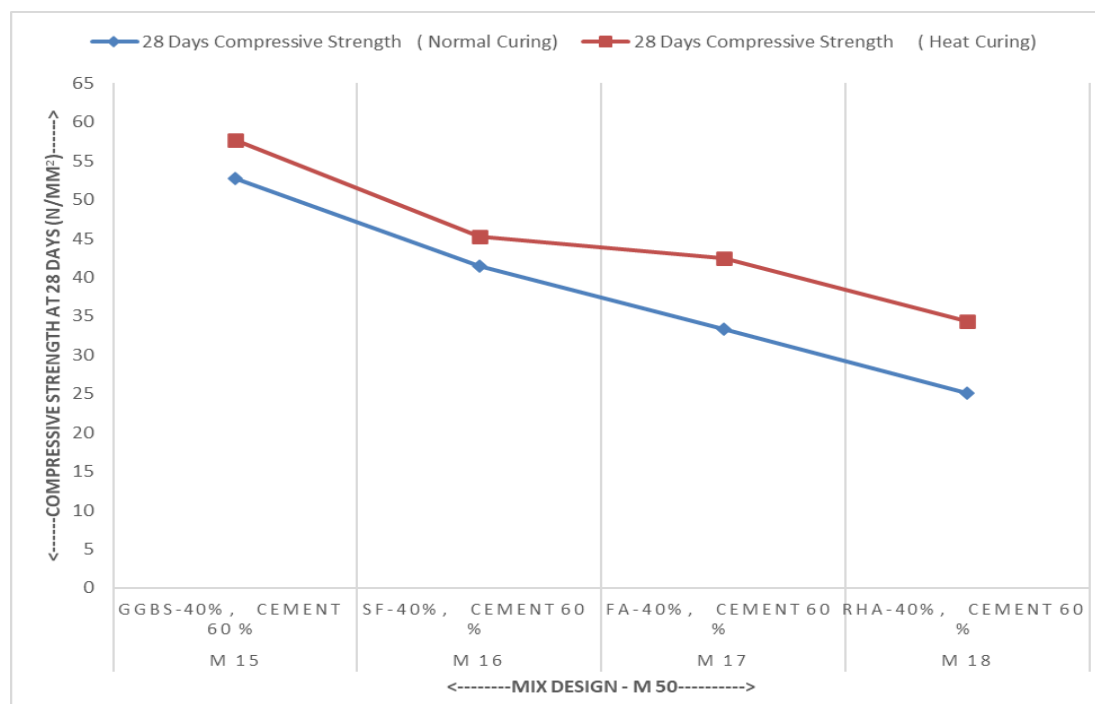


Figure 6. 40 % GP composites and 60% OPC M50 Paver Blocks Compressive Strength.

Figure 6 illustrates the influence of integrating various extra cementitious ingredients with conventional Portland cement on the M50 grade concrete mixtures compressive strength. The mixture including GGBS with a strength grade of M15 exhibited the maximum compressive strength when subjected to both normal and heat curing conditions. It was followed by the mixtures containing SF (M16), FA (M17), and RHA (M18) in descending order of strength. The compressive strength values for the M50 grade mixes are consistently greater than those reported for the M40 grade mixes, as predicted owing to the superior quality of the concrete. Under the heat curing circumstances, all mixtures exhibited a significant rise in compressive strength when compared to the standard curing conditions. When analyzing these data, it is important to take into account other considerations.

CONCLUSION

In brief, the geopolymer composite is a very promising and sustainable substitute for traditional OPC concrete. It has exceptional mechanical qualities, durability, and environmental advantages. GPC decreases the use of natural resources and addresses waste disposal problems by using industrial by-products such as FA, GGBS, SF and RHA as aluminosilicate source materials. Moreover, the manufacturing technique obviates the need of calcination, hence substantially decreasing the CO₂ emissions linked to OPC production, making GPC a more ecologically sustainable alternative. The compressive strength of GPC is a vital mechanical characteristic that has been shown to be equivalent to or greater than that of OPC concrete in several research investigations and mixture compositions. The paper shows the influence of various source materials and curing methods on the strength progression of GPC, as shown by the compressive strength data. The M40 grade concrete, when cured under normal conditions, attained a compressive strength of 48.94 MPa using the nominal OPC mix after 28 days. However, when 100% replacements of GGBS, SF, FA, and RHA were used in the mix, the resulting strengths were lower at 18.11, 16.86, 10.23, and 8.03 MPa, respectively. Nevertheless, the compressive strengths of these mixtures often rose when exposed to heat curing, with the GGBS mix displaying the greatest strength of 21.01 MPa among the 100% replacements. For M50 grade concrete, the nominal OPC mix achieved a compressive strength of 54.14 MPa with regular curing and 59.27 MPa with heat curing after 28 days. Similarly, the mixes that consisted of 100% GGBS, SF, FA, and RHA exhibited decreased strengths compared to the nominal mix under both curing regimes. Remarkably, when adding 40% supplementary materials along with 60% OPC for M40 grade, the GGBS mix attained the highest 28-day compressive strength of 41.3 MPa during regular curing and 45.54 MPa during heat curing. The mixes containing SF, FA and RHA followed in terms of strength. Comparable patterns were seen for the M50 grade mixtures. These findings highlight the capacity of GPC to attain significant compressive strengths, especially when GGBS is used as a partial substitute for OPC or in conjunction with OPC. The curing regimen also has a pivotal influence in the development of strength, since heat curing often yields greater compressive strengths in comparison to regular curing circumstances. GPC compressive strength is impacted by many elements, including as the type and quantities of source materials, the composition and concentration of the alkaline activator solutions, curing conditions, and mix design parameters. It is crucial to consider these aspects when evaluating the compressive strength of GPC. Hence, it is important to thoroughly evaluate and enhance these aspects in order to get the ideal levels of strength and performance for certain applications. GPC, apart from its mechanical characteristics, has other benefits like enhanced durability, heightened resistance to chemical assaults, and reduced permeability in comparison to OPC concrete. With the equalities, GPC is a good option for a range of applications, including precast parts, pavements, and infrastructure projects. It is well suited for harsh settings like nuclear power plants and maritime constructions. Geopolymer composites provide a promising and eco-friendly alternative to traditional OPC concrete. They have the potential to completely transform the building sector because of their better mechanical qualities, durability, and sustainability credentials.

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