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AN EXPERIMENTAL APPROACH ON THE INFLUENCE OF ADDITIION OF METAKAOLIN ON THE PROPERTIES OF GEOPOLYMER CONCRETE

Prof. Shaikh K.S. 1,
Pachkar S. S. 2,
Khan S. A. 3,
Shaikh F. S. 4,
Sayyed H. A. 5
1UG Guide , 2,3,4,5,UG Scholar
Department of Civil Engineering,VACOE, Ahilyanagar.
SPPU Pune, Maharashtra, India.

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Abstract

Geopolymer concrete (GPC) is an innovative alternative to conventional Portland cement concrete, utilizing industrial by-products such as fly ash, slag, and metakaolin as primary binders. The use of metakaolin, a dehydroxylated clay, as an additive in geopolymer concrete has garnered significant attention due to its potential to enhance the mechanical and durability properties of the material. This experimental study investigates the influence of metakaolin addition on the properties of geopolymer concrete, focusing on workability, compressive strength, Split tensile strength, and durability performance.

A series of geopolymer concrete mixes were prepared by varying the percentage of metakaolin (ranging from 20% to 100%) by weight of the binder. Sodium hydroxide (NaOH) and sodium silicate (Na2SiO3) were used as alkaline activators to synthesize the geopolymer paste. The fresh properties of the concrete, including workability and setting time, were assessed using standard test methods. Cured specimens were tested at different ages (7, 14, and 28 days) to evaluate their compressive strength, split tensile strength.

The experimental results revealed that the incorporation of metakaolin significantly improved the mechanical properties of geopolymer concrete, especially in terms of compressive and split tensile strength. The optimal metakaolin content was found to be around 80%, beyond which the strength gains plateaued or slightly decreased. The microstructural analysis indicated a denser and more cohesive gel matrix in metakaolin-blended samples, which enhanced the overall durability of the geopolymer concrete, including resistance to water absorption and chloride ion penetration.This study highlights the potential of metakaolin as an effective supplementary material to enhance the properties of geopolymer concrete, thus providing a more sustainable alternative to traditional cement-based concrete. The findings suggest that metakaolin not only improves the mechanical performance but also contributes to the environmental sustainability of geopolymer concrete by reducing the carbon footprint associated with cement production.

Keywords: Geopolymer Concrete, Metakaolin, Mechanical Properties, Durability, Sustainability, Alkaline Activators.

INTRODUCTION

In today's construction industry, the research community is actively pursuing low-carbon technologies and environmentally friendly products to support sustainable development. Ordinary Portland cement (OPC) manufacturing is a significant contributor to energy consumption and greenhouse gas emissions, releasing a substantial amount of CO2 during production (Maholtra, 2002). Roughly seven percent of global CO2 emissions result from the clinker process in OPC production, a major driver of climate change (Shi, et al., 2011). To mitigate this impact, researchers have extensively explored alternative low-carbon cementing binders. These alternatives seek to harness abundant alumina-silicate (pozzolanic) waste materials from industries, such as fly ash (Chindaprasirt, et al., 2007), bottom ash (Hardjito & Fung, 2010), cement kiln dust (Khater, 2012), silica fume (Nuruddin, et al., 2011b), and GBFS (Nath & Sarker, 2012). Alumina-silicate materials, particularly fly ash, have emerged as primary candidates for producing sustainable cement-based concrete. Researchers have also investigated partial or total replacement of these pozzolanic by-products to reduce OPC consumption (Komnitsas & Zaharaki, 2007). Additionally, alumina-silicate materials can be activated by alkaline solutions to create a cementitious binder known as alkaline-activated cement or "Geopolymer cement" (Al Bakri, et al., 2011a).

The term "Geopolymers," introduced by Joseph Davidovits in 1979, has gained significant attention as an alternative binder for construction materials (Alonso, et al., 2011; Davidovits, 1991). Geopolymers offer diverse properties and characteristics, including cost savings and reduced environmental impact (Duxson, et al., 2007a). Geopolymer cement (GP) production involves mixing alkaline solutions with raw materials to form a homogeneous slurry. Curing conditions, particularly heat curing above ambient temperatures (approximately 40 to 90°C for 6 to 48 hours), accelerate the geopolymeric reaction and enhance mechanical properties. Following heat curing, geopolymers are further cured at room temperature (Chindaprasirt, et al., 2007). Geopolymer cement's properties, tested according to OPC standards, are comparable to or even surpass those of OPC. Substituting OPC with alumina-silicate waste not only reduces costs but also decreases environmental impact, with up to 9% less CO2 emission compared to OPC binders (Turner & Collins, 2013). In the construction sector, geopolymers are produced using industrial by-products or wastes. Fly ash, a by-product of coal-fired power plants, is widely used due to its alumina-silica composition and abundance (Nath & Sarker, 2015).Numerous research papers have investigated curing conditions and their effects on geopolymer properties. Initial findings reveal that fly ash-based geopolymer cement exhibits slow strength development under ambient curing conditions (Deevasan & Ranganath, 2010), while higher strength and improved mechanical properties are observed with elevated temperature curing (e.g., in ovens) for specific durations (Raijiwala & Patil, 2010). Overcoming the limitations of heat curing, especially for precast components, is a significant challenge. To address this challenge, efforts are directed toward developing ambient-cured geopolymers that achieve reasonable strength. These efforts include using finely ground prime materials (Chindaprasirt, et al., 2010; Somna, et al., 2011), applying additional heat from various sources, or incorporating more calcium content into geopolymer mixtures (Khater, 2011; Suwan & Fan, 2014). Developing ambient-cured geopolymer cement aims not only to enable commercial viability and on-site applications but also to enhance energy efficiency and economic considerations

LITERATURE REVIEW

Mohammad Zuaiter, Hilal El-Hassan, T. El-Maaddawy, (2022): This study investigated the effects of four factors on the workability, 1- and 7-day compressive strength, and 7-day splitting tensile strength of slag-fly ash blended geopolymer concrete: additional water content, glass fibers addition, glass fiber length, and handling time.

M.Narmatha and Dr.T.Felixkala (2017):conducted the test on concrete specimens with 5, 10, 15, 20, 25% replacement of cement by metakoline and fly ash for all mix 10%.The addition of fly ash in concrete improves certain properties such as workability, later age strength development and few durability characteristics. Concrete is the high volume of fly ash and metakaolin as a partial replacement of ordinary Portland cement .The conventional concrete M60 was made using OPC 53 with metakaolin and fly ash. To evaluate optimize ratio and mechanical properties of metakaolinbased on concrete and compare with conventional mix .From the optimization 20% cement replacement by metakaolin superior than all the mixes.

A.R.R. Kalaiyarrasi(2017): The objective of this research is to synthesizeMK based GP concrete, by replacing FA in GP by MK in 25, 50, 75% and test for strength and durability. Three MK samples with Si/Al mass ratio of 0.87(M1), 1.11(M2), 1.21(M3) have been used in this research. Study of Micro structural property of MK based GP using Fourier Transform Infra-Red Spectroscopy (FTIR), Electron Dispersive Spectroscopy (EDS) and Scanning Electron Microscopy (SEM) techniques has been carried out. Evaluation of axial compressive strength of MK geopolymer brick masonry (MKBP) with aspect ratio between 2 and 5 has been done and compared with the compressive strength and Elastic modulus of Clay Brick Prism (CBP).

Prakash R. Voraa, Urmil V. Dave(2016)has evaluated that use of pozzolona materials in the place of cement has enhanced the performance of concrete. Around 20 GPC mix proportions have been casted and were tested to evaluate the mechanical properties and efficiency of Geo Polymer Concrete. Parameters such as solid to alkaline liquid ratio,Alkaline liquid ratio,period of curing,type of curing and percentage of super plasticizer has been considered for variation to study the properties of concrete. Also has been concluded that naphthalene based super plasticiser improves the workability of fresh geopolymer concrete. It was further observed that the water content in the geopolymer concrete mix plays significant role in achieving the desired compressive strength.

Siti Noorbaini Sarmin(2016) has reported on the properties of fly ash/metakaolin-based geopolymer lightweight foamed concrete with inclusion of wood particles. Class F fly ash and metakaolin was mixed with an alkaline activator solution (a mixture of sodium silicate; Na2SiO3 and sodium hydroxide; NaOH), and hydrogen peroxide; H2O2 was added to the geo polymeric mixture to produce lightweight foamed concrete. The NaOH solution was prepared by dilute NaOH pellets with distilled water. The ratio of fly ash/metakaolin and alkaline activator used was 2.5:1.0 with addition of 0%, 10%, 20% and 30% of wood particles by volume of the total mix. The reactive were mixed to produce a homogenous mixture sized 50mm and cured at two different curing temperatures (80oC for 24 hours and room temperature for seven days). experiments were set up in accordance with International standard methods of testing. In reference to the analysis and discussion, the integration of fly ash/metakaolin and wood particles enhanced the properties of the lightweight foamed concrete. The results showed that the samples which were cured at 80oC produced the maximum compressive strength, (5.71 MPa, 10.2 MPa, 7.62 MPa and 6.3 MPa) for 0%, 10%, 20% and 30% of wood particles respectively. The oven-dry density of samples cured at 80oC was greater than room temperature curing. Heat curing which caused the geo polymerization rate to increase, producing a denser matrix.

Anil Ronad et al., (2016),: In their research work the author has attempted to study the behavior of geopolymer concrete along with addition of basalt fiber on the mechanical properties of geopolymer concrete. In this work the author had used flyash and ground granulated blast furnace slag induced geopolymer concrete. The author has used here 10M concentration of sodium hydroxide solution as an alkali activator in the for of binder and also used sodium silicate to sodium hydroxide ratio of 2.5 for preparation of specimen blocks. Then after the mix done basalt fiber was introduced as an additive in range of 0 to 2.5% at a increment of 0.5% per batch. The specimen prepared was cured for 7 and 28 days. Then the specimen was tested for compression test and split tensile strength. It was found that the basalt fiber induced geopolymer concrete has attained optimum strengths at 2% of fiberratio[16]. Beyond this the strength showed a decline.

YasirSofi and Iftekar Gull (2015) The investigator in this research work had prepared M20 grade of geopolymer concrete with a nominal mix using fly ash. The author has changed the alkali activated binder solution proportion of the mix from 0.3 –0.45. Under these parameters the concrete was tested for compressive strength flexural strength and tensile strength. During the experimental investigation it was seen that the strength characteristics have changed appropriately with increase in alkali activated solution ratio till it reached an optimum value. It was further seen that with higher ratio of solution the strength value go on decreasing.

Sreenivasulu et al., (2015) In this paper the authors have tried to present research work on geopolymer concrete using granite slurryby replacing the sand. The granite slurry was replaced at various levels of 20%, 40%,60%. Geopolymer concrete so developed was composed of fly ash and ground granulated blast furnace slag with a binder material of sodium hydroxide solution having concentration of 8M. The binder ratio of sodium hydroxide and sodium silicate was taken as 2.5. Samples were prepared and tested for compression test and split tensile test at curing period of 7, 28, 90 days. The results have shown that geopolymer concrete gives better response when replaced with granite slurry up to 40%. Beyond this limit the concrete shows decreasing results.

PrasannaVenkatesanRamani et al., (2015) the authors through this paper have given remarks in strength and durability properties if geopolymer concrete where ground granulated blast furnace and black rice husk ash was used. For binder alkali solution of sodium hydroxide of 8M concentration is used and the alkali activator ratio of sodium hydroxide and sodium silicate is 2.5. Three various mixes of geopolymer concrete was prepared. The samples were oven dried at 60 °C and cured for 8hrs at room temperature. These specimens were tested for compression, split tensile, flexural, rapid chloride penetration test, accelerated corrosion test. The results shown that use of black rice husk ash upto 10% shows better results and effective against chloride penetration and corrosion resistance. Black rice husk ash 20% and 30% does not give any such satisfactory results.

P. K. Jamdade and U. R. Kawade (2014) in this paper the authors have investigated on effect of curing on strength parameters. The authors have used fly ash by replacing cement completely. The sodium hydroxide solution was used with the concentration of 15molarity and the alkaline activator solution ratio was at 2.5. Specimens were prepared and curing was done in various temperature ranges of 60 degree Celsius, 90 degree Celsius and 120 degree Celsius with 12 hours and 24 hours duration period. Compressive strength split tensile and flexural strength were carried out to determine the quality of geopolymer concrete. The author have shown here that geopolymer concrete givess good early strength in minimum period of curing. It was further seen that more curing period leads to improve the polymerization process in geopolymer concrete which ultimately will result in a better version of concrete.

AryaAravind and Mathews M Paul (2014) In this research work the researcher had studied behavior of geopolymer concrete on mechanical properties when they are infused with steel fibres. The geopolymer concrete was prepared with alkaline solution of sodium hydroxide with a concentration of 10 molarity. The sample was oven cured for 24 hours at 60 degree Celsius and 90 degree Celsius and then was cured at room temperature for three days. The sample was varied withsteel fibre ratio of 0, 0.5 and 1. The ratio of fly ash to alkaline solution was also varied from 0.3 to 0.4. The sample was tested under compressive strength split tensile strength. The results have shown that increase in sodium hydroxide solution the strength of concrete has increased. It has also been observed that infusion of steel fibres have improved the crack width pattern in geopolymer concrete.

III OBJECTIVES OF INVESTIGATION

.To determine the compressive strength, split tensile strength of fly ash/metakaolin based geopolymer concrete at various ages and also perform Rebound Hammer test..

- To study the use of industrial waste in cement as additive gives a solution to disposal problem.
- To assess the strength and durability properties of geo-polymer concrete developed.

IV. MATERIALS

1. Fly-Ash:

Fly ash is a fine, powdery residue that is produced when coal is burned in power plants. It is a pozzolanic material, which means that it can react with alkaline solutions to form a cementitious material. Fly ash is used in a variety of applications, including geopolymer concrete.

In geopolymer concrete, fly ash is activated with an alkaline solution, such as sodium hydroxide or sodium silicate. This reaction causes the fly ash to form a gel-like matrix that binds the aggregate particles together. The resulting concrete has properties that are similar to Portland cement concrete, but it is also more durable and environmentally friendly.

The compressive strength of fly ash geopolymer concrete is typically lower than that of Portland cement concrete, but it can be increased by using a higher concentration of fly ash or by adding other materials, such as silica fume. The density of fly ash geopolymer concrete is also lower than that of Portland cement concrete, but this can be an advantage in some applications, such as lightweight concrete.

Fly ash geopolymer concrete has a number of advantages over Portland cement concrete, including:

- It is more environmentally friendly, as it does not require the use of Portland cement, which is a major source of greenhouse gas emissions.
- It is more durable, as it is less susceptible to cracking and weathering.
- It has a lower density, which can make it lighter and easier to transport.
- It can be used to produce a variety of shapes and sizes, including precast concrete elements.

Fly ash geopolymer concrete is a promising new material with the potential to replace Portland cement concrete in a variety of applications. However, it is still under development, and further research is needed to improve its properties and performance.

There are two main types of fly ash available in India: Class F and Class C.

• Class F fly ash is produced from the combustion of bituminous and anthracite coals. It has a low lime content and pozzolanic properties. Pozzolanic materials are inert materials that can react with lime to form a cementitious material. Class F fly ash is the most commonly used type of fly ash in India. It is used in a variety of applications, including concrete, bricks, and mortar.

• Class C fly ash is produced from the combustion of lignite and sub-bituminous coals. It has a higher lime content than Class F fly ash and has self-cementing properties. Self-cementing materials can harden without the addition of lime. Class C fly ash is used in a variety of applications, including concrete, bricks, and grouts.

In addition to Class F and Class C fly ash, there are also other types of fly ash available in India, such as:

• Low-calcium fly ash is a type of Class F fly ash that has a low lime content. It is used in applications where the lime content of the fly ash needs to be limited, such as in concrete mixes with high water-to-cement ratios.

• High-calcium fly ash is a type of Class C fly ash that has a high lime content. It is used in applications where the lime content of the fly ash is needed to be high, such as in mortar mixes.

• High-volume fly ash is a type of fly ash that is used in high percentages in concrete mixes. It can be used to replace up to 50% of the Portland cement in concrete mixes.

The type of fly ash used in a particular application depends on the specific requirements of the application. For example, Class F fly ash is typically used in concrete mixes where the water-to-cement ratio is high, while Class C fly ash is typically used in mortar mixes.

The use of fly ash in India is regulated by the Bureau of Indian Standards (BIS). The BIS has set standards for the quality of fly ash that can be used in various applications. These standards ensure that the fly ash used in India meets the required quality and performance levels.

2. Metakaolin:

Metakaolin is a type of clay mineral that has been heat-treated to remove its water molecules. It is a pozzolanic material, which means that it can react with lime to form a cementitious material. Metakaolin is used in concrete as an admixture, which means that it is added to the concrete mix to improve its properties.

Metakaolin is important in geopolymer concrete because it is a pozzolanic material that can react with an alkaline activator to form a cementitious material. The pozzolanic reaction is a chemical reaction that occurs between silica and alumina-rich materials and an alkaline solution. This reaction produces a gel-like material that binds the aggregate particles together, forming a strong and durable concrete.

Metakaolin is a good pozzolanic material because it has a high silica and alumina content. It also has a high reactivity, which means that it reacts quickly with the alkaline activator. This makes metakaolin a good choice for use in geopolymer concrete, as it can help to produce a strong and durable concrete quickly.

Metakaolin has a number of benefits when used in concrete, including:

• Increased strength: Metakaolin can increase the strength of concrete by up to 20%. This is because the pozzolanic reaction between metakaolin and lime produces a gel-like material that fills the voids in the concrete, making it stronger.

• Reduced permeability: Metakaolin can reduce the permeability of concrete, making it more resistant to water damage. This is because the gel-like material produced by the pozzolanic reaction also acts as a barrier to water.

• Improved durability: Metakaolin can improve the durability of concrete by making it more resistant to chemical attack and weathering. This is because the gel-like material is also resistant to these factors.

• Reduced alkali-silica reactivity (ASR): Metakaolin can reduce the risk of alkali-silica reactivity (ASR), which is a type of concrete damage that can occur when concrete mixes contain certain types of reactive aggregates. This is because the pozzolanic reaction between metakaolin and lime produces a gel-like material that can coat the aggregate particles, preventing them from reacting with the alkalis in the concrete.

Metakaolin is a versatile material that can be used in a variety of concrete mixes. It is typically used in combination with Portland cement, but it can also be used as a sole cementitious material. The amount of metakaolin used in concrete depends on the desired properties of the concrete.

3. Alkali Activators:

Alkali activators are the chemicals that are used to activate the aluminosilicate precursors in geopolymer concrete. They are typically alkaline solutions of hydroxides, silicates, or carbonates. The most common alkali activators are sodium hydroxide (NaOH) and potassium hydroxide (KOH), but other alkalis such as calcium hydroxide (Ca(OH)2) and magnesium hydroxide (Mg(OH)2) can also be used.The type and concentration of the alkali activator will affect the properties of the geopolymer concrete. For example, higher concentrations of alkali activator will typically result in higher compressive strength, but they may also make the concrete more brittle.The following are some of the most important factors to consider when selecting an alkali activator for geopolymer concrete:

• Cost: Alkali activators can be relatively expensive, so it is important to choose an activator that is cost-effective.

• Availability: Alkali activators are not always readily available, so it is important to choose an activator that is easy to obtain.

• Safety: Alkali activators are corrosive, so it is important to choose an activator that is safe to handle.

• Environmental impact: Alkali activators can have a negative environmental impact, so it is important to choose an activator that has a low environmental impact.The most commonly used alkali activators in geopolymer concrete are:

• Sodium hydroxide (NaOH): NaOH is the most common alkali activator used in geopolymer concrete. It is a strong base and it is relatively inexpensive. NaOH can be corrosive, so it is important to handle it with care.

• Potassium hydroxide (KOH): KOH is similar to NaOH, but it is less corrosive. KOH is also more expensive than NaOH.

• Sodium silicate (Na2SiO3): Na2SiO3 is a solution of sodium hydroxide and silicon dioxide. It is a less strong base than NaOH, but it is still effective at activating geopolymer concrete. Na2SiO3 is also less corrosive than NaOH.

• Calcium hydroxide (Ca(OH)2): Ca(OH)2 is a base that is naturally found in lime. It is less alkaline than NaOH or KOH, but it can still be used to activate geopolymer concrete. Ca(OH)2 is also less expensive than NaOH or KOH.

• Magnesium hydroxide (Mg(OH)2): Mg(OH)2 is a base that is naturally found in dolomite. It is less alkaline than NaOH or KOH, but it can still be used to activate geopolymer concrete. Mg(OH)2 is also less expensive than NaOH or KOH.

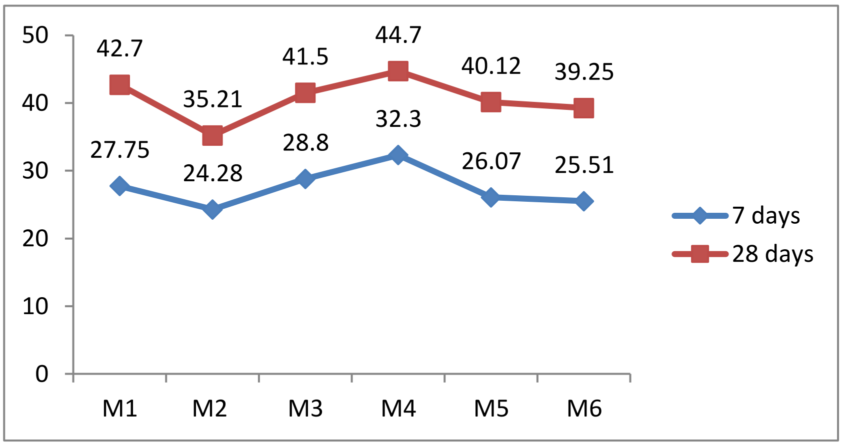
V. Testing Program

1. Compressive strength: Compressive strength test on cubes is the most common test conducted on hardened concrete because it is an easy test to perform and most of the desirable properties of concrete are comparatively related to its compressive strength. The compression test was carried out on cubical specimen of size 150mm in a compression testing machine of capacity 1000 kN. The strength is determined at 3, 7 and 28 days of casting.

Fig 1: Compression testing

Table 4.1: Compressive strength

Sr. No	Notation	Material	Compression Test (Day)	
			7 days	28 days
1	M1	CC	27.75	42.7
2	M2	GPC(100% FA)	24.28	35.21
3	M3	GPC(100% MK)	28.80	41.5
4	M4	80%Mk + 20% FA	32.30	44.7
5	M5	60%Mk + 40% FA	26.07	40.12
6	M6	40%Mk + 60% FA	25.51	39.25



Graph 1: Compressive test on cube

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2. Split tensile strength: Split Tensile Strength of concrete cylinders 150 mm diameter and 300 mm long were tested as per the procedure explained in IS 5816. Split Tensile strength was calculated as follows as split tensile strength:

Split Tensile strength (MPa) = $2P / \pi DL$,

Where, P = failure load

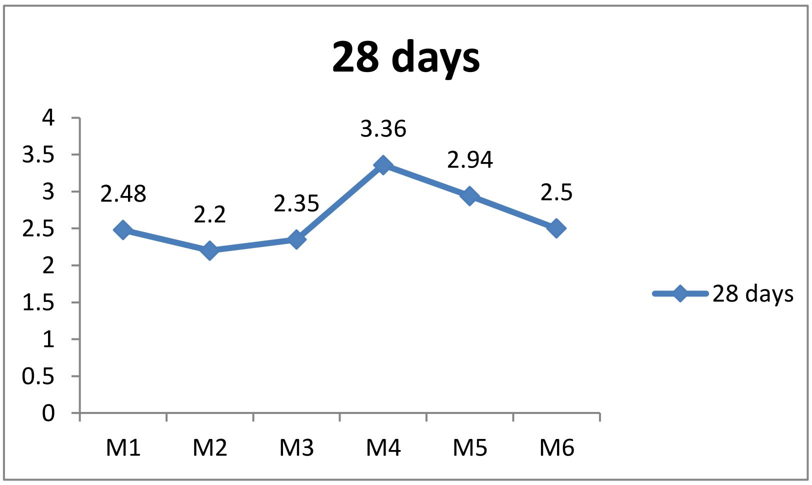
D = diameter of cylinder

L=lengthofcylinder

Fig 2 : Split Tensile testing

Table 2 : Split tensile strength of OPC

Sr. No	Notation	Material	Split tensile strength (28 Days)
1	M1	CC	2.48
2	M2	GPC(100% FA)	2.20
3	M3	GPC(100% MK)	2.35
4	M4	80%Mk + 20% FA	3.36
5	M5	60%Mk + 40% FA	2.94
6	M6	40%Mk + 60% FA	2.50



Graph 2: Split tensile strength

VI. CONCLUSIONS

• Optimum mixtures were observed as 80%MK+20%FA. Strength properties for GPC with 80%MK+20%FA gives better results compared to other mix proportions.

• The compressive strength generally increases with an increase in metakaolin ratio to flyash ratio until a certain limit depending on the molar ratios of the mix, which can contribute to the impendence of geopolymerisation, beyond which strength starts to reduce.

• Similarly, split tensile strength also improves with an increase in metakaolin content; the highest split tensile strength was achieved with Mk content of 80% and reduced significantly when it decreased to 40%.

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