Eco-Sustainable Geo-Polymer Concrete: Advancing Green Alternatives For Cement And Sand In Construction

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ABSTRACT

Global warming is a growing environmental crisis, with carbon dioxide (CO_2) emissions playing a dominant role in climate change. The cement industry is a major contributor to CO_2 emissions, especially in countries like India, the world's second-largest cement producer. To combat this, our study explores a sustainable alternative—geo-polymer concrete—by completely replacing cement with fly ash and partially substituting natural river sand with manufactured sand (M-Sand).

Our research examined the mechanical properties of this eco-friendly concrete, using a sodium hydroxide solution of 14M for the geo-polymerization process. We tested different levels of M-Sand replacement (25%, 50%, 75%, and 100%) and analyzed the compressive strength under heat curing (60°C & 80°C) and ambient curing conditions (7, 14, and 28 days). The results revealed that a 50% replacement of river sand with M-Sand provided the highest compressive strength in ambient curing conditions, highlighting its potential for sustainable construction. By adopting this approach, we can significantly reduce cement usage and mitigate CO_2 emissions, paving the way for a greener and more resilient future.

Key words Geo-polymer concrete, CO_2 emission reduction, Green building materials, Ambient curing

1. INTRODUCTION

Concrete is the most widely used construction material globally, playing a vital role in infrastructure development. At the heart of concrete production lies cement, a key binding agent responsible for its structural integrity. However, the rapid growth in cement production has raised significant environmental concerns, primarily due to its high carbon footprint. Global Portland cement production increases by approximately 9% annually, with India ranking as the second-largest producer, contributing 6.9% of the world's total cement output. Unfortunately, for every tonne of cement produced, an equivalent amount of carbon dioxide (CO_2) is released into the atmosphere, making the cement industry one of the top contributors to greenhouse gas emissions. In fact, cement industries account for nearly 8% of global CO_2 emissions, posing a serious threat to environmental sustainability. As construction demands continue to rise, the depletion of natural resources and the accumulation of industrial waste have become pressing concerns. The over-extraction of river sand for concrete production further disrupts ecological balance, while vast amounts of industrial by-products such as fly ash and bottom ash remain underutilized. Power generation in India, largely dependent on coal-based thermal plants, produces approximately 131 million tonnes of fly ash annually, with only 60% being repurposed, leaving the rest as an environmental hazard. The need for sustainable alternatives has never been more critical.

Geo-polymer concrete emerges as an innovative and eco-friendly solution, capable of addressing both industrial waste management and CO_2 emission reduction. This concrete variant replaces cement with industrial by-products such as fly ash or Ground Granulated Blast Furnace Slag (GGBS) while incorporating alternative aggregates like M-Sand and bottom ash instead of river sand. Given its pozzolanic properties and fine particle structure, fly ash serves as an ideal binder, offering a viable path toward sustainable construction practices.

2. LITERATURE SURVEY

Davidovits (1994) theorized that an alkaline liquid had the potential to react with the aluminium (Al) and silicon (Si) located in a source material of geological origin or in by-product materials such as fly ash and blast furnace slag to create binders. This reaction of alkaline liquid with aluminium and silicon is termed as polymerization process. These alumino-silicate polymers with an amorphous microstructure, which are formed in alkaline environment, are termed as geopolymers. The activation mechanism of alumino-silicate materials was proposed by Glukhovsky in 1959. This mechanism was broadly divided into three steps: (a) destruction–coagulation, (b) coagulation–condensation, and (c) condensation–crystallization. In 1979, Davidovits proposed geopolymer chemistry concept, and the properties of this new binder material. The term poly (sialate) was also suggested by him, wherein sialate is an abbreviation form for silicon-oxo- aluminate (Davidovits 2008). The chemical structure of polysialates which exists in three different features based on silicon and aluminum proportions is shown in Figure 2.1. The poly (sialate) network consists of Si^{+4} and Al^{+3} ions in IV-fold coordination, sharing oxygen ions and ranges from amorphous to semi-crystalline (Davidovits 1989, Sakulich 2011). Poly (sialate) has an empirical formula of: $M_n(-(SiO_2)_z-AlO_2)_n, wH_2O$, where „M“ is the alkali element that is used; „n“ is the degree of polymerization, „z“ value lies in between 1and 3 depending on the chemistry of the reaction, and „w“ depends on the extent of hydration reaction completed.

As mentioned earlier the geopolymerization, which is similar to hydration process in case of OPC, involves alumino-silicate oxides (Si_2O_5 and Al_2O_3) reacts with polysilicates, results in three dimensional polymeric bonds (Si-O-Al-O) under highly alkaline conditions. Sodium or potassium silicates which are available either in crystalline or non-crystalline forms are more commonly used as poly-silicates. (Davidovits 1991, Wallah and Rangan 2006). Significant contribution was made by the scientists Fernandez – Jimenez et al. (2009), Van Deventer et al. (2009) in developing different theories to explain the mechanism of geopolymerization and they have proposed a reaction mechanism for geopolymerization. They have presented a conceptual model which describes various sequential stages of geopolymerization as shown in Figure 2.2.

In summary the above schematic representation can be explained in three steps as follows (Davidovits 1999; Xu and Van Deventer 2000). 1. Dissolution of Si and Al atoms from the source material through the action of hydroxide ions in the alkali solution. 2. Transportation or orientation or condensation of precursor ions into monomers. 3. Setting or polycondensation/polymerization of monomers into polymeric structures in presence of heat media. According to Davidovits (1999), Van Jaarsveld et al. (1997) the schematic formation of geopolymer material can be understood by the following equations.

From the equation 2.2, Davidovits (1994), Hardjito and Rangan (2005), concluded that the water expels from the geopolymer matrix during the curing and further drying process. Later, water gets evaporated and leaves behind discontinuous nano-pores in the matrix. In this way the water in a geopolymer mixture, plays no role in the chemical reaction. It only serves the purpose of ensuring the workability to the mixture during handling.

Materials As mentioned, geopolymers are formed by alkali-activation of source materials which contains high levels of Silicon (Si) and Aluminium (Al). Therefore, material which contains high levels of Silicon and Aluminium in amorphous form is a possible source material in preparing a geopolymer. Three most common binding components those are reactive to alkaline substances and used in most of the previous investigations were calcinated clays (metakaolinite), coal fly ash, and ground granulated blast furnace slag.

Fly ash is a by-product of coal fired power plants. This is used as fuel in the generation of electricity. Before they are discharged into the atmosphere, a dust collection system removes the fly ash, as a fine particulate residue. In general, anthracite and bituminous coals possess high content of silica and produce low calcium fly ash, whereas, lignite or sub-bituminous coals possess high CaO content and low content of silica and alumina. Fly ash with high CaO content exhibits pozzolanic and cementitious properties, whereas the low calcium fly ash exhibits mainly pozzolanic properties. ASTM categorized the low calcium and high calcium fly ash as Class F and Class C, respectively. Class C fly ash, because of its possessing high calcium content when used in concrete works very quickly forms the hydration products as the rate of reaction is highly accelerated by the presence of high calcium. Chemical requirements of Class C and Class F according to ASTM are given in Table 2.1.

In general, in fly ash the silica content varies between 40 and 60% and the alumina content varies in between 20 and 30% (Khale and Chaudhary 2007). From the point of view of maintaining longer workability and setting time for the concrete Class C fly ash is not suitable for its use in producing mass concrete. Class F fly ash possesses high content of amorphous alumino-silicate phases and less than 10% CaO content (Hardjito and Rangan 2005). With Class F fly ash, it is possible to maintain longer workability (Sindhunata 2006a). For these fly ashes heat media is necessary to accelerate the pozzolanic reaction. Hence it was preferred by many researchers (Katz 1998, Van Jaarsveld et al. 1997, Palomo et al. 1999, Swanepoel and Strydom 2002, Fernandez-Jimenez and Palomo 2003, Rangan and Hardjito 2005, 2008) in their experimental investigations in producing geopolymers. Few researchers investigated on the activation of high-calcium fly ash (Chindaprasirt et al. 2007).

As mentioned earlier alkaline activators have the potential to react with the silicon and aluminium in the source materials and this reaction leads to the formation of alkali cement. Fernadez-Jimnez et al. (2005) proposed a descriptive model of the alkali activation of fly ash as shown in Figure 2.3. In this model first, the activator attacks the fly ash particle and opens the spheres of fly ash particles exposing small spheres inside which will also be dissolved and reaction products were formed on outside and inside of fly ash particles. In most of previous studies combination of sodium hydroxide, sodium silicate or potassium hydroxide and potassium silicate were used as the reactive agent. Davidovits et al. (1999) used sodium hydroxide solution to activate kaolinite material. In his studies Palomo (1999) concluded that the type of alkali solution employed for the activation of the fly ash has a significant role in the geopolymerization process.

Both activators combination of sodium hydroxide, sodium silicate solution and potassium hydroxide, potassium silicate were experimented by Xu et al. (2000) and it was found that portion of the mix attains better cementing properties where sodium hydroxide and sodium silicate combination was used. Better thermal stability of the meta kaolinite source material was reported by Barbosa and MacKenzie (2003) when potassium hydroxide and potassium silicate were used as activators.

Many of the previous researchers preferred combination of sodium hydroxide and sodium silicate solution as the activator due to its promising mechanical properties as well it is cheaper compared to potassium-based activators. Extensive experiments were conducted by Hardjito and Rangan (2005) in developing fly ash based geopolymer concrete where a combination of sodium hydroxide solution and sodium silicate solution was chosen to activate the fly ash. It was concluded that the compressive strength of fly ash-based geopolymer concrete increases when the sodium silicate-to-sodium hydroxide ratio by mass increases.

In geopolymer concrete a significant volume of mix is occupied by aggregates as much as the case even with the conventional concrete. An effective approach for better results is to optimize the distribution of particle sizes for the aggregate skeleton so as to minimize void space, which leads to a monetary saving when implementing geopolymer concrete (Recommended Practice: Geopolymer Concrete 2011). Hardjito and Rangan (2005) in their investigation used coarse aggregate sizes ranging from 7 to 20 mm. Fine sand from sand dunes in uncrushed form was used as fine aggregate.

Function of these admixtures is same as their use in normal concretes. Hardjito and Rangan (2005) showed the role of standard concrete admixtures, such as plasticizers in attaining greater workability to the geopolymer concretes.

In the existing literature most of the works on geopolymers were related to properties of geopolymer paste. In the recent times Hardjito and Rangan (2005) reported complete mix design details on the production of geopolymer concrete using Class F fly ash and combination of sodium hydroxide and sodium silicate solution. In preparing geopolymer pastes previous researchers expressed the mix compositions in terms of molar Si/Al ratio, molar Na/Al ratio, alkaline solution to alumino-silicate powder by mass and in terms of oxide ratios such as Na2O/SiO2, SiO2/Al2O3 and H2O/Na2O. Palomo et al. (1999) analyzed the geo-polymerization of low-calcium ASTM Class F fly ash for a molar ratio Si/Al equal to 1.81. In this work, combination of sodium hydroxide and sodium silicate solution was used as activator and specimens were cured at 65oC for 24 hours. The molar SiO2/K2O or SiO2/Na2O of the solutions was in the range of 0.63 to 1.23. Four different activator solutions were used with the ratio by mass of alkaline liquids to fly ash varying from 0.25 to 0.30. The specimens tested were 1 x 1 x 6 cm in size with a maximum compressive strength of 60 MPa.

Xu and Van Deventer (2000) prepared geopolymer specimens of size 2 x 2 x 2 cm with stilbite as the source material. It was proposed that for effective geopolymeric reaction to occur proportion of alkaline solution to alumino-silicate powder by mass should be approximately 0.33. The maximum compressive strength achieved was 19 MPa after 72 hours of curing at 35oC. Barbosa et al. (2000) using calcined kaolin as source material prepared seven mixture compositions of geopolymer paste. The ranges of ratio of molar oxides were: $0.2 < Na2O/SiO2 < 0.48$; $3.3 < SiO2/Al2O3 < 4.5$ and $10 < H2O/Na2O < 25$. In this investigation, it was concluded that the optimum composition occurred when the ratio of Na2O/SiO2 was 0.25, the ratio of H2O/Na2O was 10.0, and the ratio of SiO2/Al2O3 was 3.3.

Hardjito and Rangan (2005) were the foremost researchers who have published a work report, where the complete mixture proportions and have investigated the effect of various synthesizing parameters on fly ash based geopolymer concrete. They have determined the short-term properties of low-calcium fly ash-based geopolymer concrete by altering all the possible parameters which influence the mechanical properties. Numerous batches of geopolymer concrete were prepared using Class F fly ash as source material and mixture of sodium silicate solution-to-sodium hydroxide solution as the activator solution. Locally available aggregates were taken in different sizes ranging from 7 to 20 mm. Uncrushed material from sand dunes was used as fine aggregate. Similar to OPC the volume of aggregates in the concrete was taken about 75 to 80% of the total mass. Specimens used for testing were of size of 10 x 20 cm cylinders. Concentrations of NaOH used in this investigation were in the range of 8 molar to 16 molar. The ratio of sodium silicate solution-to-sodium hydroxide solution, by mass, varies from 0.4 to 2.5. Water to geopolymer solids by mass of the specimens were varied in the range of 0.16-0.25. Specimens were cured in the temperature range of 30 to 60oC for a duration varying from 4 to 96 hours.

Rangan, and Wallah (2006), have reported mix details of geopolymer concrete mixes as given in Table 2.2.

Considering Indian standards Anuradha et al. (2011) proposed modified guidelines for the geopolymer concrete mix design. Finally, M-30 mix proportions were reported as given in Table 2.3.

The compressive strength of geopolymer concrete is a function of many parameters, hence clear understanding of the influences of various synthesizing parameters is essential in preparing the geopolymers. Hardjito et al. (2005) conducted a detailed investigation about the influences of these parameters on compressive strength of geopolymer concrete (GPC). Various synthesizing parameters which they found to have influence on the mechanical properties were discussed as follows:

Following the suggestion made by Davidovits (2002), Hardjito et al. recommended that mixing of sodium hydroxide solution and sodium silicate solution at least one day prior to adding of the liquid to the dry materials. Time of mixing of all dry materials in the pan mixer was kept for about three minutes followed by wet mixing liquid components with dry materials for another four minutes.

According to Van Jaarsveld et al. (2003), molarity of the sodium hydroxide is a major influential aspect that determines the compressive strength of geopolymer concrete. From the experimental results Hardjito et al. (2005) have concluded that higher concentrations of NaOH yielded in higher compressive strength of geopolymer concrete (Lloyd and Rangan 2010). The reason was attributed to increased dissolution of aluminosilicates which results in formation of stronger bonds. As shown in Table 2.4 from mixtures 1 and 3, it can be observed that at a constant ratio of sodium silicate to sodium hydroxide with the increase in the concentration of NaOH, there was a significant increase in the compressive strength of concrete.

According to Hardjito et al. (2005) for a particular concentration of NaOH, keeping higher sodium silicate to sodium hydroxide solution ratio results in higher compressive strengths (Lloyd and Rangan 2010) as shown in Figure 2.5.

Total water present in the mix is taken as the mass of water added to the hydroxide solution, the mass of water in the silicate solution and the additional water added to the mix. The geopolymer solids include the mass of fly ash, the mass of sodium hydroxide pellets, and the mass of sodium silicate solids. In the laboratory tests conducted by Hardjito et al. (2005) water to geopolymer solids by mass of the specimens were varied in the range of 0.16-0.25. It was reported that the compressive strengths of specimens were decreasing and the workability was increasing as the water to geopolymer solids by mass was increasing as shown in Figure 2.6. (Lloyd and Rangan 2010).

According to Hardjito et al. (2004) geopolymerization will not be effective at lower temperatures and it was concluded that keeping higher curing temperatures yields in higher compressive strengths. However, there was no substantial increase in compressive strengths after 600C as indicated in Figure 2.7. Bondar et al. (2011) reported that when curing takes place at high temperatures, major part of the water will evaporate during the curing process and consequently it results in significant reduction in creep and drying shrinkage.

Vijai et al. (2012) performed tests on GPC using different curing conditions. The results were revealing that compressive strength of heat cured fly ash based geopolymer concrete is greater than that of fly ash based geopolymer concrete cured at ambient temperature. It was also reported that heat cured fly ash based geopolymer concrete gains strength quickly and there was no substantial increase in compressive strength after 7 days. On other hand GPC cured at ambient temperature had a significant gain in compressive strength from 7 to 28 days.

Hardjito et al. (2004) investigated the effect of curing time on GPC test cylinders. Curing periods were varied from 4 to 96 hours. As shown in Figure 2.8 for a particular curing temperature, up to 24 hours, longer curing time improved the polymerization process resulting in higher compressive strength. Memon et al. (2011)

also suggests that longer curing times improves the geopolymerization process and hence results in higher compressive strengths in geopolymer concrete.

The laboratory investigations of Hardjito et al. (2005) revealed that use of commercially available naphthalene sulphonate based superplasticizer improves the workability of the fresh concrete but had very little effect on the compressive strength up to two percent of this admixture to the amount of fly ash by mass as shown in Figure 2.9. Beyond this dosage value of 2%, there was some degradation in the compressive strength of hardened concrete. It was also suggested to not use amount of superplasticizer more than 2%, as it may leads to uneconomical solution in practice.

Davidovits et al. (1988), in his experimental investigations demonstrated some excellent properties of geopolymer materials like a high early strength, low shrinkage, and high resistance to sulfate attack, corrosion and freezing and thawing. Based on the recent investigations of the researchers some of superior performances of geopolymer concrete compared to ordinary Portland cement (OPC) concrete were presented in the following sections.

In his laboratory tests Davidovits (1988), observed that geopolymer binders hardened quickly at room temperature. At temperature of 200C after 4 hours duration these binders attained a compressive strength up to 20 MPa and at 28 days duration they have reached a compressive strength of 70-100 MPa. Comrie et al. (1988) also reported that geopolymer mortars attain high early strengths compared to ordinary Portland cement mortars. In these experimentations it was observed that 75% of the final strength was attained with in first two days of curing for a mortar mix having a compressive strength of 40MPa at a period of 28 days of curing.
Hardjito et al. (2004) reported that heat regime is necessary to accelerate the geopolymerization process consequently higher compressive strengths will be under heat curing regime, compared to ambient curing. Wallah and Rangan (2006) reported that compressive strength of fly ash-based geopolymer concrete increased as the average ambient temperature at casting increased, furthermore it was concluded that with the increase in age of the concrete there was a significant improvement in compressive strength of ambient cured geopolymer concretes. Nath and Sarker (2012) experimented on the development of ambient cured geopolymer concretes by using slag as one of the source materials. It was concluded that it is possible to achieve adequate compressive strengths even when curing was done at ambient temperatures.
Sarker (2011) demonstrated through his experimentation on steel embedded in GPC, that geopolymer concrete possesses higher splitting tensile strength and bond strengths than OPC concrete of the same compressive strength. It was also safely concluded that the existing analytical expressions for bond strength of OPC concrete can be conservatively used for calculation of bond strength of geopolymer concrete with reinforcing steel.

Wallah et al. (2006) from their limited number of test results showed that the geopolymer concrete specimens experience less creep than OPC concrete. Wallah et al. (2010) examined the creep behavior of four series of GPC specimens of varying compressive strengths (40 to 67 MPa). After one year of loading it was found out that the creep coefficient of fly ash-based geopolymer concrete is about half of that predicted using Gilbert‟s Method for OPC concrete.

Wallah (2009) reported that heat-cured fly-ash based geopolymer concrete undergoes very low drying shrinkage and the value at one-year measurement is only around 43 100 micro strain. In determining the long term properties of low calcium fly ash based geopolymers Wallah and Rangan (2006) noticed that the drying shrinkage of geopolymer concrete cured at ambient temperatures significantly higher than that of heat cured geopolymer concrete. The reason was attributed to evaporation of the excess water in the geopolymer concrete heat curing process. It was concluded in these studies that the drying shrinkage for geopolymer concrete cured at ambient temperatures was similar compared to that of OPC concrete.

Extensive research conducted by Davidovits (1994) and Song et al. (2005) have revealed many facts about resistance of geopolymer concrete to sulphate and chloride attack. It was found that after being exposed to sulphuric acid solution, except development of some fine cracks on the surface, fly ash based geopolymer concrete remains structurally intact on the other hand OPC concrete shows sign of severe damage.

This reflects better binding properties of geopolymer than cement as the bonding between aggregates and paste is strong enough so that aggregates do not get exposed on the surface. Even the mass change of fly ash based geopolymer concrete is pretty less compared to OPC concrete. In his experimental works on durability of fly ash based geopolymer concrete against sulphuric acid attack by Song et al. (2005) mass change in geopolymer concrete and OPC specimens were evaluated after exposing them to 10% sulphuric acid. In case of concrete made of OPC exposed to sulphuric acid solution, it was observed that the surface of concrete got damaged resulting in exposure of aggregates. But since fly ash geopolymer concrete shows very little cracking and compressive strength of around 40 MPa has been found even after two months of exposure for a concrete with a 28 days compressive strength of 70 MPa.

Figure 2.10 and Figure 2.11 shows comparison between fly ash geopolymer and OPC with respect to mass change in sulphate solution. So, it testifies strong bonding and thus improved resistance of fly ash geopolymer to sulphate attack. In spite of this good quality care should be taken to improve permeability and use of aggregates. Use 44 of latite aggregates must be avoided since gypsum formation and thus cracking due to expansion occurs when it comes in contact with sulphuric acid.

Brock William Tomkins (2011) investigated the chemical resistance of fly-ash based geopolymer concrete (FAGC) and red-mud based geopolymer concrete (RMGC) in comparison with performance of Ordinary Portland Cement concrete (OPC). The chemical resistance tests involve sodium hydroxide and sulphuric acid at 20o C and 90o C. Chemical and compression tests indicated that OPC experienced some strength deterioration both in acid environment and in alkaline environment in the range of -24.9 to -25.6% and -2.2 to -13.3% respectively.
FAGC was found to have better acid resistance whose strength deterioration was in the range of +3.8 to -17.6% and even experienced strength enhancement in sodium hydroxide in the range of +29.1 to +55.7%. RMGC exhibited a strength increase of 52.4% in sulphuric acid while displaying strength enhancement of +50.5% in sodium hydroxide.

Ariffin et al. (2013) investigated into the durability of geopolymer concrete (GPC) prepared using blended ash of pulverized fuel ash (PFA) and palm oil fuel ash (POFA) along with alkaline activators when exposed to 2% solution of sulfuric acid for up to 18 months. Mass changes, residual compressive strength, products of degradation and microstructural changes were examined and compared with the performance of ordinary Portland concrete (OPC). Experimental results revealed that the mass loss for blended ash geopolymer (BAG) concrete specimens was 8%, which was considerably smaller than the mass loss of OPC concrete specimens which exhibited 20% after 18 months sulfuric acid exposure. It was also reported that BAG concrete specimens had 35% compressive strength loss while the OPC concrete specimens started deteriorating in the first month of the exposure and had 68% strength loss and were severely deteriorated after 18 months of sulfuric acid exposure.

Geopolymer concrete also possesses excellent resistance against chloride attack. Chloride ingress in normal OPC concrete causes corrosion of reinforcement and disintegration of concrete accompanied by loss of strength. On the contrary in case of geopolymer concrete it was observed that there was an in increase in compressive strength. The increase in compressive strength also indicated strength formation reactions. Experimental study has shown that rate of chloride penetration shows a decreasing trend over time and also concentration in concrete is very low. Since there is no loss of strength it implies that there should not be any formation of corrosion product on the surface. Due to crystalline stress that occurs due to formation of crystalline ettringite or Friedel salt, OPC concrete disintegrates but in fly ash based geopolymer concrete there is only one crystalline phase even after sodium chloride or magnesium chloride exposure resulting in absence of any expansive product like ettringite.

Olivia et al. (2012) examined properties of fly ash geopolymer concrete subjected to continuous immersion in 3.5% NaCl solution and accelerated wetting drying at 80oC and 24-hour cycle in NaCl solution. In this investigation three geopolymer mixtures and a control mix with target strength of higher than 55 MPa were evaluated. It was reported that the cyclic exposure to seawater increased the rate of degradation of OPC concrete, but in case of geopolymer concrete no significant change in strength and degradation, due to continuous immersion and the wetting-drying cycles. It was concluded that geopolymer concrete was found to perform better under cyclic exposure than the OPC concrete based on the results when compressive strength, porosity and weight change aspects were considered.

Stanton in early 1940"s analyzed the failure of concrete due to alkali aggregate reaction and reported that it was due to expansion caused by chemical reaction between alkali in cement and silica contained in aggregate. By replacing cement to some extent by mineral admixture like fly ash the alkali aggregate reaction can be controlled substantially. While geopolymer ensures improved bonding by acting as a binder prohibiting disastrous result by alkali aggregate reaction, fly ash acts as a spice to it by controlling alkali silica reaction (ASR). Also it is recommended that water cement ratio should be low to control alkali aggregate reaction since water helps alkali-silica gel to swell. Use of fly ash geopolymer concrete utilizes low watercement ratio maintaining desired workability and hence can make concrete more impermeable and less vulnerable to such reaction. One of the important reasons for 47 using fly ash in highway construction was to inhibit the expansion resulting from ASR. It has been found that 1) the alkalis released by the cement preferentially combine with the reactive silica in the fly ash rather than in the aggregate, and 2) the alkalis are tied up in non-expansive calcium-alkali-silica gel. Thus hydroxyl ions remaining in the solution are insufficient to react with the material in the interior of the larger reactive aggregate particles and disruptive osmotic forces are not generated (Halstead 1986, Olek et al. 1986, Farbiarz and Carrasquillo 1986).

Kunal Kupwade-Patil et al. (2013) reported the findings of an experimental investigation for alkali silica reaction (ASR) between reactive aggregates and the geopolymer specimens which were prepared using one Class C and two Class F fly ash stockpiles. Potential reactivity of the aggregates via length change and compression test measurements, were done as per ASTM standards. Results suggest that the extent of ASR reaction due to the presence of reactive aggregates in fly ash based geopolymer concretes was substantially lower than in the case of ordinary Portland cement-based concrete, and well below the ASTM specified threshold. Furthermore, it was noticed in this investigation that geopolymer concrete specimens appeared to undergo a densification process in the presence of alkali solutions, resulting in reduced permeability and increased mechanical strength. It was concluded that utilization of ASR-vulnerable aggregates in the production of geopolymer concrete products could contribute to the economic appeal and sustainability of geopolymer binders in regions that suffer from in-sufficient local supply of high quality materials.

According to Davidovits (2013) in case of low calcium binders, better heat resistance of geopolymer concrete yields from a polycondensation process and not from a hydration process as OPC concrete. Hydrate tends to explode when exposed to extreme heat. Davidovits (1988 and 1994) reported that compared to Portland cement, geopolymer materials have shown a better behavior with reference to heat and fire resistance. Figure 2.12 shows compressive strength of fly ash geopolymer concrete at different temperatures.

Fly ash based geopolymer concrete can sustain when exposed to considerably high temperature. While OPC concrete degrades and degenerates at high temperature, it has been found from different study that fly ash geopolymer concrete can maintain its desired compressive strength even at 400ºC. Strength starts dropping once temperature crosses 400ºC and remains almost constant at higher temperatures. It is noteworthy here that geopolymerization process continues even at high temperature and it is the strength of the binder or bonding that prevents the concrete from disintegration. However lowest residual strength has been marked at 600 - 700ºC.

Abdulkareem et al. (2013) had conducted a research on the mechanical and microstructural characteristics of a lightweight aggregate geopolymer concrete (LWAGC) synthesized by the alkali-activation of a fly ash source (FA) before and after being exposed to elevated temperatures, ranging from 100 to 800°C. The results revealed that the LWAGC unexposed to the elevated temperatures possesses a good strength-to-weight ratio. For the exposed LWAGC to the elevated temperatures of 100 to 800°C, the results illustrate that the concretes gain compressive strength after being exposed to elevated temperatures of 100, 200 and 300°C. Afterward, the strength of the LWAGC started to deteriorate and decrease after being exposed to elevated temperatures of 400°C, and up to 800°C. Based on the mechanical strength results of the exposed LWAGCs to elevated temperatures of 100°C to 800°C, a statistical analysis and regression equation was developed, which shows the relationship between the exposure temperature and the obtained residual compressive strength. Based on the microstructure investigation of the unexposed LWAGC it was reported that a good bonding between aggregate and mortar at the interface transition zone (ITZ). However, this bonding is subjected to deterioration as the LWAGC is exposed to elevated temperatures of 400, 600 and 800°C by increasing the microcrack content and swelling of the unreacted silicates.

Hussin et al. (2014) in their laboratory investigation examined performance of blended ash geopolymer concrete at elevated temperatures. Geopolymer concrete composite was prepared using blended ash, pulverized fuel ash, and palm oil fuel ash, obtained from agro-industrial waste along with alkaline activators. The samples blended ash geopolymer (BAG) concrete and ordinary Portland concrete were heated up to 800^0C to evaluate mass loss, strength, and micro structural changes due to thermal impact. Results indicated that the BAG concrete exhibited better structural stability than OPC concrete after exposure to elevated temperatures due to more stable cross linked alumino-silicate polymer structure. It was reported that the BAG concrete had the best performance with an average of 16% strength decline compared to 50% strength decline of OPC concrete. It was observed that the strength of BAG concrete increased as temperature increased, attaining peak strength at 600^0C, whereas the OPC concrete attained peak strength at 200^0C only.

Shaikh et al. (2014) evaluated the compressive strength geopolymer concrete made of low calcium Class F fly ash, before and after exposing them to elevated temperatures of 200, 400, 600 and 800°C. Mixture of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) was used as activator solution. In this experimentation the effects of molarities of NaOH, coarse aggregate sizes, duration of steam curing and extra added water on the compressive strength of geopolymer concrete at elevated temperatures were studied. The results show that the fly-ash-based geopolymer concretes exhibited steady loss of its original compressive strength at all elevated temperatures up to 400°C regardless of molarities and coarse aggregate sizes. At 600°C, all geopolymer concretes exhibited increase of compressive strength relative to 400°C. However, it is lower than that measured at ambient temperature. Similar behavior was observed at 800°C, where the compressive strength of all geopolymer concretes were lower than that at ambient temperature, with only exception of geopolymer concrete containing 10 M NaOH. The compressive strength in the latter case was increased at 600 and 800°C. Greater loss of compressive strength at 800°C was observed in case of geopolymer concretes containing higher molarity of NaOH solution (13M and 16 M) at 800°C than that of 10 M NaOH. It was reported that geopolymer concrete containing smaller size coarse aggregate retains most of the original compressive strength of geopolymer concrete at elevated temperatures. Adverse effect of the addition of extra water on the compressive strength of geopolymer concretes at all elevated temperatures was noticed in this experimental study.

Non air entrained concrete with low water to binder ratio is durable against freezing and thawing. So it implies that if water - binder ratio is low and all water can mix up with binder and other components resulting in low permeability of concrete. It can so hinder the saturation of paste during freezing. If saturation of paste does not take place concrete would not crack even in absence of any air entraining admixture. Fly ash plays the important role by lowering water-cement ratio and reducing concrete permeability. Experiments conducted by Frantisek Skvara et al. (2006) has stated that mass of fly ash geopolymer concrete slightly changes after 150 freezing and defrosting cycles and also there was no deformation and cracking. However, concrete with up to 50% fly ash and 10% silica fume with geopolymer binder has proved most efficient. This hints at the disadvantage of having too much fly ash particles in the mixture. It means that excess or unreacted fly ash will not bind well with geopolymer matrix and will awaken the bonding only.

GPC technology is at the developmental stage, before its wide acceptance in the field. Some of the important limitations of GPC need to be overcome are as follows:

1. Development of strengths and other keys properties of GPC are directly dependent on the purity of the resource materials. Maintaining homogeneity in the source materials such as fly ash, red mud etc., and purity of alkaline materials obtained from different manufacturers for preparing activator solutions make the design of this concrete mix proportions difficult for its manufacture on a recipe.
2. Requirement of heat curing either steam or dry for setting of GPC is another major limitation for its utilizations in similar ways to that of the conventional concrete.
3. Cost of alkaline solution is high depending on the purity of its alkalies. Further, it is required to prepare the alkaline liquid by mixing both the solutions together 24 hours prior to use.
4. High alkalinity environment possesses health hazards to the workers. Higher alkalinity of the materials requires more processing resulting in more energy consumption and hence generation of greenhouse gases.
5. Unavailability of widely accepted specifications and guidelines.
6. Production of GPC requires great care in contrast to Portland cement concrete.

The need for finding an alternative for river sand arises due to the over exploitation of river sand and its related harmful consequences. M-Sand has been identified as the next potential substitute for river sand. The crushing activities result in the production of about 10-15% non valued waste in the quarries which are differently referred as M-Sand by many authors. The use of M-Sand has been dealt almost all parts of the world, but the structural use of manufactured sand is still in the research level. A good quantum of studies was made in the area of manufactured sand utilization in structural concrete in India and other countries. The attempts made by several authors have been collected and for brevity the important papers are presented here.

The greatest challenge that the concrete industry is facing the 21st century is how to achieve a sustainable pattern of growth. The task is formidable but can be accomplished provided we make a paradigm shift from the culture of accelerating construction speeds to a culture of conservation of energy and material. The current environmental issues to technology choices objecting the production of durable and environmentally friendly concrete are related as $D = f(P \times I \times W)$ by Kumar Mehta (2001). The environmental damage (D) is a function of three interlinked factors P, I and W where, P- represents the population, I- is an index of industrial and urban growth and W- an indicator of the degree to which a culture promotes wasteful consumption of natural resources. The W-factor has a multiplier effect on the environmental damage due to population growth and by controlling this factor; the 11 degree of damage can be controlled. It is suggested that, we have to examine our current economic models and technological choices that promote wasteful consumption of natural and manufactured materials.

In the conservation of energy and materials, the observation on the utilisation of recycled materials for concrete constituents is brought for prime consideration. Xiao, et al (2006) conducted investigation to analyze the relationships between the mechanical properties of recycled aggregate concrete (RAC) from 1200 test results covering as many recycled materials as possible. In the first phase, the published experimental results during 1985-2004 were analysed and data base developed. The relations between the compressive strength, density, splitting tensile strength, flexural strength, and the elastic modulus were investigated. It is reported that the interrelationships between the mechanical properties of RAC could be quite different from those of normal concrete. Some improved new equations are proposed for the prediction of the relations between the mechanical properties of RAC based on the statistical regression analysis with the least squares method. M-Sand is a problem for the people residing nearby quarries and dumping of M-Sand is an environmental issue. It’s a daily ordeal for residents of Telangana and surrounding areas whose houses, streets, shops and vehicles are invaded by pollutants from the granite quarries and stone crushing units. Exposure to such suspended particulate matter, as pollution experts call it, for long durations can cause serious respiratory problems.

Sand mining from river bed for overuse of the material has led to environmental concerns, the depleting of securable river sand deposits and a concomitant price increase in the material. The deep pits dig in the river bed effects on ground water level and erode the banks and nearby land. A 100 year old steel-concrete composite bridge (Hintze Ribeiro bridge, Portugal, 2001) collapsed killing 70 people is shown in Figure 2.13(a). Another in figure 2.13(b), is an erosion problem near piers due to illegal sand mining. The collapse was due to two decades of illegal but allowed sand extraction which compromised the stability of the bridge pillars.

It will be interesting to note that hours after the accident, the then Minister of Transportation Jorge Coelho resigned. Indian Government has also imposed ban on mining sand from riverbeds. The massive sand mining operations are regulated as with greater monitoring and strict controls imperative to save river beds. The local communities in many sand mining areas have objected the sand mining operations and frequently make agitations against the legal as well as illegal mining. The construction industries expect a serious shortage of sand in the near future due to over exploitation of river sand and seeking for alternatives.

A survey was conducted (Ekanayaka et al, 2007) in Kaluthara-Benthota sea area and a resource distribution map was plotted, samples from Muthurajawela offshore sand stick piles were collected and Cl-content was around 0.3%, where as if the seawater is gravity drained; it reduced to around the acceptable limit of 0.075%. It is found that the action of an average rain fall would be enough to reduce the Cl- contents to below acceptable levels. It is reported that offshore sand was much better than manufactured sand and shows equal average properties as river sand.

Potential Alternatives for River sand are near shore marine sand, dune sand, land based sand, offshore sand, M-Sand and manufactured sand (Ekanayaka et al, 2007). Bottom ash is also recommended as substitute for river sand (Aggarwal et al, 2007). With respect to availability, ease of extraction, environmental impact and cost, 13 offshore sand was already used in Sri Lanka mainly for road filling and it was also used for construction in all over the world.

Janani et al. (2015) dealt with experimental study of geopolymer concrete using manufactured sand (M-Sand). Due to the depletion of river sand, alternate fine aggregate was tried as replacement. When river sand is fully replaced by M-Sand, compressive strength increased by 9%, tensile strength by 12% and flexural strength by 10%.The work reported that since no cement was used in concrete, it proved to serve as greener concrete.

Nagajothi et al. (2016) carried out strength assessment of geopolymer concrete using M-Sand. The work aimed at proposing environmental friendly alternative material for cement and river sand. Geopolymer was found to be a better alternative to Cement and M-Sand to scarce river sand. All the strength parameters were investigated to arrive at the above conclusion.

In the context of increasing industrial pollutants every year, sustainability of construction industry as well as for the effective disposal of industrial wastes, geopolymers as an alternative binder receiving more and more attention. For producing the geopolymers with consistent behavior, it is highly essential to understand the process of geopolymerization, chemistry behind the process as well as various factors that influences the geopolymerization. However, the use of heat media in producing geopolymer concretes limiting its applications.

Producing geopolymers at ambient conditions by reducing its setting time is of great practical importance to widen its applications beyond the precast products. Replacing portion of low calcium fly ash results in production geopolymer concretes at ambient temperatures. The mechanical properties and the behavior the geopolymer concrete composites are also comparable to the fly ash based geopolymer concretes.

Viable natural sand resources in many areas across the world are running out, either because of extinction or sterilisation of rivers, cost of extraction or transportation, shortage of water for processing in some areas or because of environmental concerns. The current status of concrete industries facing the scarcity of fine aggregate and manufactured sand utilisation as an alternative are reviewed from a thorough literature study and the features are summarized here: Excessive extraction of sand from rivers carried out almost to the level of complete depletion and further mining is not feasible at all. Therefore it is imperative to stop further extraction of river sand and find alternative solutions immediately. Use of near shore marine sand, dune sand, land based sand, offshore sand, M-Sand manufactured sand and bottom ash have been identified as alternatives to river sand for use as fine aggregate in concrete and carried out studies on concrete. But for viability and feasibility manufactured sand is recommended for further research.

3. PROPOSED SYSTEM

The proposed system focuses on the development of geopolymer concrete as a sustainable alternative to traditional cement-based concrete. This system utilizes industrial by-products such as fly ash as a complete replacement for cement and incorporates manufactured sand (M-Sand) and bottom ash as substitutes for natural river sand. The concrete is prepared using an alkaline activator solution composed of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) to initiate the polymerization process, enhancing the binding properties of the material. The study investigates the mechanical performance of the geopolymer concrete under both heat and ambient curing conditions at different time intervals (7, 14, and 28 days). The objective is to achieve an eco-friendly, high-strength concrete that reduces CO_2 emissions while effectively utilizing industrial waste materials, thereby contributing to sustainable construction practices.

Sustainability – Eliminates the use of cement, reducing CO_2 emissions and promoting eco-friendly construction.

Waste Utilization – Effectively repurposes fly ash, bottom ash, and M-Sand, minimizing industrial waste disposal issues.

Enhanced Strength – Investigates compressive strength performance under different curing conditions.

Reduced River Sand Dependency – Utilizes M-Sand and bottom ash to mitigate the depletion of natural sand resources.

Alkaline Activation – Uses sodium hydroxide and sodium silicate solutions to improve the polymerization process.

Energy Efficiency – Analyzes the feasibility of ambient curing to reduce the need for high-temperature processing.

Long-Term Durability – Examines the structural integrity of geopolymer concrete over time for practical applications.

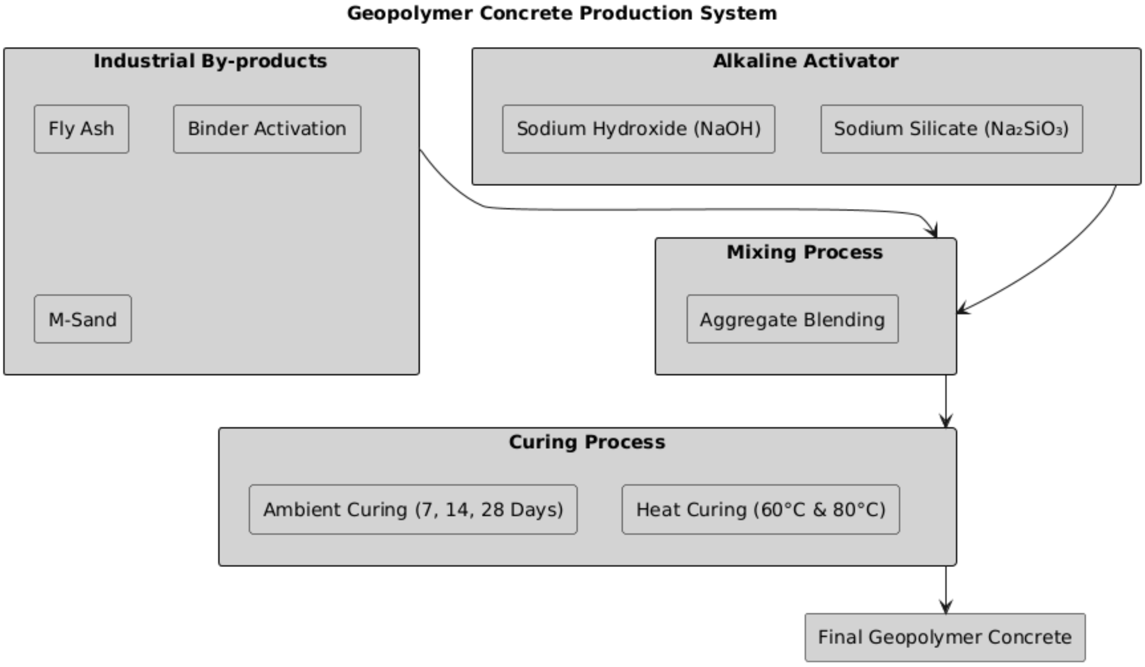

Figure 1 Presents the Block Diagram of Proposed System.

4. RESULTS AND DISCUSSIONS

The chapter presents the results obtained from the tests (discussed in Chapter 4) conducted on geopolymer concrete specimens and their composites. First of all, the results of mechanical properties of GPC (100% fly ash) and GPC with river sand replacing with M-Sand ($RS_{100}MS_0$, $RS_{75}MS_{25}$, $RS_{50}MS_{50}$, $RS_{25}MS_{75}$ & RS_0MS_{100}) specimens on mechanical properties and physical properties was presented.

4.1 Physical properties of Geopolymer concrete

Table 4.1 Physical properties of GPC cubes

Mix No.	RS – MS (%)	Shape and size test	Colour test	Structure test
M1	$RS_{100}MS_0$	For all cubes are cube shaped with sharp edges	All the cubes having the uniform colour	There are no flaws, cracks or holes present on that
M2	$RS_{75}MS_{25}$			
M3	$RS_{50}MS_{50}$			

M4	$RS_{25}MS_{75}$	and size of 15 cm x 15 cm x 15 cm	for entire structure	broken face then that is a good quality
M5	$RS_{0}MS_{100}$			

4.2 Fresh properties of Geopolymer concrete

The Slump cone test results of the Geopolymer concrete for the replacement of river sand with M-Sand by 0, 25, 50, 75 and 100 % are shown in table 5.2 and graphically represented in Fig 5.1.

Table 4.2 Slump cone test results

Mix No.	RS – MS (%)	Slump value (mm)
M1	$RS_{100}MS_{0}$	85
M2	$RS_{75}MS_{25}$	90
M3	$RS_{50}MS_{50}$	94
M4	$RS_{25}MS_{75}$	100
M5	$RS_{0}MS_{100}$	104

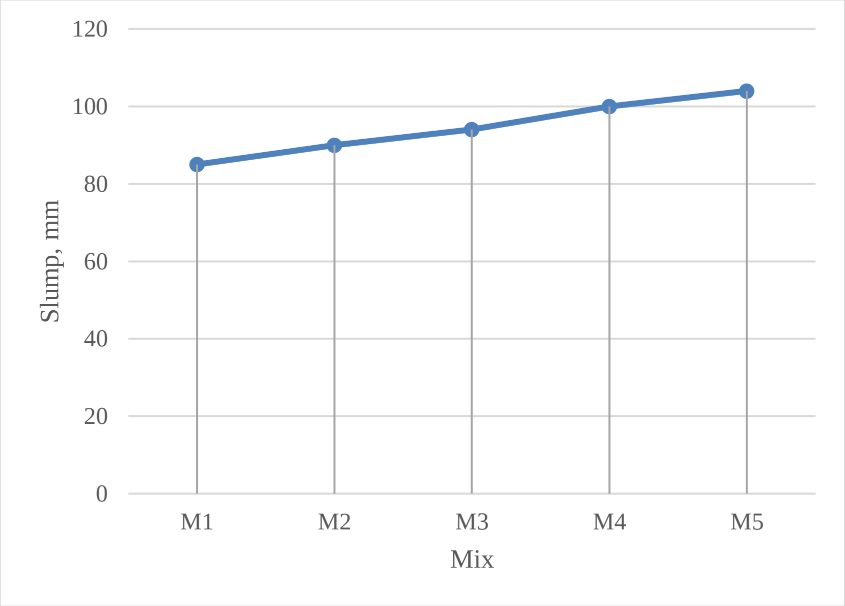

Figure 4.1 Slump test results graph

It is observed that there is increase in the workability of the Geopolymer concrete when the river sand is replaced with M-Sand . Based on the observations, all of the slump values are in the low to medium workability range.

4.3 Harden properties of Geopolymer concrete

4.3.1 Oven curing

The compressive strength by oven curing under 60^{0}c and 80^{0}c results of the Geopolymer concrete for the replacement of river sand with M-Sand by 0, 25, 50, 75 and 100 % are shown in table 5.3 and graphically represented in Fig 5.2.

Table 4.3 Compressive strength test results (Oven curing)

Mix No.	RS – MS (%)	Average Compressive strength (Mpa)	
		80^{0}c	60^{0}c
M1	$RS_{100}MS_{0}$	40.8	35.8
M2	$RS_{75}MS_{25}$	45.5	38
M3	$RS_{50}MS_{50}$	53.3	42.5
M4	$RS_{25}MS_{75}$	50.1	38.2
M5	$RS_{0}MS_{100}$	44	36

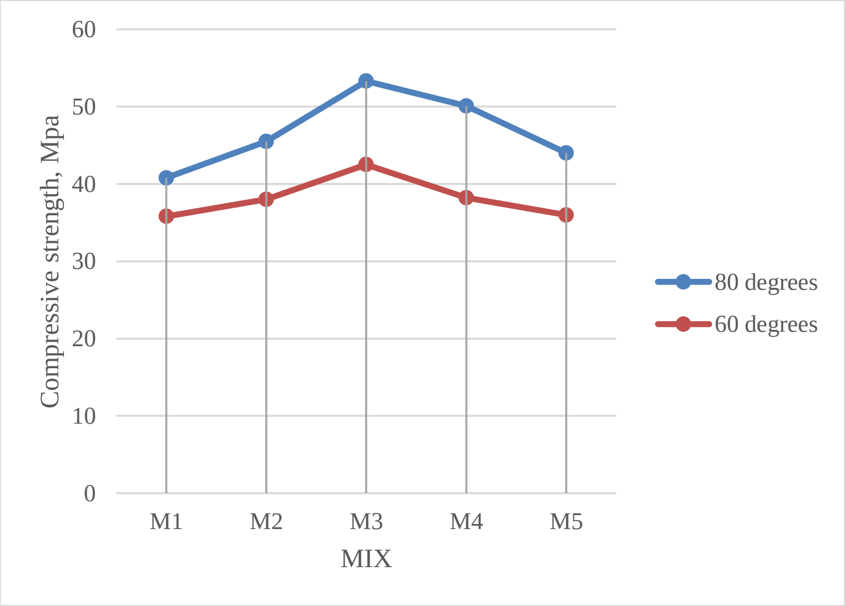

Figure 4.2 Compressive strength test results graph (Oven curing)

It is observed that there is increase in the compressive strength of the geopolymer concrete when the river sand was replaced with M-Sand . Based on the observations, all of the compressive strength values are higher for M-Sand replacement. The highest compressive strength gains for 80^{0}c as compare to the 60^{0}c. The optimum dosage of M-Sand replacement in river sand was 50%.

4.3.2 Ambient curing

The compressive strength by ambient curing under 7, 14 and 28 days results of the Geopolymer concrete for the replacement of river sand with M-Sand by 0, 25, 50, 75 and 100 % are shown in table 5.4 and graphically represented in Fig 5.3.

Table 4.4 Compressive strength test results (Ambient curing)

Mix No.	RS – MS (%)	Average Compressive strength (Mpa)		
		7days	14 days	28 days
M1	$RS_{100}MS_{0}$	15.39	30.23	54.05
M2	$RS_{75}MS_{25}$	17	36.8	57
M3	$RS_{50}MS_{50}$	21.4	44.9	61.2
M4	$RS_{25}MS_{75}$	19.2	40	58.5
M5	$RS_{0}MS_{100}$	15.23	34.3	52

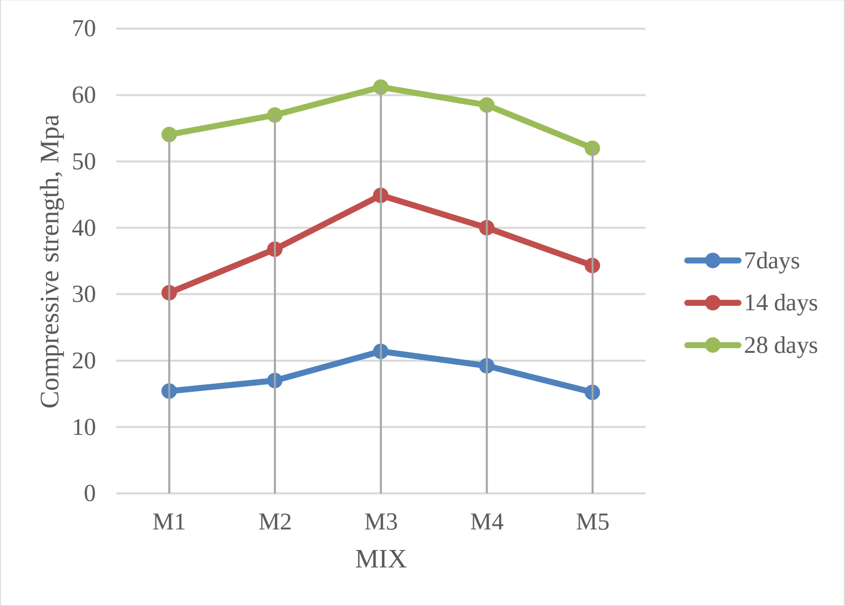

Figure 4.3 Compressive strength test results graph (Ambient curing)

It is observed that there is increase in the compressive strength of the geopolymer concrete when the river sand was replaced with M-Sand . Based on the observations, all of the compressive strength values are higher for M-Sand replacement. The optimum dosage of M-Sand replacement in river sand was 50%.

4.3.3 Comparison of curing based strength

It is observed that there is increase in the compressive strength of the geopolymer concrete when the river sand was replaced with M-Sand . Based on the comparison of oven and ambient curing, the compressive strength higher for 28days ambient curing as compare to the oven curing.

For 28days ambient curing of geopolymer concrete, the percentage increase of compressive strength value for 25%, 50%, 75% and 100% replacement of river sand with M-Sand was 5.45%, 13.23%, 8.23% and 3.8%respectively.

Table 4.5 Compressive strength test results comparison

Mix No.	RS – MS (%)	Average Compressive strength (Mpa)		
		80^0c	60^0c	28 days
M1	$RS_{100}MS_0$	40.8	35.8	54.05
M2	$RS_{75}MS_{25}$	45.5	38	57
M3	$RS_{50}MS_{50}$	53.3	42.5	61.2
M4	$RS_{25}MS_{75}$	50.1	38.2	58.5
M5	RS_0MS_{100}	44	36	52

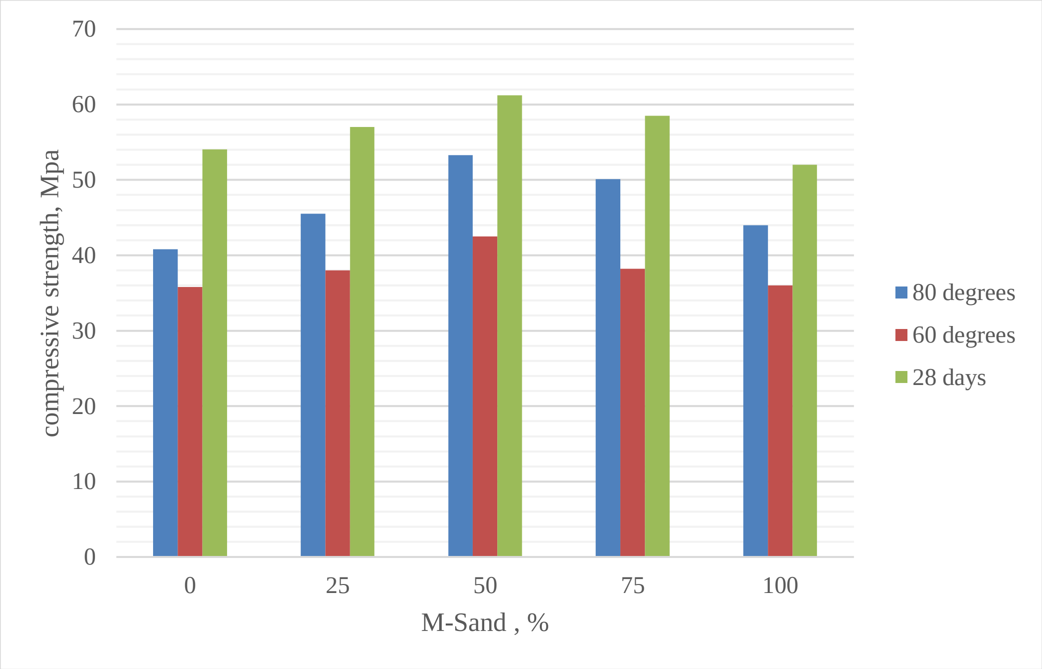

Figure 4.4 Compressive strength test results comparison graph

4.4 Indirect strength of Geopolymer concrete

Table 4.6 Indirect strength from compressive strength

Mix No.	RS – MS (%)	Strength (Mpa)				
		28 days ambient cured cube compressive strength	Indirect Tensile strength	Direct tensile strength	Shear strength	Flexural strength
M1	$RS_{100}MS_0$	54.05	5.405	4.324	6.48	5.146
M2	$RS_{75}MS_{25}$	57	5.7	4.56	6.84	5.28
M3	$RS_{50}MS_{50}$	61.2	6.12	4.896	7.344	5.47
M4	$RS_{25}MS_{75}$	58.5	5.85	4.68	7.02	5.354
M5	RS_0MS_{100}	52	5.2	4.16	6.24	5.047

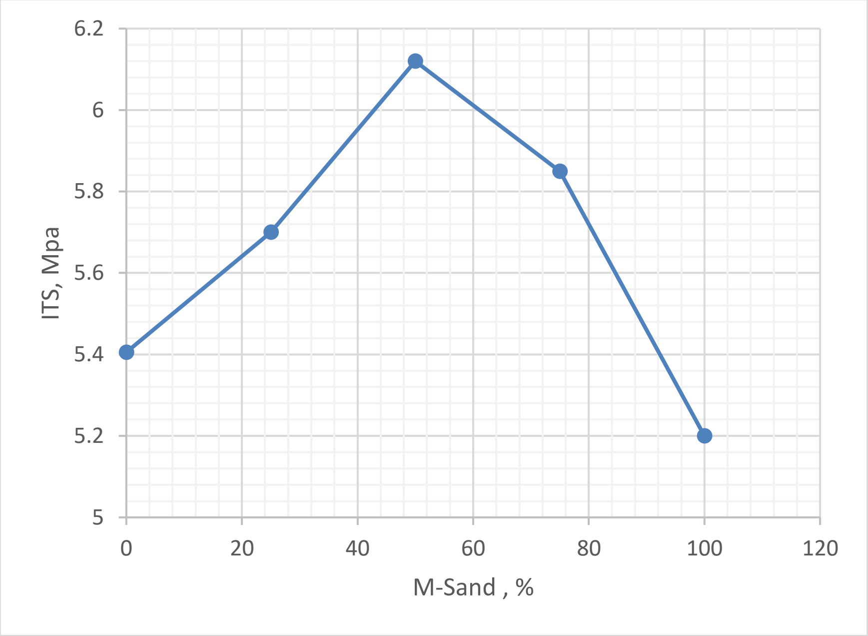

Figure 4.5 Indirect tensile strength test result graph

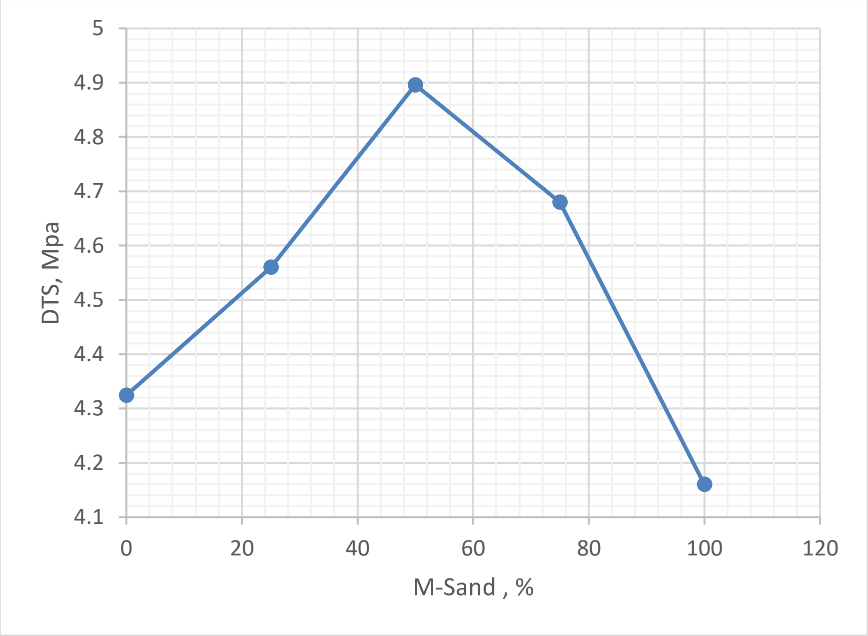

Figure 4.6 Direct tensile strength test results graph

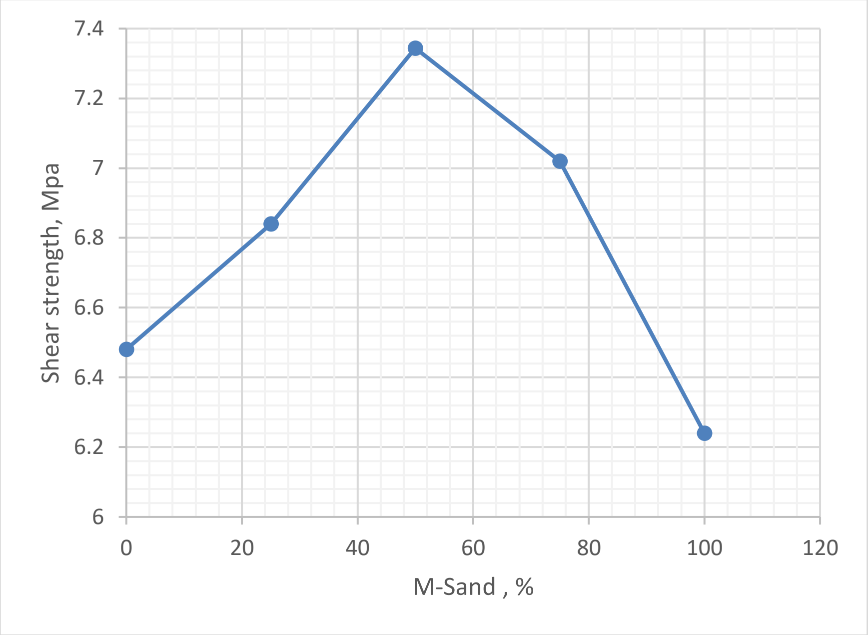

Figure 4.7 Shear strength test results graph

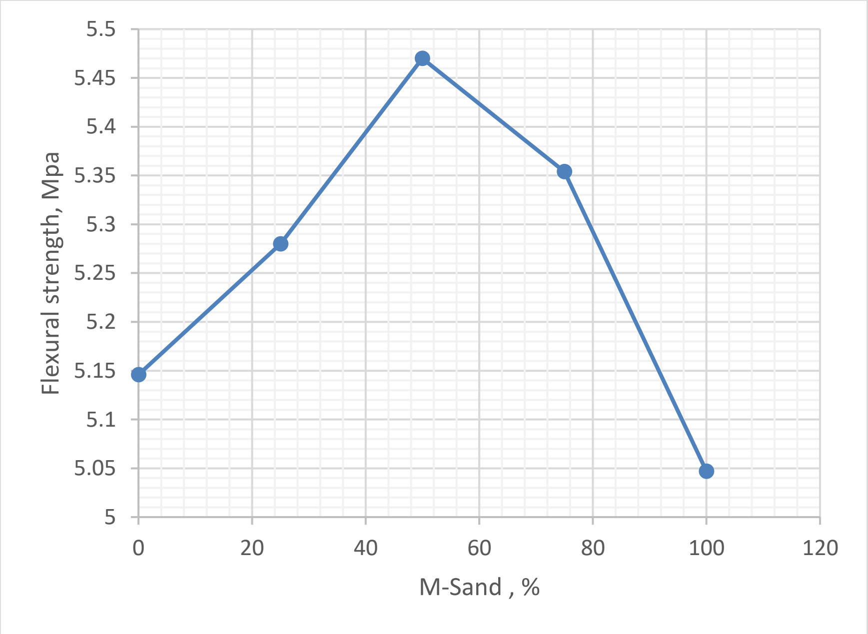

Figure 4.8 Flexural strength test results graph

It is observed that there is increase in the indirect tensile strength, direct tensile strength, shear strength and flexural or bending strength of the geopolymer concrete when the river sand was replaced with M-Sand . Based on the observations, all of the strength values are higher for M-Sand replacement. The optimum dosage of M-Sand replacement in river sand was 50%.

5. CONCLUSIONS

The study aimed to evaluate the mechanical properties of geopolymer concrete under both oven and ambient curing while assessing the impact of replacing river sand with manufactured sand

(M-Sand). Five different mix variations were tested to determine the optimal balance between strength and sustainability.

The findings revealed that while M-Sand and river sand share the same grading zone, their physical characteristics differ significantly. M-Sand particles are coarser, angular, and irregular compared to the rounded and globular nature of river sand. This variation in shape and texture influenced the compressive strength of geopolymer concrete.

As the proportion of M-Sand increased, the compressive strength of the concrete also improved, especially under ambient curing conditions. Among all the tested mixes, the concrete with 50% replacement of river sand with M-Sand exhibited superior strength at 28 days of ambient curing, surpassing even the strength results obtained from fly ash-based geopolymer concrete cured at elevated temperatures.

The percentage increase in compressive strength for 25%, 50%, 75%, and 100% replacement levels of river sand with M-Sand was recorded at 5.45%, 13.23%, 8.23%, and 3.8%, respectively. These results indicate that while higher M-Sand content contributes to strength enhancement, beyond a certain threshold, the benefits start to diminish.

Based on the experimental outcomes, the optimal replacement level of M-Sand in geopolymer concrete was identified as 50%, striking a balance between strength improvement and sustainable material utilization. This research highlights the potential of geopolymer concrete as a viable, eco-friendly alternative to conventional cement-based concrete, paving the way for greener construction practices.

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