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Enhancing Geo-Polymer Concrete Strength with Sustainable Ceramic Tile Waste as Partial Sand Replacement

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ABSTRACT

Concrete has long been the most widely used construction material due to its strength, versatility, and cost-effectiveness. However, conventional concrete production, particularly the use of Ordinary Portland Cement (OPC) as the primary binder, significantly contributes to environmental degradation. Cement manufacturing is responsible for the emission of approximately 0.8 to 1 ton of CO_2 per ton of cement produced, primarily due to the burning of fossil fuels and the processing of raw materials. This substantial carbon footprint contributes to global warming and climate change, creating an urgent need for sustainable alternatives. One promising solution is the development of geo-polymer concrete (GPC), which replaces OPC with alkali-activated binders derived from industrial by-products. In this study, fly ash and ceramic tile waste are utilized as primary binders in the production of eco-friendly geo-polymer concrete. The mixture is activated using sodium hydroxide (NaOH) at 14M concentration and sodium silicate (Na_2SiO_3) solution, eliminating the need for conventional cement. Additionally, ceramic tile waste is used as a partial replacement for fine aggregates (sand) in varying proportions: 10%, 20%, 30%, 40%, and 50%. To evaluate the mechanical performance of this sustainable concrete, compressive strength tests were conducted on specimens subjected to ambient curing (7 and 28 days) and oven curing at 60°C. The results indicate that compressive strength improves significantly with up to 20% fine aggregate replacement, beyond which a decline in strength is observed. The optimum strength is achieved under 60°C oven curing conditions, demonstrating the effectiveness of controlled curing in enhancing the mechanical properties of ceramic tile waste-based geo-polymer concrete.

This study highlights the potential of ceramic tile waste as a viable and sustainable alternative to natural sand in concrete production. By repurposing industrial and construction waste, this approach not only mitigates the environmental impact of cement production but also addresses the growing issue of ceramic waste disposal. Additionally, geo-polymer concrete reduces CO_2 emissions, conserves natural resources, and promotes a circular economy in the construction industry. In this research establishes that integrating ceramic tile waste into geo-polymer concrete mix designs is a feasible, eco-friendly, and high-performance alternative to conventional concrete. Future studies may explore additional modifications in mix proportions and long-term durability aspects to further enhance its suitability for large-scale structural applications.

Key words: Geopolymer concrete (GPC), Fly ash, Molarity, NaOH, Geo-Polymer Concrete (GPC), Alkali-Activated Binders

1. INTRODUCTION

Concrete is one of the most widely used materials in civil engineering due to its versatility, strength, durability, and cost-effectiveness. At the core of concrete production is Portland cement, which serves as the primary binding agent. However, with the increasing global demand for cement, there is an urgent need to explore alternative binders that can support infrastructure and housing development while mitigating the rising carbon dioxide (CO_2) emissions associated with cement manufacturing (Taylor et al., 2006). Cement production involves the thermal decomposition of limestone (calcium carbonate - $CaCO_3$) at high temperatures, leading to the formation of reactive calcium silicates and aluminates. Ordinary Portland Cement (OPC) is manufactured through a process that includes heating a blend of raw materials in a rotary kiln at approximately 1,450°C, cooling the resulting semi-molten clinker, and then finely grinding it with calcium sulfate to produce cement powder. This energy-intensive process releases significant CO_2 emissions, emphasizing the need for sustainable alternatives to reduce the environmental impact of concrete production.

The major raw material used is limestone i.e., calcium carbonate (CaCO3), which is blended with materials such as shales or clays to provide the necessary alumina and silica. The clinker is predominantly calcium silicate, which is rapidly cooled to stabilize a mixture of tricalcium silicate (3CaO.SiO2) and dicalcium silicate (2CaO.SiO2), with minor (but important) CaO-rich aluminates and alumino ferrite phases. The production of the clinker or Portland cement is an energy-intensive process and consumes 4 GJ per ton of cement. The manufacture of one ton of Portland cement clinker releases 0.8 to 1 ton of CO2 into the atmosphere, as indicated by the following calculations.

In cement manufacture, limestone (CaCO3) has to be decomposed as

$$CaCO_3\ (100) \rightarrow CaO\ (56) + CO_2\ (44)$$

One ton of cement contains 620 kg CaO, and hence CO_2 = 620 X 44/56 =487kg. CO_2 is also produced from fuel burning during the cement production. The amount is from 320 kg to about 450 kg and depends on the advances of the burning technique. Cement industry is responsible for the emission of approximately 5-8% of total CO2 emissions every year (Scrivener and Kirkpatrick, 2008 and Zongjin Li, 2011).

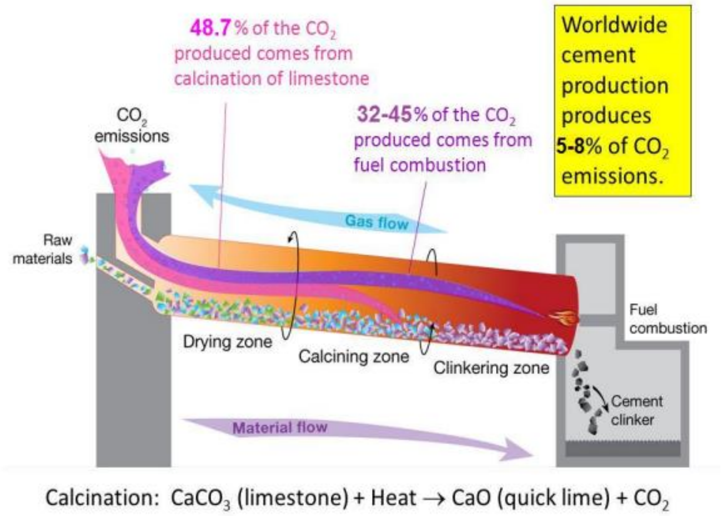


Fig.1.1 CO_2 emissions in cement manufacture
(Scrivener and Kirkpatrick, 2008 and Zongjin Li, 2011)

2. LITERATURE SURVEY

According to the American Concrete Institute (ACI) Committee 116R, fly ash is defined as 'the finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gasses from the combustion zone to the particle removal system' (ACI Committee 232 2004). Fly ash is removed from the combustion gases by the dust collection system, either mechanically or by using electrostatic precipitators, before they are discharged to the atmosphere. Fly ash particles are typically spherical, finer than Portland cement and lime, ranging in diameter from less than 1 μm to no more than 150 μm.

One of the efforts to produce more environmentally friendly concrete is to reduce the use of OPC by partially replacing the amount of cement in concrete with by-products materials such as fly ash. As a cement replacement, fly ash plays the role of an artificial pozzolan, where its silicon dioxide content reacts with the calcium hydroxide from the cement hydration process to form the calcium silicate hydrate (C- S-H) gel. The spherical shape of fly ash often helps to improve the workability of the fresh concrete, while its small particle size also plays as filler of voids in the concrete, hence to produce dense and durable concrete. Generally, the effective amount of cement that can be replaced by fly ash is not more than 30% (Neville 2000).

An important achievement in the use of fly ash in concrete is the development of high volume fly ash (HVFA) concrete that successfully replaces the use of OPC in concrete up to 60% and yet possesses excellent mechanical properties with enhanced 8durability performance. HVFA concrete has been proved to be more durable and resource-efficient than the OPC concrete (Malhotra 2002). The HVFA technology has been put into practice, for example the construction of roads in India, which implemented 50% OPC replacement by the fly ash (Desai 2004).

Any material that contains mostly Silicon (Si) and Aluminium (Al) in amorphous form is a possible source material for the manufacture of geopolymer. Several minerals and industrial by-product materials have been investigated in the past. Metakaolin or calcined kaolin (Davidovits 1999; Barbosa, MacKenzie et al. 2000; Teixeira-Pinto, Fernandes et al. 2002), ASTM Class F fly ash (Palomo, Grutzeck et al. 1999; Swanepoel and Strydom 2002), natural Al-Si minerals (Xu and van Deventer 2000), combination of calcined mineral and non calcined materials (Xu and van Deventer 2002), combination of fly ash and metakaolin (Swanepoel and Strydom 2002; van Jaarsveld, van Deventer et al. 2002), and combination of granulated blast furnace slag and metakaolin (Cheng and Chiu 2003) were investigated as source materials.

Low calcium (ASTM Class F) fly ash is preferred as a source material than high calcium (ASTM Class C) fly ash. The presence of calcium in high amount may interfere with the polymerisation process and alter the microstructure (Gourley 2003).

The most common alkaline activator used in geopolymerisation is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate (Davidovits 1999; Palomo, Grutzeck et al. 1999; Barbosa, MacKenzie et al. 2000; Xu and van Deventer 2000; Swanepoel and Strydom 2002; Xu and van Deventer 2002). The use of a single alkaline activator has been reported (Palomo, Grutzeck et al. 1999; Teixeira-Pinto, Fernandes et al. 2002).

Palomo et al (1999) concluded that the type of activator plays an important role in the polymerisation process. Reactions occur at a high rate when the alkaline activator contains soluble silicate, either sodium or potassium silicate, compared to the use of only alkaline hydroxides. Xu and van Deventer (2000) confirmed that the addition of sodium silicate solution to the sodium hydroxide solution as the alkaline activator enhanced the reaction between the source material and the solution. Furthermore, after a study of the geopolymerisation of sixteen natural Al-Si minerals, they found that generally the NaOH solution caused a higher extent of dissolution of minerals than the KOH solution.

The use of recycled materials in concrete manufacture has become more widespread in recent years. The use of recycled ceramic tile waste as aggregate in concrete would contribute to relieve industrial waste disposal problems and would help maintain natural aggregate resources.

Fengli et al. concluded that it is feasible to reuse recycled ceramic aggregate under 9.5 mm as partial replacement of natural aggregate in concrete. Since the apparent density of ordinary concrete is higher than that of recycled ceramic concrete (RCC), this can be helpful to reduce the self- weight of constructions. Under similar workability condition, when the replacement rate is lower than 20%, the splitting tensile strength of RCC is poor because the ultra-fine sand has high mud content. Moreover, when the replacement rate is greater than 40%, the compressive strength and splitting tensile strength are higher than those of the reference concrete. The use of 100% recycled ceramic as fine aggregate increases both splitting tensile strength and compressive strength significantly.

Atul Uniyal et al. They replaced the aggregates with tile powder by 5%,10%,15% and 20. From there tests they concluded the following: They found the most optimal percentage for the replacement of ceramic tile powder with cement was 15 %. Above this percentage the compressive strength of their concrete decreases.

Parminder Singh et al. They prepared three different concrete mix designs M 20, M 25 & M30 to find the effect of tile aggregates on strength of concrete and they replaced it with natural aggregates by proportion of 0%,5%, 10% & 20%. They found limited use of tile aggregate in concrete due to its flaky nature. After performing various tests they concluded that: Tile aggregate shows similar mechanical properties to that of normal aggregates but not completely same. They found out that the water absorption, crushing value and impact value, were higher than natural coarse aggregate without compromising the strength we can substitute 20% of normal 20mm aggregates in M20 grade concrete.

3 PROPOSED SYSTEM

The present work aims at evaluation of the response of ambient and heat cured geopolymer concrete in terms of its mechanical properties. The main objectives of the present project work are as follows.

1. To study the compressive strength development of ambient and oven cured geopolymer concrete by replacing 10.0% fly ash by Tile powder (TP) and fine aggregate by tile waste aggregate (TA).
2. To compare the mechanical properties of the Tile waste based geopolymer concrete (TWGC) cured under oven and in ambient conditions.

Fly ash samples are collected from NTPC Ramagundam, Telangana. Fly ash and tile powder were used as cementitious material in the replacement cement in concrete. River sand and tile waste aggregate were used as fine aggregate. Coarse aggregate was obtained from locally available sources. Combination of sodium hydroxide and sodium silicate solution was used as alkaline activator. In the experimental investigation, the evaluation mechanical properties of compressive strength of trail mix GPC.

3.1METHODOLOGY

1. Collect the Tile powder and sieved from IS Sieve 75microns. The passed from IS Sieve 75microns TP was collected and used for this project work.
2. The trail mix methodology geo polymer concrete adopted.
3. The fly-ash (class F), Tile powder prepared at laboratory with manual crushing process, Locally available river sand (ZONE - II) and coarse aggregates (NMAS 20) was used for this investigation.
4. The GPC, was cured with oven (60^0C) and ambient cured 7, 14, 28days.
5. The trail mix design mentioned below:

3.1.1 Mix design

The test specimens of 150mmx150mmx150mm cubes are used. Conventional method is adopted instead of Hobart pa mixer however conventional method is not applicable in larger applications but here the mixture proportion is different for different cubes. The main objectives of the preliminary laboratory work were:

- To familiarize with the making of fly ash-based geo-polymer concrete,
- To understand the effect of the sequence of adding the alkaline activator to the solids constituents,
- To observe the behaviour of the fresh fly ash-based geo-polymer concrete,
- To understand the basic mixture proportioning of fly ash-based geo-polymer concrete.

3.1.2 Mixture proportions

The main objective is to find compressive strength for GPC. Standard shape of 150mmx150mmx150mm cube taken and the density of geo-polymer concrete is assumed as 2500 Kg/m^3. The rest of the calculations are done by considering the density of concrete.

- The total volume occupied by coarse aggregate is adopted as 70-80%.
- The alkaline liquid to fly ash ratio is 0.3 to 0.5
- Ratio of sodium silicate solution-to-sodium hydroxide solution, by mass, of 0.4 to 2.5. This ratio is fixed at 2.5 for all mixtures.
- Molarity of sodium hydroxide (NaOH) solution taken as 14M.
- Super plasticizer 0 – 5% of total cementitious material,

4. RESULTS AND DISCUSSIONS

This chapter presents the results obtained from the tests (discussed in Chapter 4) conducted on Tile waste based geopolymer concrete specimens and their composites. First of all, the results of mechanical properties of GPC (100% fly ash), GPC with 90% fly ash – 10% tile powder and GPC with river sand replacing with tile waste aggregate (M0, M1, M2, M3, M4, M5, M6) specimens on mechanical properties and physical properties was presented.

4.1 Physical properties of Geo polymer concrete

Table 4.1 Physical properties of GPC cubes

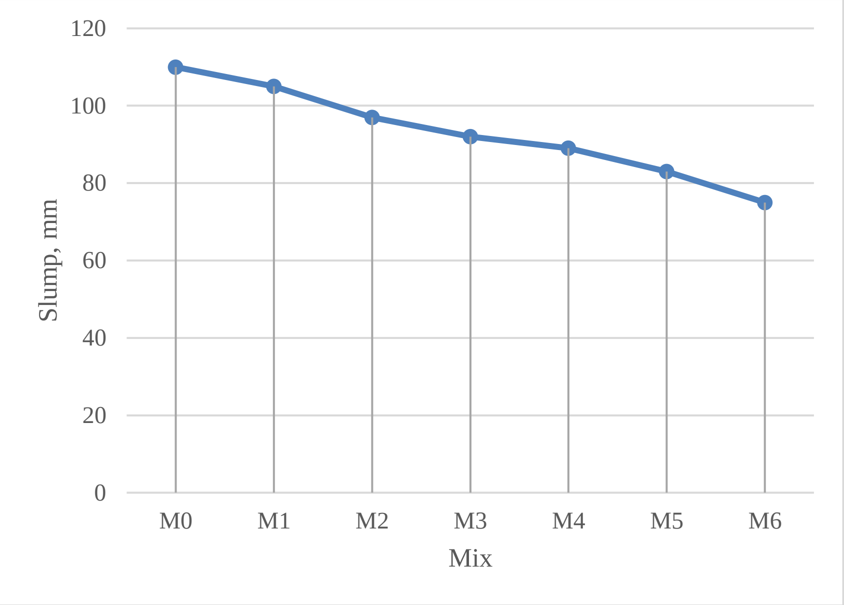
Mix No.	tile waste powder(%) - tile waste aggregate %	Shape and size test	Colour test	Structure test
M0	0% - 0%	For all cubes are cube shaped with sharp edges and size of 15 cm x 15 cm x 15 cm	All the cubes having the uniform colour for entire structure	There are no flaws, cracks or holes present on that broken face then that is a good quality
M1	10% - 0%			
M2	10% - 10%			
M3	10% - 20%			
M4	10% - 30%			
M5	10% - 40%			
M6	10% - 50%			

4.2 Fresh properties of Geo polymer concrete

The Slump cone test results of the Geo polymer concrete for the replacement of river sand with tile waste aggregate by 0, 10, 20, 30, 40 and 50 % are shown in table 5.2 and graphically represented in Fig 5.1.

Table 4.2 Slump cone test results

Mix No.	tile waste powder(%) - tile waste aggregate %	Slump value (mm)
M0	0% - 0%	110
M1	10% - 0%	105
M2	10% - 10%	97
M3	10% - 20%	92
M4	10% - 30%	89
M5	10% - 40%	83
M6	10% - 50%	75



Graph 4.1 Slump test results graph

It is observed that there is decrease in the workability of the Geopolymer concrete when the river sand is replaced with Tile waste aggregate. Based on the observations, all of the slump values are in the low workability range.

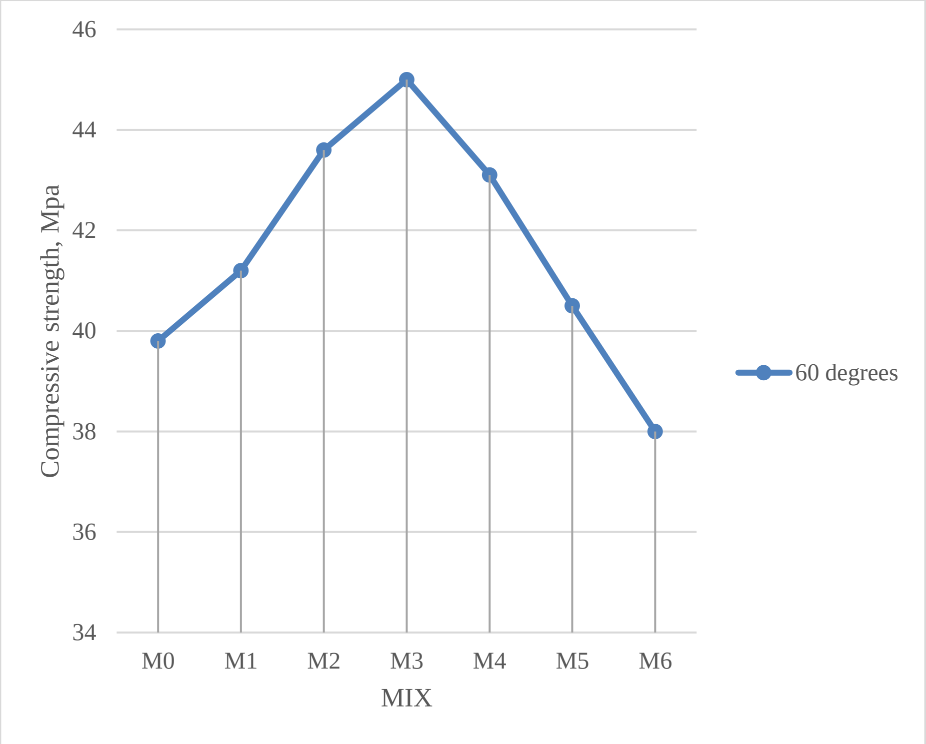
4.3 Harden properties of Geo polymer concrete

4.3.1 Oven curing

The compressive strength by oven curing under 60^0c results of the Geopolymer concrete for the replacement of river sand with tile waste aggregate by 0, 10, 20, 30, 40 and 50 % are shown in table 4.3 and graphically represented in Fig 4.2.

Table 4.3 Compressive strength test results (Oven curing)

Mix No.	tile waste powder(%) - tile waste aggregate %	Average Compressive strength (Mpa)
		60^0c
M0	0% - 0%	39.8
M1	10% - 0%	41.2
M2	10% - 10%	42
M3	10% - 20%	43.3
M4	10% - 30%	41.5
M5	10% - 40%	39
M6	10% - 50%	35.6



Graph 4.2 Compressive strength test results graph (Oven curing)

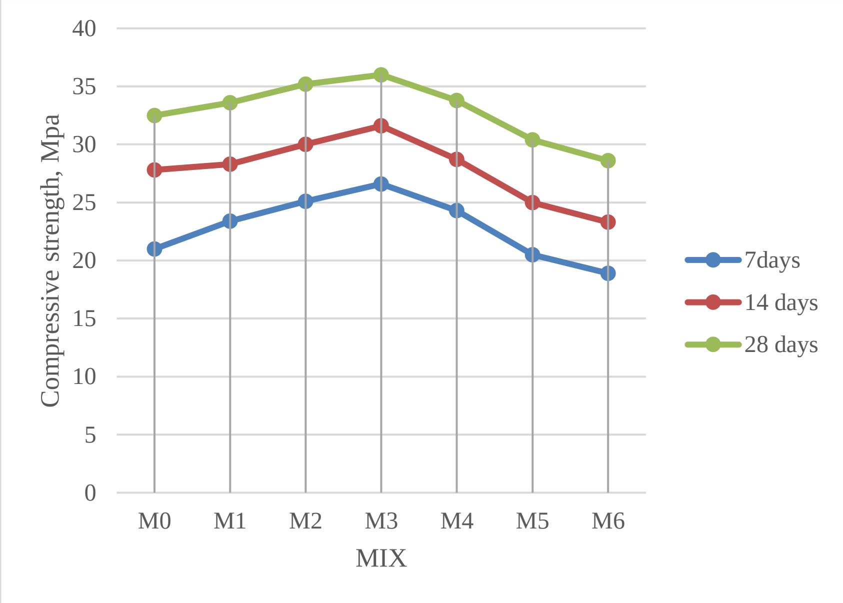
It is observed that there is increase in the compressive strength of the geo polymer concrete when the river sand was replaced with Tile waste aggregate. Based on the observations, all of the compressive strength values are higher for tile waste replacement. The optimum dosage of tile waste aggregate replacement in river sand was 20%.

4.3.2 Ambient curing

The compressive strength by ambient curing fewer than 7, 14 and 28 days results of the Geopolymer concrete for the replacement of river sand with tile waste aggregate by 0, 10, 20, 30, 40 and 50 % are shown in table 5.4 and graphically represented in Fig 5.3.

Table 4.4 Compressive strength test results (Ambient curing)

Mix No.	tile waste powder(%) - tile waste aggregate %	Average Compressive strength (Mpa)		
		7days	14 days	28 days
M0	0% - 0%	21	27.8	32.5
M1	10% - 0%	23.4	28.3	33.6
M2	10% - 10%	25.1	30	35.2
M3	10% - 20%	26.6	31.6	36
M4	10% - 30%	24.3	28.7	33.8
M5	10% - 40%	20.5	25	30.4
M6	10% - 50%	18.9	23.3	28.6



Graph 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 Tile waste. Based on the observations, the compressive strength values are higher for tile waste replacement. The optimum dosage of Tile waste replacement in river sand was 20%.

4.3.3 Comparison of curing based strength

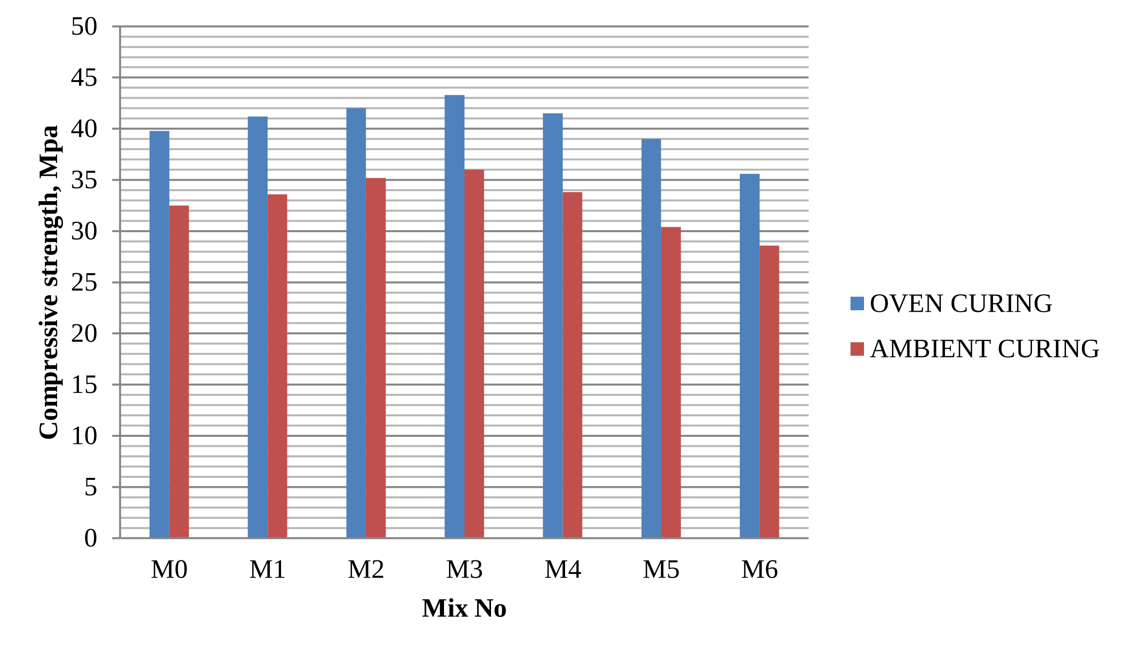
It is observed that there is increase in the compressive strength of the geopolymer concrete when the river sand was replaced with Tile waste aggregate. Based on the comparison of oven and ambient curing, the compressive strength higher for 28days ambient curing as compare to the oven curing.

For 28days ambient curing of geo polymer concrete, the percentage increase of compressive strength value for by 20% replacement of river sand with tile waste aggregate was 10.7%.

For 60^0c oven curing of geo polymer concrete, the percentage increase of compressive strength value for by 20% replacement of river sand with tile waste aggregate was 8%.

Table 4.5 Compressive strength test results comparison

Mix No.	tile waste powder(%) - tile waste aggregate %	Average Compressive strength (Mpa)	
		60^0c oven curing	28 days ambient curing
M0	0% - 0%	39.8	32.5
M1	10% - 0%	41.2	33.6
M2	10% - 10%	42	35.2
M3	**10% - 20%**	**43.3**	**36**
M4	10% - 30%	41.5	33.8
M5	10% - 40%	39	30.4
M6	10% - 50%	35.6	28.6



Graph 4.4 Compressive strength test results comparison graph

From the above graphs it shows that, for oven curing gained higher strength compare to the 28days ambient curing.

5. CONCLUSIONS

The use of waste construction materials is becoming increasingly important due to the growing volume of material waste resulting from urbanization and population growth. Among various waste materials, ceramic tile aggregates have gained attention due to their availability, affordability, and potential as an alternative to natural aggregates. This study aims to evaluate the mechanical properties of geo-polymer concrete (GPC) using ceramic tile waste in both oven-cured (60°C) and ambient-cured conditions. Additionally, the research investigates the partial replacement of 10% fly ash with tile powder in GPC. A total of seven different mix proportions were considered, with varying percentages of tile waste powder and tile waste aggregate (0%-0%, 10%-0%, 10%-10%, 10%-20%, 10%-30%, 10%-40%, and 10%-50%). The study revealed that ceramic tile aggregates possess properties suitable for use in geo-polymer concrete, effectively replacing fine aggregates. The compressive strength results indicated that 20% replacement of fine aggregate with tile waste yielded the highest strength among all tested mixes. Furthermore, a mix with 10% tile powder replacing fly ash and 20% tile waste replacing sand achieved higher strength compared to other replacement levels. The results also showed that oven curing at 60°C significantly enhanced compressive strength, with a 20% replacement of river sand with tile waste aggregates leading to an 8% increase in strength under oven curing and a 10.7% increase under ambient curing.

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