An investigation on the effect of curing conditions on the mechanical and microstructural properties of the geopolymer concrete

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Abstract
Geopolymer concrete represents the future of green and sustainable concrete. It has a large impact on the construction industry owing to its better performance than that of conventional Portland cement concrete. This study aimed to identify the effect of curing conditions on the physical, mechanical, and microstructural properties of specimens using ambient curing and oven-curing. In the experimental analysis, we tested slump and setting time for physical properties, density and drying shrinkage for chemical properties, compressive strength, indirect tensile strength, modulus of rupture, Poisson’s ratio, and elastic modulus for mechanical properties, rebound strength, and UPVT for nondestructive and x-ray diffraction, and thermogravimetric analysis for microstructural analysis. After the experimental analysis, it was concluded that the density, Poisson’s ratio, and dry shrinkage were higher for ambient-cured specimens than for oven-cured specimens, whereas the compressive strength, indirect tensile strength, modulus of rupture, and elastic modulus of oven-cured specimens were higher than those of ambient-cured specimens. The nondestructive tests, rebound tests, and UPVT show that the oven-cured specimens are better in quality and strength than the ambient cured specimens. In microstructural analysis, x-ray diffraction showed that the oven-cured specimens had a lower intensity of mineral oxides than the ambient-cured specimens in microstructural analysis. The matrix of the ambient-cured specimens was thermally stable up to 800 °C and retained 92% of its original mass, whereas the matrix of the oven-cured specimens retained 94% of its mass up to 800 °C in the thermogravimetric analysis.

Abbreviations

GPC Geopolymer concrete
OPC Ordinary Portland cement
GGBFS Ground granulated blast furnace slag
XRD X-ray diffraction
TGA Thermogravimetric analysis
SEM Scanning electron microscope
EDS Energy-dispersive x-ray spectroscopy
NaOH Sodium hydroxide
Na₂SiO₃ Sodium silicate
ASTM American society for testing and materials
ACI American concrete institute
UPV Ultrasonic pulse velocity
ELASTIC MODULUS Modulus of elasticity
SNF Sulphonated Naphthalene Formaldehyde
PCE Polycarboxylate ester

1. Introduction

GPC is in high demand in the present era due to its sustainability and economic quality. It is highly resistant to severe conditions for a long duration without degradation of strength. The flyash, GGBFS, metakaolin, rice husk ash, and pozzolanic materials contain high silica & alumina, except for silica fume used as a binding material in the GPC mix design (Verma and Dev 2018). The alkaline solution activates the pozzolans in the GPC mix, containing sodium or potassium hydroxide and sodium or potassium silicates (Krivenko and Kovalchuk 2007). It directly reduces the carbon footprint due to the replacement of the cement content in the concrete mix.

Around 8% of carbon dioxide is emitted during the cement production process all over the world. The geopolymerisation reaction occurs during the setting and strengthening of the geopolymer matrix. It contains the various phases of the reaction. The geopolymer matrix is primarily amorphous, and it has a three-dimensional inorganic structure. Equation (1) shows the initial reaction that occurs during geopolymerisation, called dissolution (Xu and Deventer 2002).

After the initial dissolution, the reaction reduces the water to build the end product, shown in the equation (2). Davidovits, in 1978, first gave the name of the reaction and product name called geopolymerisation and geopolymer an inorganic matrix. Geopolymers have different bonding than cement bonding in the matrix during strengthening(Davidovits 1989, Davidovits and Quentin 1991). The geopolymerisation reaction is affected by various parameters, like alkali metals present, silica/alumina ratio, the molarity of sodium or potassium hydroxide, and water content (Verma and Dev 2017). The PCE-based superplasticizer is used to obtain self-compacting concrete in Portland cement concrete (Verma and Nigam 2017), whereas the GPC obtains self-compacting concrete using an SNF-based superplasticizer without any destruction of strength or performance (Verma and Dev 2021c). The liquid-to-binder reaction is critical in the matrix-strengthening reaction (Verma and Dev 2021b). The GGBFS dosage increment in the mix reduces the workability and setting time (Verma and Dev 2021a). The sodium hydroxide molarity and alkaline ratio in the GPC mix design play an essential role in the strength development of concrete (Verma and Dev 2020).

\[
n(\text{Si}_2\text{O}_5\text{Al}_2\text{O}_3) + 2n\text{SiO}_2 + 4n\text{H}_2\text{O} + \text{NaOH} \rightarrow \text{Na}_n^+ \text{Si}_n\text{O}_{2n+2} \text{Al}^3-\text{OH}_2 - n\text{S} - n\text{OH}_3
\]

(1)

\[
n(\text{OH})_3 - \text{Si} - \text{O} - \text{Al}^3-\text{OH}_2 - \text{O} - \text{Si} - (\text{OH})_3\text{NaOH} \rightarrow \text{KOH} (\text{Na}_n^+, \text{K}_n^+) (\text{Si} - \text{O} - \text{Al}^3-\text{O} - \text{Si} - \text{O} - ) + n\text{H}_2\text{O}
\]

(2)

Fog-cured samples have a more significant proportion of absorption. This phenomenon might be connected to the geopolymer matrix’s ability to retain water, resulting in a more open microstructure in this form of concrete (Bondar et al. 2010, Bondar et al. 2015). Heat curing helps speed up the geopolymerisation procedure since compressive strength may be created at a young age (Albitar et al. 2015). The oven-drying curing specimens generated 90% of the 28-day compressive strength in 3 days, whereas the ambient-curing specimens attained 57–82 percent. Nevertheless, the ultimate strength of the ambient-curing specimens was somewhat more remarkable than the matching oven-drying cured specimens at 28 days. After 7 days, there is no discernible improvement in compressive strength in the oven-cured specimens (Islam et al. 2015).

The curing temperatures have an impact on the elastic modulus of alkali-activated concrete. The static modulus of elasticity rose with increasing curing temperature until it reached a limit that appears to be connected to the water to binder ratio at an early age. The static modulus of elasticity falls if water is lost owing to evaporation during curing at a higher temperature before the full strength is achieved. The compressive strength of geopolymer concrete is unaffected by a 60-min rest interval between the casting of specimens and the start of curing (Hardjito et al 2004).

The presence of water in the geopolymer and its subsequent removal by evaporation certainly plays a role in achieving a crack-free geopolymer. The fine structure of the microporosity would determine the capillary pressure of occluded water that would promote cracking, and further precise studies in this direction are necessary (Finnie et al 2007). The addition of water, 10M NaOH solution, and NSF also affect the flow and strength. The addition of these liquids improves the geopolymer mortars’ workability. Water is shown to be the
most effective, resulting in a significant increase in flow with just a minor drop in strength. The addition of a 10 M NaOH solution enhances the flow marginally while keeping the geopolymer mortar’s strength. Water and Na ions are necessary for the geopolymerisation process since they are part of the geopolymer system. The addition of NSP to geopolymer mortars does not influence the flow of the mortars (Sathonsaowaphak et al 2009). The workability of concrete improves as the amount of time spent mixing it by hand grows, with a maximum of 20 to 30 min being advised (Kumar et al., 2015).

With initial and ultimate setting durations of almost 3 and 10 h, respectively, increasing the mixing time can considerably delay the setting of water glass-activated slag pastes. It provides a practical, effective method of limiting the quick unfavorable setting of these materials, potentially simplifying a wide range of technological applications (Palacios et al 2008). When high molarity NaOH is employed, a naphthalene sulphonate polymer-based superplasticizer has little to no influence on the slump and negatively influences fly ash-based geopolymer concrete. When added as an addition to the binder, the conventional superplasticizer usually employed with ordinary Portland cement does not appreciably improve the overall workability of the mix. On the contrary, it reduces the geopolymer matrix’s strength. The performance of concrete with superplasticizer at elevated temperatures is similarly lacking. The use of superplasticizers in geopolymer concrete for high-temperature performance is not recommended (Kong and Sanjayan 2010).

The cure period ranged from 4 to 96 h (4 days). The polymerization process was enhanced with a more extended curing period, resulting in increased compressive strength. Up to 24 h of curing time, the rate of development in strength was high; beyond that, the growth in strength was only modest. As a result, the heating curing duration does not need to exceed 24 h (Lloyd and Rangan 2010). Higher compressive strength is achieved by heating over 6 to 24 h. The rise in strength after 12 h, however, is not considerable (Patankar et al. 2014).

The longer pre-curing at room temperature in an atmosphere of more than 95% relative humidity is helpful for more significant strength development before heat application (Kani and Allahverdi 2009). The temperature influence depends on the period of curing. Curating at high temperatures for merely 1 h was not responsible for significant changes in strength development, but for prolonged treatment, the reaction rate had been significantly accelerated, and strength had increased at an early age (Rovnaník 2010). The combination of interaction between fly ash and GGBFS controls geopolymerisation at 60°C. The C-S–H and A–S–H gels in the reaction products confirm this interaction. This enhancement in the compressive strength of the slag addition can be caused by the development and compactness of the microstructure of the gel (C–S–H and A–S–H). Mixing the concrete materials is essential to getting a dense mix or proper mix in the final concrete pouring or molding. The GPC specimens are highly resistant severe conditions compared to conventional concrete specimens (Kumar et al. 2021, Kumar et al. 2022).

According to the findings of (Nematollahi and Sanjayan 2014), fly ash based Geopolymer paste activated by only NaOH solution (8.0 M concentration), naphthalene (N) based SP (second generation) was a useful type, resulting in a 136% increase in relative slump without having any adverse effect on the compressive strength when compared to the fly ash-based Geopolymer paste without using any SP. The most effective type of modified polycarboxylate (PC) based SP (latest generation) was found to be the most effective in the case of fly ash based Geopolymer paste activated by multi-compound activator (Na2SiO3/NaOH = 2.5), resulting in a 39–45 percent increase in relative slump and a maximum 29 percent decrease in compressive strength when compared to the fly ash based geopolymer paste without the use of any SP. It was discovered that the polycarboxylate-based superplasticizer had a retarding impact on alkali-activated fly ash/ slag pastes while having no influence on the heat of hydration, and that it enhanced the workability more considerably than the naphthalene-based superplasticizer in this study. The presence of polycarboxylate-based superplasticizers at concentrations more than 2 weight percent had a favorable influence on the development of compressive strength before 7 days, but it might have a negative effect beyond this time period (Jang et al 2014). Because of its intrinsic stability in alkaline media, it is possible to achieve the largest reduction in yield stress in alkali-activated slag cements by including a naphthalene-derivative HRWRA into NaOH-activated slag pastes and mortars. In contrast, the other admixtures used in alkali-activated slag pastes and mortars have little effect on the rheological characteristics of the mixes under consideration (Palacios et al. 2008).

2. Experimental program
The three major sections are materials and their properties, synthesis or mixing and casting, and experimental test setups.

2.1. Materials
It includes coarse aggregates with a maximum size of 20 mm and M-sand as a fine aggregate on substitute sand, locally accessible primary substances used in the GPC. For triggering the pozzolanic binder, water and
superplasticizers are used. Flyash and GGBFS were utilized as binders in GPC and alkaline solutions. Figure 1 describes the raw materials in pictorial form to work on a new mix without destroying its strength and durability.

2.1.1. Aggregates

Delhi stone dust sand is used in the laboratory for sampling and testing. The sample weight obtained is 1000g for sand/stone-dust gradation, and the weight retained or passed through many sieves is calculated. Figure 2 shows the gradation curve of the coarse and fine aggregates. The modulus of fineness is an empirical fact that is added to each standard sieve, ranging from 80 mm to 150 mm, and divided by an arbitrary number of 100. That is why the fineness modulus = \( (10.7 + 4.05 + 61.9 + 74.9 + 87.6) / 100 = 2.756 \). The sand is medium since the fineness module ranges from 2.6 to 2.9. The sand is grade II, with a passing percentage of a 600 sieve of between 35 and 59. From the grading curve, the coefficient of 12 is greater than 6, and the coefficient of curvature is 1.33 and is calculated as \( D_{10} = 0.1, D_{30} = 0.4, D_{60} = 1.2 \). The sand is so well classified. The specific gravity of the substances examined and their values of 2.62 and 1.21%, respectively, for the pycnometer. The silt and bulk densities are 6% and 1610 kg m\(^{-3}\), respectively. Table 1 depicts the properties of fine aggregates (stone dust).

The aggregates 20 mm and 10 mm are employed in the GPC mix design as 60/40 mass ratio. The sieve analysis is conducted for particle size and coarser aggregate graduation. The sample fineness modulus \( (13.2 + 41.85 + 78.45 + 95.15 + 99.6 + 5 \times 100) / 100 = 7.29 \). The fineness modulus, specific gravity,
water absorption, crushing value, impact value, abrasion value, flakiness index, and elongation index of coarse aggregates were examined in the laboratory. All qualities of coarse units are suggested under the Indian standard regulations for construction purposes. The specific gravity, water absorption, crushing value, impact value, abrasion value, flakiness index, and elongation index of the aggregate samples are 2.79, 0.2%, 23%, 22%, 8%, 24%, and 30%, respectively (IS 2386 Part I (1997), IS 2386 Part III (1997), IS 2386 Part IV (1997), IS 2386 Part V (1997), IS 383 1970, 1997). Table 2 depicts the properties of coarse aggregates.

### Table 2. Properties of coarse aggregate.

| S. No. | Test               | Results          |
|-------|--------------------|------------------|
| 1.    | Fineness Modulus   | 7.29             |
| 2.    | Specific Gravity   | 2.79             |
| 3.    | Water absorption   | 0.2%             |
| 4.    | Crushing Value     | 23%              |
| 5.    | Impact Value       | 22%              |
| 6.    | Flakiness Index    | 24%              |
| 7.    | Elongation Index   | 30%              |
| 8.    | Abrasion value     | 8%               |

Table 1. Properties of fine aggregate/stone dust (M-Sand).

| S. No. | Test                     | Results          |
|--------|--------------------------|------------------|
| 1.     | Zone                     | Zone II          |
| 2.     | Grade                    | Well Graded      |
| 3.     | Fineness Modulus         | 2.756 (Medium sand) |
| 4.     | Specific Gravity         | 2.62             |
| 5.     | Water absorption         | 1.21%            |
| 6.     | Silt Content             | 6%               |
| 7.     | Bulk density             | 1610 kg/m$^3$    |

Table 3. Chemical composition.

| Minerals            | Flyash | GGBFS  |
|---------------------|--------|--------|
| SiO$_2$             | 45.8   | 34.52  |
| Al$_2$O$_3$         | 21.4   | 20.66  |
| CaO                 | 13.7   | 32.43  |
| Fe$_2$O$_3$         | 12.6   | .57    |
| MgO                 | 1.3    | 10.09  |
| SO$_3$              | 1.9    | .77    |
| LOI$^a$             | 0.1    | 0.3    |

LOI $^a$ Loss of Ignition

### 2.1.2. Alkaline solution

As chemical solution components, sodium hydroxide and sodium silicate activate pozzolanic materials such as flyash and GGBFS. The sodium hydroxide and sodium silicate were purchased from Central Drug House (P) Ltd. The 96 percent minimum test in acidimetric form demonstrates its appearance as a white deliquescent flake with solubility in a 10% solution in water. In the design of the GPC mix, sodium silicate, which is also a component of the alkaline solution, is employed to activate the Flyash and GGBFS. It is a thick, tacky/slightly hazy liquid that is miscible with water and has a minimum assay of Na$_2$O titrimetric of 10% and a specific gravity of 1.42.

The alkali activators (include sodium hydroxide and sodium silicate) were mixed before 20–24 h, it not includes the superplasticiser. The alkali solution is made before 24 h due the activation of sodium silicate to react with the binding materials mineral oxides.

### 2.1.3. Superplasticizer and water

Conplast SP 430 is based on SNF, utilized as a superplasticizer in the GPC design mix. It has the appearance of a dark liquid and has up to 2% air entrainment with a specific gravity of 1.18 at 25 °C (IS 9103 1999 1999). Tape water is used in the GPC mix design, which has a 6-pH level.
2.1.4. Pozzolans
Flyash is produced in thermal power plants as a byproduct of coal combustion for electricity generation. Flyash is harvested at the Guru Nanak Dev Thermal Plant in Bhatinda, Punjab, India. Flyash is classified as Class C in the ASTM C618–2019 standard (ASTM C 618 19, 2019). Table 3 provides the chemical compositions of the sample materials, and figure 3(b) shows a scanning electron microscopy image of the porous spherical flyash particles. The elemental component graph of the material analyzed by EDS is depicted in figure 3(d). The XRD graph of samples is shown in the figure 3(a).

GGBFS is produced by isolating molten slag with the assistance of high-pressure water jets. Because molten slag separation precludes crystallization, the final products are glassy and granular aggregates. The finished
product is crushed, pulverized, and segregated for a variety of purposes. GGBFS is working on a project at the Bhilai Steel Plant in Durg, Chhattisgarh, India. Table 3 reveals the chemical contents of the sample materials, and figure 3(c) shows a scanning electron microscopy image showing the porous indeterminate form of GGBFS particles. The elemental component graph of the material analyzed by EDS is depicted in figure 3(e).

2.2. Synthesis
For one batch, all of the basic materials are mixed into a 40-litre capacity mix. Figure 4(a) shows a picture of the pan mixture during mixing. The alkaline chemical and the sodium hydroxide, sodium silicate, and superplasticizer were mixed 24 h before casting. At the time of mixing, pour the coarse aggregate into the combination, then the sand or fine aggregate and thoroughly mix, then the chemical into the mix, and finally the extra water as needed during the mixing. Mix the concrete for 10–15 min in the pan mixture (IS 12119 1987, 1999). The appropriately mixed concrete plastic paste is formed in the moulds for the cubes, cylinders, and beams (IS 1199 1959, 1959, IS 10086 1982, 2008). After three days of casting, the specimens were de-molded and cured in the oven for 24 h, shown in the figure 4(b), and in ambient-curing, shown in figure 4(c). Table 4 summarizes the raw material mix composition for the GPC. The molarity of the sodium hydroxide and liquid to binder ratio are taken 14 M, 6 from the references (Verma and Dev 2021b).

There are two types of curing is showed in the manuscript that are ambient-curing and oven-curing. In the ambient curing, the samples were kept in the open surroundings or environment without any changes. The samples were hardened and strengthen continuously with the increment of age. In the oven-curing, the samples were kept in the oven for 24 h at temperature of 80 °C after demoulding. The humidity factor is not included in the research parameters, but it would be maintained around 90–95.
2.3. Test setups
All experiments are carried out in the concrete laboratory on the GPC mix in its fresh or hardened state.

2.3.1. Physical properties tests
The slump test is used to determine the workability of a fresh geopolymer concrete blend. The top diameter, bottom diameter, and height of the slump apparatus are 100 mm, 200 mm, and 300 mm, respectively. Millimetres are used to measure the slump (IS 7320 1974, 2008).

The setting time of the fresh GPC was found through the penetrometer test on the concrete sample. It determines both the initial setting time and the final setting time of the fresh sample (ASTM C403/C403M 16 2019).

2.3.2. Chemical properties tests
Density is used to assess the chemical properties of GPC mix samples. Before the 28-day destructive inspection, the weight of cube samples was used to test the density of the mix design. It directly indicates the hardness and strength of the concrete specimens (ASTM C138/C138M 17a 2019).

The drying shrinkage occurs in the concrete specimens after the evaporation of water from the mix or formation of end products of the bond because end products take less volume than the volume of the raw products, and the length comparator of the concrete or mortar specimens is at the micron reading level (ASTM C157/C157M 08 2008).

2.3.3. Mechanical properties tests
The GPC mix designs cubic samples of dimension 150 mm *150 mm *150 mm are used to test the compressive strength of the specimens. The samples were tested in an axial loading mode on a universal Testing Machine at a loading rate of 5.2 kN/s (IS 516 1959, 2004).

The splitting tensile strength of cylindrical samples with diameters and heights of 150 mm and 300 mm is measured. In the universal testing machine, transverse loads are applied to the cylinder to investigate the splitting tensile strength of the GPC cylinder specimens (IS 5816 1999 1999).

The width, height, and length of the beam sample are 100 mm, 100 mm, and 500 mm, respectively, for measuring the flexural strength of the GPC mix design. At the flexural testing machine, the beam specimen was subjected to a two-point load or flexural tensile test to determine the flexural strength of the GPC mix specimen (IS 9399 1979, 1979).

The cylindrical samples have a diameter of 150 mm and a length of 300 mm, and they would be used to measure the modulus of elasticity and Poisson’s ratio of the GPC mix design. In the universal testing machine, the axial load is applied to the cylinder to analyze the vertical and horizontal strain of the GPC cylinder specimen to measure the modulus of elasticity and Poisson’s ratio (ASTM C469/C469M 14 2019).

2.3.4. Non-destructive tests
Those tests conducted in the laboratory and the field to detect strength or quality without destruction are non-destructive tests.

The rebound test is based on the apparatus’s check of surface hardness, and it is performed on cube samples 7 days, 14 days, 28 days, 42 days, and 56 days after casting. It was performed on all types of sample cubes and cylinders to determine the strength of the mixed sample (IS 13311-2 (1992)).

The ultrasonic pulse wave frequency travels through the sample in the UPVT. The greater the UPV indicates, the greater the strength and efficiency of the GPC specimen. Two transducers, an electrical pulse generator, an amplifier, and an electronic timing unit, are used in the research apparatus. The ultrasonic pulse wave is sent through the transducers and an electronic timing machine (IS 13311 Part1 1992).

### Table 4. Mix design of GPC.

| Material                  | Quantity (kg m$^{-3}$) |
|---------------------------|------------------------|
| Flyash                    | 303.75                 |
| GGBFS                     | 101.25                 |
| Coarse Aggregates (20 mm) | 761                    |
| Coarse Aggregates (10 mm) | 508                    |
| Fine Aggregates/Stone dust| 683                    |
| Sodium Hydroxide          | 46.28                  |
| Sodium silicate           | 115.72                 |
| Superplasticiser          | 4.05                   |
| Water                     | 20.25                  |
2.3.5. Microstructural analysis

The microstructural analysis checks the effect of various parameters on the geopolymer matrix chemistry. The bond-forming or chemical reaction end products phase analysis is performed in the laboratory using an XRD test to determine if the phase formation is crystalline or amorphous with oxides (ASTM D934 13, 2014). The TGA tests the thermal stability of the materials up to 800 °C. The temperature increases at 10 °C m−1 and continuously checks the sample’s weight retention from room temperature to 800 °C.

3. Results and discussion

All the experimental tests and their results are described briefly in this section and discussed in the prior works of literature.

3.1. Physical properties

The physical property analysis tests the workability and initial & final setting time of the GPC. The slump test is used to find workability, whereas the penetrometer test is used to find the initial and final setting time of the fresh GPC. Table 4 describes the mixed design of the raw content of the GPC. The value of the fresh GPC is found at 75 mm, whereas the initial setting time and final setting time are 70 min and 160 min, respectively.

3.2. Chemical properties

Their chemical properties mean that chemistry directly plays a vital role in their denseness and their shrinkage. It includes the density and drying shrinkage of the GPC mix design specimens.

3.2.1. Density

The density of the GPC mix design was determined by the cube specimen’s weight 28 days after its casting. It is easily calculated through the equation of mass by volume. The ambient-cured specimens’ density is higher than the oven-cured specimens. The density of the ambient cured specimens, and oven-cured specimens average 2494 kg m−3 and 2487 kg m−3. Hardjito et al (2004) also stated that the density of the ambient-cured flyash-based GPC is higher than the oven or heat cured specimens.

3.2.2. Drying shrinkage

The drying shrinkage of the GPC mix design was determined through the length comparator tested at 7, 14, 28, 42, 56, 70, and 84 days after the casting. Figure 5 describes the graph of both cured GPC mix specimens tested on various days. It shows that the ambient cured GPC mix specimens got higher drying shrinkage than the oven-cured specimens. The dried shrinkage occurred in 95% of the tests, with only minor variations. The ambient cured specimen and oven-cured specimen maximum drying shrinkage found in the 84-day test was 729 microns and 538 microns. According to (Palacios and Puertas 2011), the drying shrinkage of ambient-cured specimens is greater than that of heat-cured specimens (Palacios et al 2008, Palacios and Puertas 2011). Drying shrinkage occurs in the conventional concrete due to the evaporation of capillary water from matrix, and its increases with the increment of surrounding temperatures, but in the geopolymer concrete the wetting curing is not done. The oven-cured specimens fasten the reaction and make the bonds faster and retain the water content in the matrix,
whereas in the ambient-cured specimens’ matrix the reaction occurring is slower and the water evaporation are higher with the time.

3.3. Mechanical properties
The mechanical properties of the GPC mixed design are determined through the various tests being conducted on the specimens. It includes the poison ratio, elastic modulus, compressive strength, indirect tensile strength, and flexural strength of the GPC mix design.

3.3.1. Poisson’s ratio
The Poisson’s ratio of the GPC mix design is determined in the UTM cylinder specimen test. The Poisson’s ratio is directly calculated by the ratio of lateral strain to the linear strain. These strains are determined by the testing of the cylinder in UTM applying longitudinal loading on the specimen. LVDT is used to directly get the results of strains, including both linear and lateral. The ambient cured specimens have a higher Poisson’s ratio than the oven-cured specimens. Ambient-cured and oven-cured specimens have Poisson’s ratios are .16 and .14, respectively.

3.3.2. Elastic modulus
The cylinder specimens determine the elastic modulus of the GPC mix design. It is calculated through the stress-strain relation using a stable modulus as per the IS code. It demonstrates that the elastic modulus of ambient-cured specimens is lower than the elastic modulus of oven-cured specimens. The elastic modulus of ambient cured and oven cured specimens is 22.1GPa and 24GPa, respectively.

3.3.3. Compressive strength
Concrete’s compressive strength, also known as its characteristic strength, is a fundamental mechanical property. It is determined through the tests conducted on the cube specimens as per the IS code in the UTM. The uniaxial static load was applied during the compressive strength test on cube specimens, and figure 6(a) describes the graph between compressive strength versus time of both cured specimens. The tests were performed on specimens 7, 14, 28, 42, and 56 days that had been cast on both ambient cured and oven-cured specimens. It shows that the oven-cured specimens have a higher compressive strength than the ambient cured specimens.

The specimen’s compressive strength was found to be around 95% after a 28-day test. Nagalia et al (2016) stated that the compressive strength increases with the temperature increment (Nagalia et al 2016). According to (Heah et al 2011), ambient-curing of GPC specimens delayed setting time and resulted in more significant strength formation than ambient-cred specimens (Heah et al 2011). The compressive strength of the ambient-cured and oven-cured specimens was 24.8 MPa and 35 MPa after 28 days, respectively.

3.3.4. Splitting tensile
The splitting tensile strength is also called indirect tensile strength, determined through the tests conducted on the cylinder specimens in which the load was applied statically along the lateral direction of the specimens. This test is also conducted on the UTM. Figure 6(b) describes the graph between the splitting tensile strength versus time of both ambient-cured and oven-cured specimens.

It shows that the oven-cured specimens have a higher strength than the ambient-cured specimens. The tests were performed on specimens 7, 14, 28, 42, and 56 that had been cast on both ambient cured and oven-cured specimens. It also has a similar strength pattern to compressive strength. The maximum splitting tensile strength of ambient-cured and oven-cured specimens is 4 MPa and 5.2 MPa at 56 days, respectively.

3.3.5. Flexural strength
The modulus of rupture is another name for flexural strength. It could be determined through the prism shape of specimens tested in the flexural testing machine. All of the specimens were subjected to a two-point static load in the lateral direction. The tests were performed on specimens 7, 14, 28, 42, and 56 days that had been cast on both ambient cured and oven-cured specimens.

Figure 6(c) describes a graph between the flexural strength and age of concrete specimens of both cured samples. It shows a similar pattern of flexural strength to the compressive strength and splitting tensile. The oven-cured specimens have a higher flexural strength than the ambient-cured specimens. A 28-day test of both ambient-cured and oven-cured specimens revealed 98% flexural strength. The flexural strength of the ambient-cured and oven-cured GPC specimens was 3.8 MPa and 5.5 MPa in a 28-day test, respectively. It has a compressive strength of approximately 16%. The ratio of flexural strength to the compressive strength of the GPC specimens is higher than conventional Portland cement concrete (Joseph 2015).
3.4. Non-destructive tests

The non-destructive test is used to determine the strength or quality of a concrete specimen without causing it to be destroyed. It comprises the rebound hammer test as well as the UPV test.

3.4.1. Rebound strength

According to the IS code, the rebound strength shows the similar compressive strength of the concrete specimens with a precision of 20%. The surface hardness of the specimen determines the specimen’s strength. All cube specimens of both cured conditions were tested for rebound strength on 7, 14, 28, 42, and 56 days after casting and before the destructive test on the samples. The rebound strength of oven-cured samples is greater than that of ambient-cured samples of the same GPC mix, and figure 6(d) describes the graph of rebound hammer test strength with the age of the GPC of both ambient-cured and oven-cured specimens. It shows a very similar pattern of strength to the compressive strength of the GPC specimens.

The rebound strength of ambient-cured specimens and oven-cured specimens is 26.1 MPa and 35.9 MPa after 28 days, respectively. Thus, in the 28-day tests performed on specimens of both cured conditions, approximately 98% of the strength was measured.

![Figure 6](image_url)
3.4.2. UPVT
The UPV test is used to determine the intensity or quality of an ultrasonic pulse wave by monitoring its passing time. The time would increase if the quality or strength of the specimens deteriorated. The UPV test detects the development of a crack inside the specimen. UPV tests are performed on cube samples of GPC mix 7 days, 14 days, 28 days, 42 days, and 56 days after casting and before destructive testing on the samples. The device measures the duration of the UPV wave and computes the velocity, which determines the quality of GPC samples.

Figure 6(e) describes the graph between UPV versus age of the GPC of both ambient-cured and oven-cured specimens. It shows a similar pattern to the rebound strength graph, which shows that the oven-cured specimen’s UPV is higher than the ambient-cured specimens. After 56 days of testing, the maximum UPV of ambient-cured and oven-cured specimens is 3.12 km s$^{-1}$ and 4.61 km s$^{-1}$, respectively.

3.5. Microstructural analysis
The microstructural analysis of the GPC matrix shows the internal chemistry occurs in the different conditions determined through the various tests: XRD analysis, FTIR analysis, SEM analysis, and TGA-DTG analysis. In addition, it describes the internal chemistry that directly affects the performance of the specimen, which includes both strength and durability properties.

3.5.1. XRD
The XRD examination of the materials defines the intensity of the different oxides contained in the material. The XRD test is performed on tiny particles in powder form that are less than 150 microns in size. It specifies the intensity of the mineral oxide count in the sample. Figure 7 depicts an XRD graph of GPC samples, including (A) ambient-cured GPC specimens and (B) oven-cured GPC specimens. It demonstrates that the intensity of the oven-cured sample is lower than that of the ambient-cured sample due to the decrease of the oxide mineral components during oven-curing. However, the intensity pattern of both cured samples follows a similar trend. After 28 days, a sample is obtained from the destructive test on the cube and chosen as the optimal strength combination for the XRD test. The XRD test results describe the crystal shape of the mineral oxides and their intensities in the correct pattern. The quartz (silica) has the most prominent peak in the pattern in both cured conditions.

3.5.2. SEM Analysis
The SEM analysis of both conditions cured hardened GPC specimens depicts the differences of the chemical reaction that occurred, in which check the image at the 2-micron level. The ambient-cured specimens hardened linearly with the time passage, whereas the oven-cured specimens got the strength or hardened spontaneously. The oven-drying condition accelerates the geopolymerisation reaction and strengthens the specimens at an early age. Figure 8 shows the SEM images of (a) ambient-cured specimen and (b) oven-cured GPC specimen. It shows that the ambient-cured specimens show fewer pores than the oven-cured specimen image. The oven-cured
specimens reduce the water from the matrix after curing. The geopolymer paste matrix provides honeycomb structures after the elevated temperature exposure (Fan et al 2018).

3.5.3. TGA

TGA-DTG tests provide thermal analysis of materials, evaluating weight as the temperature increases at a rate of 10 °C per minute up to 800 degrees celsius. The TGA-DTG test sample is produced in the lab by grinding and sieving the materials to 150-microns. The graph of TGA-DTG of A) ambient-cured B) oven-cured specimens of the GPC mix is shown in the figure 9. It demonstrates that the weight preserved as a percentage of oven-cured samples is more significant than ambient-cured samples up to 800 °C. The weight preserved by ambient-cured and oven-cured samples is 92% and 94%, respectively, since some water evaporates during the curing time in the oven-cured specimens. In addition, the sample materials have far better stability than other concrete materials, such as OPC concrete. At 800 °C, it lowers weight by up to 8% and exhibits a similar derivative pattern.

4. Correlation between mechanical properties

GPC mechanical characteristics demonstrate a linkage to each other after a long-term experimental examination. Based on the findings of destructive experiment testing of various specimens, the correlation equation between compressive strength, splitting strength, flexural strength, and elastic modulus was presented.
4.1. Correlation between splitting tensile strength and compressive strength

The proposed equation (3) between the compressive strength and splitting strength relationship in fly ash-slag-based GPC was developed through experimental research into various tests performed on the same mix design and using two types of curing: ambient-curing and oven-curing. Figure 10 shows the graph of correlation equation generation between compressive strength and splitting tensile strength. Equation (4) from the ACI committee’s report on high strength concrete and equation (5) presented by the Euro-International committee for concrete in CEB/FIP in 1990 (International, Cof E 1990, Russell et al 1997). The equation (6) for the connection between splitting and compressive strength is provided by an ACI standard and report (ACI 318–14) (Committee 2014). The connection equation was proposed by Ahmed et al (7), and Ryu et al. suggested the equation (8) to predict splitting strength based on GPC compressive strength(Ryu et al 2013, Ahmed et al 2020). Gardener et al represented the correlation between the splitting tensile equation (9), whereas Raphael et al proposed a correlation equation (10) between splitting tensile and compressive strength (Gardner and Poon 1976, Gomes et al 2020). In their book published by Tayler & Francis, De-larrard also proposed a correlation equation (11) (Larrard 1999). Table 5 depicts the all-correlation equations described in the literature and analyses the various correlation equations numerically between the splitting tensile and compressive strength.

\[ f_{st} = -0.92 + 0.16f_c \]  

\[ f_{st} = 0.59\sqrt{f_c} \]  

\[ f_{st} = 0.301f_c^{0.67} \]  

\[ f_{st} = 0.56f_c^{0.5} \]  

\[ f_{st} = 0.462f_c^{0.55} \]  

\[ f_{st} = 0.17f_c^{0.75} \]  

\[ f_{st} = 0.6f_c^{2/3} \]  

\[ f_{st} = f_c^{7} \]  

\[ f_{st} = 0.6 + 0.06f_c \]

Where; \( f_c \) is characteristic strength in MPa, \( f_{st} \) is flexural strength in MPa

4.2. Correlation between flexural strength and compressive strength

In the oven curing situation, GPC specimens of various mixes obtained compressive strength and flexural strength, which provides the equation (12) of the correlation between the compressive strength and flexural strength and the other equations presented by other authors or codes. Figure 11 shows the graph of correlation

![Figure 10. Correlation graph between the compressive strength and splitting tensile strength.](image-url)
equation generation between compressive strength and flexural tensile strength. The ACI Committee’s equation (13) in the state-of-the-art report on high-strength concrete and equation (14) are elaborated on in the ACI committee’s building code requirements for structural concrete. AS 3600–2009 specifies the RCC design technique and equation (15) relating flexural strength to compressive strength (Concrete 2009). Equation (16) from the Indian code of practice for plain and reinforced concrete and equation (17) from Ahmed’s 2014 international journal of structural engineering, vol. 5. Bellum et al presented the link between compressive and flexural strength in equation (18). Mhaiskar and Naik proposed a correlation equation (19), whereas Juki et al the equation (20) (Juki et al 2013). Table 6 depict the suggested equation in conjunction with the other related equations.

\[
Proposed \quad Eq.: \quad f_{\beta} = -1.23 + 0.19f_c 
\]

\[
ACI363R - 92: \quad f_{\beta} = 0.94\sqrt{f_c} 
\]

\[
ACI \quad 318 - 99: \quad f_{\beta} = 0.62\sqrt{f_c} 
\]

\[
AS \quad 3600: \quad f_{\beta} = 0.6\sqrt{f_c} 
\]

\[
IS \quad 456 - 2000: \quad f_{\beta} = 0.7\sqrt{f_c} 
\]
Where; $f_{c}$ is characteristic strength in MPa, $f_{fs}$ is flexural strength in MPa.

### 4.3. Correlation between the elastic modulus and compressive strength

The elastic modulus assesses the resistance capacity of the elastic deformation caused by the applied load. GPC’s elastic modulus was calculated using ASTM C469/469M-14. Following the experimental research, the connection equation (21) between elastic modulus and compressive strength was presented for elastic modulus prediction based on compressive strength. Figure 12 shows the graph of correlation equation generation between compressive strength and elastic modulus. The elastic modulus of typical concrete is anticipated using equation (22) for density ranges ranging from 1442 to 2483 kg m$^{-3}$ (Committee 2014), according to ACI 318–14.
Table 7. Correlation between the splitting tensile and compressive strength equations.

| fc  | Proposed Eq | ACI 318–14 | CEB-FIP | IS 456–2000 | Lee & Lee | Nath & Sarker | Bellum et al | Hardjito et al | Diaj-loya et al |
|-----|-------------|------------|---------|------------|-----------|--------------|-------------|---------------|----------------|
|     | $E_c = (15080 + 240f_c)$ | $E_c = 0.43\times f_c^{1.5}$ | $E_c = 0.85\times f_c^{1.5}$ | $E_c = 500\times f_c^{1.5}$ | $E_c = 5300\times f_c^{0.5}$ | $E_c = 3510\times f_c^{0.5}$ | $E_c = 3282\times f_c^{0.5}$ | $E_c = 2707\times f_c^{0.5}$ | $E_c = 0.037\times f_c^{1.5}$ |
| 15.00 | 18680.00 | 20367.98 | 20919.65 | 19364.92 | 13070.92 | 13594.17 | 12711.13 | 15784.17 | 17698.03 |
| 17.50 | 19280.00 | 22215.96 | 22022.67 | 20916.30 | 13760.11 | 14683.38 | 13729.39 | 16624.19 | 19116.05 |
| 20.00 | 19880.00 | 23749.85 | 23025.06 | 22360.68 | 14386.41 | 15697.20 | 14677.35 | 17406.07 | 20435.92 |
| 22.50 | 20480.00 | 25190.53 | 23947.02 | 23717.08 | 14962.47 | 16649.39 | 15567.89 | 18140.43 | 21675.57 |
| 25.00 | 21080.00 | 26553.15 | 24802.99 | 25000.00 | 15497.29 | 17550.00 | 16410.00 | 18835.00 | 22848.06 |
| 27.50 | 21680.00 | 27849.17 | 25603.63 | 26220.22 | 15997.55 | 18406.60 | 17210.95 | 19495.63 | 23963.24 |
| 30.00 | 22280.00 | 29087.51 | 26357.11 | 27386.13 | 16468.33 | 19223.06 | 17976.25 | 20126.85 | 25028.79 |
| 32.50 | 22880.00 | 30275.24 | 27069.81 | 28504.39 | 16913.64 | 20010.08 | 18710.28 | 20732.27 | 26030.79 |
| 35.00 | 23480.00 | 31418.10 | 27746.83 | 29580.40 | 17336.65 | 20765.44 | 19416.57 | 21314.83 | 27034.18 |
| 37.50 | 24080.00 | 32520.83 | 28392.34 | 30618.62 | 17739.97 | 21494.27 | 20098.06 | 21876.92 | 27983.04 |
| 40.00 | 24680.00 | 33587.37 | 29009.75 | 31622.78 | 18125.75 | 22199.19 | 20757.19 | 22420.57 | 28900.76 |
(ACI Building Code). For typical concrete, the CEB-FIP provides an equation (23) for elastic modulus prediction based on compressive strength (International, C of E 1990). The Indian standard code represents the equation (24) for estimating elastic modulus for average weight conventional concrete, IS 456 2000 (2000) Lee and Lee suggested equation (25) to predict the elastic modulus of GPC (Lee and Lee 2013) and Nath and Sarker provided equation (26) to predict the elastic modulus of ambient-cured low-calcium fly ash blended GPC; (Nath and Sarker 2017). Bellum et al. suggested equation (27) to estimate elastic modulus using fly ash-GGBFS-based GPC (Bellum et al. 2019). Hardjito et al. proposed a correlation equation between elastic modulus and compressive strength of the flyash-based GPC. Table 7 depicts the suggested equation in conjunction with the other related equations.

\[
\begin{align*}
\text{Proposed} & \quad E_c = 15.08 + 0.24f_c'\quad \hfill (21) \\
\text{ACI 318 - 14:} & \quad E_c = 0.043 \times \rho^{1.5} \times \sqrt{f_c'}\quad \hfill (22) \\
\text{CEB - FIP:} & \quad E_c = 0.85 \times 2.15 \times 10^4(f_c'/10)^{1/3} \quad \hfill (23) \\
\text{IS 456 - 2000:} & \quad E_c = 5000\sqrt{f_c'}\quad \hfill (24) \\
\text{Lee and Lee:} & \quad E_c = 5300f_c'^{1/3}\quad \hfill (25) \\
\text{Nath and Sarker:} & \quad E_c = 3510\sqrt{f_c'}\quad \hfill (26) \\
\text{Bellum et al:} & \quad E_c = 3282\sqrt{f_c'}\quad \hfill (27) \\
\text{Hardjito et al:} & \quad E_c = 2707\sqrt{f_c'} + 5300\quad \hfill (28) \\
\text{Diajło et al:} & \quad E_c = 0.037 \times \rho^{1.5} \times \sqrt{f_c'}\quad \hfill (29)
\end{align*}
\]

Where $E_c$ is elastic modulus in MPa, $\rho$ is the density of the concrete in kg/m$^3$ and $f_c'$ is characteristic strength in MPa

5. Conclusions

This conclusion is based on all results from the experimental investigation conducted on the GPC identical mix design specimens. All types of specimens cured in both types of conditions are ambient-cured and oven-cured. After the experimental investigation generates the correlation equations among the mechanical properties are as follows

- The ambient cured GPC mix specimens got higher density and drying shrinkage than the oven-cured specimens.
- The ambient cured specimens have a higher Poisson’s ratio than the oven-cured specimens, whereas the oven-cured specimen’s elastic modulus is higher than the ambient-cured specimens.
- The oven-cured specimens have a higher compressive strength, splitting tensile, and flexural strength than the ambient cured specimens.
- The rebound strength and UPV of oven-cured samples are more significant than the ambient-cured samples of the same GPC mix.
- The intensity of the oven-cured sample is lower than the ambient-cured sample due to the decrease of the oxide mineral components during oven-curing. However, the intensity pattern of both cured samples follows a similar trend.
- The weight preserved as a percentage of oven-cured samples is more significant than ambient-cured samples up to 800°C. The weight preserved by ambient-cured and oven-cured samples is 92% and 94%, respectively.
- As per the experimental results, proposed the correlation equation between compressive strength and splitting tensile strength is $f_{st} = -0.92 + 0.16f_c$, correlation equation between compressive strength and flexural strength is $f_{fs} = -1.23 + 0.19f_c$ and correlation equation between the compressive strength and elastic modulus is $E_{c} = 15.08 + 0.24f_c'$. 


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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Declarations

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The authors declare that they have no conflicts of interest in this work.

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Code availability

Not applicable

Authors contributions

All authors were involved in every phase of the paperwork, and all authors read and approved the final manuscript.

Ethics approval

Not applicable

Consent to participate

All the authors are informed about the submission and consent to publish the manuscript.

Consent for publication

The authors give their consent for publication.

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All authors declared that the manuscript follows all the ethical standards.

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