International Journal of Creative and Open Research in Engineering and Management
ISSN: **3108-1754 (Online)**
Volume 02 Issue 04 April-2026 | Impact Factor: 3.5

# Effect of Mix Proportion and Curing Conditions on Compressive Strength of Geopolymer Concrete

**[1]Manoj Kumar Patel, [2]Akhand Pratap Singh, [3]Prof. R.R.L. Birali**
[1]M.Tech. Scholar[1], [2]Assistant Professor, [3]Professor
Department of Civil Engineering
[1,2]Shri Rawatpura Sarkar University, Raipur
[3]MATS University, Aarang - 493441, Raipur

**How to Cite this Article**:

Patel, M. K. (2026). Effect of Mix Proportion and Curing Conditions on Compressive Strength of Geopolymer Concrete. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(04). https://doi.org/10.55041/ijcope.v2i4.650



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**Abstract:-** Geopolymer Concrete is an eco-friendly and sustainable construction material that utilizes industrial by-products rich in silica and alumina, such as Fly Ash and Ground Granulated Blast Furnace Slag (GGBS), in combination with alkaline activators like Sodium Hydroxide (NaOH) and Sodium Silicate ($Na_2SiO_3$). The binding mechanism in Geopolymer concrete is based on polymerization, which eliminates the need for Ordinary Portland Cement (OPC) and significantly reduces carbon dioxide emissions. The construction industry is a major contributor to environmental pollution due to large-scale production of OPC, where approximately one ton of $CO_2$ is emitted per ton of cement produced. In this context, Geopolymer concrete emerges as a promising alternative for sustainable development. This study focuses on the effect of mix proportion and curing conditions on the compressive strength of Geopolymer concrete. Different proportions of Fly Ash and GGBS were used to prepare Geopolymer mixes and their strength behavior was evaluated under varying curing conditions, including ambient curing and dry heat curing at elevated temperatures. Cube specimens of size 150 × 150 × 150 mm were cast and tested for compressive strength at different curing ages.

The results indicate that the compressive strength of Geopolymer concrete increases with an increase in GGBS content and a corresponding decrease in Fly Ash content. It was also observed that heat curing significantly enhances early strength development compared to ambient curing. Furthermore, geopolymer concrete continues to gain strength beyond 28 days, unlike conventional OPC concrete. The rest period prior to curing and curing temperature were found to play a crucial role in strength development. In this study, the ratio of Sodium Silicate to Sodium Hydroxide ($Na_2SiO_3$:NaOH) was maintained at 1.8. A super-plasticizer dosage of 1.5% of the total binder content (Fly Ash + GGBS) was used to improve workability, along with additional water amounting to 10% of the binder content. The findings of this study aim to determine optimum mix proportions and curing conditions for geopolymer concrete using materials readily available in the Indian market.

**Keywords:** Geopolymer Concrete, Fly Ash, GGBS, Mix Proportion, Curing Conditions, Sodium Hydroxide, Sodium Silicate, Compressive Strength.

# 1. Introduction

One of the most critical challenges faced in the present era is global warming, primarily driven by the emission of greenhouse gases. The cement industry is a major contributor to this issue, as it releases a significant amount of carbon dioxide and other pollutants into the atmosphere. In comparison to conventional Portland cement-based binders, alternative binders have demonstrated considerable environmental and economic advantages. These alternatives are not only cost-effective but also contribute to reduced environmental impact.

In recent years, there has been a growing emphasis on sustainable construction materials and practices. This has led to extensive research and development aimed at identifying suitable alternatives to Ordinary Portland Cement (OPC). Among these, Geopolymer Concrete (GPC) has emerged as a promising solution. It utilizes industrial by-products such as fly ash and slag, resulting in significantly lower carbon emissions. Due to its reduced environmental footprint, GPC can be considered a more sustainable and eco-friendly construction material compared to conventional concrete. Although Geopolymer technology is relatively modern in its current form, its fundamental principles have historical relevance. Some studies suggest that similar binding mechanisms might have been used in ancient constructions such as the pyramids of Giza. Despite its potential, the large-scale application of Geopolymer concrete is still limited. However, rapid advancements are being observed in regions such as Europe and Australia, where research is focused on overcoming practical challenges associated with its use. One of the major challenges in the adoption of Geopolymer concrete is the handling of highly alkaline activating solutions and the requirement of controlled curing conditions, particularly elevated temperatures. To address these limitations, ongoing research is directed towards developing more practical and user-friendly Geopolymer systems that minimize the need for high alkalinity and complex curing processes. Although the technology is still evolving, its superior durability and long-term performance make it a suitable candidate for specialized applications, including structures exposed to aggressive environmental conditions such as bridges. To promote awareness and advancements in this field, various workshops and technical programs are being organized both in India and internationally. These initiatives involve contributions from leading researchers, including experts from organizations such as CSIR–SERC, and provide valuable insights into emerging trends and technologies in geopolymer research.

## 1.1 Problem Statement

One of the biggest challenges faced by the world today is global warming and climate change. A major reason for this is the emission of greenhouse gases such as carbon dioxide, nitrogen oxides, and sulphur oxides. The total global emission of carbon dioxide is about 23 billion tonnes per year, which is a very large and concerning amount. Out of this, the Portland cement industry alone contributes nearly 7%. The production of Portland cement requires about 2 tonnes of raw materials to produce 1 tonne of cement, and during this process, approximately 0.87 tonnes of carbon dioxide is released into the atmosphere. In addition, around 3 kg of nitrogen oxides, ground-level smog, and about 0.4 kg of very fine particulate matter (less than 10 microns) are also emitted. These fine particles are harmful to human health, especially the respiratory system.

Although efforts are being made to reduce emissions by improving technology and efficiency, there is a limit to these improvements because cement production mainly depends on the calcination of limestone. Limestone mining also creates environmental problems such as land degradation, disturbance of water systems, and air pollution. Since the cement industry handles huge amounts of dry materials, even a small percentage of dust released into the air can be harmful to both humans and the environment. Therefore, dust emission remains a major issue.

From a sustainability point of view, the cement industry cannot be considered fully sustainable because it depends on mining and its products are not recyclable. To address this issue, industrial by-products such as fly ash from thermal power plants and slag from the steel industry can be used as alternative binders instead of cement. This approach can reduce the consumption of natural resources, lower energy usage, and decrease greenhouse gas emissions. In this way, waste materials can be converted into useful construction materials like geopolymer concrete.

## 1.2 Objectives

- To study how the compressive strength of geopolymer concrete changes with different percentages of Fly Ash and GGBS.
- To evaluate the compressive strength of concrete at 3, 7, 28, and 56 days.
- To analyze the effect of different curing temperatures on strength.
- To understand the importance of the rest period in geopolymer concrete.
- To use industrial waste materials as a replacement for cement and develop an eco-friendly concrete.

### 1.3 Scope of the Project Work

The production of Ordinary Portland Cement (OPC) releases a large amount of carbon dioxide, which is a major cause of global warming. Therefore, there is a need for an alternative eco-friendly material to reduce environmental impact. Geopolymer concrete can serve as a suitable replacement for OPC. Geopolymer concrete uses industrial waste materials such as Fly Ash and Ground Granulated Blast Furnace Slag (GGBS), which are produced in large quantities by thermal power plants and steel industries. Using these materials helps in solving the problem of waste disposal. In addition, the use of geopolymer concrete can reduce carbon dioxide emissions and support sustainable construction. Since these materials are waste products, they are also more economical compared to cement, making geopolymer concrete a cost-effective and environmentally friendly solution.

## 2. Methodology

Material was collected from suitable location and was sent to laboratory to know the chemical composition of different materials. After the results were obtained, materials were finalized to use in GPC for e.g. Fly Ash was tested to know whether the fly ash is Class C fly ash or Class F fly ash. Similarly, properties of GGBS, Sodium Silicate were also found out.

## 3. Material Used

### 3.1 Fly Ash

Fly Ash was obtained from NTPC Thermal Power Plant, Sipat located in Bilaspur district of Chhattisgarh, which is approximately 120 km from Raipur. The coal for the power plant is sourced from nearby coal mines of the Korba region in Chhattisgarh.

The sample of Fly Ash was submitted to a NABL approved testing laboratory in Raipur, Chhattisgarh to determine its physical and chemical properties. The table below shows the properties of Fly Ash:-

***Table 3.1: Properties and Composition of Fly Ash Used in Mix***

| S. No. | Parameters | Test Results | Requirements as in IS:3812 (P-1) : 2013 (SPFA) | Method of Test w.r.t. IS. |
|---|---|---|---|---|
| **A.** | **Physical Properties:-** | | | |
| **1** | Specific Gravity | 2.21 | ----- | 1727:1967 |
| **2** | Fineness ($m^2/kg$) | 360 | 320 Min | 1727:1967 |
| **3** | Particles Retained in 45μ sieve | 20.8 | 34 Max | 1727:1967 |
| **4** | Lime Reactivity, $N/mm^2$ | 5.1 | 4.5 Min | 1727:1967 |
| **5** | Compressive Strength at 28 days, % by PCM | 89.6 | 80% of the corresponding PCM cubes, Min | 1727:1967 |
| **6** | Soundness by Autoclave Test expansion % | 0.052 | 0.8 Max | 1727:1967 |
| **B.** | **Chemical Properties:-** | | | |
| **1** | $SiO_2+Al_2O_3+Fe_2O_3$ % by Mass | 90.6 | 70.0 Min | 1727:1967 |
| **2** | $SiO_2$ % by Mass | 48.2 | 35.0 Min | 1727:1967 |
| **3** | Reactive Silica % by Mass | 27.8 | 20.0 Min | 3812 (P-1):2003 |
| **4** | MgO % by Mass | 2.5 | 5.0 Max | 1727:1967 |
| **5** | Total Sulphur as $SO_3$, % by Mass | 1.2 | 3.0 Max | 1727:1967 |
| **6** | Total Chlorides, % by Mass | 0.017 | 0.05 Max | 4032:1985 |
| **7** | Loss on Ignition, % by Mass | 1.1 | 5.0 Max | 1727:1967 |

The above test parameters, sample complies with requirements of IS: 3812 (P-1):2013 (SPFA). Also the above fly ash complies with ASTM C618 Low calcium Fly Ash and can be called as Class F Fly Ash.

### 3.2 GGBS

Commercially available GGBS of JSW brand was obtained having following chemical properties:-

***Table 3.2: Chemical Composition of Ground Granulated Blast Furnace Slag used in Mix***

| **Parameter** | **JSW GGBS** | **Asperis:12089–1987 (Reaffirmed2008)** |
|---|---|---|
| Cao | 37.34% | --- |
| $Al_2O_3$ | 14.42% | --- |
| $Fe_2O_3$ | 1.11% | --- |
| $SiO_2$ | 37.73% | ---` |
| Magnesium Oxide (Mgo) | 8.71% | Max.17.0%` |
| Manganese Oxide (MnO) | 0.02% | Max.5.5% |
| Sulphide Sulphur | 0.39% | Max.2.0% |
| Loss on Ignition | 1.41% | --- |

The results showed that the presence of $SiO_2$ and $Al_2O_3$ in considerable amount confirmed that JSWGGBS can be used to partially replace Fly Ash. However, high amount of CaO may cause hindrance in polymerization of GPC.

### 3.3 Sodium Silicate Solution

Commercially available Loba Sodium Silicate Solution Extra Pure was obtained having following physical and chemical properties:-

***Table 3.3: Properties and composition of Sodium Silicate***

| **S. No.** | **Particulars** | **Properties** |
|---|---|---|
| 1 | Physical state at $20^0$ C | Liquid |
| 2 | Ph Value | 11.2 |
| 3 | Boiling Point [$^0$C] | $100^0$ C |
| 4 | Vapour Pressure [$20^0$C] | 14 mm Hg @ $20^0$C |
| 5 | Vapour Density | 0.7 |
| 6 | Solubility in Water [% weight] | Soluble in water |
| 7 | Colour | Opaque Viscous |
| 8 | Melting point/ Freezing Point [$^0$C] | $0.6^0$ C |
| 9 | Evaporation | >1 |
| 10 | Vapour Pressure mm/Hg | 14 mm Hg @ $20^0$C |
| 11 | Density [$g/cm^3$] | 1.39 |

**Specification:-**

***Table 3.4: Specification of Loba Sodium Silicate***

| | |
|---|---|
| Appearance | Clear colorless solution |
| Assay (as $Na_2O$) | 7.5-8.5% |
| Assay (as $SiO_2$) | 25-28% |
| Free alkali | Passes test |

Clearly, from the above table, $Na_2O$:$SiO_2$ ratio can be seen to have anywhere between 2.9 to 3.73 which is considered to be an important parameter and affects ultimate strength of GPC.

### 3.4 Sodium Hydroxide and Preparation of Solution of Desired Molarity

Sodium Hydroxide is a common chemical and can be obtained easily in any chemical shop. In this study, Sodium Hydroxide obtained was in pallet form. To prepare solution of desired molarity, the calculation is shown below taking example to prepare 16M solution:-

Different types of units are used to express concentration of a solution. The most common unit of expressing concentration of a solution is molarity. Molarity (M) is the concentration of a solution expressed as the number of moles of solute per litre of solution:

$$Molarity = \frac{(Number\ of\ moles\ of\ solute)}{Volume\ of\ solution\ in\ litre}$$

### 3.5 Super-plasticizer

The super-plasticizer used in this study was obtained from an authorized distributor, Fosroc Chemicals (India) Pvt. Ltd.- Raipur Distributor, and is commercially available under the brand name Conplast SP430. This super-plasticizer is naphthalene-based, unlike the newer generation polycarboxylate-based super-plasticizers commonly used in the concrete industry.

### 3.5.4 Properties

***Table 3.5: Properties of Super-plasticizer***

| | |
|---|---|
| Specific Gravity | 1.24 to 1.26 * |
| Chloride Content | Nil to IS:456* |
| Air Entrainment | Approx.1% additional air is entrained |

## 4. Experimental Work

### 4.1 Determination of Water Absorption and Specific Gravity for Coarse Aggregates

### 4.1.1 Procedure

The aggregate to be tested is washed properly so that any dust on the surface is removed and then any excess water is drained and around 2 kg of aggregate is placed inside the wired basket and the basket is immersed in the bucket filled with water. The wired basket should be immersed in such a way that it has a cover of at least 50 mm of water at the top. The temperature of the water should be maintained anywhere between 20° to 30°C. The entrapped air between the aggregates is removed by lifting the basket up and down several times and after the entrapped air is removed the basket along with the aggregates is kept immersed in water filled bucket for period of 24 hours. After 24 hours, by the time when aggregate has absorbed water, the basket along with aggregates is weighed while immersed in water by suspending it with digital weigh balance. The weight is noted down and marked as W1 g.

***Figure 4.1: Weight of Aggregate Along With Wired Basket Immersed in Water Filled Bucket***

After this the basket and aggregates are removed from the water and the excess surface water is allowed to be drained. Then the aggregate is transferred onto a dry cloth and aggregates are rubbed with the cloth to bring them into the surface dry condition. The wired basket is again returned into the water filled bucket and air bubbles are removed by shaking the basket in water and then the weight of empty basket in immersed condition is noted down and marked as W2 g.
By the time the aggregate transferred onto the absorbent cloth have come onto saturated surface dry condition i.e. no further water/moisture can be removed with help of cloth. At this point, the surface dried aggregate is weighed on a weigh balance by transferring it onto a tray. The tray should be tarred first or the weight of tray should be subtracted

separately from the total weight to get the weight of SSD aggregates. This weight of SSD aggregates is marked as W3 g. Then the Aggregate along with the tray is kept into the oven where the temperature is set to 110°C for 24 hours. Next day, the tray is removed, cooled down and it is then weighed and marked as W4 g. Similarly, at least 2 observations are to be carried out.

**4.1.4 Calculation**

Weight of wired basket + saturated aggregate immersed in water = W1g
Weight of wired basket immersed in water = W2g
Therefore, Weight of saturated aggregate in water = W1 –W2 = Wsg
Weight of saturated surface dry aggregate = W3g
Weight of water equal to the volume of the aggregate = W3-Ws
Weight of oven dried aggregate = W4g

**Observation**

| | 7 mm | 14 mm | 20 mm |
|---|---|---|---|
| W1 | 1665 | 4080 | 2370 |
| W2 | 535 | 535 | 535 |
| Ws | 1130 | 3545 | 1835 |
| W3 | 1803 | 3377 | 2996 |
| W3-Ws | 673 | 168 | 1161 |
| W4 | 1785 | 3316 | 1785 |

1. Water Absorption = $\frac{[(W3-W4)\times 100]}{W4}$

For 7 mm aggregate, Water absorption =1.0084%
For 12 mm aggregate, Water absorption = 1.83%
For 20 mm aggregate, Water absorption = 0.9774%

2. Specific Gravity = $\frac{(Dry\ weight\ of\ aggregate)}{Weight\ of\ equal\ volume\ of\ water\ as\ that\ of\ aggregate}$

$\frac{W4}{W4-Ws} = \frac{W4}{W3-(W1-W2)}$

For 7 mm aggregate, Specific Gravity=2.6523
For 12 mm aggregate, Specific Gravity = 2.67
For 20 mm aggregate, Specific Gravity = 2.555

**Limits**: The specific gravity of aggregate ranges should be between 2.5 to 3.0.
The water absorption of aggregates should be between 0.1 to 2.0%.

**4.2 Determination of Water Absorption and Specific Gravity for Coarse Aggregates**

***Figure 4.2: Pycnometer***

1. A weigh balance having ability to measure weight between 0.5g to 3.0 kg. The weigh balance should be of such a type that it should be able to weigh the pycnometer filled with water and sand.
2. A heat oven to maintain temperature of above 100°C. Preferably 110°C.
3. A tray to weigh and keep the sand inside oven.
4. Agitating rod, funnel and a set of filter paper.

**4.2.3 Procedure**

1 kg sample of sand to be tested for the above listed properties shall be collected in a tray and should be filled with distilled water. It should be kept in mind that the sand to be tested must pass from IS 4.75 mm sieve and the w = temperature of distilled water shall be anywhere between 20°C to 30°C. After the sand has been immersed the sand should be shaken gently with help of agitating rod. This is done in order to escape out the air bubbles entrapped with in the sand. Leave the sample in immersed condition for 24 hours. Next day, the water from the tray should be drained very carefully by passing it through a filter paper. Any sand particles that are entrapped in the filter paper shall be returned back into the tray. After this the saturated sand should be stirred with agitating rod for time till the sand achieves surface dry condition and no extra water is seen on the sample. This can be made out from observing the free movement of each sand particle without actually sticking with each other due to excess water. Then the saturated surface dry sand shall be weighed and marked as A. Then this sample shall be introduced into a pycnometer filled with distilled water. This will emit out any air entrapped in the sand. The pycnometer shall also be rotated around its axis to take care of any extra air bubbles and make sure that they are emitted out. Then the pycnometer shall be completely filled with distilled water up to its apex. Any water droplets sticking to the pycnometer on outer surface shall be wiped off and whole assembly shall be weighed and marked as B. Then all of the sand along with water shall be transferred from pycnometer to the tray. Care shall be taken that whole sand particles are transferred. Then the pycnometer should be filled with distilled water again up to its apex like before and weighed and marked as C. Then water contained in the tray having sample shall be drained off by allowing it to pass through filter paper and again any particles of aggregate entrapped in filter paper shall be returned into the tray. The sample along with the tray shall be then placed inside an oven where temperature of 110°C shall be maintained. Then the sand shall be weighed and marked as D. At least 2 observations shall be made.

**4.2.4 Calculations**

1. Water absorption $= \frac{\boldsymbol{A-D}}{\boldsymbol{D}} \times 100$

$$= \frac{\mathbf{500-496}}{\mathbf{496}} \times \mathbf{100} = 0.80\%$$

Therefore water absorption of fine aggregate is 0.80%

2. Specific Gravity $= \frac{D}{A-(B-C)} \times \mathbf{100}$

$$= \frac{496}{500-(1826-1514)} \times \mathbf{100} \quad = 2.64$$

Therefore the specific gravity of fine aggregate is 2.64.

## 5. Mix Design

### 5.1 Mix Design Procedure

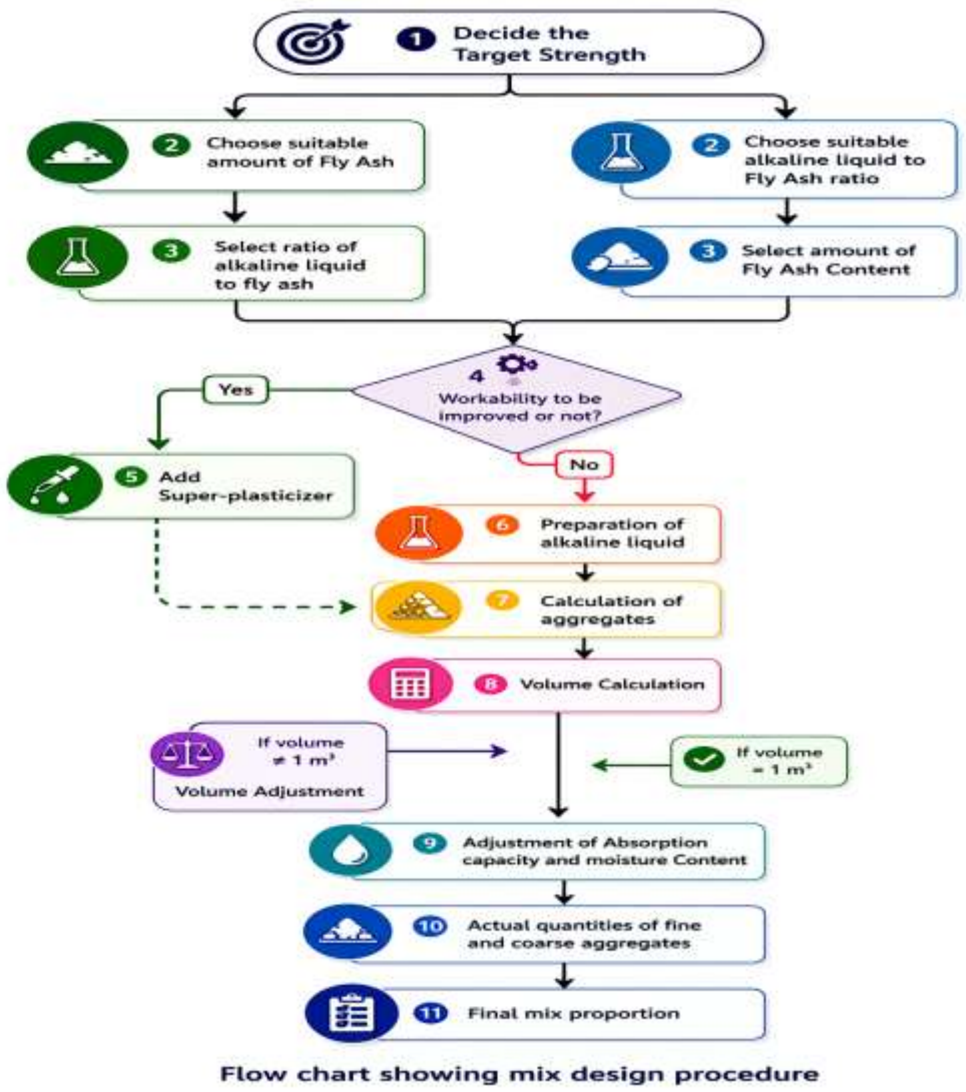



*Figure 5.1: Flow Chart Showing Mix Design Procedure*

### 5.3 Mix Design Calculation

1. **Let the unit weight of concrete** = 2400 Kg/m$^3$
2. **Mass of aggregate** = 0.77×2400 =1848 Kg/m$^3$

   Out of which,

   15% 20 mm Aggregate = 0.15×1848

   = 277.2 Kg/m$^3$

   20% 14 mm Aggregate = 0.20×1848

   =369.6Kg/m$^3$

35% 7 mm Aggregate = 0.35×1848

=646.8Kg/m$^3$

30% Fine Sand = 0.30 ×1848

=554.4 Kg/m$^3$

**3. Mass of Fly Ash and Alkaline Liquid**

=2400 –1848

=552 Kg/m$^3$

Take AL to FA ratio = 0.35

AL/FA =0.35

(AL+FA)/FA= (0.35+1)/1 552 / FA = 1.35 / 1
FA=552/ 1.35

= 408.88 i.e. 408 kg/m$^3$

∴ AL = 552 - 408.88

=143.11 i.e. 144 kg/m$^3$

Take $Na_2SiO_3$: NaOH = 2.5:1

Therefore NaOH = 41.14 kg/m$^3$ and, $Na_2SiO_3$ = 103 kg/m$^3$

**4. Sodium Silicate Solution having water as 66.5%**

Therefore, water per cubic meter from $Na_2SiO_3$ = (66.5/ 100) × 103

= 68.495 Kg

Geopolymer Solids in mix = 103-68.496 = 34.505

**5. Also, Water per cubic meter from sodium hydroxide solution 26 % Solids and 74% water, therefore,**
Solids = (26/100) ×41.14 =10.6964 kg/m$^3$

Water = (74/100) ×41.44 =30.7436 kg/m$^3$

Total mass of water = 68.495 +30.7436 = 99.2386 kg/m$^3$

It should be kept in mind that while mixing the concrete water in surface dry condition shall be used therefore water

absorbed by aggregate should also be considered while taking out total mass of water in Geopolymer Concrete Mix.
Total mass of solids = (FA +$Na_2SiO_3$+NaOH) Solids

= 408+34.505 +10.6964

= 453.20

Therefore the water to Geopolymer solids ratio comes out to be

=99.2386 / 453.20 = 0.218

Super-plasticizer can be used as 3% to 5% of mass of fly ash.
The above mix design was used to develop 5 different mixes of Geopolymer Concrete.
In first mix, the content of fly ash and GGBS was kept to be $F_{80}G_{20}$, Similarly for the second mix content of fly ash and GGBS was kept $F_{60}G_{40}$ and for the third mix it was kept $F_{40}G_{60}$. Firstly these three mixes were casted and then tested to know the effect of percentage of fly ash and GGBS on compressive strength of Geopolymer concrete. Twelve specimen of each mix were casted to know the compressive strength at 3, 7, 28 and 56 days. After these mixes were tested, 4$^{th}$ mix and 5$^{th}$ mix was developed using the optimum mix obtained from the above results. These two mixes were casted to know the change in compressive strength of GPC under Ambient curing and Oven dry curing and also to check the change in compressive strength and behaviour of GPC under effect of given Rest Period.

**5.4 Size of Test Specimens**

Test specimens cubical in shape shall be 15 × 15 × 15 cm. If the largest nominal size of the aggregate does not exceed 2 cm, 10 cm cubes may be used as an alternative. Cubes were casted to perform check on compressive strength of Geopolymer Concrete.

**5.5 Preparation of Moulds**

Prior to mixing and casting of specimen one of the most important and time consuming work is preparation of moulds. Moulds should be prepared such that all surfaces of moulds are cleaned and oiled properly [fig 6.2 (a) and (b)] and all the bolts are tightened so that it shall not allow any leakage of mortar.


(a) (b)

***Figure 5.2: Surface Cleaned and Oiled Moulds***

Special care should be taken while applying oil. Excessive amount of oil can lead to presence of bug holes on the surface of concrete after demoulding. A suitable brush or cloth should be used while applying oil on the surface of moulds. Also type of oil used is very important as the purpose of oil is to provide necessary lubrication so that concrete may not stick to the surface of moulds and it should be easy to demould the specimen. If suitable oil is not used then it may break your specimens and whole procedure is to be repeated again. The oil used in this study was Waste Black Oil easily available at any workshop at no cost or very minimal charges at it shall not allow any leakage of mortar.

**5.6 Mixing**

All of the mixing of concrete was done by hand mixing only. All of the ingredients of Geopolymer Concrete like Fly Ash, GGBS, Coarse Aggregate and Fine Aggregate were first weighed as per mix design proportion and then mixed on floor which was prepared for saturated surface dry condition so that floor shall not absorb any water from the mix neither shall it release more water into the mix.

Mixing of Geopolymer concrete was carried out in two steps:

a) Dry Mix
b) Wet Mix

**5.6.1 Dry Mix: -** Firstly, fly ash, GGBS, coarse aggregate, fine aggregate were mixed thoroughly to obtain homogeneous mixture of GPC.

***Figure 5.3: Constituents of Geopolymer Concrete***


*Figure 5.4: Dry Mixture*

**5.6.2 Wet Mix:** Side by side, wet mix was prepared which consisted of sodium silicate solution, sodium hydroxide solution, super-plasticizer and water as specified in mix design in suitable proportion.

*Figure 5.5: Wet Mixture*

**5.6.3 GP Mix: -** The next step after obtaining both the mixes is to combine these to mixes to finally obtain Geopolymer concrete mix. It should be kept in mind that all of the wet mix should be introduced with dry mix within $1/3^{rd}$ of the total mixing time. Homogeneous mixing shall be carried out until the constituents achieve same colour and all the constituents have evenly mixed.

*Figure 5.6: Homogeneous Geopolymer Concrete Mix*

**5.7 Casting and Placing of Geopolymer Concrete**

After the concrete was evenly mixed and had achieved same colour all over the concrete was placed into the prepared cube moulds. Concrete was placed in three layers and each layer was compacted with help of tamping rod. After filling the mould the top surface was levelled i.e. any mortar in excess was removed to maintain the dimensions of specimen. The top surface was levelled and finished with help of trowel.

*Figure 5.7: Levelling and Finishing of Top Surface*

After this, the concrete filled moulds were kept on table vibrator for period of 3 minutes. This action emits out air bubbles which are entrapped inside the concrete while placing. Here compaction takes place in two stages. Firstly, the concrete vibrates and all aggregates settle down under the force of gravity. In second stage concrete behaves as a semi liquid and mortar travels to the top surface and all bubbles and air voids are emitted.

***Figure 5.8: Table Vibrator to Emit out Entrapped Air***

***Figure 5.9 Air Bubbles Travelling to the Top of the Surface***

After all bubbles are emitted, specimens are given final finishing to the level their top surfaces. The cubes are left for period of 24 hours (if rest period not considered) to attain hardening and strengthening. After this step, demoulding of specimens comes into the picture.

**5.8 Demoulding and Curing**

After the concrete has hardened over period of 24 hours or more in case of rest period, the specimens are demoulded. However, In case of rest period specimens should be demoulded after the decided rest period has elapsed i.e. 3 days or 5 days as the case may be. In this study significance of rest period was also studied separately. The specimens under Mix 5 were studied for change in compressive strength of GPC and behaviour of GPC with and without rest period. Under this Mix, Three specimens were demoulded after 24 hours of casting whereas other three specimens were demoulded after 72 hours of casting day. It was found that Rest Period did not have any noticeable difference in compressive strength but it was necessary for the specimens demoulding in order to get clear edged cubes. Specimens which were demoulded without rest period did not come out clear and the edges were broken and in some cases the concrete was stuck with the moulds itself as can be seen in Fig 5.10 & Fig 5.11 below.

***Figure 5.10: Broken Edge of Cube Demoulded Without Rest Period***

**6.9 Testing of Specimens**

The entire specimen was tested as per directions given in IS 516 (1959). To check compressive strength of concrete using Geopolymer Concrete cubes, Compression Testing Machine was used. The load for compression testing machine was set as specified in IS 516 i.e. 140 kg/cm$^2$/minute. The load shall be applied slowly without shock and increased continuously until the resistance of specimen (Concrete Cube) to increasing load breaks.

***Figure 5.13: Compression Testing Machine***

**Calculation of Load:**

Load as per IS Code =140kg/sqcm/min

1 Kg = 9.81 N

1000 N =1 KN

∴ (140×9.81 / 1000) =1.373 KN

1 min =60 seconds
But load specified in IS 516 is in kg/sqcm/minute
∴ 1.373 × surface area of cube
= (1.373 ×15 ×15 ) / 60
= **5.148 kn/sec**

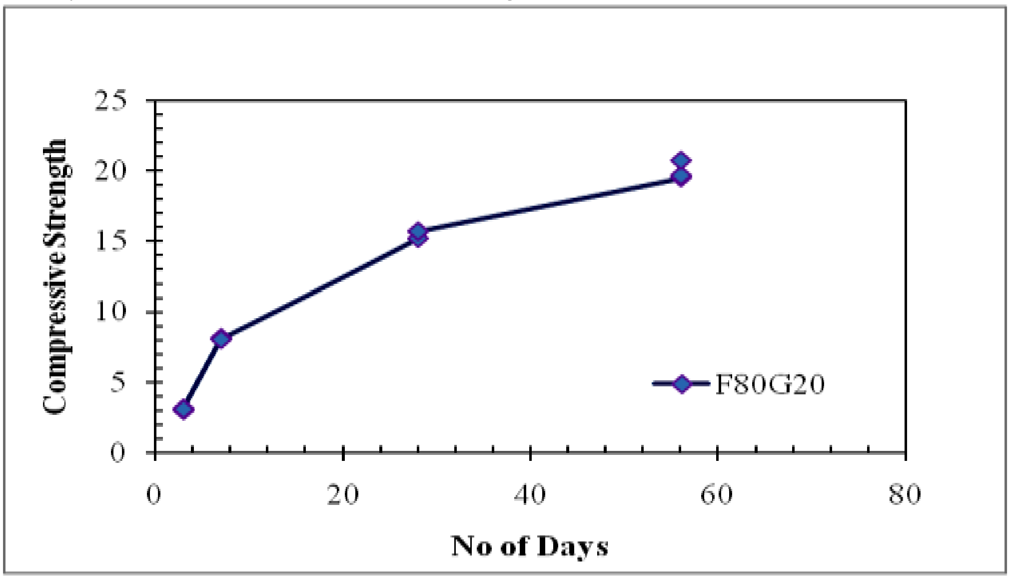
## 6. Results and Discussions

After all the specimens were tested for their compressive strength, following observations were made.

***Table 6.1: Compressive Strength Test Results for Mix 1:$F_{80}G_{20}$***

| **Size of Samples: 150 mm×150 mm ×150 mm<br>Rate of Loading = 5.148 KN/sec** | | | | |
|---|---|---|---|---|
| **S. No.** | **Age of Sample (Days)** | **Weight of Sample (kg)** | **Density (kg/m$^3$)** | **Compressive Strength (Mpa)** |
| 1 | 3 Days | 7.710 | 2284.44 | 3.02 |
| 2 | 3 Days | 7.790 | 2308.14 | 3.16 |
| 3 | 3 Days | 7.790 | 2308.14 | 3.11 |
| 4 | 7 Days | 7.770 | 2302.22 | 8.08 |
| 5 | 7 Days | 7.780 | 2305.18 | 8.17 |
| 6 | 7 Days | 7.710 | 2284.44 | 8.04 |
| 7 | 28 Days | 7.750 | 2296.29 | 15.2 |
| 8 | 28 Days | 7.780 | 2305.18 | 15.7 |
| 9 | 28 Days | 7.790 | 2308.14 | 15.7 |
| 10 | 56 Days | 7.710 | 2284.44 | 19.51 |
| 11 | 56 Days | 7.770 | 2302.22 | 19.66 |
| 12 | 56 Days | 7.790 | 2308.14 | 20.71 |

From the above table 6.1, it can be seen that for Mix 1 having fly Ash 80% and GGBS 20%, the average compressive strength for 3, 7, 28 and 56 days was found to be 3.09MPa, 8.09MPa, 15.53MPa and 19.96 respectively. Where average density of concrete was found to be 2300 kg/m$^3$.



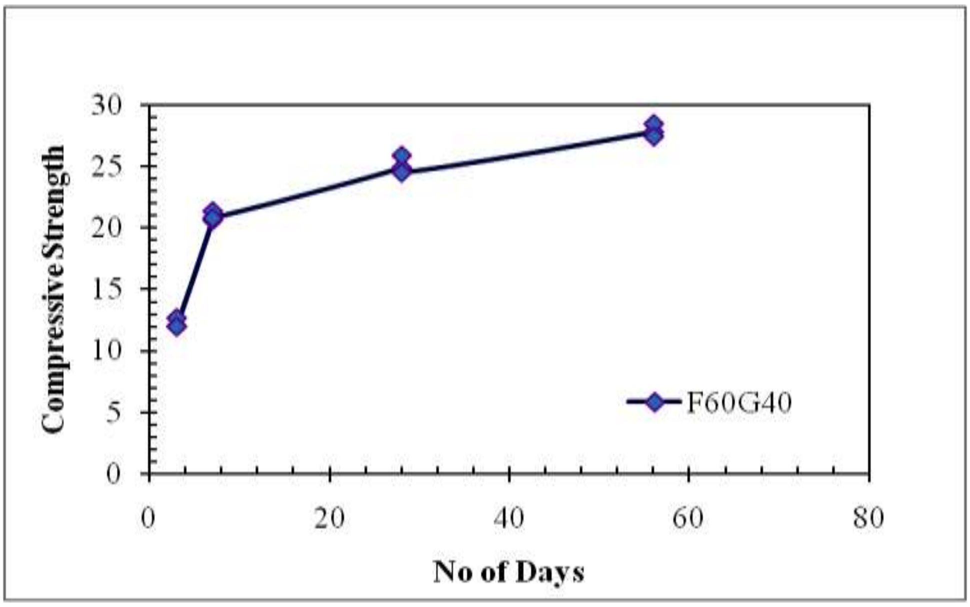

***Graph 6.1: Rise of Compressive Strength with age of Sample***

From the above graph it can be seen that the compressive strength has risen rapidly for the initial 3-7 days after that a rising curve can be seen which shows that the gain in compressive strength is almost uniform for 28 days and 56 days. There was 22% increase in compressive strength after 28 days. This shows that unlike Portland cement concrete, Geopolymer concrete gains strength even after 28 days. It was also observed that the specimens gained their 41% of their total compressive strength within 7 days.

***Table 6.2: Compressive Strength Test Results for Mix 2: $F_{60}G_{40}$***

| Size of Samples: 150 mm×150 mm ×150 mm<br>Rate of Loading = 5.148 KN/sec | | | | |
|---|---|---|---|---|
| **S. No.** | **Age of Sample (Days)** | **Weight of Sample (kg)** | **Density (kg/m³)** | **Compressive Strength (Mpa)** |
| 1 | 3 Days | 7.800 | 2311.11 | 12.00 |
| 2 | 3 Days | 7.790 | 2308.14 | 12.66 |
| 3 | 3 Days | 7.800 | 2311.11 | 11.97 |
| 4 | 7 Days | 7.850 | 2325.92 | 20.62 |
| 5 | 7 Days | 7.820 | 2317.03 | 21.37 |
| 6 | 7 Days | 7.790 | 2308.14 | 20.80 |
| 7 | 28 Days | 7.820 | 2317.03 | 24.90 |
| 8 | 28 Days | 7.820 | 2317.03 | 25.90 |
| 9 | 28 Days | 7.830 | 2320.00 | 24.50 |
| 10 | 56 Days | 7.820 | 2317.03 | 27.82 |
| 11 | 56 Days | 7.850 | 2325.92 | 28.48 |
| 12 | 56 Days | 7.820 | 2317.03 | 27.44 |

From the above table 6.2, it can be seen that for Mix 2 having fly Ash 60% and GGBS 40%, the average compressive strength for 3, 7, 28 and 56 days was found to be 12.21MPa, 20.93MPa, 25.1MPa and 27.91MPa respectively. Where average density of concrete was found to be 2316 kg/m$^3$.



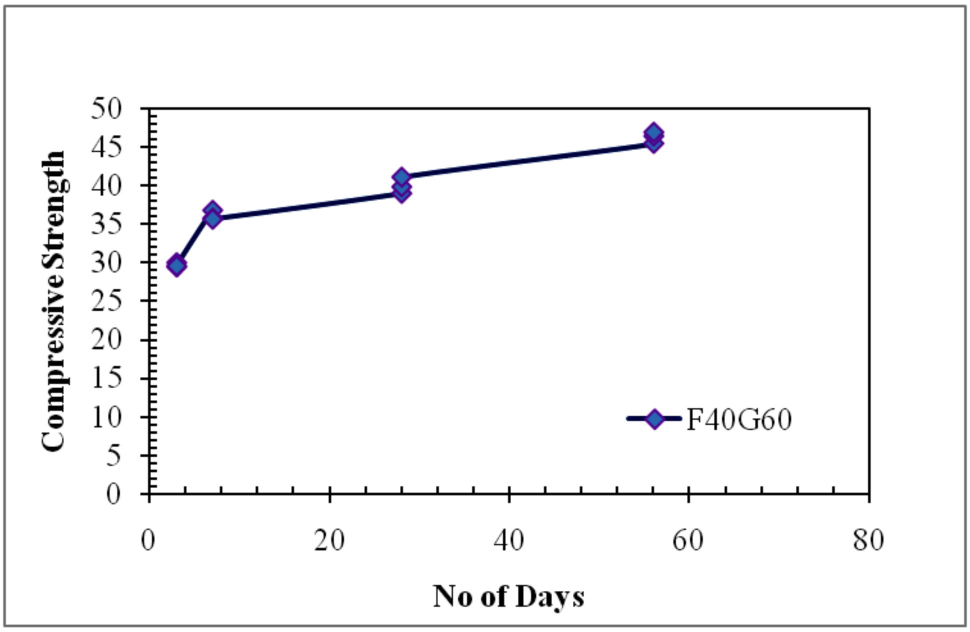

***Graph 6.2: Rise in Compressive Strength with age of Sample***

Similarly, for the above graph it can be seen that the rise in compressive strength is very rapid for initial 7 days i.e. 20.93MPa after which again a straight line can be seen which shows that for 28 days and 56 days the rise in compressive strength was uniform. There was 10% gain in compressive strength even after 28 days. Again the specimens achieved their 75% of total strength within 7 days of ambient curing.

***Table 6.3: Compressive Strength Test Results for Mix 3: $F_{40}G_{60}$***

| **Size of Samples: 150 mm×150 mm ×150 mm<br>Rate of Loading = 5.148 KN/sec** | | | | |
|---|---|---|---|---|
| **S. No.** | **Age of Sample (Days)** | **Weight of Sample (kg)** | **Density ($kg/m^3$)** | **Compressive Strength (Mpa)** |
| 1 | 3 Days | 7.88 | 2334.81 | 30.08 |
| 2 | 3 Days | 7.87 | 2331.85 | 29.52 |
| 3 | 3 Days | 7.87 | 2331.85 | 29.66 |
| 4 | 7 Days | 7.86 | 2328.88 | 36.84 |
| 5 | 7 Days | 7.88 | 2334.81 | 35.82 |
| 6 | 7 Days | 7.88 | 2334.81 | 35.68 |
| 7 | 28 Days | 7.89 | 2337.77 | 39.02 |
| 8 | 28 Days | 7.86 | 2328.88 | 39.86 |
| 9 | 28 Days | 7.86 | 2328.88 | 41.11 |
| 10 | 56 Days | 7.88 | 2334.81 | 45.46 |
| 11 | 56 Days | 7.89 | 2337.77 | 46.40 |
| 12 | 56 Days | 7.87 | 2331.85 | 46.90 |

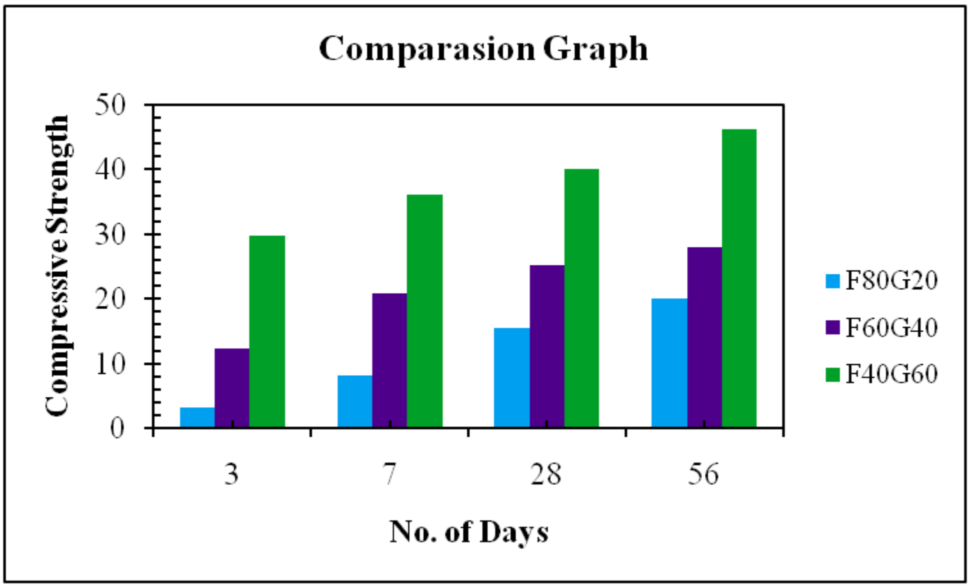
From the above table, it can be seen that for Mix 3 having fly Ash 40% and GGBS 60%, the average compressive strength for 3, 7, 28 and 56 days was found to be 29.75MPa, 36.11MPa, 40MPa and 46.25MPa respectively. Where average density of concrete was found to be 2333 $kg/m^3$.




***Graph 6.3: Rise in Compressive Strength with Age of Sample***

Again, for the above graph it can be seen that the rise in compressive strength is rapid for first 7 days and after 7 days a straight line can be seen which shows that the rise in compressive strength was uniform. Here the specimens achieved 16% of their total compressive strength even after 28 days of curing. The specimens gained 78% of their compressive strength within 7 days of ambient curing.

**Discussion:** With respect to above observation tables it can be clearly seen that the strength of Geopolymer Concrete has increased with the increase in proportion of GGBS and decrease in proportion of Fly Ash. Strength at 28 days increased from 15.53MPa to 25.1MPa to 40 MPa for Mix 1, Mix 2 and Mix 3 respectively. Also it was noticed that Geopolymer concrete gains its compressive strength even after 28 days. Hence, strength at 56 days of curing is made necessary to be observed. The increase in compressive strength was very rapid in all the cases for the first 7 days after which uniform rise in compressive strength was seen. Therefore, further in this study Mix design same as that of Mix 3 was used to study other properties of Geopolymer Concrete such as significance of Rest Period and effect of curing temperature on compressive strength.




***Graph 6.4: Comparison for Strength Gained by Different Mixes at Different Days***

Clearly, it can be seen from the above graph that the compressive strength for the mix F40G60 the compressive strength was found to be remarkably higher than other mixes. It can be observed that as the percentage content of GGBS increased the compressive strength of Geopolymer concrete also increased.

***Table 6.4: Compressive Strength Test Results for Mix 4:$F_{40}G_{60}$: Ambient Curing and Heat Curing***

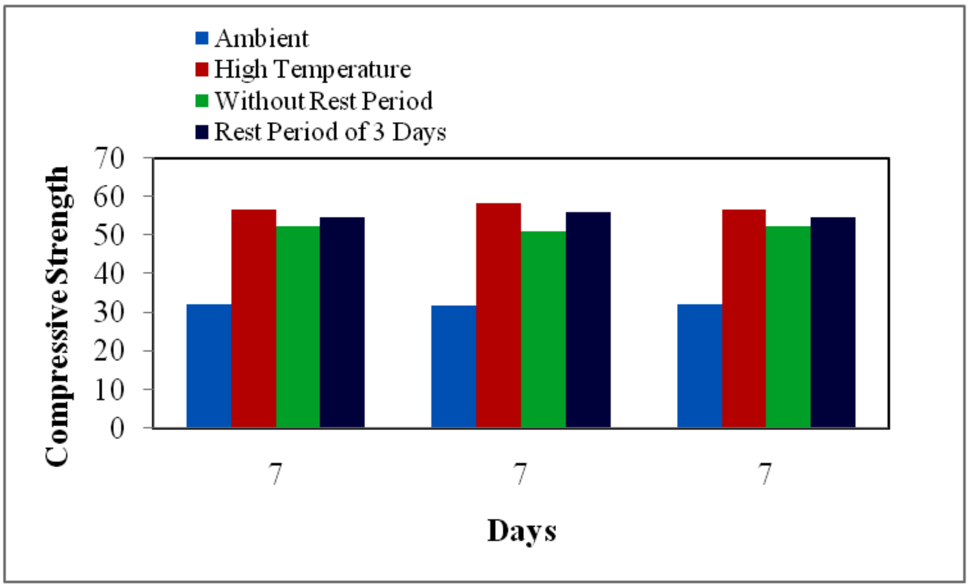
| | | **Size of Samples: 150 mm×150 mm ×150 mm<br>Rate of Loading = 5.148 KN/sec** | | | |
|---|---|---|---|---|---|
| **S. No.** | **Age of Sample (Days)** | **Type of Curing** | **Weight of Sample (kg)** | **Density (kg/m³)** | **Compressive Strength (Mpa)** |
| 1 | 7 Days | Ambient | 7.86 | 2328.88 | 32.13 |
| 2 | 7 Days | | 7.81 | 2314.07 | 31.9 |
| 3 | 7 Days | | 7.85 | 2325.92 | 32.25 |
| 4 | 7 Days | High Temperature | 7.82 | 2317.03 | 56.7 |
| 5 | 7 Days | | 7.82 | 2317.03 | 58.4 |
| 6 | 7 Days | | 7.81 | 2314.07 | 56.6 |

From the above table it can be seen that the first three cubes which were cured in a room at ambient conditions in open air achieved average compressive strength of 32.09MPa, whereas, the last three cubes which were cured in Hot Air Oven at temperature of 75° C achieved higher compressive strength of 57.23MPa. It was clear from the results that under high temperature Geopolymer concrete achieves higher compressive strength and is highly recommended where high strength is required. This type of curing is possible in pre-cast concrete industries.

*Table 6.5: Compressive Strength Test Results for Mix 5:$F_{40}G_{60}$: Rest Period*

| | | **Size of Samples: 150 mm×150 mm ×150 mm Rate of Loading = 5.148 KN/sec** | | | |
|---|---|---|---|---|---|
| **S. No.** | **Age of Sample (Days)** | **Exposure Condition** | **Weight of Sample (kg)** | **Density (kg/m$^3$)** | **Compressive Strength (Mpa)** |
| 1 | 7 Days | Without Rest Period | 7.860 | 2328.88 | 52.3 |
| 2 | 7 Days | | 7.810 | 2314.07 | 51.00 |
| 3 | 7 Days | | 7.850 | 2325.92 | 52.4 |
| 4 | 7 Days | Rest Period of 3 Days | 7.820 | 2317.03 | 54.9 |
| 5 | 7 Days | | 7.820 | 2317.03 | 56.00 |
| 6 | 7 Days | | 7.810 | 2314.07 | 54.8 |

From the above table it can be seen that the first three cubes which were demoulded after 24 hours of casting and heat cured had an average compressive strength of 52MPa, whereas, the last three cubes which were given rest period of three days had an average compressive strength of 55.23MPa. The difference in compressive strength was not very significant, however it was observed that cubes with rest period were demoulded with neat and clean edges and surface whereas cubes without rest period, those were demoulded within 24 hours of casting broke their edges and some of the specimen surfaces sticked with the surface of mould. Therefore, Rest period is recommended while developing Geopolymer Concrete.




*Graph 6.5: Comparison of Compressive Strength for Different Type of Curing and Rest Period*

From the above graph it can be clearly seen that the heat cures samples showed remarkably higher compressive strength than ambient cured samples. Therefore, Heat curing is recommended for Geopolymer concrete. However, talking about rest period there was no significant change in compressive strength between the two type of specimens but rest period had its own importance in Geopolymer concrete for e.g. it was important to provide rest period to get clear edged specimens without breaking them. Rest of the significance of rest period is studied further in conclusion.

## 7. Conclusion and Future Scope

### 7.1 Conclusion

Based on the present study on the effect of mix proportion and curing conditions on the compressive strength of geopolymer concrete, the following conclusions are drawn:

1. It was observed that the compressive strength of geopolymer concrete ($Na_2SiO_3$:NaOH = 1.75 with 8M NaOH solution) increases with an increase in GGBS content and a corresponding decrease in fly ash content, showing the significant influence of mix proportion.
2. The compressive strength at 28 days was found to be 15.53 MPa, 25.10 MPa, and 39.99 MPa for the three mixes, which further increased to 19.96 MPa, 27.91 MPa, and 46.25 MPa at 56 days. This indicates continuous strength gain in geopolymer concrete beyond 28 days, unlike conventional concrete.
3. The rest period was found to have no significant effect on compressive strength. However, providing an adequate rest period before demoulding is important to achieve smooth surface finish and well-defined edges of the specimens.
4. Curing conditions have a strong influence on strength development. The compressive strength increases with increase in curing temperature, and hot air curing at around 75°C is recommended for better performance.
5. Proper lubrication of moulds is necessary before casting. Non-sticky oil with good lubricating properties should be used. Excess application of oil should be avoided as it may lead to surface defects such as bug holes in the specimens.
6. The use of a table vibrator was found effective in removing entrapped air and improving compaction of geopolymer concrete. Other suitable vibration methods can also be used.
7. To achieve good workability, super-plasticizer dosage can be increased up to 10% of the total binder content (Fly Ash + GGBS). Additional water should be avoided as it disturbs the geopolymer mix proportions and affects strength.

**7.2 Future Scope**

Based on the present study on the effect of mix proportion and curing conditions on the compressive strength of geopolymer concrete, the following areas can be explored in future:
1. Further studies can be carried out by using different molarity levels of NaOH and varying the ratio of $Na_2SiO_3$ to NaOH to understand their effect on strength and durability.
2. The use of other industrial by-products such as silica fume, rice husk ash, and red mud can be investigated to develop more sustainable geopolymer mixes.
3. Different curing methods such as steam curing, sunlight curing, and ambient curing can be studied in detail to make geopolymer concrete more practical for field applications.
4. Long-term properties such as durability, permeability, resistance to acid attack, sulphate attack, and chloride penetration can be analyzed.
5. The behavior of geopolymer concrete under different loading conditions such as flexural strength, split tensile strength, and fatigue can be studied.
6. The use of fibers (steel, glass, polypropylene) can be explored to improve mechanical properties and crack resistance.
7. Development of geopolymer concrete using locally available materials in different regions can be carried out to make it more economical and widely applicable.
8. Advanced techniques such as machine learning and optimization methods can be used to predict compressive strength and optimize mix design.

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