

## Durability Study on the Red mud-based Ternary Blended Geopolymer Concrete

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### Abstract

Concrete made with geopolymer technology is thought to be both pro-ecological and minimal cost-effective. Geopolymer concrete manufacture aids in the conversion of industrial by-product materials into reusable products. Geopolymer concrete outperforms OPC concrete in terms of strength. The ternary blended high-molarities (12M) geopolymer concrete used in this experiment was made of red mud (RM), fly ash (FA), and Ground granulated blast furnace slag (GGBFS). The current study intended to establish the best ratio of RM - FA - GGBFS -based ternary geopolymer concrete. The compressive strength, split tensile strength, and flexural strength tests were performed to determine the strength properties and water absorption, permeability, and sorptivity tests determined the durability characteristics. The results shows that the proportions of RM-based ternary GPC with RM: FA:GGBFS in 45:35:20 ratio resulted in a significant increase in the synthesis. This resulting in improved mechanical and microstructural properties than the other proportions. Higher results were also seen at the aforementioned ratio in the chemical analysis performed on the ternary-based geopolymer paste to determine the maximum pH value. The study's findings are encouraging sustainable and cost-effective routes for dealing with the industrial by-products that are presently produced in multiple regions.

**Keywords:** fly ash (FA), geopolymer concrete, Ground Granular Blast Furnace Slag (GGBFS), Mechanical strength characteristics, Red mud (RM), water absorption, sorptivity.

### 1. Introduction

Because of its availability, convenience of use, cost-effectiveness, and superior mechanical and durability features, Ordinary Portland cement (OPC) is the most commonly preferred binder in construction [1]. Infrastructure construction is accelerating to meet urban demand, and so as a result, cement consumption has increased. The per-year cement output is 3.1 BT/year, and this amount is expected to increase by 4 billion tons /yr [2]. Furthermore, by 2050, global cement consumption is expected to reach 5.5 gigatonnes/yr [3]. Cement manufacturing emits carbon dioxide (CO<sub>2</sub>), which contributes to global warming. This is because cement is an energy-intensive product that depletes natural resources and releases 0.8T of CO<sub>2</sub> every tonne produced [4, 5]. Furthermore, as urbanization evolved, the supply of by-products increased and is today plentiful in India. RM is a kind of solid waste produced by the alumina manufacturing sector as a by-product. The report's goal is to look into the viability of making RM a better alternative for traditional Portland cement. Due to heat curing, geopolymer concrete may only be utilized in precast construction. The researcher's major goal is to increase the desirable features of the mix by curing it at room temperature, allowing it to be employed in a broad variety of applications in construction projects.

### *Objective*

In the construction industry, modified RM is utilized as a binding agent for cementitious materials. The project's goal is to research the use of modified RM and its features. The present investigation has been carried out with the listed goals in consideration:

1. To create ternary blended geopolymer pastes including modified RM, GGBFS, and FA in varying proportions.
2. To find the maximum pH values for all ternary mixes, use chemical analysis with different molarities of sodium hydroxide in the AAS solution.
3. To investigate to determine mechanical characteristics for all ternary blended mixtures and compare strength results to pH values determined from chemical analysis.
4. The mechanical characteristics of RM-based ternary blended geopolymer concrete specimens were evaluated at ambient temperature and oven curing temperatures for 7, 28, and 56 days.
5. Water absorption, permeability, and sorptivity tests will be performed and the results examined to assess the durability attributes of ternary blended specimens.
6. Analyze and evaluate the outcomes of RM-based ternary blended geopolymer concrete with traditional concrete samples of the same grade.

## **2. literature review**

Needing a large quantity of area for proper disposal has a substantial influence on the earth and land use. Byproducts such as FA, GGBFS, alccofine, and rice husk ash are pozzolanic and can be used in place of cement as additional cementitious components [6]. As a result, there is an urgent need for researchers to develop replacement binders to complement or reduce the usage of cement in concrete, as well as to employ industrial by-products to reduce pollution. In 1970, Dr. Joseph Davidovits invented geopolymer concrete by activating the aluminosilicate ingredient with an alkaline solution. The alkaline activator, high silicate source materials, and curing conditions all have an impact on geopolymer concrete efficiency [7]. An appropriate design and application of geopolymer materials will reduce greenhouse gas emissions by 3/4 while also resolving issues about OPC manufacturing and the unregulated disposal of industrial by-products through reuse [8]. Industrial byproducts rich in silica and alumina, such as fly ash, blast furnace slag, alccofine, silica fume, and rice husk ash, can be used to make geopolymer. Geopolymers are made by dissolving rich silicate compounds in an alkaline solution, which results in a 3-D polymer link structure of silicones and aluminum silicates [9]. Geopolymer has been demonstrated to outperform regular Portland cement in terms of advanced strengths, quicker setting time, longer sustainability, higher acid and corrosion resistance, lower thermal conductivity, and shrinkage [9, 10]. The majority of previous studies used heat curing to finish the geopolymerization technique for the FA-based geopolymer [11]. For example, [12] observed that FA-based geopolymer curing at room temperature results in a delayed increase of strength and prolonged curing periods. This is viewed as a limitation for geopolymer concrete on the job site since it restricts the production of precast pieces. As a consequence, most research combined FA and GGBFS to widen the usage of geopolymer concrete in the building sector. GGBFS enhanced curing durations and strength properties during ambient temperature curing because of the elevated calcium content [13]. The main reaction product of the FA-based geopolymer concrete was alkali silicate hydrate, whereas the GGBFS generated calcium silicate hydrate gel [14]. The addition of alccofine to geopolymer concrete increased its strength and microstructure at an early age [15]. The geopolymer's properties were modified by the supply and kind of materials [16], the molarity of sodium hydroxide [17], the sodium silicate to sodium hydroxide ratio [18], the b/a ratio [19], the ratio between solids to liquids [20], and the curing temperature.

### *2.1 Literature summary*

In this study, experimental and durability experiments were carried out on the RM-based ternary blended, high-molarity [12M] geopolymer concrete with FA and GGBFS ratios. The water to binder ratio at 0.25, the superplasticizer is 0.8 percent by weight of the binder and the alkali-activated solution ratio was 2.5 taken for the preparation of the GPC. Furthermore, a strength compared with the same grade of OPC specimens was performed to investigate the possibility of geopolymer concrete blenders replacing regular Portland cement in traditional concrete making.

### 3. Materials & Methods

#### 3.1. Materials

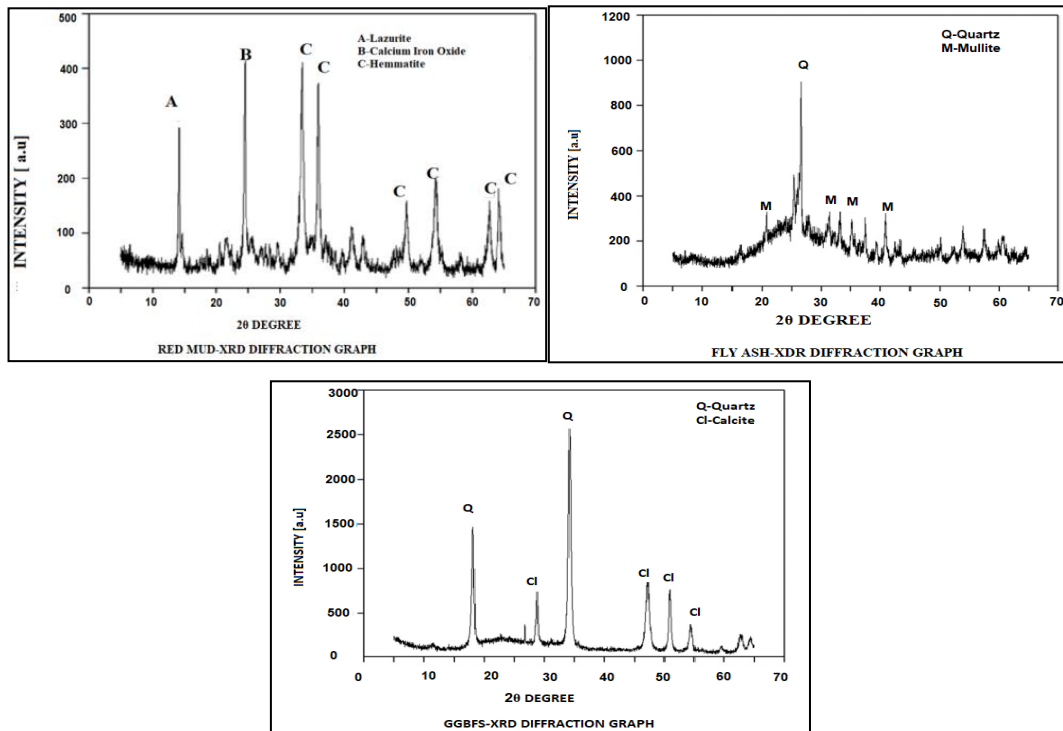
The basic components evaluated in the current study included RM, FA, GGBFS, NaOH flakes in molarities 4M, 6M, 8M, 10M, 12M, and 14M, sodium silicate, river sand, coarse aggregate, Fosroc Conplast SP 430 DIS as a superplasticizer, and potable water.

**Table 1.** Chemical compositions of binders [by weight]

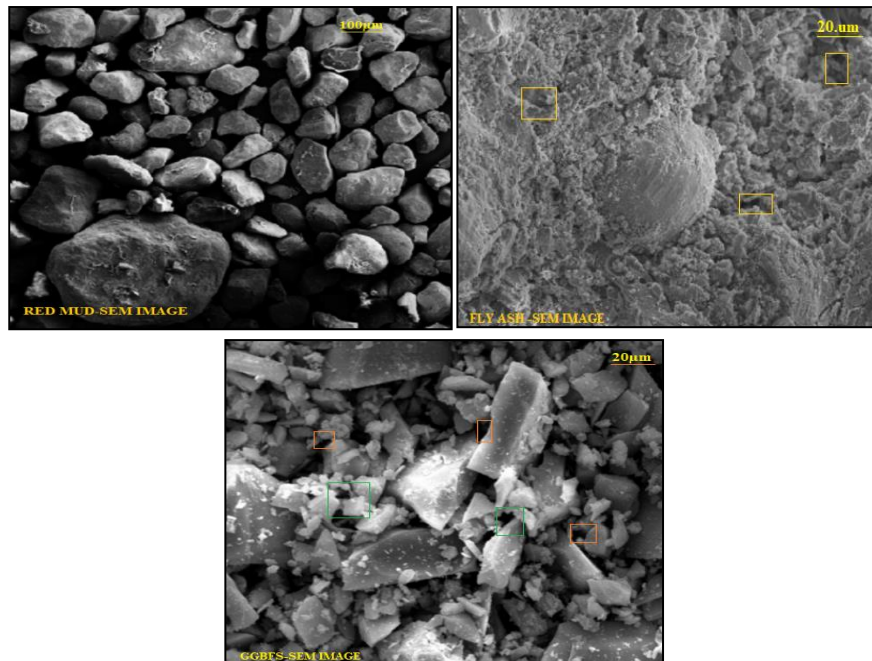
BINDER/COMPOSITION	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	MgO	TiO <sub>2</sub>	SO <sub>3</sub>
RED MUD	20.97	22.36	34.52	3.96	8.83	2.45	1.4	4.98	3.01
FLY ASH	32.17	58.87	2.93	0.79	0.37	1.14	0.92	-	0.49
GGBFS	17.14	32.52	1.22	34.22	0.16	0.07	9.65	-	0.88

### 4. Microstructure characterization of base materials

This test's resources mostly consist of RM, FA, and ground granular blast furnace slag. All three materials are derived from the previously listed sources. The RM was gently roasted and shredded to a maximum diameter of 0.16 mm. Figures 2 and 3 show the XRD patterns of RM, FA, and GGBFS. There were no identifiable wide humps in RM, indicating a lack of amorphous phases. The phase of Hematite, Calcium Iron Oxide, and Lazurite was visible in the RM XRD diffraction. A Quartz and Mullite peak appeared, suggesting that Quartz and Mullite were present in the FA XRD pattern. A massive hump formed in the FA sample between 15° and 40°, indicating that the FA comprised a significant amount of amorphous phases [21]. The presence of Ca [OH]2 is shown by the XRD pattern of pulverized granular blast furnace slag.



**Figure 2.** RM, FA, and GGBFS raw materials microstructure pattern (XRD diagram)



**Figure 3.** RM, FA, and GGBFS raw materials SEM pictures

## 5. Mix Design

Table 2 shows the restrictions of material ratios for geopolymer concrete formulations, as per Davidovits J. The alkaline solution to binder ratio should be between 0.3 and 0.45, and the  $\text{Na}_2\text{SiO}_3$  to NaOH solution ratio should be between 2.0 and 2.5. The aggregate composition of geopolymer concrete in the mass varies between 65 and 85%, with fine aggregate accounting for 30% of total aggregate volume. The concentration of superplasticizer varies from 1.5 to 4 percent by mass of the binder component. If necessary, the extra water content of 0.02 to 0.06 percent by mass of cementitious material may be provided.

**Table 2.** Material ratio limiting values in Geopolymer concrete

Geopolymer concrete mixes with limiting values	
Water content ratio	Total mass binder 0.02-0.06 percentage
Sodium silicate /Sodium hydroxide	2-2.5
Water /Binder	0.16-0.24
Percentage of Total Aggregates	65-85 percentage
Percentage of Fine Aggregate	30 percentage
Liquid Binder ratio	0.3-0.45
Superplasticizer	1.5-4 percent of binder

### 5.1. Specimens' preparation

Ten geopolymer mixes were developed in the second phase utilizing varied RM - FA -GGBFS-based ternary blended geopolymer concrete mixes, as shown in table 3. According to much research, the sodium silicate to sodium hydroxide ratio is established at 2.5, and the solution molarities were established at 12M. Since the stiffness of the alkaline solution generated by Sodium Silicates and Sodium Hydroxide surpasses that of water, geopolymer concrete becomes less workable, necessitating the use of a superplasticizer. Following IS 9103 1999, a sulphonated naphthalene-based superplasticizer [Fosroc Conplast SP430] was used in this experiment. Aida Mohd Mortar [24] and Ramesh [25] earlier showed that the preparation of new geopolymer concrete samples was identical to that of OPC concrete. All of the requisite quantities of RM, FA, and GGBFS were blended for 2 minutes to form the geopolymer concrete. After that, the total aggregates were blended into the dry mix until it was uniform.

The blended alkaline solution was then added for 4 minutes, followed by a superplasticizer (0.8 percent binder wt percent) and additional water during the mixing [26]. The mixing operation was repeated several times until a homogenous fresh mix was obtained. Following that, freshly mixed geopolymer concrete was placed in three layers into 150-mm cubes, Prismatic molds (100X 100X 500 mm), and cylindrical molds (150 X 300

mm) following IS 516. The geopolymer concrete samples were compacted using a vibrating table to remove air pockets, and the casting specimens were allowed to cure for 24 hours at room temperature. The remolded specimens were put at room temperature for curing after a 24-hour rest period, a technique known as ambient curing.

**Table 3.** RM based ternary blended geopolymer concrete mix proportions in weights

MIX PROPORTIONS				BASE MATERIAL Kg/m <sup>3</sup>			FA	CA	SP	AAS %
MIX ID	RM	FA	GGBS	RM	FA	GGBFS	Kg/m <sup>3</sup>	Kg/m <sup>3</sup>	Kg/m <sup>3</sup>	
SS1	35	55	10	122.57	192.61	35.02	504	1176	7.2	2.5
SS2	40	50	10	140.08	175.1	35.02	504	1176	7.2	2.5
SS3	45	40	10	157.59	157.59	35.02	504	1176	7.2	2.5
SS4	50	35	10	175.1	140.08	35.02	504	1176	7.2	2.5
SS5	55	30	10	192.61	122.57	35.02	504	1176	7.2	2.5
SS6	35	45	20	122.57	157.59	70.04	504	1176	7.2	2.5
SS7	40	40	20	140.08	140.08	70.04	504	1176	7.2	2.5
SS8	45	35	20	157.59	122.57	70.04	504	1176	7.2	2.5
SS9	50	30	20	175.1	105.06	70.04	504	1176	7.2	2.5
SS10	55	25	20	192.61	87.55	70.04	504	1176	7.2	2.5

## 6. Test Methods

### 6.1. Determination of the maximum pH values from the RM based ternary blended GP mixes

In this experiment, RM was obtained in a semi-solid form from the factory storage pond and dried to zero moisture in an oven at 100°C for 5 hours. The dry RM was ground into a fine powder using a rotary mill and then mixed with FA and GGBFS in the quantities specified in the table below. Chemical analysis will be used to evaluate the pH values of all mixes including varying molarities of NaOH to discover the optimal mix of the RM-based ternary blended geopolymer paste.

### 6.2. Strength properties procedures

#### 6.2.1. RM-based ternary blended GPC flowability

The slump cone test was used to assess the flowability of newly mixed GPC with different RM, FA, and GGBFS ratios. The slump cone test was done using freshly mixed GPC per IS 1199: 1959. The slump value was calculated using the height gap between the top of the mold and the top center of the fallen concrete sample [27]. A graded tapping rod with a diameter of 16 mm was also used to obtain the slump value.

#### 6.2.2. Compressive Strengths

After 7, 28, 56 curing ages under ambient and oven conditions, the compressive strengths of ternary mixed geopolymer concrete were tested using a sample [28]. A revolving drum mixer was used to guarantee that the mix was uniform and free of lumps. For the oven curing, the curing temperature was kept between 90°C and 110°C for more than 3 hours inside the oven. A compression testing machine was used to evaluate the samples after 7, 28, and 56 days of rest following demolding.

#### 6.2.3. Split Tensile Strengths

The split tensile strength of geopolymer concrete is tested using cylindrical molds 150 X 300 mm in size. The specimens are oven cured at 90-110°C for 4 to 6 hours before being normal cured for 7, 28, and 56 days, respectively. Under these curing conditions, split tensile strengths were determined with a universal testing machine (UTM).

#### 6.2.4. Flexural Strengths

The elasticity of fracture approach was used to assess the flexural strength of geopolymer concrete by subjecting basic rectangular beam samples to three-point bending loads using the universal testing machine (UTM). The flexural strength of geopolymer concrete was evaluated using prismatic molds (100X 100X 500 mm), and the specimens were oven cured for 4-6 hours at 90-110°C before being cured for 7, 28, and 56 days, respectively. The flexural strength of geopolymer concrete under these curing conditions was measured in the

results session.

### 6.3. Durability testing Procedures

#### 6.3.1. Water absorption

Concrete's water absorption property is important to its durability. Environmental temperature and relative humidity have a significant impact on water absorption. Water absorption was measured experimentally over a range of relative humidity values. The test compared the water absorption capabilities of geopolymer with control concrete. The weight difference between the specimen after complete drying in an oven at 105°C and being submerged in water will be used to assess the absorption characteristic of concrete.

The water absorption equation is as follows:

$$\text{Percentage of absorption} = [A-B]/B * 100$$

Here,

A = Unit wet mass in kg.

B = Unit dry mass in kg.

Limiting values for the water absorption, the marine code BS 6349 states that water absorption shall not exceed 3% or 2% in severe situations such as very aggressive chloride or freeze-thaw exposure.

#### 6.3.2. Water permeability

The permeability of concrete samples with dimensions of 150 x 150 x 150 mm cubes was determined using concrete water permeability equipment following IS: 3085 – 1965 [30]. Surface-dry the specimen and quantify it to the nearest 0.5 mm. It must be positioned in the cell's middle, with the bottom end resting on the sill. The amount of permeate and gauge-glass readings must be recorded at regular intervals. Darcy's law, provided in the equation, was used to get the permeability coefficient in cm/sec.

$$K = \frac{(Q*L)}{(A*T*H)}$$

K = Permeability coefficient in cm/set;

Q = the amount of water flowing in ml for the length of the test in a steady-state condition

A = surface area of the sample in cm<sup>2</sup>

T = Q is usually measured in seconds., and

H/L = pressure head to specimen thickness ratio

#### 6.3.3. Sorptivity Test

The exposed face of concrete cubes 150x150x150 mm in size was covered with resin on four adjacent sides to allow for unidirectional absorption. Before coating, the sample blocks were cured for 6 hours in a hot-air oven at 105°C. After that, they were submerged in water for 10 1 mm vertically. During immersion, a phase difference of 5, 10, 20, 30, 40, 50, 60, 70, 80, and 90 minutes were evaluated. Samples were weighed and recorded at each time interval, and their original mass before water exposure was compared.

The total water absorption/ unit area of the inflow surface increases as the square root of elapsed time (t);

$$I = S.t^{1/2} \text{ therefore } S = I/ t^{1/2} \text{ -----[1]}$$

Here,

S = Test sample sorptivity in mm;

T = Time taken in minutes;

$$I = \Delta w/Ad \text{-----[2]}$$

$\Delta w$  = weight difference after test time =  $W_2 - W_1$ ,

$W_1$  = Oven dry weight of cube in grams,

$W_2$  = Sample weight in grams after every period in minutes.

$A$  = The contact area of the sample surface via which water penetrated.

$d$  = Water density

## 7. Results And Discussions

### 7.1. Max pH value

The mix with RM, FA, and GGBFS at 35:45:20 [SS6] and 35:55:10 [SS1] established the maximum value in the pH. This set was selected to test the strength characteristics of the RM-FA-GGBFS-based ternary geopolymer concrete in the second phase of this study. The minimum pH combination for the paste was reported to be reported at the mix SS1 [12.44] ratio of 35: 55:10. The maximum pH valued geopolymer paste mix was illustrated in fig 4.

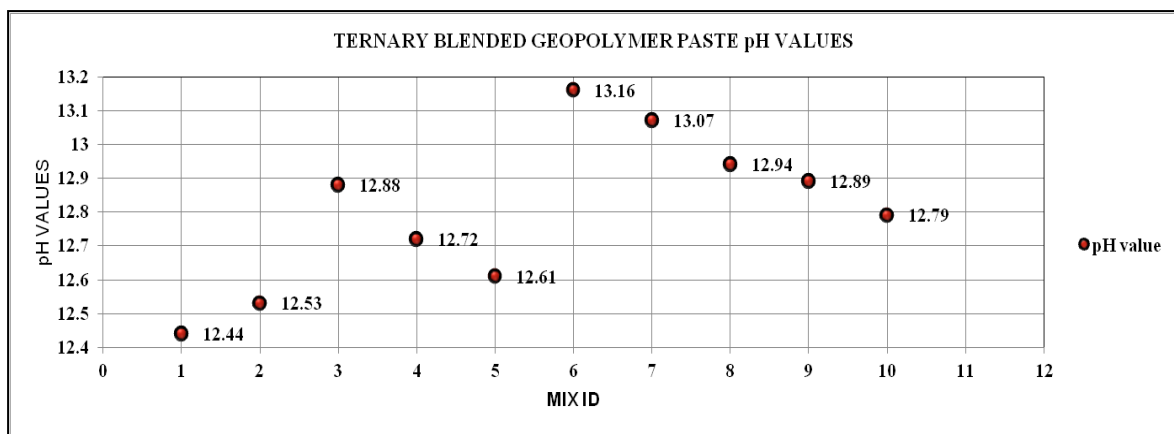


Figure 4. Graphical exposure of RM based ternary blended geopolymer paste pH values at different weight compositions

### 7.2. Workability

The workability of ternary blended geopolymer concrete was ensured under IS 1199: 1959 in a way equal to that of OPC concrete. The slump cone, Vee bee time, and compaction factor data for each mix are shown in Fig 5. The mix SS6 with the ratio of 35:45:20 had the greatest droop of 52 mm, while the mix SS10 with the ratio of 55:25:20 had the least slump of 34 mm. Increasing the RM % decreases the viscosity of the mix, causing the slump to climb. This clearly shows that the presence of red soil in the mix has a major influence on the workability of new geopolymer concrete. Enhancing the RM proportion from 35 to 55 reduced the slump of the ternary blended geopolymer concrete from 52 to 34 mm in the current study. Similarly, [33] reached the same conclusion.

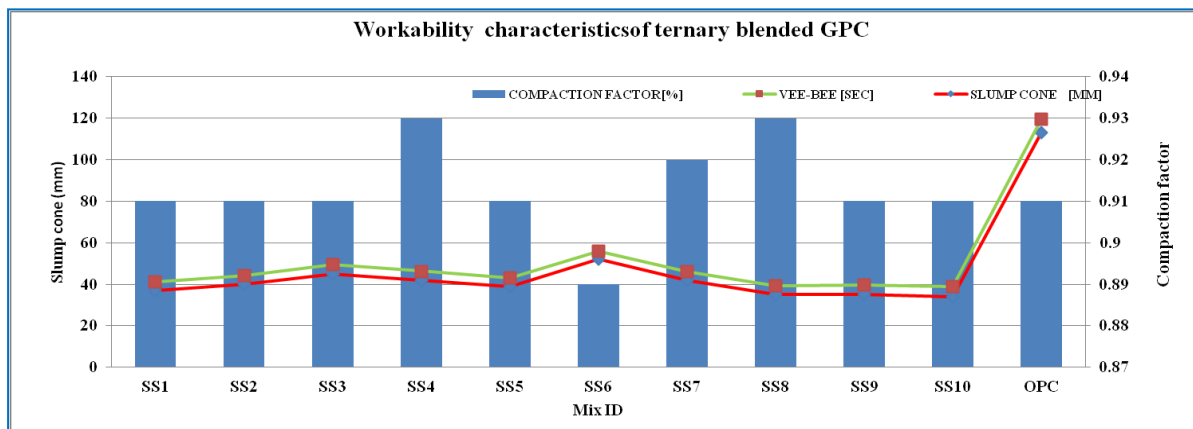


Figure 5. Graphical representation -workability properties of RM based ternary blended geopolymer concrete

### 7.3. Setting Time

According to IS: 4031 (Part 5) – 1988. The VICAT apparatus, which is under IS: 5513 – 1976, is used to calculate the start and final setting times of cement. The Vicat test was used to assess the setting time of cement concrete pastes in a room chamber at 23°C. The Vicat initial time of setting is the time that elapses between the initial contact of cement with water and the penetration of 25 mm. The first penetration measurement that did not create a complete circular impression on the specimen surface is defined as the Vicat's final time of setting the endpoint. Figure 5 depicts the setting periods for both the geopolymer concrete mix and the standard concrete. To improve responsiveness and strength, RM has taken on a fine powdered form. We used GGBFS to shorten the setup time. Because of the quick reactivity and finer fineness of RM and GGBFS, cracks occur. An RM-FA-based mix is the best choice for reducing cracks and achieving the specified setting time.

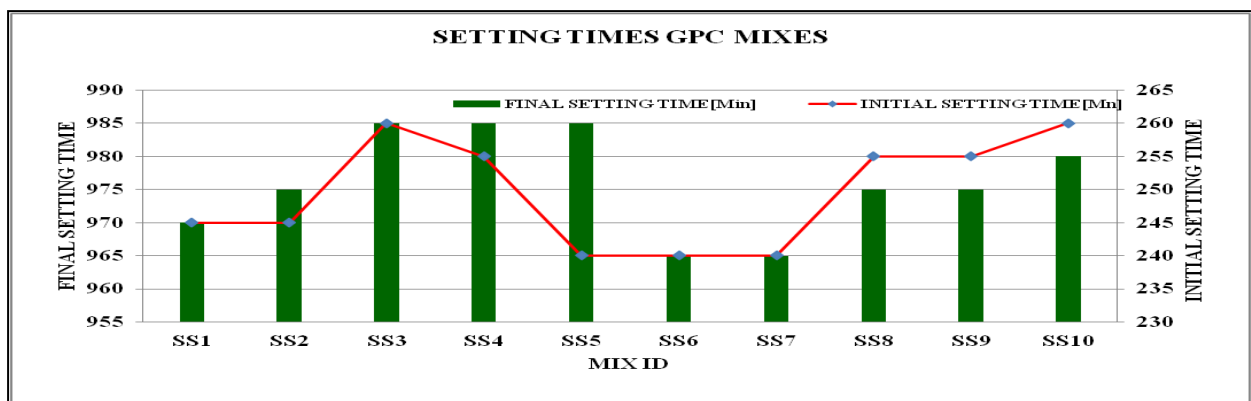


Figure 6. Setting times of the RM-based ternary blended geopolymer concrete mixes

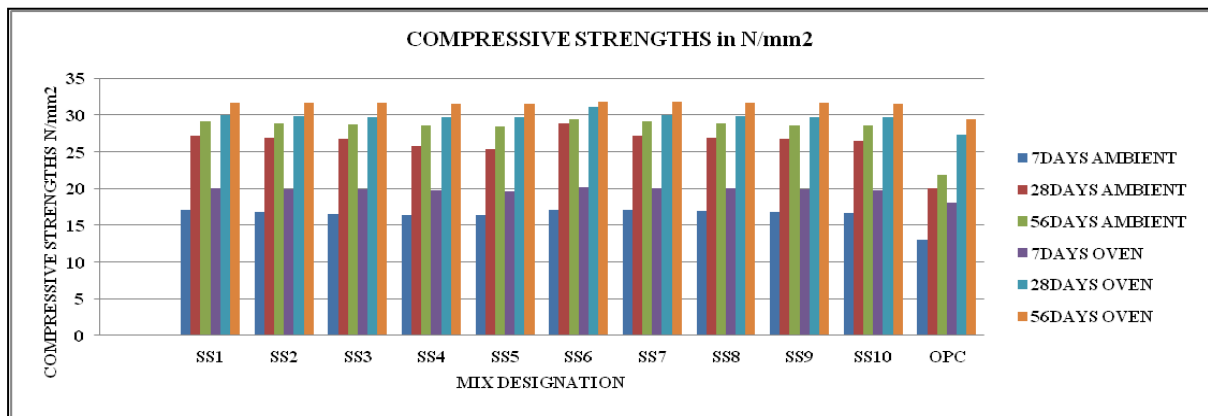
### 7.4. Compressive strengths

Table 5. Displays the compressive strength of 12M ternary mixed geopolymer concrete with various RM, FA, and GGBFS ratios. It reported that the mix SS5 had the lowest compressive strength of 16.37 N/mm<sup>2</sup> at 7 days, 27.22 N/mm<sup>2</sup> at 28 days, 29.12 N/mm<sup>2</sup> at 56 days, and 19.63 N/mm<sup>2</sup> at 7 days, 29.63 N/mm<sup>2</sup> at 28 days, 31.49 N/mm<sup>2</sup> at 56 days respectively both ambient and oven curing regimes. While the SS6 mix with a ratio of 35:45:20 had maximum compressive strengths of 17.12 N/mm<sup>2</sup> at 7 days, 28.91 N/mm<sup>2</sup> at 28 days, 29.42 N/mm<sup>2</sup> at 56 days, and 20.13 N/mm<sup>2</sup> at 7 days, 31.06 N/mm<sup>2</sup> at 28 days, and 31.82 N/mm<sup>2</sup> at 56 days under both ambient and oven curing conditions. This means that when the RM ratio increased from 35 to 55, the compressive strength dropped owing to a reduction in the geopolymerization processes [34]. The higher silicate solution hampered geopolymerization, resulting in a loss in compressive strength.

Table 4. Ternary blended RM based geopolymer concrete compressive strengths in N/mm<sup>2</sup> about 7, 28, and 56 days different curing regimes

MIX ID	Compressive Strengths N/mm <sup>2</sup>					
	Ambient Curing			Oven Curing		
	7days	28days	56days	7days	28days	56days
SS1	17.02	27.22	29.12	19.97	29.92	34.07
SS2	16.81	26.93	28.85	19.91	29.83	33.82
SS3	16.58	26.81	28.71	19.83	29.77	33.79
SS4	16.41	25.76	28.57	19.72	29.71	33.61
SS5	16.37	25.41	28.46	19.63	29.63	33.54
SS6	17.12	28.91	29.42	20.13	31.06	34.12
SS7	17.02	27.18	29.17	20.02	29.94	33.94
SS8	16.88	26.93	28.82	19.97	29.85	33.81
SS9	16.81	26.74	28.63	19.88	29.74	33.73
SS10	16.72	26.52	28.57	19.81	29.69	33.61
OPC	13	20	21.8	18.12	27.37	29.47

The compressive strengths with different curing ages were [35] reported similar types of outcomes. Fig 7. Demonstrates that when the RM ratio increased from 35 to 55, the workability and initial setting times reduced, resulting in a delay in the synthesis protocol and it leads to reporting fewer strength values. The combination of SS6 with RM, FA, and GGBFS at ratios of 35, 55, and 20 increased the dissolution of Si and Al from the binder components, resulting in siloxane and aluminosilicate oligomers with the maximum compressive strength of the above stated [36]. Furthermore, when the RM ratios increased from 33 to 55, the aluminum silicate and sodium silicate ratios impacted significantly, and the compressive strength decreased from 28.91 N/mm<sup>2</sup> to 25.41 N/mm<sup>2</sup>. The alkaline activator solution's NaOH ratio aids in the breakdown of binder and the transfer of ions. As a strength-developing chemical, the effective interaction of CaO and SiO<sub>2</sub> produced the calcium silicate hydrate (C–S–H) gel. Where compared with the compressive strengths of OPC specimens, the increment in strength values of ternary blended geopolymer concrete specimens at 56 days curing ages in ambient oven curing conditions were 34%, 32%, 32%, 31%, 31%, 35%, 34%, 32%, 31%, 31% and 16%, 15%, 15%, 14%, 14%, 16%, 15%, 15%, 14%, 14% respectively.



**Figure 7.** Graphical representation-ternary blended RM based geopolymer concrete compressive strengths N/mm<sup>2</sup> about 7, 28, 56 days different curing regimes

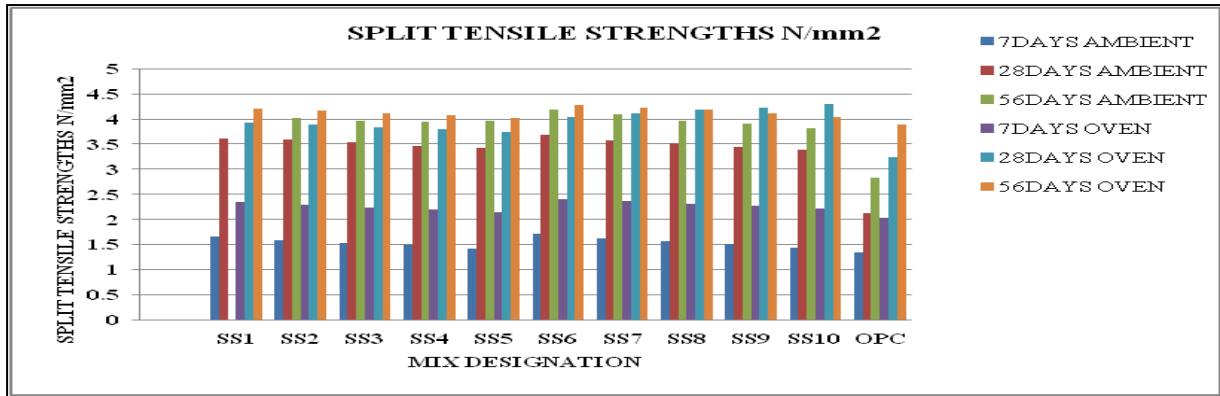
### 7.5. Split tensile strengths

At 7, 28, and 56 days under ambient curing circumstances, the split tensile strengths of RM-based ternary blended geopolymer concrete specimens were 1.78 N/mm<sup>2</sup>, 3.96 N/mm<sup>2</sup>, 4.64 N/mm<sup>2</sup>, and 1.66 N/mm<sup>2</sup>, 3.34 N/mm<sup>2</sup>, 4.02 N/mm<sup>2</sup>, respectively. The most intriguing finding was that the ternary mixed geopolymer concrete exhibited greater strengths than the target OPC specimens, as shown in table 5.

**Table 5.** Ternary blended RM based geopolymer concrete split tensile strengths in N/mm<sup>2</sup> about 7, 28, and 56 days different curing regimes

MIX ID	Split tensile Strengths N/mm <sup>2</sup>					
	Ambient Curing			Oven Curing		
	7days	28days	56days	7days	28days	56days
SS1	1.65	3.61	4.09	2.35	3.92	4.21
SS2	1.59	3.59	4.02	2.29	3.89	4.17
SS3	1.53	3.54	3.96	2.24	3.83	4.12
SS4	1.49	3.47	3.94	2.19	3.79	4.07
SS5	1.42	3.42	3.96	2.14	3.74	4.01
SS6	1.71	3.69	4.18	2.41	4.04	4.28
SS7	1.62	3.58	4.09	2.37	4.11	4.23
SS8	1.57	3.51	3.96	2.31	4.18	4.19
SS9	1.51	3.44	3.91	2.27	4.23	4.12
SS10	1.43	3.39	3.82	2.21	4.29	4.03
OPC	1.34	2.12	2.82	2.02	3.24	3.89

Figure 8 depicts a graphical depiction of the split tensile strength values of RM-based geopolymer concrete specimens. When compared to split tensile strengths of target samples, the increment in strength values of ternary blended geopolymer concrete specimens at 56 days curing ages in ambient oven curing conditions were 45 %, 43 %, 40 %, 40 %, 48 %, 45 %, 40 %, 39 %, 35 % and 8 %, 7 %, 6 %, 5 %, 3 %, 10 %, 9 %, 8 %, 6 %, 4 %.



**Figure 8.** Graphical representation-ternary blended RM based geopolymer concrete split tensile strengths N/mm<sup>2</sup> about 7, 28, 56 days different curing regimes

### 7.6. Flexural strengths

Flexural strengths of RM-based ternary blended geopolymer concrete specimens at 7, 28, and 56 days under both curing conditions must be more than 2.12 MPa, 3.08 MPa, and 3.21 MPa, respectively. Table 6 shows the flexural strengths of geopolymer concrete specimens at 7, 28, and 56 days under ambient and oven curing regimes. This indicates that GPC values are significantly greater than OPC results.

**Table 6.** Ternary blended RM based geopolymer concrete flexural strengths in MPa about 7, 28, and 56 days of different curing regimes

MIX ID	Flexural Strengths N/mm <sup>2</sup>					
	Ambient Curing			Ambient Curing		
	7days	7days	7days	7days	7days	7days
SS1	2.34	3.69	4.92	2.48	4.21	6.21
SS2	2.31	3.61	4.84	2.45	4.13	6.01
SS3	2.29	3.54	4.79	2.41	4.07	5.83
SS4	2.26	3.49	4.73	2.37	3.98	5.42
SS5	2.22	3.41	4.67	2.32	3.92	5.24
SS6	2.37	3.74	5.01	2.54	4.28	6.42
SS7	2.27	3.67	4.95	2.48	3.98	6.35
SS8	2.24	3.63	4.87	2.41	4.04	6.29
SS9	2.21	3.59	4.81	2.38	4.16	6.01
SS10	2.19	3.54	4.77	2.32	4.21	5.87
OPC	2.12	3.08	3.21	2.21	3.39	4.61

Figure 9 depicts a graphical depiction of the flexural strength values of RM-based geopolymer concrete specimens. The most noteworthy observation was that the RM-based ternary mixed geopolymer concrete had lower strengths in ambient curing than in oven curing, while the difference was too small to be meaningful. When the flexural strengths of geopolymer specimens were compared to those of OPC specimens at 56 days curing age, the increases in strength values were %, 51 %, 49 %, 47 %, 45 %, 56 %, 54 %, 51 %, 50 %, and 48% in ambient curing and 34 %, 30 %, 27 %, 18 %, 14 %, 39 %, 38 %, 36 %, 31 %, and 27 % in oven curing. Under both curing conditions, the same pattern was seen in all curing ages of the specimens.

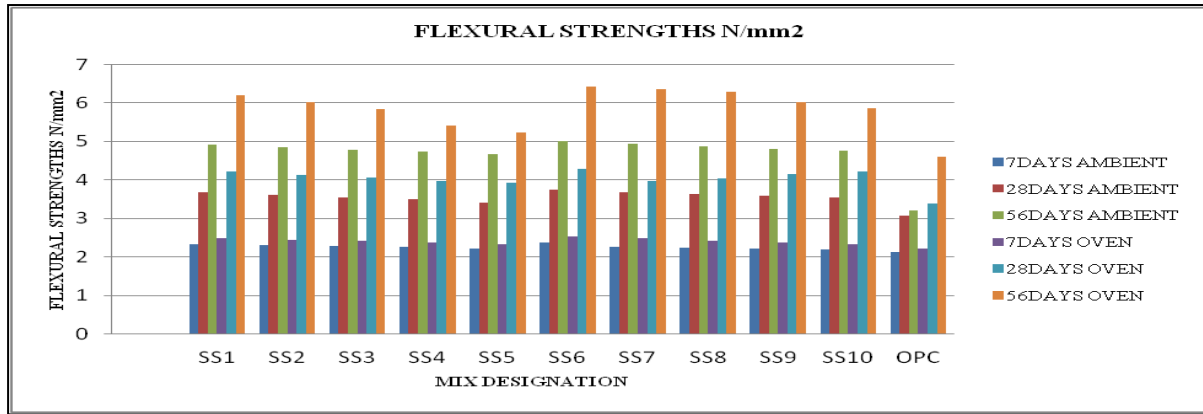


Figure 9. Graphical representation-ternary blended RM based geopolymer concrete flexural strengths MPa about 7, 28, 56 days different curing regimes

### 7.7. Durability properties

#### 7.7.1. Water Absorption Test

The properties of the water absorption in concrete have a significant impact on the structure's longevity. Water penetration deteriorates concrete, and corrosion of the bars happens in reinforced concrete structures, resulting in cracking and spalling of the concrete and, eventually, a reduction in the structure's life span. The outcomes of the water absorption test are shown in fig 10. Water absorption of RM-based ternary mixed geopolymer concrete is lower than that of control concrete, according to the results. Even though the % weight gain difference is relatively modest.

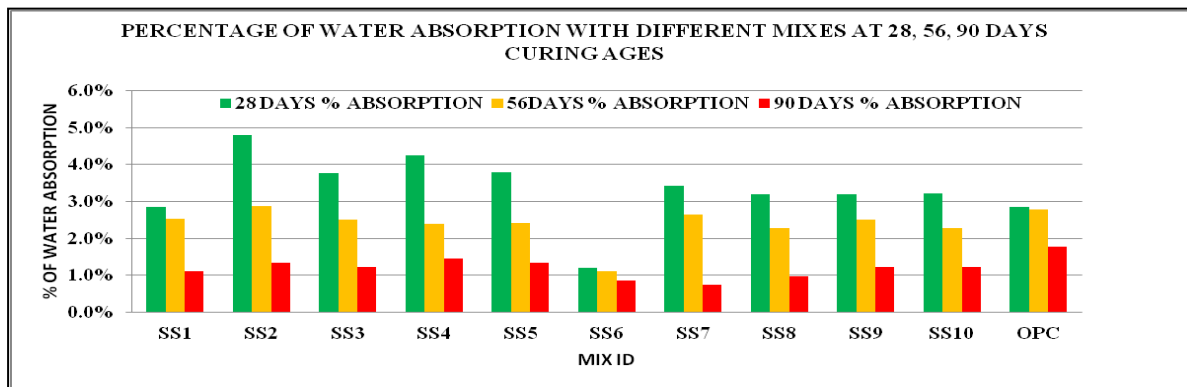


Figure 10. Water absorption percentage of different ternary blended geopolymer mixes

#### 7.7.2. Water Permeability Test

The permeability coefficient can be evaluated by Darcy's law as

$$K = \frac{Q}{A \times T \times (H / L)}$$

here,

K= Permeability coefficient in m/sec

Q = Water collected in ml,entire test lap

T = Time = 360000sec

A = Sample test face area = 0.01767 m<sup>2</sup>

H/L = Pressure head to thickness of the sample = 100/0.15 = 666.67

Compressive strength has been demonstrated to be an excellent predictor of permeability performance. Fig11. & 12. depicted the variations in permeability of GPC specimens after 28, 56, and 90 days of the oven and ambient curing. GPC concrete has lower permeability coefficients than OPC concrete. The limiting value of the permeability coefficient by IS:3085-1965 is shown in table 10.

**Table 10.** Coefficient of permeability values – IS: 3085-1965

COEFFICIENT OF WATER PERMEABILITY IS:3085-1965				
Water Permeability	Very Low	Low	Medium	High
Coefficient of permeability (x 10 <sup>-9</sup> )	< 0.5	0.5-1.0	1.0-2.0	>2.0

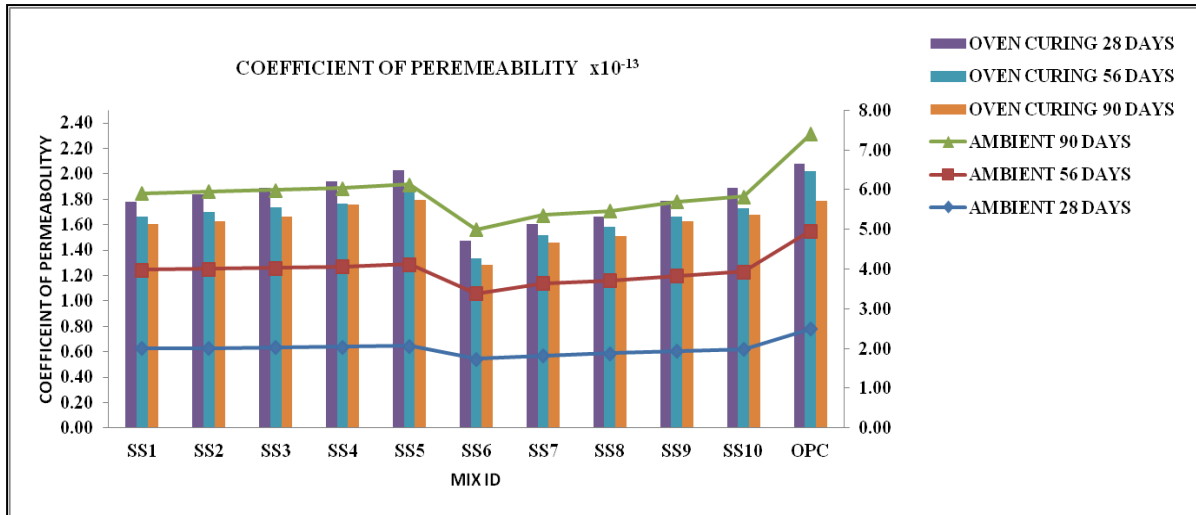
Because the dissolving of NaOH particles requires a lesser volume of water in the manufacturing of 12M NaOH solution. As a result, the loss of water space in geopolymer concrete owing to evaporation is limited, resulting in fewer pores and making the geopolymer concrete more impermeable. Mix proportions SS6 and SS7 demonstrated lower permeability than other mixes, including the control mix, in both ambient and oven curing trials. Tables 11&12 provided the experimental values of the coefficient of permeability on GPC specimens under oven and ambient curing conditions.

**Table 11.** Coefficient of permeability values with different geopolymer mix specimen in ambient curing

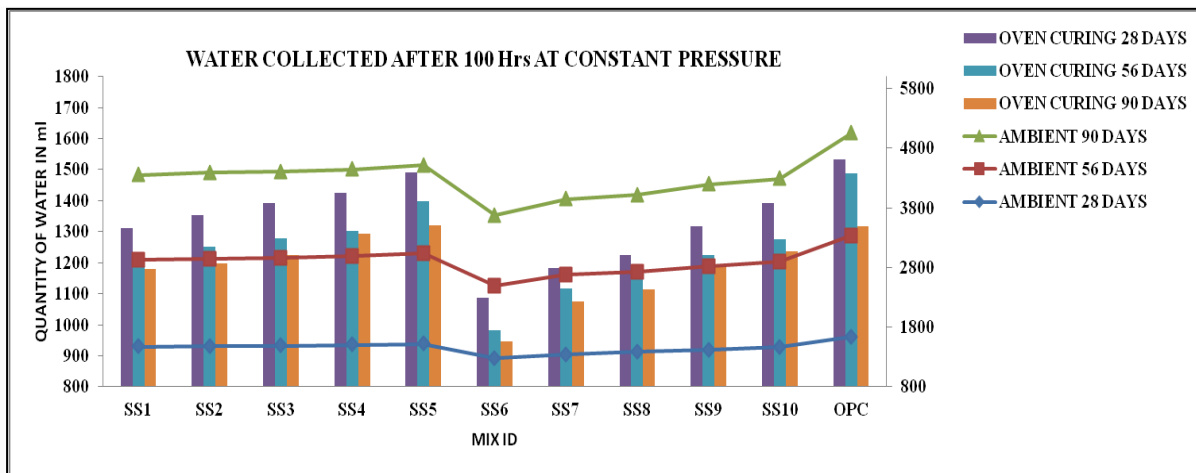
Mix Id	Pressure head [H m]	Quantity of Water Collected[ml]			Coefficient of Permeability [mm /sec <sup>-1/2</sup> x 10 <sup>-9</sup> ]			% Reduction with OPC		
		28 days	56 days	90 days	28 days	56 days	90 days	28 days	56 days	90 days
SS1	100	1474	1456	1422	2.00	1.98	1.93	20.31	19.60	20.65
SS2	100	1482	1467	1437	2.01	1.99	1.95	19.67	19.00	19.81
SS3	100	1491	1473	1445	2.03	2.00	1.96	19.19	22.82	19.36
SS4	100	1506	1481	1457	2.05	2.01	1.98	18.37	16.84	18.69
SS5	100	1521	1513	1481	2.07	2.06	2.01	17.56	16.45	17.35
SS6	100	1281	1213	1182	1.74	1.65	1.61	30.57	33.02	34.04
SS7	100	1346	1332	1270	1.83	1.81	1.72	27.05	26.45	29.13
SS8	100	1384	1346	1291	1.88	1.83	1.75	24.99	25.68	27.96
SS9	100	1421	1401	1372	1.93	1.90	1.86	22.98	22.64	23.44
SS10	100	1463	1432	1397	1.99	1.95	1.90	20.11	20.93	22.04
OPC	100	1845	1811	1792	2.51	2.46	2.43			

**Table 12.** Coefficient of permeability values with different geopolymer mix specimen in oven curing

Mix Id	Pressure head [H m]	Quantity of Water Collected[ml]			Coefficient of Permeability [mm /sec <sup>-1/2</sup> x 10 <sup>-9</sup> ]			% Reduction with OPC		
		28 days	56 days	90 days	28 days	56 days	90 days	28 days	56 days	90 days
SS1	100	1311	1226	1179	1.78	1.67	1.60	14.43	17.61	10.48
SS2	100	1352	1251	1198	1.84	1.70	1.63	11.75	15.93	9.04
SS3	100	1392	1278	1226	1.89	1.74	1.67	16.58	14.11	6.91
SS4	100	1426	1302	1294	1.94	1.77	1.76	6.92	4.17	1.75
SS5	100	1491	1398	1319	2.03	1.90	1.79	2.68	6.05	-0.15
SS6	100	1086	983	946	1.48	1.34	1.28	35.84	33.94	28.17
SS7	100	1182	1116	1076	1.61	1.52	1.46	22.85	25.00	18.30
SS8	100	1225	1167	1113	1.66	1.59	1.51	20.04	21.57	15.49
SS9	100	1316	1224	1195	1.79	1.66	1.62	14.10	17.74	9.26
SS10	100	1392	1275	1237	1.89	1.73	1.68	9.14	14.31	6.07
OPC	100	1532	1488	1317	2.08	2.02	1.79			



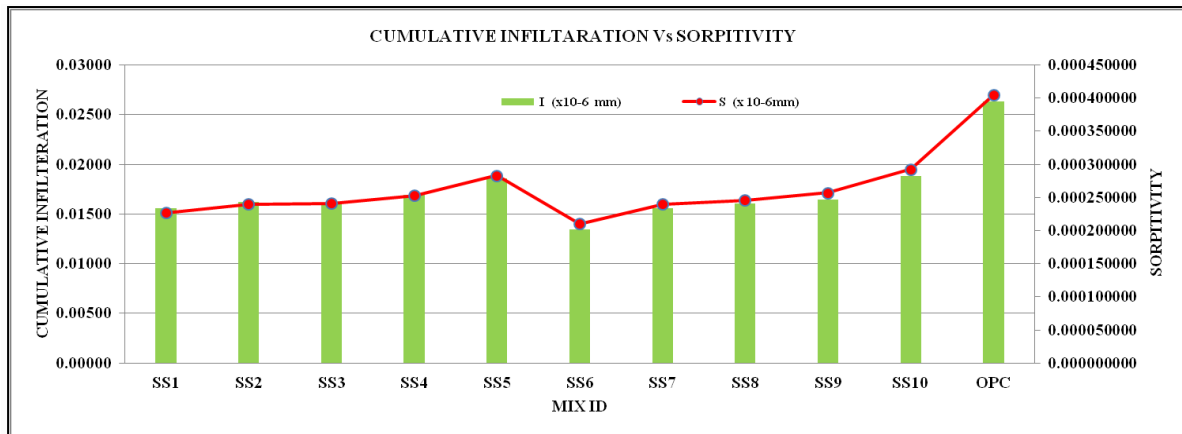
**Figure 11.** Coefficient of permeability values with different ternary based geopolymer concrete specimens



**Figure 12.** Quantity of water collected after 100hrs test period with different ternary based geopolymer concrete specimens

### 7.7.3. Sorptivity Test

Fig 13 shows the sorptivity test results of RM-based ternary blended geopolymer concrete mixes at various time intervals. It can be shown that, except SS1, the remaining mixes, SS5 and SS6, have a high sorptivity in the concrete specimens, including the target mix. In this case, SS6 with a mixed percentage of 35% RM+45% FA+20% GGBFS has the lowest sorptivity. As a result, the inclusion of RM up to a certain degree tends to lower the sorptivity coefficient favorably. Furthermore, increasing the proportion of RM impacted the transmission of water through capillarity in concrete, as demonstrated in the maximum sorptivity values of mixes SS2-SS5 and SS7-SS10. GGBFS, on the other hand, has a substantial role in repelling water uprising, as evidenced when it was lacking in SS2-SS5. When compared to control samples, the proportion of Superplasticizer and the high molarity of NaOH used to have stronger resistance to water penetration, with a reduction of up to an acceptable percentage.



**Figure 13.** Graphical demonstration of cumulative infiltration Vs sorptivity of the ternary blended geopolymer mix specimens

## 8. Conclusion and Future Work

The current study focuses on the strength characteristics of ternary blended geopolymer concrete based on FA, RM, and GGBFS. The curing regime has a considerable influence on the strength properties of geopolymer concrete. The strength properties in ambient curing circumstances will decrease as the amount of RM component in GPC increases. Mechanical strength qualities will be improved during oven curing as the number of RM increases. The alkaline nature of RM, FA, and GGBFS is found to be greater in ternary blended geopolymer paste with the source materials than in binary combinations with the same materials, according to the pH analysis of the ternary blended geopolymer paste with the source materials. The polymerization procedure began quickly, and the strength enhancement is found to be greater with a mix of 20% GGBFS rather than a blend of 10% GGBFS-based GPC. GPC specimens cast with 20% GGBFS cured in ambient and oven curing had greater mechanical strength properties than 10% GGBFS specimens in both curing regimes. When the compressive strengths of OPC specimens were compared to the compressive strengths of ternary blended geopolymer concrete specimens with 56 days of curing ages, the increase in strength values was 31% -35% in oven curing and 14% -16% in ambient curing. In terms of split tensile strengths compared with OPC values, the ternary blended GPC specimens gained 40%-48% strength under ambient curing and 4% -10% in oven curing conditions were observed. When GPC specimens were compared to OPC specimens at 56 days of curing age, the increases in strength values were 45% -56% ambient curing and 14% -39% oven curing conditions, respectively. According to the findings of the tests, the rise in mechanical strengths in geopolymer paste increases as the pH value increases. The percent of water absorption decreases as the number of FA increases and RM decreases in the mix of geopolymer concrete irrespective of the curing period. The proportion of water absorption lowers with the curing period the irrespective quantity of base materials in the mix. All the durability properties indicate that the geopolymer concrete mixture prepared with RM: FA: GGBS: 35:45:20 proportions produces dense concrete with a less porous- structure. This study can be extended to study the microstructure characteristics of RM-based ternary blended GPC.

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