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Regression and Cluster Analysis of GGBS based geopolymer compositeat different proportion of Ceramic Dust

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In compare to Portland cement, geopolymer have much lower CO_2 emissions, which led to growing interest in their use as an environmentally sustainable binder. The investigation of the strength in compression and durability characteristics of geopolymer composite produced at various calcined clay and ground granulated blast furnace slag (GGBS) proportions (up to 50:50) with 12M of sodium hydroxide and ratio of sodium silicate to sodium hydroxide as 2. The strength of the produced composites was evaluated after 7, 28, 56 and 90 days of ambient air curing. The durability characteristics were evaluated using Rapid Chloride Permeability Test (RCPT), acid and sulfate attack using 5% MgSO4 and 5% H2SO4 solutions respectively and for the integrity using ultrasonic pulse velocity (UPV) test. Test results showed that the developed GPC (Geopolymer composite) has several advantages over standard concrete. The strength in compression (MPa) of the SC100 (standard concrete) as compared to Geopolymer Concrete in Compressive strength was increased by replacing GGBS with calcined clay up to 10%. At 56 and 90 days, the compressive strength of 10% calcined clay samples were improved by 20.15% and 21.60% respectively as compared to the SC100. Correlations showed that strength is having a strong relationship with the chloride ion permeability and the pulse velocities.

Keywords: Sustainable environment, Geopolymer composite, Chloride ion permeability, Acid attack; Sulfate attack

1 Introduction

Concrete mix is a widely used building material around the globe because of its less cost, long life, easy accessibility of its ingredients, easy mouldability, and so on[1-3]. Ordinary Portland cement (OPC) is the binder that binds the rest of the ingredients of the concrete[4]. However, the production of OPC is an energy-intensive operation that covers nearly 5-7% of overall global CO_2 emission, and is the primary source of global warmingwhich means, it affected the sustainable environment[5,6]. According to another study, the manufacture of 1 tonne of OPC emits an almost equal amounts of CO_2 into the atmosphere. As a result of this issue, new renewable OPC-free concrete binders and supplementary cementitious materials (SCMs) are being used to partially substitute a considerable volume of OPC in concrete[7-8]. Agricultural and industrial waste materials such as silica fume, fly ash, GGBS, bagasse and rice husk ash etc. have been found to be useful in concrete applications for keeping a sustainable environment; however, such materials can only be utilized for part replacement of OPC but could not completely replace it[9–12]. Davidovits conceived the idea of such materials which can be developed by reacting silica and alumina with alkali-activating solutions[13]. Fly ash, metakaolin, rice husk ash, ggbs and other materials rich in alumina and silica are the most useful material due to its accessibility[14,15].The alumina-silicate clay minerals metakaolinite, illite, and

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montmorillonite were calcined at different temperatures to create geopolymer cements. Due to their widespread occurrence in the natural world, cheaper extraction costs, and relatively less environmental footprint, these substances have the potential to be employed as raw materials in geopolymer synthesis[16]. Geopolymers are eco-friendly cementitious materials that can be developed by combining ground granulated blast furnace slag, Na_2SiO_3, and NaOH solution[17].

The use of geopolymer as binders in concrete is getting popular in the building industry due to environmental advantages as well as improved durability and mechanical properties. Many researchers focused on the effect of changing the parameters such as ggbs proportioning, metakaolin proportioning, curing conditions, activating solution, NaOH concentration and silicate to hydroxide ratio etc. of geopolymer composite on the strength and durability properties[18,19]. When iron, coal, and limestone/dolomite are melted together, the result is a by-product known as blast furnace slag (BFS). Researchers have shown that granulated slag after grinding may be utilized as a source of alumina and silica in GPC to reduce the amount of traditional cement needed[20]. According to researchers when the mixing period is increased, the geopolymer's rheological and strength qualities improve[21]. Apart from the molarity of NaOH and silicate to hydroxide ratio, GPC mechanical characteristics are also influenced by other parameters such as curing technique and curing duration[22,23]. Amin Noushini et al. have conducted the experimental investigation of the durability and mechanical properties of Fly ash (Class-F) based GPC under ambient as well as heat curing for 8, 12, 18 and 24hrs (at the temperatures of 60°C, 75°C and 90°C). They found that heat curing at 75°C and for a duration of 18 to 24 hours tends to improve the strength and electrical resistivity values[24]. Similar results have been obtained when cement is replaced with other aluminosilicates such as GGBS, RHA, metakaolin etc. at varying NaOH concentrations. Silicate to hydroxide ratio of 0.5 to 10 has been used by the researchers for the manufacture of the activating solution but the highest feasibility was obtained for the ratio range of 1.5 to 2.5 only[25–29]. Geopolymer composite based on coal fly ash could be 10–30% less expensive than OPC concrete. At atmospheric curing conditions also the geopolymer composite can set and harden. Concrete structures have to be able to sustain the attack of the atmosphere, acids, sulfates, chlorides etc. and abrasion, or some other degradation mechanism that affects the long-term strength of concrete [30,31].

Calcined clay was employed as a substitute for GGBS in GPC in this study. Calcined clay was employed in percentages of ten percent, twenty percent, thirty percent, forty percent, and fifty percent. 12M molarity of NaOH solution was used in this investigation with the ratio of Sodium silicate to sodium hydroxide was 2. Compressive strength and durability tests (acid attack, UPV, sulphate attack, and RCPT) were used to study the produced GPC. A correlation of compressive strength values with the chloride ion permeability and the UPV values was also established.

2 Material and Methods

2.1 Materials

GGBS and calcined clay has been obtained from a local supplier (Astra Chemicals Ltd.) in Chennai. Table 1 shows the chemical composition of both aluminosilicates which were given by the supplier. According to IS 1727:1967, the specific gravity (SG) of GGBS and clay were observed to be 2.83 and 2.52, respectively. Sub-angular aggregates and medium sand from zone III were employed. Aggregates filtered through a 10 mm sieve and retained on a 4.75 mm sieve were obtained in 40% ratio, while those filtered through 20 mm sieve and held on 10 mm sieve were obtained in 60% ratio. The specific gravity, fineness modulus and water absorption of FA (fine aggregates) were 2.64, 2.87 and 0.97% respectively. Water absorption and specific gravity of CA (coarse aggregate) were 0.53% and 2.71. Hydroxide and sodium silicate were combined to produce the activating solution applied in this work. A 12 M NaOH solution was obtained by adding 480 gm of solid NaOH in 1000 gm of potable water. Water glass used in alkaline activator contains

Table 1 — Chemical composition of GGBS and Calcined Clay (CC)

S. No	Composition	GGBS Proportion (%)	CC Proportion (%)
1	CaO	32.79	0.74
2	SiO_2	30.34	46.08
3	Al_2O_3	14.11	39.91
4	MgO	7.75	-
5	Fe_2O_3	2.83	1.31
6	Na_2O	-	0.12
7	TiO_2	-	2.52
8	LOI	0.26	9.7

33.35% total soluble silicates by mass, 14.10% total alkalinity by mass, and 52.55% water. A Silicate to hydroxide ratio of 2 was used for preparing the activating solution. The specific gravity of Na_2SiO_3 was 1.55. Soda flakes, when comes in contact with water cause exothermic reactions with a release of enormous heat so the preparation of the activating solution was done at least 24hrs before using it.

2.2 Mix proportion

A total of six GPC mixes were produced in the present study in which the GGBS has been replaced partially with calcined clay in proportions of 0, 10, 20, 30, 40 and 50 percent by mass of GGBS. All of the GPC mixes were activated with an alkaline solution at a concentration of 12 M sodium hydroxide. The activating solution-to-binder ratio was kept constant across all of the mixtures at 0.4. Table 2 shows the proportion of GGBS and Calcined in the concrete mix.

2.3 Methodology

All of the materials for geopolymer composite, such as GGBS, calcined clay, FA, CA (coarse aggregates), and activating solution, among other things, that are necessary for the production of the requisite GPC mix are monitored carefully. In the first step, the aluminosilicates (slag and clay) were put into the electrically operated mixer with CA and FA and the mixer is run for two more minutes in dry condition. In the next step, activating solution along with the required quantity of water was added to the mixer, and the mixing was conducted for another five to six minutes. The cubical moulds and cylindrical moulds were filled in 3 stages, compacting the mix 25 times after each stage, after greasing the moulds from the inside. The concrete in the moulds was compacted with the help of a vibrating table. For 20–30 seconds, the moulds vibrated. All of the GPC specimens were removed from the moulds after 2 days and placed in ovens for temperature curing for the next 1 day at a stable temp. of 60°C. The oven was turned off for 24 hours, but the moulds were kept in the oven for another 1 day so that they could reach their regular temperature. After temperature curing, the GPC samples were kept in the open air to cure for a period until they were tested.

Table 2 — Sample ID of Concrete Sample

Sample ID	Cement (%)	GGBS (%)	Calcined Clay (%)
SC100	100	0	0
S100	0	100	0
S90C10	0	90	10
S80C20	0	80	20
S70C30	0	70	30
S60C40	0	60	40
S50C50	0	50	50

2.4 Testing

2.4.1 Compressive Strength Test

Cube specimens of 10 cm side were examined for compressive strength after 7, 28, 56 and 90 days according to IS 456-2000[32]. The numbers that were determined for the compressive strength constituted an average of the data from three different specimens. The compressive strength evaluation was carried out with the assistance of a compression machine that had a capacity of 1500 KN.

2.4.2 Chloride Ion Permeability Test

As a quick and easy way to measure concrete's resistance to chloride ion infiltration, the rapid chloride permeability test (RCPT-ASTM C 1202) is frequently employed. The RCPT value represents an electrical measure of concrete's resistance to the infiltration of chloride ions. The GPC was subjected to an RCPT test to determine its permeability properties. RCPT test was conducted on cylindrical specimens with diameters of 10 cm and heights of 5 cm, respectively. Four identical sections were cut into cylinders 10 cm 20 cm in height along their length to provide the samples used for the RCPT test. The top component was eliminated and the remaining three pieces were employed in the experiment.

2.4.3 Ultra Sonic Pulse Velocity Test

The UPV Test records how long it takes for an ultrasonic pulse to penetrate the concrete. Good density, uniformity, homogeneity, etc. can be inferred from the results of the UPV Test and the time taken for transit. The quality of concrete can be evaluated using the ultrasonic pulse velocity test in accordance with IS: 13311 (Part 1) - 1992. The UPV test was done on cubical moulds with dimensions of 100 mm^3 respectively. The GPC was subjected to a UPV test to verify its homogeneity and integrity.

2.4.4 Acid Attack

The concrete samples were placed in the acidic solution for 28 days so that the acid attack resistance ability could be evaluated. To create the acidic solution in accordance with the ASTM standards, 5% sulphuric acid solution was used. After 4 weeks of ambient air drying, the GPC samples were submerged in a 5% by weight H_2SO_4 solution for the next 4 weeks, 8 weeks and 3 months before testing. Acid attack on sample was performed by following the guide line of ASTM C1898-20 code.

2.4.5 Sulfate Attack

A Sulfate solution was prepared in a lab using magnesium sulfate. Under these situations, 5% of magnesium sulfate compounds dissolved in tap water are kept in a 40-L tub. The GPC and standard concrete cube specimens were tested for sulfate attack by submerging them in a magnesium sulfate solution for 28, 56, and 90 days respectively and checking the effect of magnesium sulfate attack on the mass of the specimens of GPC. After 4 weeks of ambient air drying, the GPC samples were submerged in a 5% by-weight magnesium sulfate solution for the next 4 weeks, 8 weeks and 3 months before testing. Sulfate attack on sample was performed by following the guide line of ASTM C 1012.

3 Result and Discussion

3.1 Workability

The workability of all the samples was measured using a slump cone test as specified in IS: 1199-1959[33]. The slump values for SC100, S100, S90C10, S80C20, S70C30, S60C40 and S50C50 specimens were 8.6, 7.9, 7.4, 6.8, 5.4, 4.1 and 3.3 cm respectively. The slump value of standard concrete was higher as compared to GGBS concrete because of the angular form of GGBS, which affects the fluidity of the concrete mixes[34]. Consequently, the fluidity of the concrete mixes is reduced. In addition to this, GGBS has a higher degree of fineness than OPC. As a consequence of this, the gaps in between the cement particles were filled with fine GGBS powder, which has a greater surface area. This led to an increase in the amount of particle contact[35]. Figure 1 shows that the workability of the GPC mix began to decrease as the amount of calcined clay in the mix increased. Since the calcined is very light in weight and has high absorption capacity so the water content available for mixing got reduced as a result of the absorption of water by calcined clay.

3.2 Strength in compression

The test results for ordinary cement concrete, GGBS, and calcined clay-based GPC are represented graphically in Fig. 2. The strengths, in MPa, of the

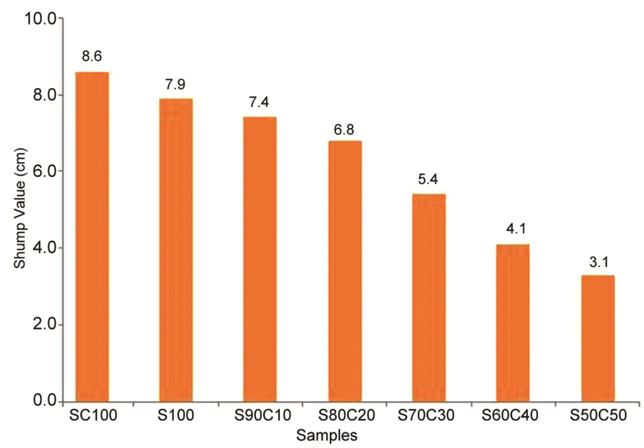

Fig. 1 — Slump values.

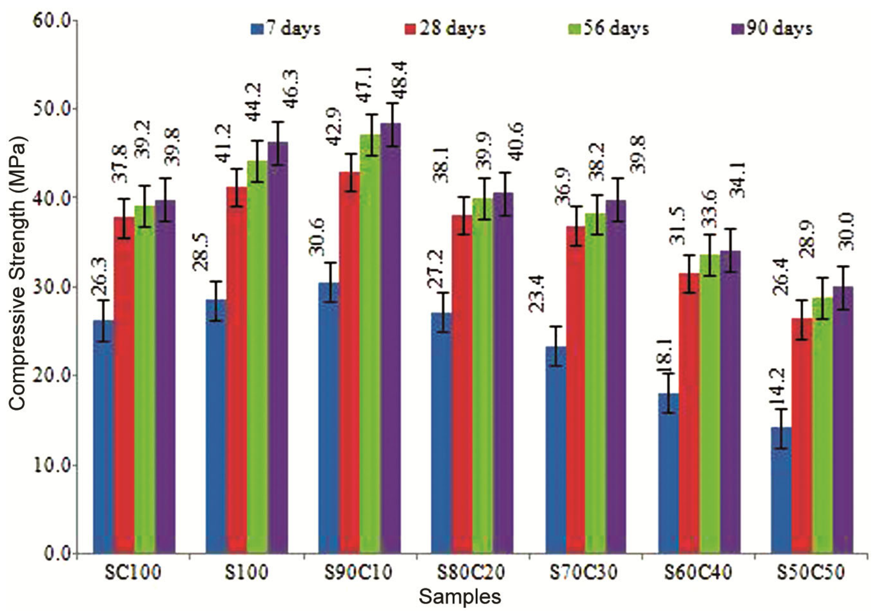

Fig. 2 — Compressive strength of standard and geopolymer composite.

SC100 and S100 samples at 7, 28, 56 and 90 days of curing were obtained as 26.3, 37.8, 39.2, 39.8 and 28.5, 41.2, 44.2 and 44.6 respectively. It is clear that irrespective of the curing age, the strength of the S100 samples is always found greater than that of the standard cement concrete samples. As increasing the number of days of curing, the compressive strength of the sample also increased. Curing is one method that permits increasing its potential strength. Curing implies that concrete continues to hydrate, which ultimately results in the material gaining strength even after it has been placed. In order to ensure continuous hydration in the concrete, it is necessary to keep the temperature and moisture content at an acceptable level for an adequate amount of time[36]. Ahmet Emin Kurtoglu et al. have also reported similar results for compressive strength when controlled mixes containing 100% GGBS and 100% OPC were investigated[37]. The increased strength of the S100 samples is due to the formation of geopolymeric gel (C-A-S-H and N-A-S-H) along with the calcium silicate hydrate (C-S-H) gel which provides additional strength to the GGBS-based concrete [38]. The addition of calcined clay (up to 10%) has maximum improvement to GGBS-based geopolymer composite. The strengths, in MPa, of the S100, S90C10, S80C20, S70C30, S60C40 and S50C50 samples at 28 days of curing were found to be 41.2, 42.9, 38.1, 36.9, 31.5 and 26.4 respectively. The improvement in compression strength till the 10 percent substitution of GGBS with clay might be attributed to the filling of voids by clay particles and pozzolanic activity caused by both GGBS and calcined clay[39]. The particles of clay may have occupied the void spaces and therefore have enhanced the GPC's pore structure[40]. Further addition of CC, beyond 10 percent, resulted in decreased strength which might be attributed to GPC sample instability, indicating a delay in the production of the calcium silicate hydrate gel and the polymeric phases. Also, a greater volume of clay might have formed agglomerates, which are gathered in a limited region.

3.3 Resistance to Acid Attack

The sulphuric acid solution had an impact on the GPC in terms of a decrease in the mass of samples and a variation in the strength. Figure 3 depicts the decrease in mass of the sample. The mass loss in standard concrete samples was found to be comparably quite considerable when compared to geopolymer composite samples. The S80C20 sample showed the lowest mass loss due to acid attack as compared to standard concrete. After increasing the amount of calcined clay in the GPC mixes the mass loss of samples was increased as compared to S80C20 samples. The filling of pores and cracks by micro clay particles, as well as the decrease in capillary action, are the reasons for the reduced mass in GPC when compared to standard concrete[41]. Mostafavafaei et al. checked the effect of acid attack on fly ash-based geopolymer mortar with calcium aluminate cement and found that the mass loss of Geopolymer mortar

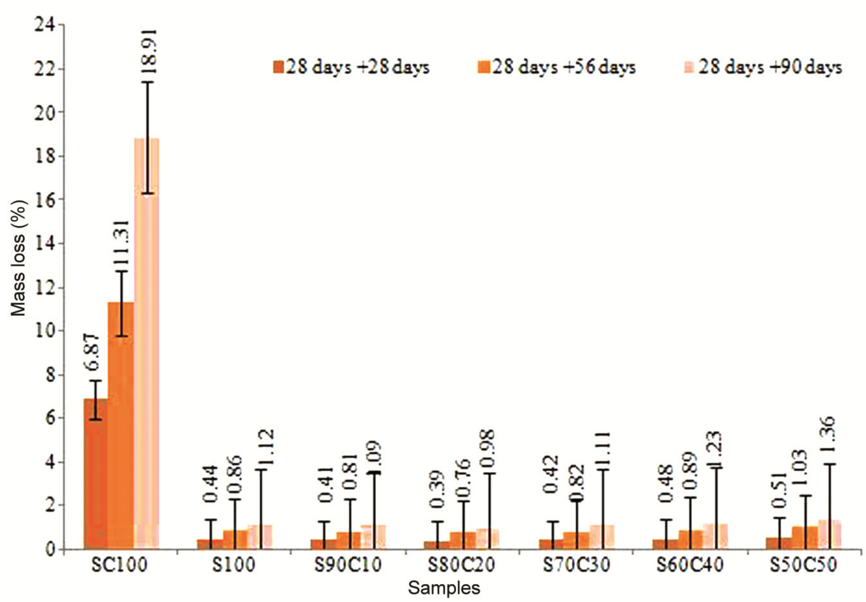

Fig. 3 — Mass loss of sample due to acid attack.

was reduced less as compared to standard mortar. S80C20 samples had the lowest reduction in mass among the GPC specimens [42]. The interaction between the acidic H_2SO_4 and the alkaline GPC samples is responsible for the loss of mass of GPC. The absorption of more acidic solutions eroded the matrix, resulting in a loss of mass.

3.4 Resistance to Sulfate Attack

The impact of sulfate on the developed GPC, in terms of mass loss, has been assessed using 5% by weight $MgSO_4$ after 28, 56 and 90 days of submergence post 4 weeks of ambient air curing. The reduction in the mass for the specimens is shown in Fig. 4. The impact of $MgSO_4$ solution on normal concrete and GPC was evaluated after 28 days of ambient air curing. After 28, 56 and 90 days, the mass loss of normal concrete subjected to submergence in 5% $MgSO_4$ solution was 3.29%, 6.54% and 10.29% respectively. After 28 days of submergence, the mass loss for S100, S90C10, S80C20, S70C30, S60C40 and S50C50 specimens was 0.93%, 1.02%, 1.22%, 1.41%, 1.69%, and 1.82% respectively. After 56 days of submergence, the mass loss for S100, S90C10, S80C20, S70C30, S60C40 and S50C50 specimens was 1.72%, 1.89%, 1.96%, 2.34%, 2.48% and 2.81% respectively. After 90 days of submergence, the mass loss for S100, S90C10, S80C20, S70C30, S60C40 and S50C50 specimens was 2.36%, 2.59%, 2.71%, 2.98%, 3.29% and 3.71% respectively. Mass loss owing to sulfate attack improved with both the amount of calcined clay and the length of time. This could be due to the increasing quantity of calcined clay causing impediments in the geopolymeric phase, resulting in a poor geopolymeric matrix in the mixture[43].

3.5 Chloride Ion Permeability

The electrical conductivity of normal and geopolymer composite samples was estimated using RCPT. This test primarily assesses the concrete's resistance to chloride ion permeation. Figure 5 shows the charge passed (in coulomb) through the standard sample and all the GPC samples after 28, 56 and 90 days of ambient air. The charge transmitted through the samples at 28, 56 and 90 days of testing is largely in the moderate range according to ASTM C1202. It can also be observed that when the duration is prolonged, the charge transmitted decreases. This is due to the rise in the density of the mix over time. The presence of Na_2SiO_3 is another factor for the moderate and low permeability values[44]. The present investigation employed sodium hydroxide of molarity 12M and Na_2SiO_3/NaOH ratio of 2. At 28, 56 and 90 days of testing, the charge transmitted through SC100 samples was 1660 coulombs 1482 coulombs and 1647 coulombs respectively. After 28 days, the charge transmitted, in coulombs, through S100, S90C10, S80C20, S70C30, S60C40 and S50C50 samples was 1166, 1092, 1210, 1659, 2354, and 2966 respectively. After 56 days, the charge transmitted, in coulombs, through S100, S90C10, S80C20, S70C30,

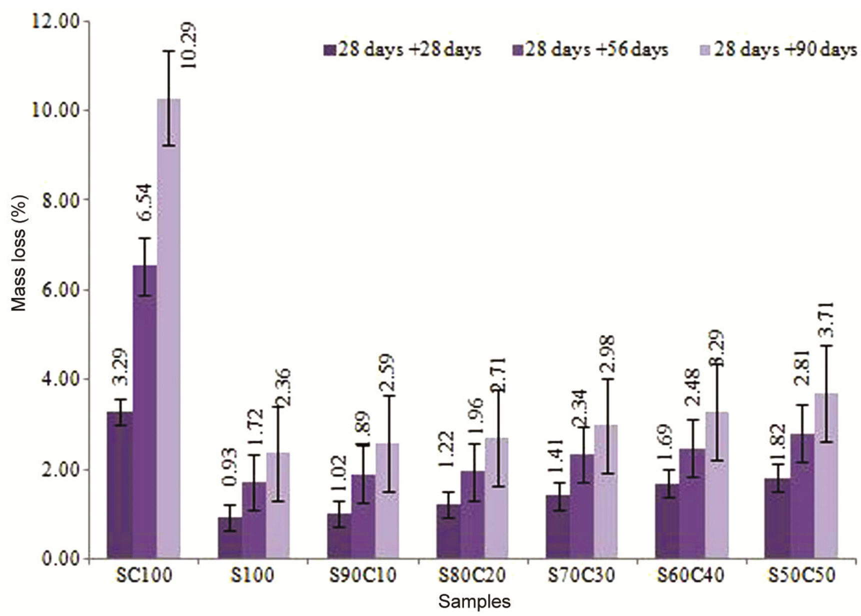

Fig. 4 — Mass loss of samples due to sulfate attack.

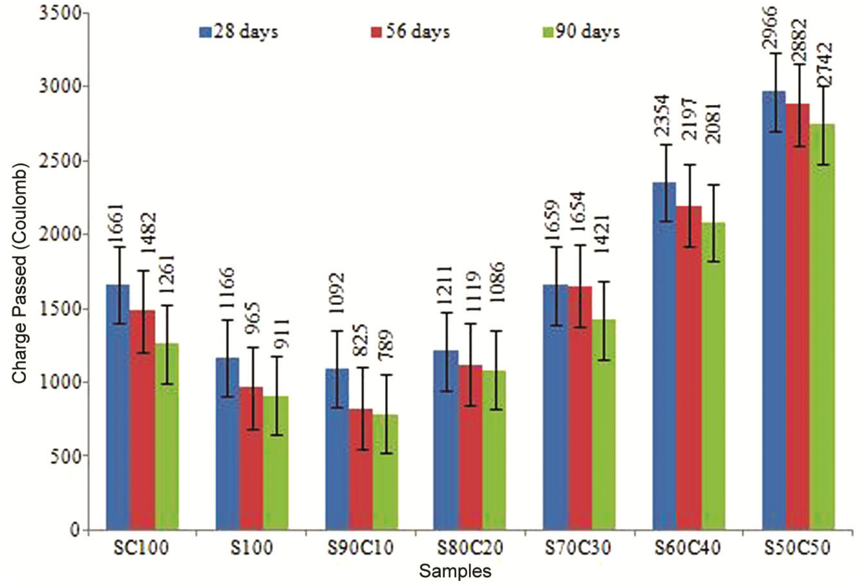

Fig. 5 — Rapid chloride penetration test value of samples.

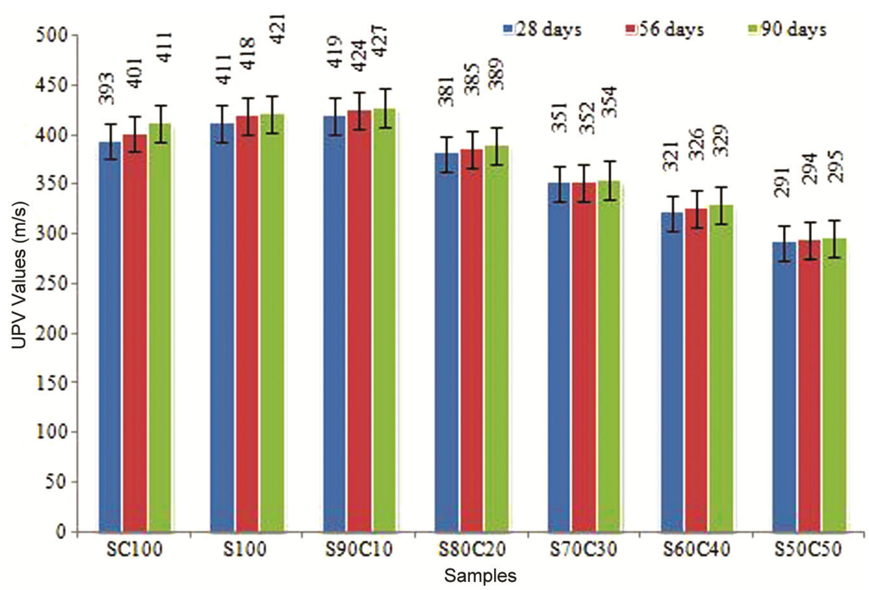

Fig. 6 — UPV value of standard concrete and geopolymer composite.

S60C40 and S50C50 samples was 965, 825, 1119, 1654, 2197 and 2882 respectively. After 90 days, the charge transmitted, in coulombs, through S100, S90C10, S80C20, S70C30, S60C40 and S50C50 samples was 910, 789, 1086, 1421, 2080 and 2742 respectively. The inclusion of 12 M sodium hydroxide and Na_2SiO_3 in the alkaline activator accounts for the reduced permeation through the GPC samples as compared to the SC100 sample. Permeability decreased further across GPC samples up to S90C10 samples and then began to rise when the quantity of calcined clay was increased. Due to the fact that the pores and cracks in the mix were at their lowest levels at 10% calcined clay substitute, the mix had the lowest permeability; however, as the fraction of clay is enhanced, the obstruction of the fine particles to the development of polymeric phase is increased, resulting in the mix having reduction integrity.

3.6 Ultrasonic Pulse Velocity (UPV) Test

The findings of the ultrasonic pulse velocity testing are shown in Fig. 6. At 28, 56 and 90 days of testing, the results of UPV for SC100 and S100 specimens are almost similar. UPV results for

S90C10 samples increased to 4188 from 3926 m/s after 4 weeks and enhanced to 4244 meter/second from 4012 meter/second after 8 weeks and increased to 4266 meter/second from 4096 meter/second after 3 months. The improvement in UPV results for S90C10 samples shows that the GPC matrix has relatively fewer pores and cracks. The filling of pores in the mix of concrete by micro clay particles is responsible for this improvement in UPV values. As the proportion of clay was increased further, the UPV value also decreased. The decreasing UPV values might be due to calcined clay aggregation at greater proportions of calcined clay[45]. The GPC specimens with 10%, 20%, and 30% calcined clay substitution are considered high-quality concrete, while 40% and 50% calcined clay substitution samples are considered medium-quality concrete. Because 10%, 20% and 30% replacement of calcined clay satisfied the requirement of the grade of concrete after increasing the percentage of calcined clay in the GPC mix did not satisfy the requirement of M30 grade of concrete [46].

3.7 Correlation between strength in Compression with RCPT

Figure 7 indicates the experimentally determined relationship between RCPT and strength in compression of GPC prepared with various amounts of calcined clay and GGBS. The linear equation indicates the percent relationships between RCPT (C) and strength in compression (σ), along with the coff. of determination (R^2) obtained from the equation below:

$$y = -1.108x + 58.45 \quad \dots (1)$$

The following coefficient of determination (R^2 = 0.928) suggests that the data points and the regression curve of RCPT and compressive strength test values [47] have a good relationship. Equation (1) indicates that the strength in compression increases as the chloride permeability decreases. It was indicating that when the samples have lower permeability values then the value of compressive strength was increased. So the value of R^2 was higher.

3.8 Correlation between strength in compression with UPV

Figure 8 indicates the experimentally determined relationship between UPV and strength in compression of GPC prepared with various amounts of calcined clay and GGBS. The linear equation indicates the link between UPV (U) and compressive strength (σ) in percent, as well as the coefficient of determination (R^2) calculated using the equation below:

$$y = 73.79x + 879.4 \quad \dots (2)$$

The following coefficient of determination (R^2 = 0.883) suggests that the data points and the regression curve of ultrasonic pulse velocity and compressive strength values[48] have a good connection. Equation (2) indicates that the strength in compression increases as the ultrasonic pulse velocity enhances. Because the compressive strength values is directly proportional to the values of ultrasonic pulse velocity. When the value of compressive strength was improved then the values of UPV were improved.

3.9 Cluster

Multivariate statistical techniques are frequently used for the classification, analysis, and interpretation

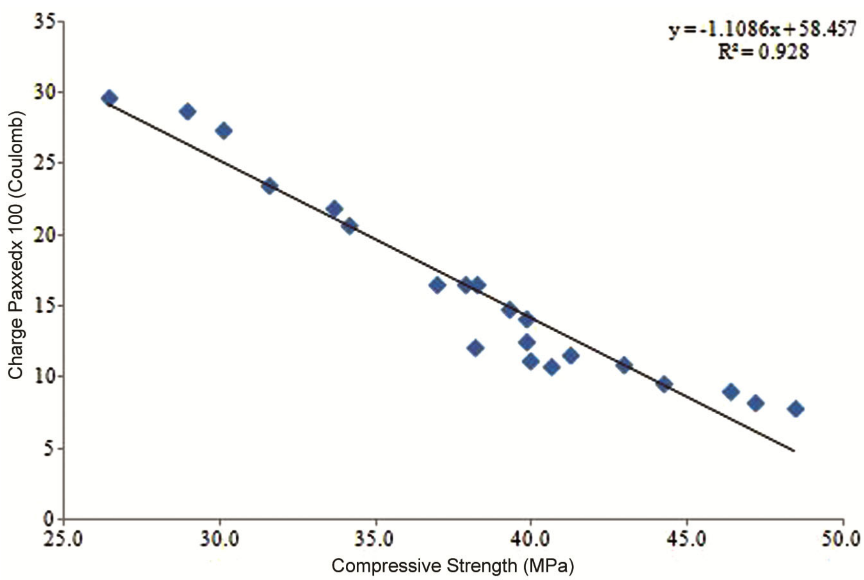

Fig. 7 — Correlations between strength in compression with RCPT.

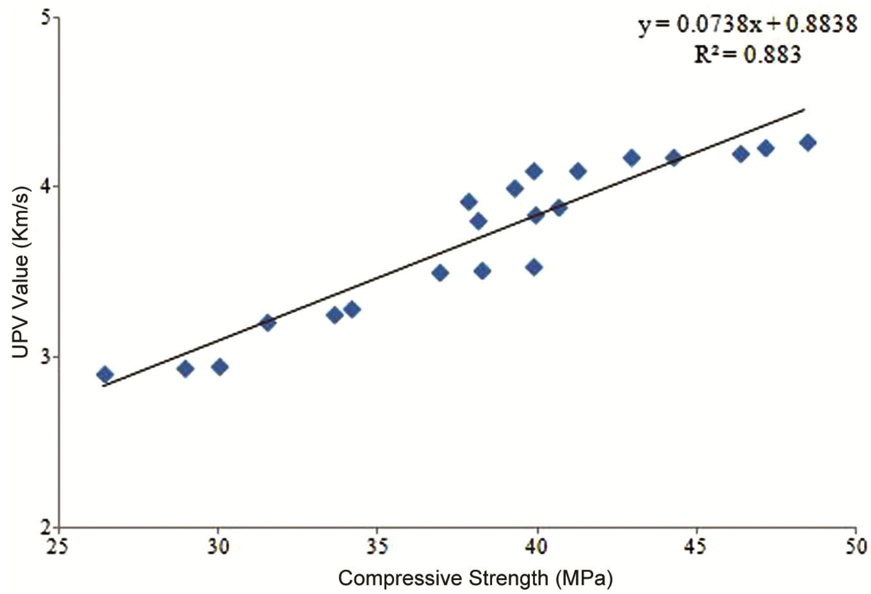

Fig. 8 — Correlations of compressive strength with UPV.

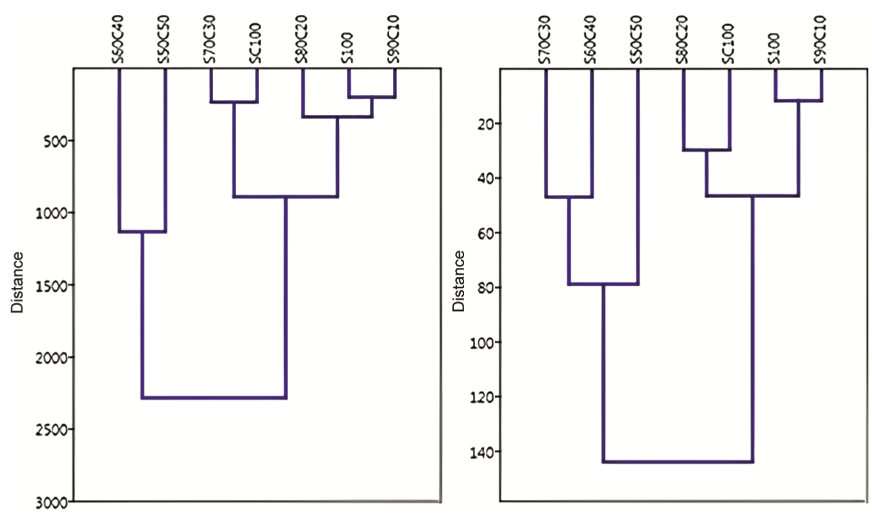

Fig. 9 — Cluster Analysis of (a) RCPT and (b) UPV value.

of enormous data sets. It is also possible to reduce the dimensionality of complicated datasets while keeping as much of the original information as possible by employing these techniques[49]. Cluster analysis (CA) is a subfield of unsupervised pattern classification that involves the grouping of objects intocategories (clusters) based on similarities within a category and differences between categories. The below Fig. 9 displayed the results of a cluster analysis of Rapid Ion Chloride Permeability and UPV.

The outcomes of CA (Cluster Analysis) are useful for data analysis and revealing patterns. The Euclidean distance, defined as the square root of the average squared difference between two sets of data, is a frequently used measure of how similar two situations are to one another. Sample S100, SC100 and S50C50 were show similar trend with the sample of S90C10, S70C30 and S60C40.

4 Conclusion

The mechanical and durability qualities of GPC mixes containing CC as a substitute material in proportions of 10% to 50% were investigated in this study. The analysis revealed that S90C10 outperformed the other GPC mixes in terms of both mechanical and durability characteristics. The compressive strength was also shown to be correlated to RCPT and UPV. The following are some of the results of a study:

- Compressive strength and durability were increased by replacing it with calcined clay. In geopolymer composite, the optimal dose of calcined clay as a GGBS substitute was 10%. At 56 days, the compressive strength was improved by 20.15% compared to the SC100, and at 90 days it was enhanced by 21.60% respectively.
- The UPV values of GPC with up to 10 percent calcined clay replacement were improved.
- When the GPC and standard concrete samples were subjected to acidic and sulphate environments, there was a substantial difference in strength loss and mass loss. The performance of GPC was superior to that of standard concrete.
- The addition of up to 10% calcined clay to geopolymer composite resulted in the highest reduction in chloride ion penetration.
- The data points and regression curve of strength in compression with RCPT and UPV data had a strong correlation.
- Cluster analysis showed a good value of resistance of permeability and UPV of samples S100 and S90C10.

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