Mechanical and Durability Properties with Regression Analysis of 12M GGBS-Based Geopolymer Mortar

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Abstract - *Environmental issues related to OPC manufacture have led to a need for alternative binder materials in the building industry. Geo-polymer is one such technology, and there is evidence to show that it is effective in providing equivalent or even better results with the added benefit of being environmentally friendly. This paper provides results of an experimental analysis of a geo-polymer mortar made up completely of GGBS as a binder material and activated using a 12-molar concentration of sodium hydroxide and sodium silicate in a 1:2 ratio. All mortar specimens used a binder-sand ratio of 1:3 and were cured under normal room temperature. The study focused on three important aspects; compressive strength, water absorption and Ultrasonic Pulse Velocity (UPV) tests conducted at 7, 14 and 28 days, and compared with those of OPC mortar samples prepared under similar conditions. The test results favor the geo-polymer mix: Compressive strength increases from 23 MPa at 7 days to 33 MPa at 28 days, outperforming the control sample at each stage. Water absorption decreases progressively from 5% to 3%, indicating a denser structure, while UPV results increased from 3.8 km/s to 4.7 km/s. From regression analysis, there was even further proof of this through a high negative correlation coefficient (R^2 = 0.8674) between compressive strength and water absorption and a very high positive correlation coefficient (R^2 = 0.934) between compressive strength and UPV. All this is to show that the GGBS geo-polymer mortar is not only comparable but better than the conventional OPC mortar when it comes to its properties and durability.*

Key Words: GGBS, Compressive Strength, Geo-polymer Mortar, Regression Analysis, Ultrasonic Pulse Velocity (UPV), Water Absorption, Durability

1. INTRODUCTION

The world observes a unique rise in the usage of cement-based construction materials as a result of a rapid growth in infrastructure development activities in all parts of the world. OPC, as a common construction material, is present in the entire construction industry; however, its production involves a high amount of energy consumption and results in significant environmental damage. The production of cement results in nearly 8% of carbon dioxide emissions in the world, as calculated by various estimation techniques that highlight limestone calcination and clinker production, which are carried out at high temperatures, as major sources of emission [1]–[3]. The production of cement results in greenhouse emissions, depletion of natural resources, and increased energy consumption, which are major concerns for sustainability and environmental protection [4].

The process of rapid cooling of molten blast furnace slag, which is obtained during iron smelting, leads to the production of GGBS as a by-product of industrial processes [5]. GGBS is found to contain high percentages of calcium oxide (CaO), silica (SiO_2) and alumina (Al_2O_3), which react strongly when exposed to alkaline substances. GGBS is activated by alkaline solutions that contain sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), resulting in two chemical reactions that form calcium-alumino-silicate-hydrate (C-A-S-H) gel and sodium-alumino-silicate-hydrate (N-A-S-H) gel [6]. The hybrid gel composition of GGBS forms geo-polymer material that is characterized by high mechanical strength, dense microstructure, and durability [7].

Researchers have carried out a lot of research on geo-polymer concrete, but they have shown limited interest in researching the geo-polymer mortar, which has a number of applications [8]. The geo-polymer mortar can be used for a variety of applications, which include masonry work, repair work, precast, and rendering work [9]. The geo-polymer mortar system can offer a number of advantages over the conventional cement mortar system, which are as follows: high early strength, low shrinkage, chemical protection, and durability under extreme environmental conditions [10].

The use of GGBS as a sole binder for geo-polymer mortar is more advantageous since it allows the geo-polymer mortar to set under the ambient temperatures required to carry out the actual work [11]. GGBS-based geo-polymer mortar allows the development of adequate strength under the usual curing conditions, making it more appropriate for actual construction works compared to the use of fly ash-based geo-polymers, which require high temperatures to set [12]. The geo-polymer mortar strength depends on the amount of alkaline solution added to the mixture; the concentration of sodium hydroxide determines the amount of silica and alumina content dissolved from the GGBS particles, which in turn determines the rate of the geo-polymerization process. The reactivity of GGBS increases when a higher molarity solution is used, which increases the rate of geo-polymerization [14]. However, the use of a high molarity solution results in the geo-polymer mortar setting too fast, leading to difficulties in workability and an increase in project cost. Studies have shown that the concentration of sodium hydroxide solution used ranges between 8M and 14M [15]. The best combination of reactivity, strength development, and workability is provided by a 12M solution of NaOH, as indicated by the findings of various researchers [16]. The microstructure of mortar developed through the 12M alkaline activation process ensures high density and compactness, resulting in high mechanical strength and durability properties, including resistance against water absorption and permeability [17]. Engineers make use of the compressive strength of mortar as an important property to evaluate its load-bearing capacity. The development of compressive strength in geo-polymer mortar is based on two parameters: degree of geo-polymerization and gel development [18]. The application of GGBS-based geo-polymer mortar helps in attaining high early strength development, which is beneficial for precast and fast-track building processes.

Researchers have increasingly used statistical and analytical techniques over the last few years, applying regression analysis for the development of prediction models in construction materials research. Regression analysis allows for the establishment of relationships between input variables (such as curing age) and responses (such as compressive strength, water absorption, etc.). These prediction models can help minimize the number of tests required while determining optimal mix design parameters.

2. MATERIALS AND METHODS

2.1 Materials Used

2.1.1 Ground Granulated Blast Furnace Slag (GGBS)

The current study adopted selected materials to develop a sustainable geo-polymer mortar with high-performance properties. Ground Granulated Blast Furnace Slag (GGBS) was used as the sole binder material [19]. GGBS was supplied by a local steel plant and met the requirements of the ASTM C989 standard. The material contained high calcium content along with adequate levels of silica and alumina, a specific gravity of around 2.9, and existed in a dry powder form.

2.1.2 Fine Aggregate

Natural river sand was used as the fine aggregate for this study, as it was free from organic impurities and noxious substances. Sand that passed through a 4.75 mm sieve was selected, having a fineness modulus of 2.6, which enabled good workability and density in the mortar mix. The sand was oven-dried before mixing.

2.1.3 Alkaline Activator

A combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions was used as the alkaline activator to activate the GGBS binder. The fineness modulus of the sand used with the activator was confirmed at 2.6 through sieve analysis using a 4.75 mm sieve, ensuring adequate workability of the mix [20].

2.2 Preparation of Alkaline Activator Solution

The sodium hydroxide solution with a concentration of 12M was prepared a day in advance to ensure complete dissolution. For its preparation, the required quantity of NaOH pellets was slowly added to the measured water under constant stirring to prevent excessive heat generation [21]. The sodium hydroxide solution was mixed with the sodium silicate solution after cooling both to room temperature, at a fixed Na_2SiO_3/NaOH ratio of 2.5 by mass. The alkaline activator solution was prepared at least 24 hours before mixing with GGBS.

2.3 Mix Proportioning

The geo-polymer mortar mix ratio of binder to sand was kept at 1:3. The ratio of alkaline activator solution to binder was kept constant at 0.5 for all mixes to attain sufficient workability and strength [22]. The mix proportions used in the study are summarised in Table -1. The proportions were kept constant across all mixes in order to isolate and investigate the effect of curing age on the mechanical and durability properties.

Table -1: Mix Proportion (kg/m^3)

MATERIAL	QUANTITY
GGBS (kg)	500
Sand (kg)	1500
Sodium Hydroxide – NaOH (kg)	85
Sodium Silicate – Na_2SiO_3 (kg)	165
Alkaline Solution : Binder Ratio	0.5
NaOH : Na_2SiO_3	1 : 2

2.4 Mixing Procedure

The first step involved dry mixing of GGBS with fine aggregate for 2 to 3 minutes, ensuring uniform distribution of both materials. The dry mix was then subjected to gradual addition of the pre-prepared alkaline activator solution and mixed until a uniform, workable mix was achieved, taking all necessary precautions to avoid segregation and air entrainment.

2.5 Casting of Specimens

Fresh geo-polymer mortar was cast in steel cube moulds with dimensions of 70.6 mm × 70.6 mm × 70.6 mm, poured in two layers. Each layer was compacted using tamping rods until all entrapped air was expelled. The surface was then levelled and smoothed. The moulds were covered with a plastic sheet to retain moisture and left undisturbed for 24 hours.

2.6 Curing Regime

Specimens were demoulded after 24 hours and cured under ambient laboratory conditions at a temperature of 27 ± 2°C, relying on the natural environment rather than heat curing. This ambient curing method was adopted to simulate the actual site conditions under which GGBS-based geo-polymer mortar would be used.

2.7 Test Methods

2.7.1 Compressive Strength Test

The compressive strength test was carried out as per Indian Standard IS 4031 (Part 6). Cube samples were tested at 7, 14, and 28 days of curing using a compression testing machine of sufficient capacity [24].

2.7.2 Water Absorption Test

Water absorption tests were carried out as per ASTM C642. Samples were oven-dried at 105°C until a constant weight was obtained and then immersed in water for 24 hours [25]. The gain in weight was recorded and the percentage absorption calculated to evaluate the porosity of the geo-polymer mortar.

2.7.3 Ultrasonic Pulse Velocity (UPV) Test

UPV tests were performed as per IS 13311 (Part 1) using a non-destructive ultrasonic testing device. Transducers were placed on opposite faces of the cube specimen and the transit time of the ultrasonic wave recorded. The resulting pulse velocity was used to evaluate the internal quality of the geo-polymer mortar.

2.7.4 Regression Analysis

Linear regression equations were developed from the experimental data to establish the relationship between curing age and the measured properties – compressive strength, water absorption, and UPV – using the coefficient of determination (R^2) to assess the strength of each relationship. The relationship between UPV and compressive strength was also examined in order to assess the viability of UPV as a predictor of compressive strength in geo-polymer mortar.

3. RESULTS AND DISCUSSION

3.1 Compressive Strength

The compressive strength development of the G12M (1:2) GGBS geo-polymer mortar was compared with that of traditional OPC mortar at 7, 14, and 28 days. The compressive strength of the G12M mix was consistently higher than that of OPC mortar at every stage. At 7 days, the G12M mix achieved 23 MPa compared to 21 MPa for OPC mortar. This increased to 27 MPa at 14 days, compared to 24 MPa for OPC mortar, and reached a maximum of 33 MPa at 28 days, compared to 28 MPa for OPC mortar (Fig-1). The continuous strength gain of the geo-polymer mortar, particularly at 28 days, reflects a more complete geo-polymerization process compared to the hydration of traditional cement mortar.

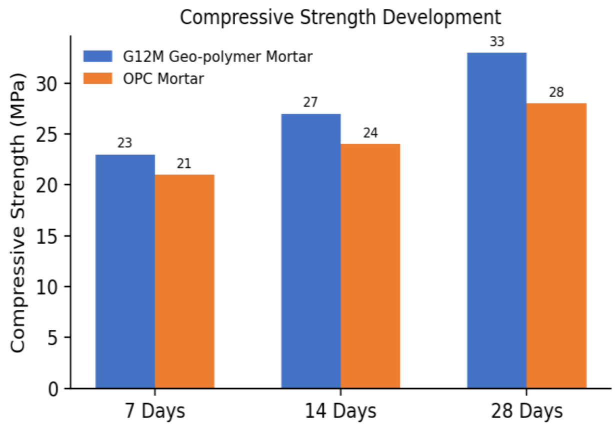

Fig-1: Compressive strength at different curing ages

3.2 Water Absorption

The water absorption behaviour of G12M (1:2) geo-polymer mortar was compared with OPC mortar at various curing ages. At 7 days, the water absorption of G12M was 5% compared to 8% for OPC mortar, a reduction of 37.5%. At 14 days, absorption reduced to 4% for G12M against 7% for OPC mortar (a 42.9% reduction), and at 28 days it reduced further to 3% for G12M against 6% for OPC mortar, a 50% reduction (Fig-2). The lower water absorption of the GGBS-based geo-polymer mortar at later ages reflects a denser, more sealed microstructure that restricts moisture ingress, indicating better durability than OPC mortar.

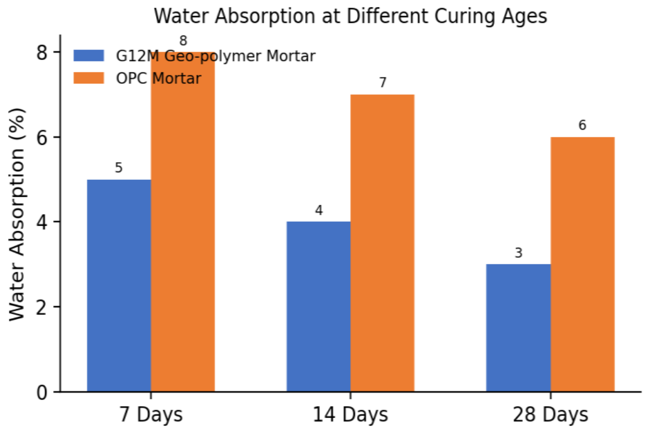

Fig-2: Water absorption at different curing ages

3.3 Ultrasonic Pulse Velocity

The UPV values obtained for the G12M (1:2) geo-polymer mortar mix were compared with the conventional OPC mortar mix at different ages. At 7 days, the G12M mix recorded a UPV of 3.8 km/s against 3.4 km/s for OPC mortar, an increase of 11.8%. The UPV of the G12M mix increased to 4.3 km/s at 14 days, reflecting progressive densification of the matrix with a reduction in internal voids. At 28 days, the G12M mix recorded a UPV of 4.7 km/s compared to 4.1 km/s for OPC mortar, an increase of 14.6% (Fig-3). UPV values above 4.5 km/s are generally taken to indicate excellent quality mortar, confirming the high internal structural integrity and denser microstructure of the GGBS geo-polymer mortar relative to OPC mortar.

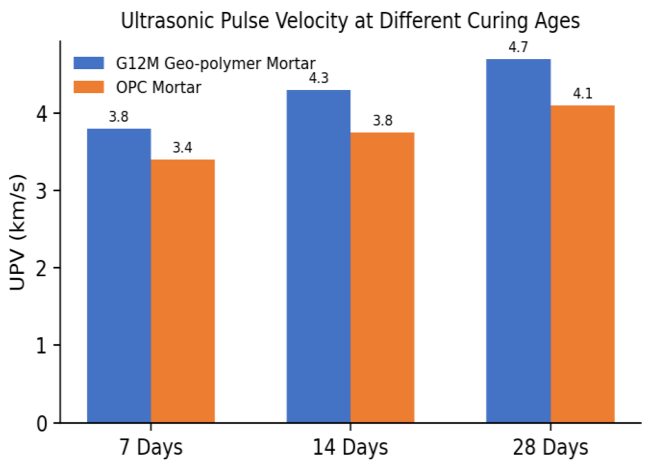

Fig-3: UPV at different curing ages

3.4 Regression Analysis

3.4.1 Regression Analysis between Compressive Strength and Water Absorption

The scatter plot in Fig-4 shows a negative linear relationship between compressive strength and water absorption. As compressive strength increases from 21 MPa to 33 MPa, water absorption decreases from 7.1% to 3.2%. The best-fit equation ($y = -0.287x + 12.828$) indicates that for every 1 MPa increase in compressive strength, water absorption decreases by 0.287%. The coefficient of determination ($R^2 = 0.8674$) indicates a strong correlation, with nearly 87% of the variation in water absorption explained by the variation in compressive strength. This negative correlation confirms that mortar with higher compressive strength has lower porosity and permeability due to a denser microstructure.

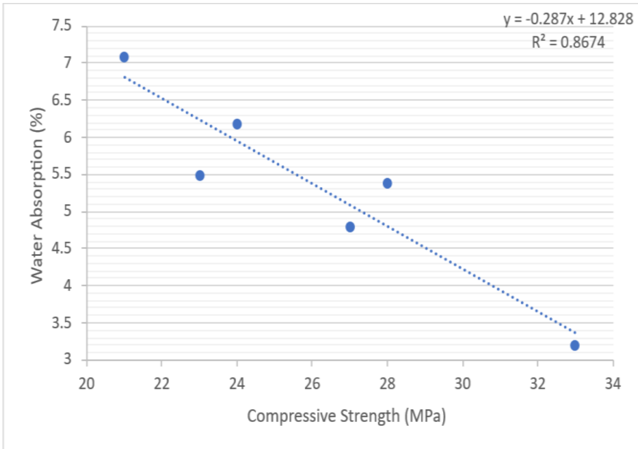

Fig-4: Plot of compressive strength and water absorption

3.4.2 Regression Analysis between Compressive Strength and UPV

The scatter plot in Fig-5 illustrates a positive linear relationship between compressive strength and UPV. As compressive strength increases from 21 to 33 MPa, UPV increases from 3.4 to 4.7 km/s. Using the regression equation ($y = 0.1022x + 1.3601$), every 1 MPa increase in compressive strength corresponds to an increase of about 0.102 km/s in UPV. The high coefficient of determination ($R^2 = 0.934$) shows a strong positive relationship, with 93% of the variation in UPV explained by changes in compressive strength. This confirms that as the material gains compressive strength, its density also increases.

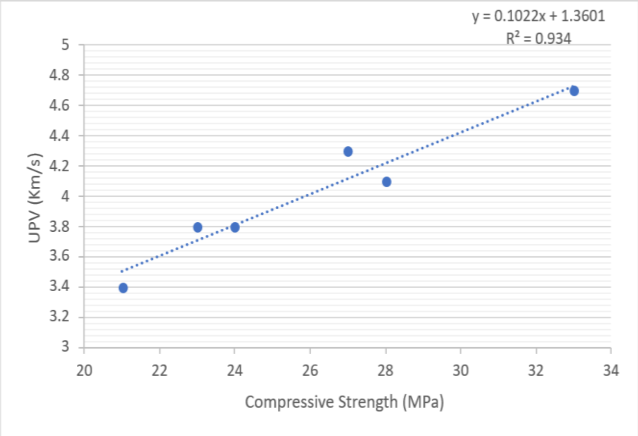

Fig-5: Plot of compressive strength and UPV

4. CONCLUSIONS

The main aim of the present study was to evaluate the mechanical and durability properties of 12M GGBS geo-polymer mortar cured under ambient conditions and to compare them with OPC mortar. Based on the experimental results and regression analysis, the following conclusions can be drawn.

The GGBS geo-polymer mortar showed higher compressive strength than OPC mortar at all curing ages (7, 14, and 28 days), increasing from 23 MPa at 7 days to 33 MPa at 28 days due to the formation of C-A-S-H and N-A-S-H gel structures during geo-polymerization. This confirms that GGBS geo-polymer mortar can achieve high compressive strength under ambient curing, without the need for heat curing.

The water absorption results showed a significant reduction in permeability, decreasing from 5% at 7 days to 3% at 28 days, which is considerably lower than that of OPC mortar. This indicates refinement of the pore structure and development of a compact microstructure, resulting in good resistance to moisture penetration.

UPV results improved from 3.8 km/s to 4.7 km/s, confirming better homogeneity, fewer internal voids, and higher overall quality compared to OPC mortar. The regression analysis confirmed strong relationships between compressive strength and the durability parameters: a strong negative correlation with water absorption (R^2 = 0.8674) and a strong positive correlation with UPV (R^2 = 0.934). An increase in strength was accordingly associated with a decrease in porosity and an improvement in internal structure, supporting the use of UPV as a practical, non-destructive indicator of the compressive strength and quality of GGBS-based geo-polymer mortar.

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