

Analysis of the effect of curing and mixing periods on mechanical properties of the geopolymer composite

Research Article

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Abstract: Geopolymer concrete (GPC) can be substituted for Portland cement concrete because it is cement-free, environmentally friendly, cost-effective, durable, and highly performing. It is an excellent solution for sustainable growth in the building sector. The curing and mixing periods are essential for making homogeneous, compact, or highly dense concrete. The primary aim of this research was to analyze the effect of mixing and curing periods on the physical, chemical, and mechanical characteristics of GPC. The experimental analysis investigated its physical properties, chemical properties, and mechanical properties. After the experimental investigation, it was concluded that the workability and setting time decreased with the increase in mixing time. Regarding chemical properties, the density of GPC specimens reduced as the curing time increased, and it increased as the mixing time increased, although drying shrinkage decreased under both scenarios. For mechanical properties, the compressive strength, splitting tensile strength, flexural strength, and elastic modulus initially increased with the increase in mixing and curing time up to 24 h but decreased significantly afterward. In the analysis of the non-destructive test, the rebound strength and ultrasonic pulse velocity exhibited the same pattern as the destructive mechanical characteristics, with the 24-h curing period achieving the highest point among all other curing times. This research found that the optimum oven curing period for GPC was 24 h for gaining mechanical and chemical properties because the mixing and curing periods play an essential role in gaining strength.

Keywords: Geopolymer concrete • Alkali-silica reaction • Sustainable Construction • Durability • Heat curing

1. Introduction

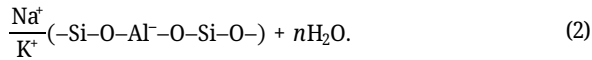
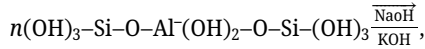
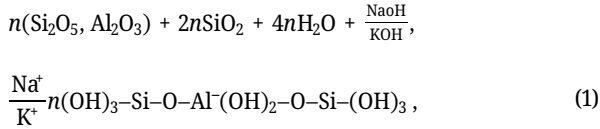
Geopolymer concrete (GPC) is in great demand now because it is economically valuable and has long-term viability. It can survive adverse conditions for a lengthy period without degrading its strength. Pozzolanic materials like fly ash, ground granulated blast-furnace slag (GGBFS), metakaolin/calcined clay, rice husk ash, and others include significant amounts of silica and alumina, except silica fume, which is used as a binder in the building of GPC mix. An alkaline solution activates the GPC mixture's pozzolans, which contain sodium/potassium hydroxide or sodium/potassium silicate. Because the removal of cement from the

concrete mix results in an immediate reduction in the carbon footprint, around 8% of the world's total carbon dioxide emissions are generated during the production process for cement. A process known as geopolymerization takes place when the geopolymer matrix is being set and strengthened. It incorporates all the steps of the reaction [1,2].

The geopolymer matrix is a three-dimensional structure mainly composed of amorphous inorganic materials. The first reaction, known as dissolution, occurs throughout the geopolymerization process and is shown by equation (1). After the first process of dissolving the matrix, the amount of water required to make the end product decreases, as shown in equation (2). Davidovits (1978) developed geopolymerization and a geopolymer for the process and

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result, respectively. A geopolymer is an inorganic matrix. In the process of matrix strengthening, geopolymers exhibit a bonding that is distinct from cement [3,4].



Alkali metals, the molarity of either sodium hydroxide or silica to alumina, and the quantity of water present may influence the geopolymerization process. Self-compacting concrete may be achieved with Portland cement concrete (PCC) using a superplasticizer based on polycarboxylate. On the other hand, self-compacting GPC can be produced using a superplasticizer based on sulphonated naphthalene formaldehyde, and there is no reduction in the concrete's strength or performance [5]. The ratio of liquid to binder is a significant factor in strengthening the matrix. Adding GGBFS to the mix decreases the workability and speeds up the setup time. Sodium hydroxide molarity utilized in the GPC design mix and alkaline ratio are essential components in producing concrete strength [6,7]. GPC has been allowed to cure for longer, anything from 6 to 96 h (4 days), and has a greater compressive strength. However, after 48 h, there is hardly any discernible improvement in strength. Extended heating periods, ranging from 6 to 24 h, significantly enhance the compressive strength [8]. The duration of exposure to elevated temperatures within this specified range contributes to progressive strengthening of the material's compressive characteristics. The observed improvement in potency after a 12-h duration is not statistically significant [9]. To optimize the material strength, it is advisable to allow for an extended stabilization period at ambient temperature, particularly when exposed to a relative humidity of 95% or higher. This extended stabilization, coupled with the influence of temperature, is crucial in promoting further growth in the material's strength. It is noteworthy that temperature conditions influence the duration necessary for the complete curing process. Hence, it is recommended to facilitate an extended stabilization period under ambient conditions before applying heat, ensuring optimal material performance. Curing at a higher temperature for 1 h did not affect strength development. At the same time, treatment for a more extended period accelerates the response rate and increased early-age strengths [10,11].

By incorporating nanoparticles, such as calcium carbonate, into the GPC or alkali-activated concrete, the mechanical characteristics of the material may be improved. Extending the curing time significantly enhances the geopolymerization process, resulting in notable improvements in compressive strength [12]. The rate of strength gain is remarkably rapid within the initial 24 h of the curing period but gradually tapers beyond that point. Consequently, the heat-curing process can be at most 24 h. Notably, samples subjected to fog treatment exhibit a higher absorption percentage, likely attributed to the geo-polymer paste's inclination to retain water, thereby contributing to a more porous microstructure [13].

The acceleration of compressive strength through heat curing expedites the completion of the geopolymerization process. While heat-cured specimens achieve an earlier compressive strength, it is noteworthy that the final strength of ambiently cured specimens surpasses that of their 28-day oven-dried counterparts. Remarkably, within 3 days, oven-dried specimens reach 90% of the compressive strength achieved at 28 days, whereas ambient samples only get a range of 57–82% [14]. Beyond 7 days, the increase in compressive strength for oven-cured specimens becomes negligible, a trend observed consistently across all tests. This intricate interplay between curing methods and the resulting compressive strengths underscores the need for a nuanced understanding of the temporal evolution of GPC properties [15,16].

The elastic modulus of GPC reacts variably at various curing temperatures. The static elastic modulus increases with the increase in curing temperatures up to the optimum point that early age is observed to be related to the water-to-binder ratio. This limit is reached when the material reached its maximum curing capacity. If water is evaporated during higher-temperature curing and lost before achieving full strength, the final product will be weaker, and the static modulus of elasticity will be diminished [17,18].

Curing at room temperature is not feasible since doing so would cause a delay at the beginning of the process of setting. Increasing the temperature made it easier for reactive species to dissolve, significantly increasing the material's strength. The geopolymerization procedure was improved using a longer curing time for the finished product. The reaction was altered when it was cured for a longer time at a higher temperature. This caused partial water evaporation and the creation of microcavities, which caused the sample to fail at a later age [19,20]. The flexural strength of GPC treated at room temperature evolved analogous to the compressive strength development. Compared to a combination that did not include additives, a flexural strength

increase was seen by adding 6% OPC, 10% GGBFS, and 2% CH. It was discovered that the flexural strength of GPC was greater than that of OPC concrete despite both types having the same compressive strength. Calculation based on AS 3600-2009 may be used to produce an educated guess on the flexural strength of GPC after curing in ambient circumstances [21,22].

At 600°C, fly ash and GGBFS interaction dominates the geopolymerization process. The reaction results contain both the C–S–H gel and A–S–H gel, which is evidence of this interaction. The inclusion of slag correlates with an increase in compressive strength. This relationship could be connected to the development of the gel phases (C–S–H and A–S–H), as well as the compactness of the microstructure [23].

A significant factor is the temperature at which a geopolymer based on metakaolin can set and become rigid. The material will be put in less than 4 h at a temperature close to ambient temperature. When the mixture was worked at temperatures as low as 100°C, the setting time was pushed back by about 4 days; moreover, this had little impact on the quality and characteristics of the product after it had been hardened for 28 days. The exploration of the mechanical characteristics of geopolymer materials through experimentation has revealed a pronounced influence of curing temperature on both early-age and ultimate mechanical properties [24,25]. Elevating the curing temperature has been identified as a pivotal factor in enhancing early-age compressive and flexural strengths, with optimal values achievable in as little as 1 day. It is noteworthy, however, that the 28-day strengths were comparatively lower when compared to specimens cured at room temperature or reduced temperatures. This observation underscores the nuanced relationship between the rapid development of a rigid framework and the attainment of high-quality geopolymer materials [26,27].

Importantly, this phenomenon highlights that expedited early-age strength gain only sometimes translates into superior long-term performance. Additionally, the duration of the curing process significantly influences how temperature impacts the material properties. Understanding these dynamics is crucial for optimizing the curing conditions of geopolymer materials and ensuring their overall mechanical efficacy over varying time frames [28,29].

GPC presents a compelling alternative to traditional PCC, offering a cement-free, environmentally friendly, cost-effective, and high-performance solution for sustainable development in the construction industry. This article investigates a crucial aspect of GPC and its physical, chemical, and mechanical characteristics. The novel contribution of this research lies in its detailed examination of how mixing and curing periods influence GPC properties. The

mixing period varied from 5 to 30 min, and the curing period varied from 4 to 72 h in the oven. The oven temperatures were kept constant at 80°C.

2. Materials and methods

The research presented in this article was based on experimental methodologies and was conducted within the confines of the institution's concrete laboratory. This study delves into practical and hands-on investigations, leveraging the facilities and resources available in the laboratory to meticulously explore and analyze key aspects related to the subject matter. This experimental approach ensures a robust and empirically supported foundation for the findings and conclusions detailed in subsequent sections. The concrete laboratory of the institution serves as a controlled and conducive environment, providing the necessary infrastructure to carry out comprehensive experiments, assessments, and analyses pertinent to the research objectives outlined in this study.

2.1 Materials

Pozzolans, alkaline solutions, aggregates, superplasticizers, and water are the primary components of GPC.

2.1.1 Binding materials

Fly ash was collected from the NTPC-Dadri, Gautam Buddha Nagar, Uttar Pradesh. Fly ash has been designated as class C in compliance with ASTM C618-19. Mineral components are included in fly ash and GGBFS samples, together with their percentage ages [30].

Figure 1 depicts the fly ash and GGBFS XRD graphs, which describe the strength of the crystalline mineral component contained in the samples.

SEM images of fly ash and GGBFS are both shown at a resolution of 2 μm in Figure 2a and b, respectively. This resolution is used to identify the shape of the particle size. Fly ash is a porous disc, while GGBFS particles have a more irregular appearance and are composed of a flaky material.

2.1.2 Alkaline solution

Alkaline solutions of sodium hydroxide and sodium silicate were used in the study. CDH (P) Ltd. supplied the NaOH and Na_2SiO_3 solutions. In the mixed pattern, they served the purpose of an alkaline activator. While NaOH was obtained as flakes, Na_2SiO_3 was obtained as a thick,

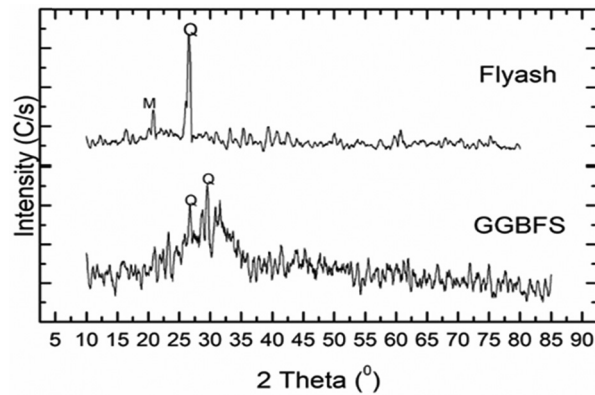


Figure 1. Picture of XRD analysis of fly ash and GGBFS.

murky liquid. According to the research, the purity ratio of NaOH must be at least 96.0. The titrimetric minimum for Na₂O in Na₂SiO₃ was 10%, while the gravimetric minimum for SiO₂ was 25.5–28.5%.

2.1.3 Aggregates

Stone dust or manufactured sand is often employed as a fine aggregate in GPC mix designs. Several tests were conducted on the stone dust sample to verify the laboratory materials' reliability. The m-sand was a well-graded zone-II medium sand with specific gravities of 2.62, bulk densities of 1610 kg/m³, silt contents of 6%, and water absorption of 1.21%. The coarse aggregate crushed locally was included in the GPC mix, including particles of 10 and 20 mm size. Figure 3a displays the gradation curves of

well-graded stone dust and coarse aggregate used in the experimental investigation.

2.2 Synthesis

The general-purpose computing mix design may be generated using the multivariate adaptive regression spline model. The ingredients, aggregates, fly ash, and GGBFS were thoroughly mixed for 5 min, then the alkaline solution with the water additive was poured into it. A fresh blend in the pan is shown in Figure 3b. The newly developed GPC combination was cast in the shapes of cubes, cylinders, and prisms. After 3 days, the specimens were opened and cured for 24 h at 60°C in an oven. This addresses the various mix design ingredients used in the

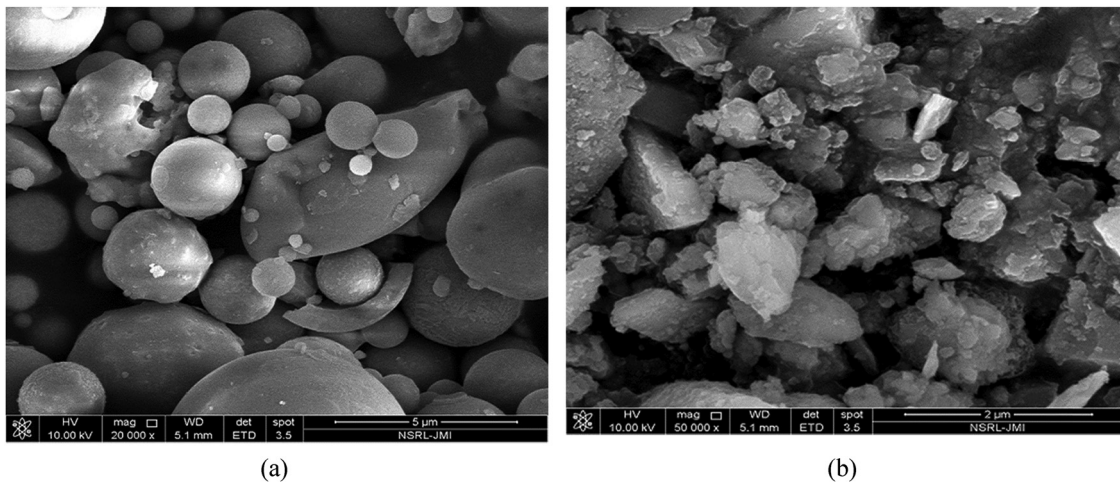
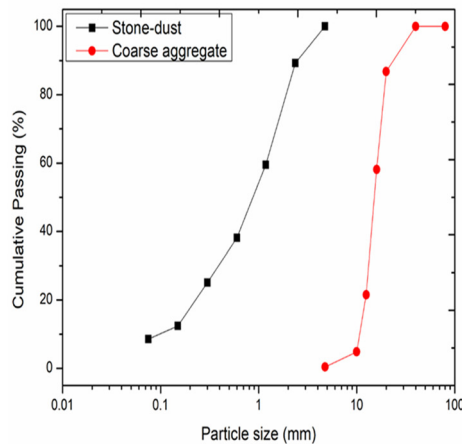


Figure 2. (a) Fly ash SEM image and (b) GGBFS SEM image.



(a)



(b)

Figure 3. (a) Gradation curves of coarse and fine aggregates and (b) picture during mixing.

GPC mixtures, and approximately 200 samples were collected for the experimental research [31,32].

2.3 Experimental setup

The experimental setup for testing GPC typically involves a range of specialized equipment to assess its mechanical and structural properties. Standard components include molds for casting specimens such as cubes and cylinders, a mixing apparatus for preparing the geo-polymer mix, and a curing chamber to control environmental conditions during the curing period. For evaluating compressive strength, a compression testing machine was employed to subject cube and cylinder specimens to controlled loads until failure occurred. Non-destructive testing techniques, such as ultrasonic pulse velocity test (UPVT) or rebound tests, require specific equipment like transducers, an electrical pulse generator, an amplifier, and an electronic timing unit. The experimental setup plays a critical role in obtaining accurate and reliable data on the performance of GPC, ensuring that the material meets the desired standards for strength, durability, and overall structural integrity.

2.3.1 Fresh concrete properties

The slump test is a crucial measure to assess the workability of freshly mixed GPC. The apparatus used for the slump test has a top diameter of 100 mm, a bottom diameter of 200 mm, and a height of 300 mm. The depth of the

slump, expressed in millimeters, is a crucial indicator of the mixture's workability. A penetrometer apparatus was used to estimate the setting time of the new GPC in the concrete sample. This apparatus determines the concrete mix samples' initial and final setting times.

The chemical characteristics of GPC mix samples were evaluated by measuring and utilizing the density. The density of the mix design was determined before the destructive examination at 28 days by testing the weight of the cube samples. This indicates the abrasiveness and tenacity of the concrete samples. To assess drying shrinkage in the concrete resulting from water evaporation or the formation of end products of the bond, a length comparator was utilized for concrete or mortar specimens at the micron level. This detailed analysis helped to understand the physical changes in the concrete over time.

2.3.2 Mechanical properties

For determining compressive strength in GPC, cube-shaped samples measuring 150 mm on each side were used. These samples were subject to evaluation on a universal testing machine using an axial loading mode with a loading rate set at 5.2 kN/s. Cylindrical samples with dimensions of 150 mm in diameter and 300 mm in height were utilized to assess the splitting tensile strength. During testing, the universal testing machine applied transverse weights to the cylinder, which conducted the necessary tests to determine the splitting tensile strength.

To evaluate the flexural strength and mix design, beam samples with dimensions of 100 mm in width, 100 mm in height, and 500 mm in length were employed. A flexural tensile test was conducted on the beam specimen using the flexural testing equipment. This test can be either a flexural test or a two-point load test. Cylindrical samples with diameters of 150 mm and lengths of 300 mm were employed to measure the Poisson ratio and elasticity modulus. These samples underwent an axial force application to determine their lateral and linear strain. The information obtained from this process is crucial for calculating the elastic modulus and Poisson's ratio using the universal testing apparatus.

2.3.3 Non-destructive test (NDT)

NDT involves assessing the strength or quality of a material without causing any damage to it. This testing can be performed in a laboratory setting or the field. The assessment of surface hardness serves as the foundation for the rebound test, which was conducted on cube samples at different curing ages (7, 14, 28, 42, and 56 days). This procedure was applied to every type of sample cube and cylinder to ascertain the overall robustness of the combined sample.

In the UPVT, ultrasonic pulse waves were transmitted through the specimens. A high UPV reading indicates that the GPC specimen possesses high strength and efficiency. The testing apparatus includes two types of transducers: an electrical pulse generator, an amplifier, and an electronic timing unit. These components work together to transmit and measure the ultrasonic pulse waves, providing valuable insights into the material's properties and performance. The UPVT is crucial for evaluating the integrity and durability of the GPC specimens under investigation.

4. Results and discussion

All the specimens of the GPC tested at 7, 14, 28, 42, and 56 days include cubes, cylinders, and prism-shaped specimens. The duration of the mixing process ranged from 5 to 30 min. The identical mix specimens were cured at various periods in the oven at 600°C. Figure 4a shows a picture of curing cube specimens.

4.1 Effect of mixing time

To examine the fresh characteristics, mechanical properties, chemical properties, and microstructural analyses for

the same mix design, GPC raw components were mixed between 5 and 30 min in a pan mixture.

4.1.1 Physical properties

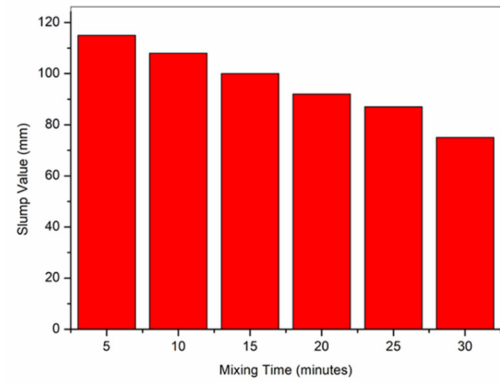
The workability of the GPC mix diminished as the mixing time increased sequentially from 5 to 30 min. The behavior of the slump with increasing mixing time is shown in Figure 4b, which demonstrates that the slump value reduced successively with increasing mixing time or period. The slump value dropped significantly when the mixing period increased constantly from 5 to 30 min. The freshly mixed concrete mix's workability was evaluated using the slump test. In the building industry, the slump value increased when superplasticizers and water were added to a mixed design. The GPC fresh mix setting time decreased with the increase in mixing time in the pan mixture. As the mixing time increased, both the initial and final set times decreased. Figure 4c displays a graph of the change in the setting time with mixing time, which shows that the setting time decreased slightly with the increase in the mixing period from 5 to 30 min. The mixing period would increase the density of the mix and the reaction of the geopolymerization, which would reduce the setting time of the mix. The GPC fresh mix setting time also reduced with the increase in the fineness of fly ash or the addition of nanoparticles [33].

The Na_2O concentration and the w/c ratio significantly impacted the initial and final setting times. By increasing the Na_2O concentration, the geopolymerization processes may be accelerated, resulting in a substantial reduction in both setting periods. As the liquid-to-solid ratio increased, the geopolymer paste's initial and final setting periods did as well. More studies should be done on setting retarders to lengthen setting periods because the final setting durations of geopolymer samples are shorter than those of PC paste. Alkali-activated slag paste's final setting periods were shortened as the activator's sodium content increased. The final setting times of the liquid sodium silicate-activated slag paste decreased as the silica modulus increased. More studies are needed regarding using setting retarders to lengthen the setting periods because the setting times for PC paste and liquid sodium silicate are substantially shorter than those for these materials [34].

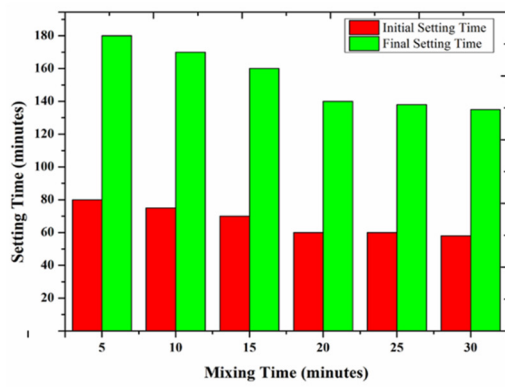
The mass ratio of the alkaline liquid to the fly ash, along with the composition of the alkaline solution, played a crucial role in determining how quickly GPC was affected. The amount of K_2O in the solution and the temperature substantially impacted the setting time. Note that the quantity of Na_2O in the mixture and the $\text{SiO}_2/\text{Na}_2\text{O}$ ratio significantly affect the workability, setting time, and physio-mechanical properties. At normal temperatures,



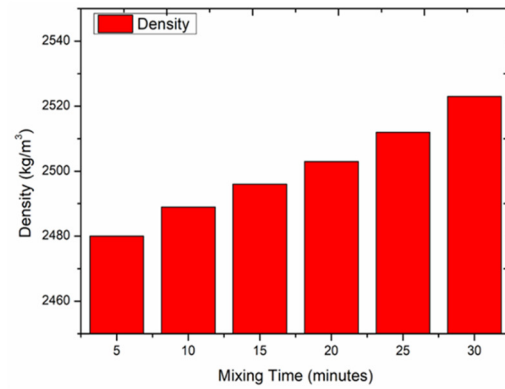
(a)



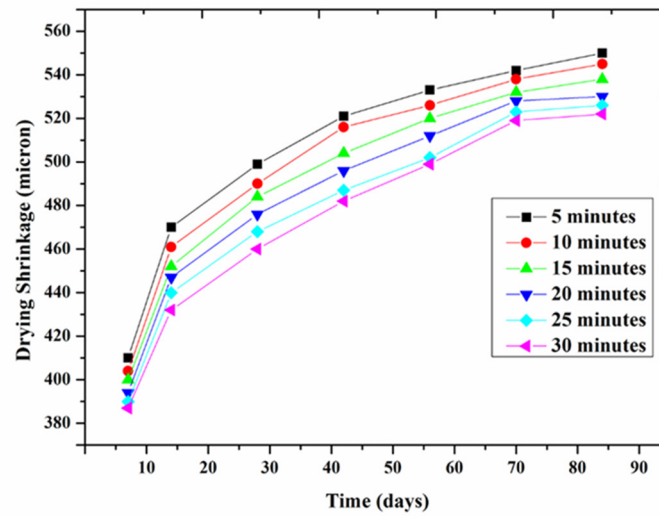
(b)



(c)



(d)



(e)

Figure 4. (a) Picture of oven-curing of specimens, (b) slump value variation with the mixing time, (c) setting time variation with the mixing time, (d) density variation with the mixing time, and (e) drying shrinkage variation with the mixing time.

geopolymer cement hardens quickly. Increased fly ash solubility in alkaline liquids improves polymerization and gel phase hardness, leading to a quicker setting. The activator's alkalinity causes the release of Ca, Si, and Al from the slag during alkali activation. Next, a layer of hydrate reaction byproducts that quickly develops around the unreacted slag particles must be passed by the ions produced by those particles to proceed. Because hydroxide increases slag breakdown and improves the solubility of silica and alumina, alkaline conditions speed up the activation process [35,36].

4.1.2 Density

The density of the GPC mix design specimens was calculated using equation (3), where D denotes the density, M is the weight of the specimen, and V is the volume of the specimen.

$$D = M/V. \quad (3)$$

The density of concrete mix specimens increased as the mixing time increased from 5 to 30 min. Figure 4d depicts a density vs concrete mixing time graph, which demonstrates that the density increases with an increase in the mixing time or duration. The mixing time enhances the correct packing of particles of various sizes present in the mixture [37]. At 5 and 30 min of concrete mixing, the corresponding densities of mix specimens are 2,480 and 2,523 kg/m³, respectively.

4.1.3 Drying shrinkage

Figure 4e demonstrates that GPC mix drying shrinkage reduces as the mixing time of new concrete in the pan mixture increases, which shows that the increase in the mixing period provides better packing properties. When the packing of the material's quality increases, it directly increases the density and reduces the drying shrinkage. The mixing time for fresh mix specimens varies from 550 to 410 μm , from 5 to 30 min. The optimum quantity of water used in the mix gives better packing and lower drying shrinkage because a minimal amount of water is available to evaporate. The drying shrinkage increases as the amount of combined water evaporates [38].

4.1.4 Compressive strength

Due to the proper arrangement of raw materials in the mix, GPC specimens' compressive strength continuously increases with the concrete mixing time. Specimens' compressive strength was calculated using equation (4), where P is the load applied to the cube specimens in Newton, A is

the surface area of the cube specimens in mm², and S is the strength of the cube in MPa.

Figure 5a describes the GPC specimen's compressive strength mixed from 5 to 30 min. The specimens are tested at 7, 14, 28, 42, and 56 days after the casting.

$$S = \frac{P}{(A)}. \quad (4)$$

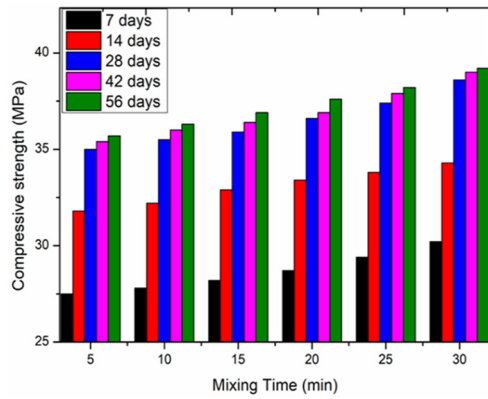
The maximum compressive strength at the 56-day test of 30 min of mixing samples was 39.2 MPa. The compressive strength increase variation is very marginal with the mixing time increase. A high alkali hydroxide concentration may produce high compressive strength; if the concentration is too high, the ultimate strength will suffer. Although the strength increased significantly and the setting time shortened with the addition of more mineral contents or curing in water, an optimum high alkali hydroxide concentration might cause the specimen to become brittle and sensitive to weathering. As a result, whereas a high alkaline content might hasten the polymerization process and enhance the mechanical properties, exceeding the optimum concentration reduces the strength and durability [39].

The amount of aluminosilicate gel produced during the geo-polymerization process determines the compressive strength of the paste. The compressive strength generally increased as the degree of geopolymerization increased. Additionally, polycondensation of oligomeric precursors took place in the presence of soluble silica, a crucial stage in developing the strength of geopolymeric materials. The geopolymer matrix may be classified into two groups: unreacted or partially unreacted basic ingredients and the gel phase. The compressive strength of geopolymer paste should be significantly influenced by the amount of gel and the aggregate's interaction with the gel [40].

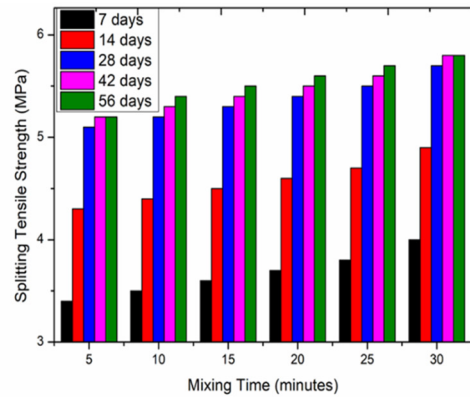
Because the silica modulus and the Na₂O concentration of the alkaline activator are negatively correlated, it must be recognized that a decrease in the silica modulus value corresponds to an increase in the sodium ion concentration. The primary function of the sodium ion in the first-stage dissolution of aluminosilicates during the geo-polymerization process and a three-dimensional network charge balance at the final stage may only be accounted for by an increase in the Na₂O content, which accelerated geo-polymerization reactions and caused the reactivity to reach its optimal level, leading to further enhancements [41].

4.1.5 Splitting tensile strength

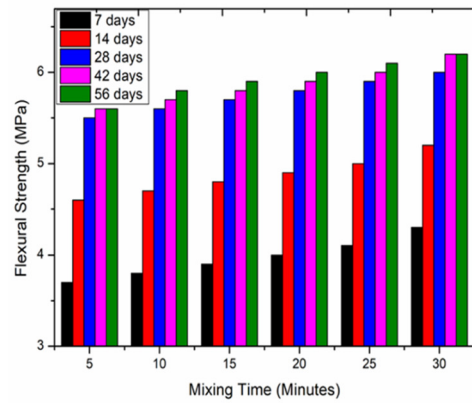
The GPC mix specimens' splitting tensile strength follows a similar pattern to their compressive strength. When the



(a)



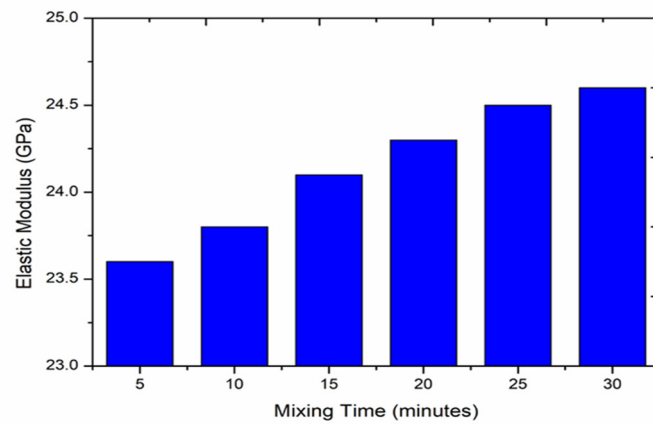
(b)



(c)



(d)



(e)

Figure 5. (a) Compressive strength of GPC mix, (b) splitting tensile strength variation of GPC, (c) flexural strength variation with mixing time, (d) picture of elastic modulus finding setup, and (e) graph of elastic modulus variation with mixing time.

time spent for mixing concrete was from 5 to 30 min, the splitting tensile strength increased. The graph in Figure 5b shows how the splitting tensile fluctuates with concrete mixing time. The strength development of specimens slightly increases with mixing time. The splitting tensile strength for 5 and 30 min of mixed specimens are 5.2 and 5.8 MPa, respectively, at 56 days of testing. The splitting tensile strength is calculated using equation (5), where “ P ” is the static load in Newton, “ l ” is the length of specimens in mm, “ d ” is the diameter of specimens in mm, and “ F_{st} ” is the splitting tensile strength in MPa. All the specimens were tested at 7, 14, 28, 42, and 56 days after the casting [42,43].

$$F_{st} = \frac{2P}{\pi ld}. \quad (5)$$

The UTM was used to test the specimens in the laboratory. The specimens were subjected to static stress at a rate of 2.4 MPa/min.

4.1.6 Flexural strength

Concrete’s modulus of rupture is also known as its flexural strength. It was determined using the flexural testing equipment to examine the beam-form samples. The machine provided the data in the form of a load at destruction. The flexural strength was calculated using equation (6) or (7), where “ P ” is the point load applied to the specimen in Newton, “ l ” is the length of the specimen in mm, “ b ” is the width of the specimen in mm, “ d ” is the depth of the specimen in mm, “ F_{fs} ” is the flexural strength of the specimen in MPa, and “ a ” is the shortest length from beam failure cracks to the end of the specimen section. If the length is more than 13 cm, then equation (6) was used to calculate the flexural strength, or if the length is less than 13 cm, then equation (7) was used to calculate the flexural strength.

$$F_{fs} = \frac{Pxl}{bd^2}. \quad (6)$$

$$F_{fs} = \frac{3Pxa}{bd^2}. \quad (7)$$

GPC mix specimens’ flexural strength followed a pattern similar to that of the compressive strength. It increased as the concrete mixing time increased, and the 30-min mix of GPC specimens had the highest strength compared to other concrete mixing times. Figure 5c depicts the relationship between the flexural strength and concrete mixing time [44]. To determine the flexural strength, GPC specimens were tested for 7, 14, 28, 42, and 56 days. The flexural

strength of concrete mixed for 5 and 30 min was 5.6 and 6.2 MPa, respectively.

4.1.7 Poisson ratio and elastic modulus

The Poisson ratio and elastic modulus were established by testing cylindrical specimens subjected to a static force in the specimen’s longitudinal direction to determine the Poisson ratio and elastic modulus. Figure 5d depicts the apparatus used to measure the Poisson ratio and elastic modulus. The linear variable differential transformer was used to measure the strain on specimens. The lateral strain to longitudinal strain ratio was used directly to compute the Poisson ratio [45].

The ASTM C469 M-14 code was employed for the elastic modulus calculation. Figure 5e describes the graph of elastic modulus variations with different concrete mixing times. The elastic modulus simultaneously increased with the increase in mixing time in the pan mixture. The GPC specimens were tested after 28 days to find the Poisson ratio and elastic modulus [46].

The maximum elastic modulus was 24.6 GPa after 30 min of concrete mixing in the pan mixture. It increased slightly with an increase in mixing time from 5 to 30 min. The Poisson ratio of mixed specimens remained the same from 5 to 20 min, but it decreased from 25 to 30 min. The Poisson ratio was calculated from 5 to 20 min and from 25 to 30 min and days 15 and 16, respectively. Using equation (8), we calculated the Poisson ratio of the specimens, where μ is the Poisson ratio, d is the lateral strain, and l is the linear strain.

$$\mu = |d|/l. \quad (8)$$

4.1.8 NDTs

NDTs are those that determine the quality and strength of specimens without destroying them. The two primary tests performed on the specimens are the rebound strength and UPV tests.

4.1.9 Rebound strength

The rebound strength was analyzed using specimens of any form and surface, including cubes, cylinders, and prisms. It is directly proportional to the specimen’s surface hardness. To determine the average strength, a minimum of ten penetrations were performed on a single surface. The rebound strength had a similar pattern to compressive strength samples; however, it displayed a little greater

strength than compressive strength. Figure 6a shows rebound hammer strength variation with the period of mixing samples tested at 7, 14, 28, 41, and 56 days. The rebound strength increased with the increase in concrete mixing time in the pan mixture. The maximum rebound strength was found after 30 min of concrete mix samples [47].

4.1.10 UPVT

The UPVT is an NDT that examines the strength of material samples without causing harm. This test determines the quality of material samples by transmitting an ultrasonic pulse wave through them and measuring the transit duration. The shorter travel time shows the high quality of the specimens and vice versa. Figure 6b shows the graph between the UPV variations in the specimens and the concrete mixing time. The UPV variations show a similar pattern to rebound strength, and the UPV grows as the concrete gets stronger [48].

The maximum UPV found during 56 days for 30 min of mixed specimens and the minimum UPV at 7 days for 5 min of mixed specimens were 3.41 and 4.86 km/s, respectively. The UPV value grew as the concrete got stronger with the increase of mixed time. A tiny bit of UPV increased consecutively with the mixed time of specimens at 5, 10, 15, 20, 25, and 30 min: 4.61, 4.63, 4.69, 4.73, 4.79, and 4.86 km/s, respectively, at 56 days' specimens' test [49].

4.2 Effect of the curing period

The similar mix design specimens need curing for a period ranging from 4 to 72 h.

4.2.1 Density

The GPC specimen's density diminished as the curing time in the oven increased. Figure 7a depicts the fluctuation in density concerning curing periods. The 4 h curing period specimens had the highest density, whereas the 72 h curing period specimens had the lowest.

4.2.2 Drying shrinkage

At 7, 14, 28, 42, 56, 70, and 84 days, the GPC specimens' drying shrinkage was examined. The drying shrinkage diminished as the curing duration of the specimens in the oven increased. The samples fixed for 4 h exhibit the greatest drying shrinkage, while specimens cured for 72 h exhibit the least drying shrinkage across all curing durations. The graph in Figure 7b depicts the drying shrinkage behavior of different curing duration specimens [50,51].

4.2.3 Compressive strength

GPC specimens' compressive strength increased as the curing time of the specimens in the oven increased. Figure 7c shows the compressive strength of several specimens on different testing days. At 7, 14, 28, 42, and 56 days after collection, the samples were examined. The compressive strength increased rapidly from 4 to 24 h of the curing period, but after the curing period, it showed a minor increase. The NaOH–Na₂SiO₃ mix was made 1 day ahead and used to activate the geopolymer paste in combination with Na₂O as a mixture of 8.5–11% fly ash. Geopolymer paste specimens with Na₂O containing 8.5% showed superior results in residual compressive force than

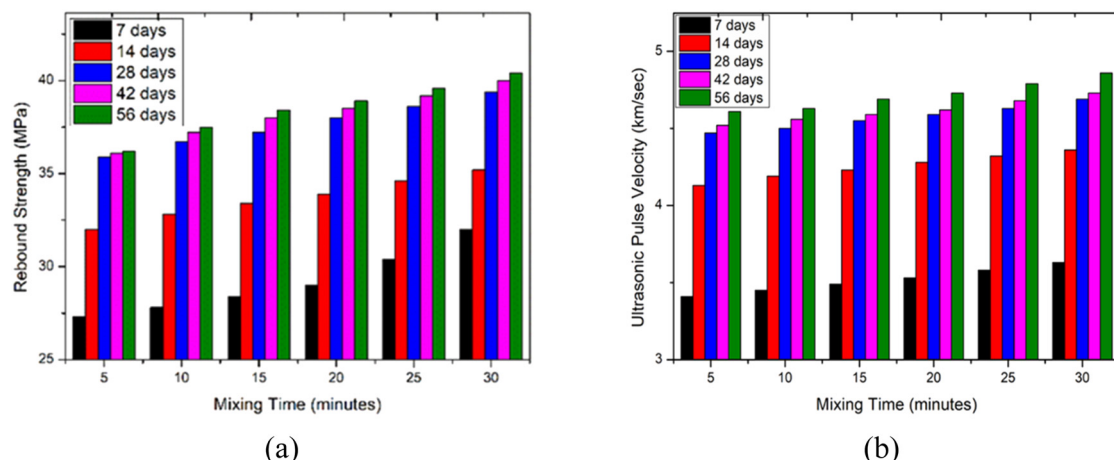


Figure 6. (a) Rebound strength variation with the mixing time and (b) UPV variations with the mixing time.

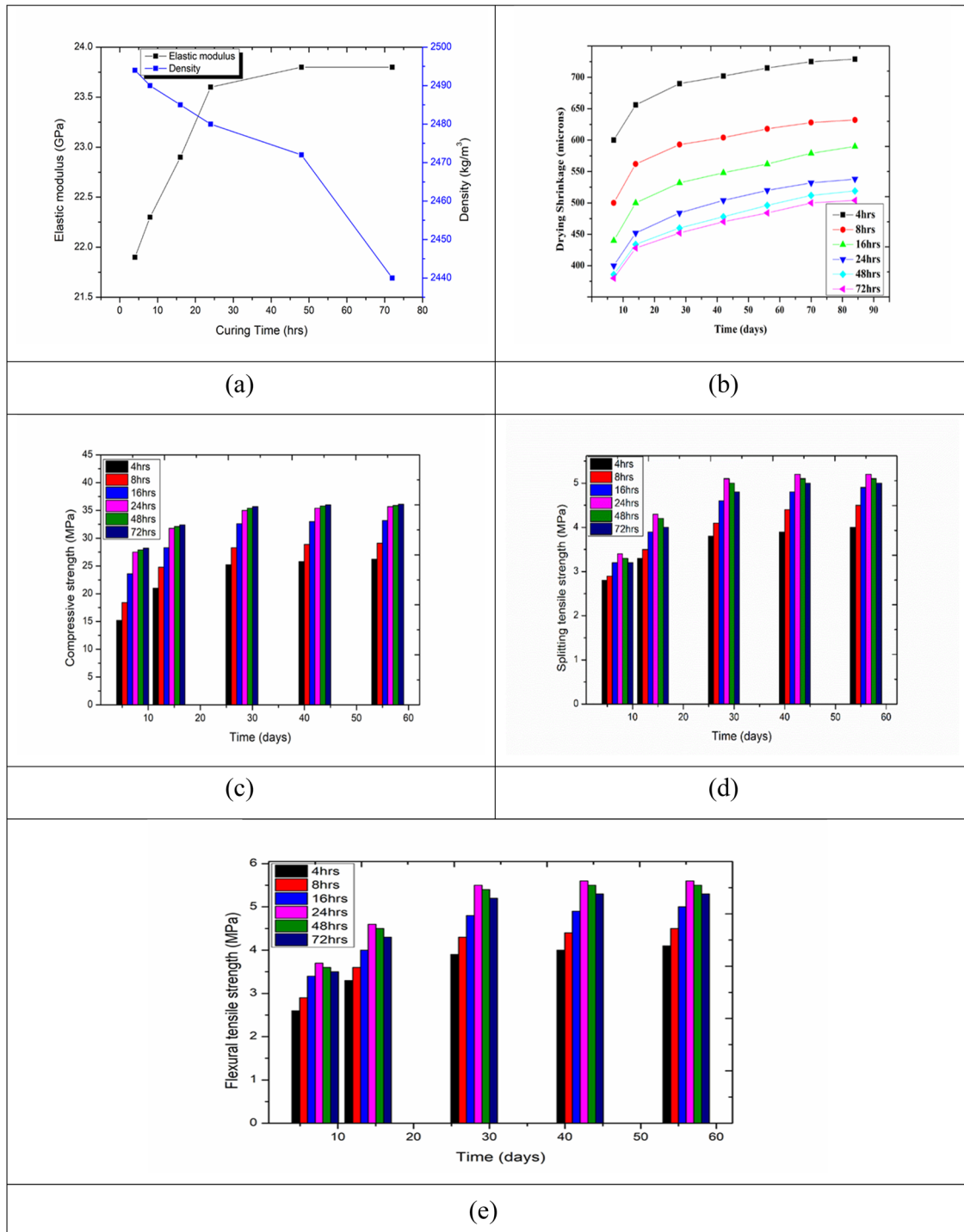


Figure 7. (a) Density and elastic modulus variation with the curing time, (b) graph between the curing period and drying shrinkage, (c) compressive strength variation with the curing time, (d) splitting tensile variation with the curing period, and (e) flexural strength variation with the curing period.

specimens with a greater Na_2O concentration. Compressive mechanical strengths of 50 MPa were achieved after 28 days with 50% slag and 50% fly ash activated with 10 M NaOH [52].

4.2.4 Splitting tensile strength

Indirect tensile strength is another name for splitting tensile strength. The splitting tensile strength of the GPC specimens increased as the curing duration increased from 4 to 24 h but then declined significantly after 24 h. Figure 7d depicts the variance in splitting tensile behavior with curing time. At 7, 14, 28, 42, and 56 days after curing, all of the specimens were examined. The splitting tensile strength first increased significantly with the curing duration from 4 to 24 h and then decreased somewhat beyond the 24 h curing period increase. At 28 days, about 95% splitting tensile strength was observed in all specimens from the curing period [53,54].

4.2.5 Flexural strength

There is another name for flexural strength, which is the modulus of rupture. It is possible to ascertain this through an experiment carried out in a flexural testing machine using prism-shaped specimens. It can be seen that flexural strength follows a pattern fairly dissimilar to indirect tensile strength. The flexural strength grew with each hour of curing time, from 4 to 24 h; however, it started to diminish once 24 h of curing time have passed. The graph of the change in the flexural strength behavior throughout various curing times is shown in Figure 7e. At the end of 7, 14, 28, 42, and 56 days, each specimen that had been cured for

a varied amount of time was put through a series of tests. At the end of the curing time, about 95% splitting tensile strength was observed in all tested specimens. It has been determined that a curing time of 24 h produced the best results [55].

4.2.6 Elastic modulus and Poisson ratio

The elastic modulus and the Poisson ratio may be calculated by experimenting on cylindrical specimens in the UTM. During this experiment, stress was applied along the longitudinal axis of the specimens, which allows for the calculation of the elastic modulus and Poisson ratio. Figure 7a depicts the behavior change of the elastic modulus concerning various curing times of the GPC specimens. The elastic modulus increased with the increase in the curing period, from 4 to 72 h in a row in order [56–58]. After testing for 28 days, the elastic modulus and the Poisson ratio were determined for the specimens. The maximum elastic modulus was found in specimens with a 72 h curing period, whereas the minimum elastic modulus was found in specimens with a 4 h curing period. The Poisson ratio of the specimens was 16 for the 4, 8, and 16 h curing period specimens and 15 for the 24, 48, and 72 h curing period specimens [56,57].

4.2.7 NDTs

The tests that are considered to be non-destructive are those that determine the quality and strength of the GPC specimens without inflicting any harm to the specimens themselves. It consists of the rebound strength test in addition to the UPVT.

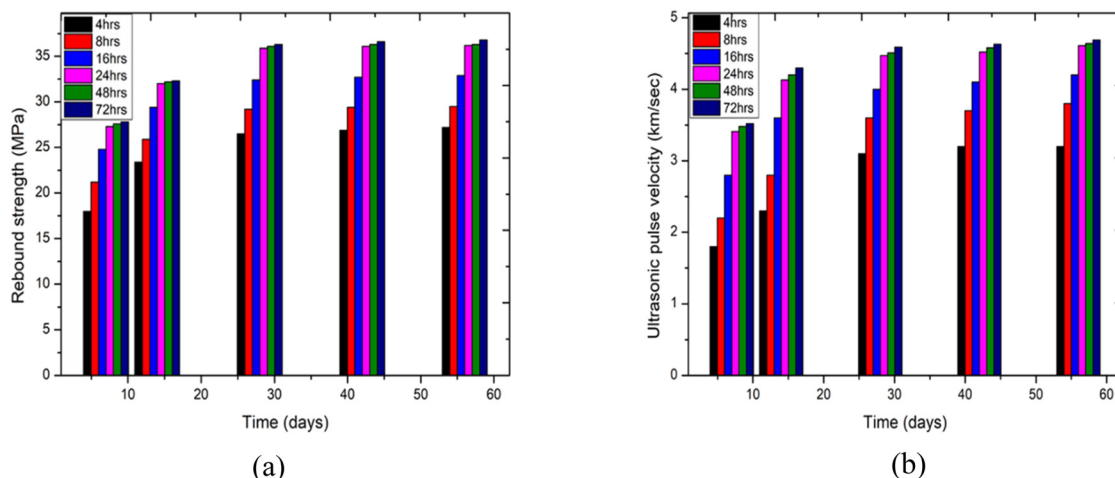


Figure 8. (a) Rebound strength variation with the curing period and (b) UPV variation with the curing period.

4.2.8 Rebound strength

The rebound strength test was used to assess the strength of concrete or any other hard material based on the findings of an indentation penetration test performed on the specimens' surfaces. To determine the strength of a single specimen, a minimum of nine penetration tests are needed to be performed on a single surface. Figure 8a depicts the graph of rebound strength behavior fluctuation with various curing times of the GPC specimens. The pattern of the compressive strength of the specimens is also seen in the rebound strength graph. All of the specimens that were cured for varying amounts of time were evaluated after 7, 14, 28, 42, and 56 days [59].

4.2.9 UPVT

Additionally, the UPVT did not cause any damage. This was done by keeping track of the amount of time, or UPV, that travels through the concrete sample to determine the quality of the concrete. Because the UPV falls as the quality of the specimens improves, it is easy for it to see any fractures that develop on the interior of the samples. Figure 8b illustrates the variance in UPV behavior that results from the use of various curing times [60].

It demonstrates a pattern that is analogous to the rebound strength. Tests were conducted on specimens at 7, 14, 28, 42, and 56 days after the specimens had been healed. The UPV increased with the increase in the curing period, from 4 to 72 h. The UPV rapidly increased with the increase from 4 to 24 h, but it increased negligibly beyond the 24 h curing period. Around 98% of the UPV was obtained on the specimens at 28 days of tests [55].

5. Conclusions

Following a comprehensive examination of GPC specimens through experimental investigations, specifically scrutinizing the influence of concrete mixing time and curing duration on physical, chemical, mechanical, and microstructural attributes, definitive conclusions have been drawn. The series of tests conducted on cube, cylinder, and prism specimens at intervals of 7, 14, 28, 42, and 56 days yielded the subsequent findings:

- The workability, as indicated by the slump value, exhibited a diminishing trend in the GPC mix when the concrete mixing time was extended from 5 to 30 min. Concurrently, the setting time experienced a reduction under the same conditions. This trend suggests that an increase in the mixing time adversely impacted both the

workability and setting time in the GPC mix. These findings emphasized the importance of carefully optimizing the concrete mixing duration to achieve the desired workability and setting characteristics in GPC. The density of concrete mix specimens increased during the first 30 min of mixing and decreased with longer curing times. As the mixing time extended, the drying shrinkage of GPC mix specimens decreased, particularly with extended oven-curing periods.

- The highest compressive strength, reaching 39.2 MPa, was observed in specimens with a 30 min mixing time during the 56-day test. The increase in the compressive strength was marginal relative to the mixing time and increased with longer curing periods in the oven. The splitting tensile strength and flexural strength of GPC mix specimens followed a trend similar to compressive strength, increasing with increasing concrete mixing time (5–30 min) and curing period (4–24 h). However, a slight decrease was observed beyond the 24 h curing period.
- The UPV variations align with the rebound strength pattern, increasing with longer concrete mixing times and curing periods of up to 72 h. The UPV showed a rapid rise from 4 to 24 h, plateauing thereafter beyond the 24 h curing period.
- In the future, curing and mixing periods will play a pivotal role in designing GPC. So, it helps the future application of research in the fields. This could be applied to constructing roads, buildings, bridges, and any other smart structures.

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Author contributions

Conceptualization: M. V. and R. K. M.; methodology: M. V. and R. K. M.; software: A. K. and R. K. M.; validation: M. I. K. and J. M. K.; formal analysis: M. V. and R. K. M.; resources: M. I. K. and J. M. K.; writing – original draft: M. V.; writing – review and editing: R. K. M., M. I. K., and J. M. K. All authors have read and agreed to the published version of the manuscript.

Conflict of interest statement

The authors declare no conflict of interest.

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