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Impact of variations in the molarity of sodium hydroxide on metakaolin-ground granular blast-furnace slag-based geopolymer concrete

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Abstract:
The present study investigates the optimization of geopolymer concrete mixes with the addition of metakaolin and ground granular blast-furnace slag as binding agents, ensuring a sustainable and eco-friendly alternative to conventional concrete. In this study, different proportions of the input parameters, such as the molarity of sodium hydroxide, ratio of sodium silicate to sodium hydroxide, and ratio of fixed alkali activator to binder have been considered. Attributes such as compressive strength, ultra-sonic pulse velocity, electricity resistance, mass loss, and strength variation due to acid attack for six geopolymer concrete mixes have been evaluated at different ambient curing periods. In addition, the mathematical relationship, i.e., linear regression, between these properties was also evaluated. The results show that a sodium silicate to sodium hydroxide ratio of 1,8; n sodium-hydroxide molarity of 14, and an alkali activator to binder ratio of 0,45 demonstrated the highest strength (43,3 MPa), electrical resistivity (35,1 K.Ohm.cm), and pulse velocity (4,2 km/s) with the minimal effect of H2SO4 solution on mass (1,2 %) and strength (5,8 %). Additionally, statistical analysis indicated a strong relationship of compressive strength with other properties, which improved as the curing days extended from 28 (Avg. R2=0,68) to 56 (Avg. R2=0,74) days. The outcomes of the study are expected to contribute to the advancement of sustainable construction by providing relevant data regarding material selection, ensuring quality, and optimizing geopolymer concrete production with metakaolin and ground granular blast-furnace slag.

Keywords:
geopolymer concrete; metakaolin; ground granular blast-furnace slag; compressive strength

1 Introduction

The demand for cement has been increasing for several reasons, including rapid urbanisation, infrastructure development, industrialisation, reconstruction, renovation, and population growth [1, 2]. Large quantities of carbon dioxide (CO_2) and other greenhouse gases are emitted during cement production, thereby contributing to global warming and climate change [3, 4]. However, significant amounts of energy and water are required during production, leading to the loss of natural resources and pollution of water and the environment [5, 6]. Cement production and consumption must be reduced because of its adverse effects on the environment, human health, and natural resources [7-9]. Various researchers have developed sustainable and eco-friendly alternative methods to incorporate waste materials that require less energy and produce less emissions into cement [10, 11]. Geopolymer concrete (GPC) is a new type of concrete that has recently gained attention as a sustainable alternative to conventional concrete owing to its potential to reduce the negative environmental impacts associated with concrete manufacturing while maintaining the necessary construction qualities [12-14]. In the 1980s, Davidovits began working with synthetic geopolymers that utilised waste and industrial materials [15, 16]. In recent years, GPC has been produced by incorporating various industrial by-products such as silica fume [17], fly ash [18], ground granular blast-furnace slag (GGBFS) [19], and other agricultural residues such as rice-husk ash [20, 21]. Furthermore, compared to conventional concrete, GPC has better durability and a stronger compressive strength [2, 22] because it is denser, more durable, and formed by using a lower water-to-binder ratio [23].

Metakaolin (MK), a type of calcined clay derived from the calcination of kaolin clay, has garnered interest in recent years. Unlike other cement-replacement materials, such as supplementary cementitious materials (SCMs), MK sets itself apart as it is not a waste product from industrial activities, nor is it entirely natural [24, 25]. Instead, it originates from kaolinite clay minerals and is processed for various uses, including applications in cementitious systems. MK is primarily produced through calcination, involving the thermal treatment of kaolin clays within a temperature range of approximately 600 to 800 °C. It belongs to the category of new-generation mineral admixtures that can serve as SCMs, offering both technical and environmental advantages. MK can be utilised as a partial substitute for cement in concrete mixtures in its finely ground form. GGBFS is a secondary material generated as a byproduct during the production of iron in a blast furnace [25, 26]. The predominant constituents of this material are primarily silicate and aluminosilicate compounds resulting from the fusion of calcium, necessitating periodic removal from the blast furnace. The particles of interest are subsequently subjected to a grinding process, reducing their size to less than 45 μm [27]. This reduction in size leads to a significant increase in the surface area of the particles, which ranges from 400 to 600 m²/kg. It primarily consists of calcium oxide (CaO), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), and magnesium oxide (MgO), along with trace amounts of various other minor oxides [27, 28].

Previously, researchers conducted a comprehensive study on GPC and examined its performance using different binders and parameters. The properties of binder-based GPC are significantly affected by aggregate amount, water/solid ratio, sodium silicate/sodium hydroxide (NS/NH) ratio, and Al/binder ratio. In addition, a considerable increase in the aggregate content and higher NS/NH and Al/binder ratios also affect the compressive strength [24, 29, 30]. The studies in the literature have evaluated GPC by varying liquid-to-binder ratios from 0,40 to 0,70 and using a varying range of curing temperatures, from 60 to 120 °C. A higher liquid-to-binder ratio improves the workability of concrete, although it also reduces the density of concrete. Based on these observations, the optimum strength was achieved at a ratio of 0.60. The elevated temperatures increase the early-age strength but do not significantly effect on the strength parameters observed as the temperature increases beyond 100 °C [31, 32]. In another experimental study, in which GGBS and MK were used as cementitious materials in GPC, the influence of the ratio of NS and NH at various molarities (8, 10, 16, and 20 M) on the hardened properties was determined. Up to 16 M, the strength characteristics of GPC improved with increasing activating content. In addition, a consistent weight loss in the range of 2-7 % also suggested the improved durability features. These findings confirmed that the strength and durability characteristics of GPC are significantly regulated by the water/binder ratio and the ratio of alkaline activator to the binder [25, 33, 34]. Furthermore, a study was conducted to identify the optimal combination of aluminosilicates and an Al/binder ratio of 0.45 after 7-, 28-, and 90-day curing periods. The results revealed that incorporating a higher percentage of GGBFS and increasing the molarity of NH led to significant improvements in both the strength and durability of the GPC. These findings suggest that carefully selecting a higher GGBFS percentage and optimising the molarity of NH can effectively enhance the performance and durability of GPC for various applications [18, 35]. Similarly, in another investigation, tests were conducted to examine the effects of various NS/NH and Al/binder ratios on the compressive strength of GPC. These findings suggest that increasing the NS/NH and Al/binder ratios increases the compressive strength of GPC Mixes. However, the positive effect of an adequate molarity of the mixes facilitates the geopolymerisation process. Beyond the appropriate limit, increasing the NS/NH and Al/binder ratios did not result in significant improvements in the compressive strength [36, 37]. A detailed analysis examined the behaviour of MK-based GPC at different temperatures, including both ambient and elevated temperatures of 200 °C, 400 °C, and 600 °C. Modifications in its mechanical properties, such as compressive, tensile, flexural strengths, and other characteristics, were noticed when the GPC was subjected to diverse temperature ranges and microstructural changes in its matrix. The results of the study indicated that GPC performs very well by providing significant resistance to elevated temperatures, indicating that its features provide thermal stability to structures [2, 38, 39]. Another study was conducted on GGBS and MK to evaluate their resistance against sulphate and acid attacks at two different molarities of NH (8 and 10). The results suggested that the compressive strength exhibited significant resistance against sulphate and acid attacks under ambient conditions. In addition, even after 28 days of exposure to sodium sulphate and sulphuric-acid solutions, the concrete specimens were entirely unaffected, indicating the remarkable durability of the MK-GGBS-based GPC [24, 40].

Based on the aforementioned studies, the existing research work aims to expand the understanding of GPC by specifically determining the impact of the molarity of NH on its mechanical, durability, and nondestructive attributes. Although previous studies have reported the impact of the concentrations of different binders and activators on GPC performance, only a limited number of studies have focused on the nuanced impact of NH molarity, specifically when utilising MK and GGBFS as binders. Adopting a similar approach followed in the previous studies, the objectives of the present study are to examine the effect of NH molarity on the mechanical (compressive strength), durability (acid attack), and nondestructive properties (ultra-sonic pulse velocity (UPV) and electrical resistivity (ER)) of GPC with constant proportions of MK (70 %) and GGBFS (30 %) as binders. In the experiment, the molarity of sodium hydroxide (NH) was varied from 12 to 14, the ratio of NH to NS ranged from 1,8 to 2,2; and the ratio of alkali activator (Al) to binder was kept constant at 0,45. In addition, statistical tools, such as linear regression, were employed to analyse the relationship between the properties considered in this study. The comprehensive approach utilised in this study can add significant knowledge to the production of sustainable GPC with optimised characteristics for practical applications in the construction sector.

2 Methodology

2.1 Materials and methods

This investigation employed various types of materials to achieve the objectives of the project, which are discussed in detail in this section. The chemical and physical characteristics of the materials used in the experiments are also discussed.

2.1.1 Metakaolin

MK used in this experiment was purchased from Sri Durga Mines & Minerals Company, Telangana, India. The MK utilised in this study had specific physical characteristics and chemical compositions, as listed in Table 1 and Table 2, respectively.

Table 1. Physical characteristics of MK

Parameter	Physical characteristic
Colour	White powder/Off white
Bulk density (gms/ltr)	350
pH	6,8
Yellow index	4
Oil absorption	55
Particle size (μm)	< 2
Surface area (m^2/g)	20

Table 2. Chemical composition of MK

Parameter	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	CaO	LOI
MK	53	42	1,3	0,8	< 1	< 1	< 1	< 1

By examining the information provided in Table 2 regarding the chemical composition of MK, the sum of silica, alumina, and iron oxide was determined to be 96,3 %, which is more than 70 %, making it a suitable pozzolanic material. Figure 1 depicts the visual appearance of MK, which provides insight into its colour, and Figure 2 depicts the X-ray diffraction (XRD) pattern of MK, which provides essential information on its crystalline structure and the presence of particular mineral phases.

Figure 1. Appearance of MK

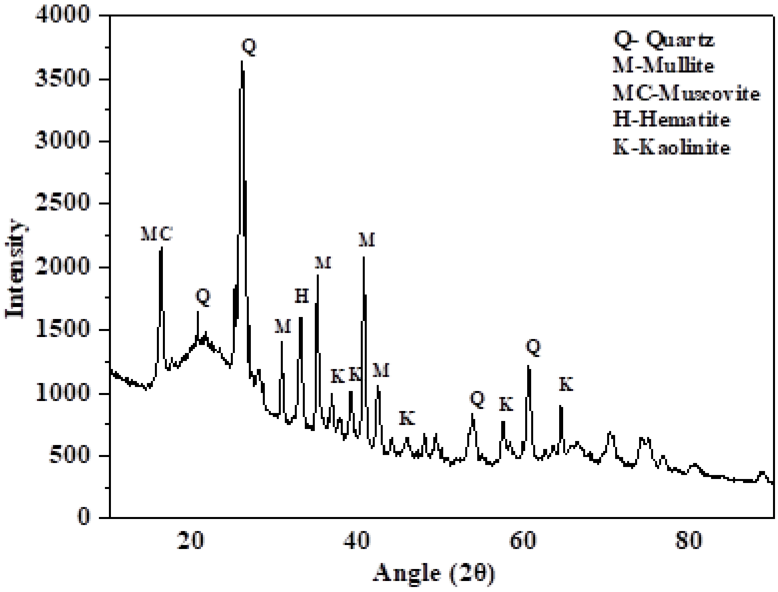

Figure 2. X-ray diffraction pattern of MK

2.1.2 Ground Granular Blast Furnace Slag (GGBFS)

The GGBFS was manufactured by Astra Chemicals in Chennai, Tamil Nadu, India and used in accordance with the guidelines given in Indian Standard Code IS 12089:1987 [41]. The GGBFS utilised in the experiment contained specific properties, such as a grey-white colour. Tables 3 and 4 provide additional details regarding the physical characteristics and chemical composition of GGBFS, respectively.

Table 3. Physical characteristics of GGBFS

Serial No.	Parameter	Physical characteristic
1	Particle size (µm)	15
2	Density (g/cc)	2,9
3	Fineness (m^2/kg)	450
4	Colour	Grey white
5	Specific gravity	2,9
6	pH	10,5

Table 4. Chemical composition of GGBFS

Parameter	SiO_2	CaO	Al_2O_3	MgO	Fe_2O_3	Na_2O	K_2O	LOI
GGBFS	36,5	38	15	9	1,7	0,5	< 1	1,5

GGBFS is a versatile material with diverse chemical compositions. The predominant chemical components found in GGBFS include silica, calcium oxide, and aluminium oxide. Figure 3 depicts the texture of GGBFS and Figure 4 shows the XRD pattern of GGBFS, which provides essential information on its crystalline structure and the presence of particular mineral phases.

Figure 3. Visual appearance of GGBFS

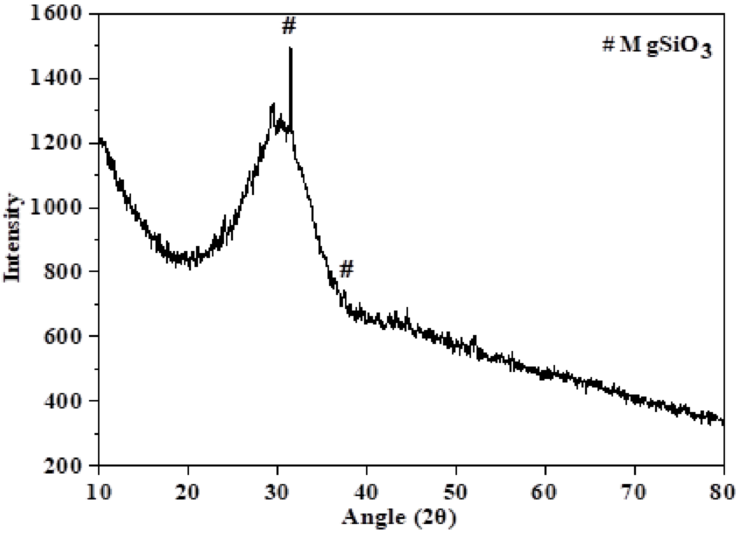

Figure 4. X-ray diffraction pattern of GGBFS

2.1.3 Alkali activator

Alkali activators are essential for the entire procedure of the production of MK-GGBFS-based GPC. The primary function of these activators is to initiate the reaction between the aluminosilicate materials and alkaline solution, leading to a geopolymer binder. In this study, two alkali activators, NS and NH, were used, each with specific properties affecting the geopolymerisation process.

- Sodium hydroxide - in this study, NH pellets with an absolute purity of 98% were dissolved in pure water. The procedure was performed to ensure complete NH dissolution as well as sufficient dispersion and hydration of the hydroxide ions. To achieve optimal results, the NH pellets and water were blended for 24 h before the mixing of the concrete. The strength and durability of GPC may be influenced by the excessive heat released during the exothermic reaction between the NH pellets and water, owing to an increase in the heat of hydration [42].
- Sodium silicates - A 52-grade NS was obtained from Garg Chemicals Industry in Jalandhar, Punjab, India, and its constituents comprised the following mass

percentages: 14,7 % Na_2O (sodium oxide), 29,4 % SiO_2 (silicon dioxide), and 55,9 % H_2O (water), as per the manufacturer.

2.1.4 Coarse aggregate

According to Indian Standard code IS 383-2016, the use of different aggregate sizes confirms the formation of concrete [43]. Table 5 presents the essential details regarding the physical characteristics of coarse aggregate (CA) employed in this study. The CA sizes adopted for this study were 20 mm and 10 mm, based on their significance in achieving the desired characteristics and performance of the GPC. The addition of these specific CA sizes aims to improve the overall strength and durability of the GPC. Figure 5 illustrates the 20 mm and 10 mm aggregates used in the experiment.

Figure 5. Coarse aggregate utilized in the experiment with different sizes: (a) 20 and (b) 10 mm

Table 5. Properties of coarse aggregate

Parameters	20 mm		10 mm	
	Requirement as per IS: 383-1970	Percentage passing	Requirement as per IS: 383-2016	Percentage passing
20 mm sieve	85-100 %	96,3 %	95-100 %	97,5 %
10 mm Sieve	0-20 %	13,6 %	85-100 %	96,4 %
Specific Gravity		2,90	-	2,85
Water Absorption (%)		0,33	-	0,40
Bulk Density (kg/m^3)		1576	-	1680
Elongation		11 %	-	9 %
Aggregate Impact Value		9,12	-	9,12
Flakiness		14 %	-	11 %
Fineness Modulus		7,35	-	7,35

2.1.5 Fine aggregate

Fine aggregates (FA) employed in the current experiment were obtained from a local distributor in Jalandhar, Punjab, India. The characteristics of FA were assessed and found to conform to the requirements established in IS: 383-2016 [43]. The absorption of water and specific gravity of FA were 1,5 % and 2,6; respectively. The particle-size distribution curves of the fine and coarse aggregates are presented in Figure 6.

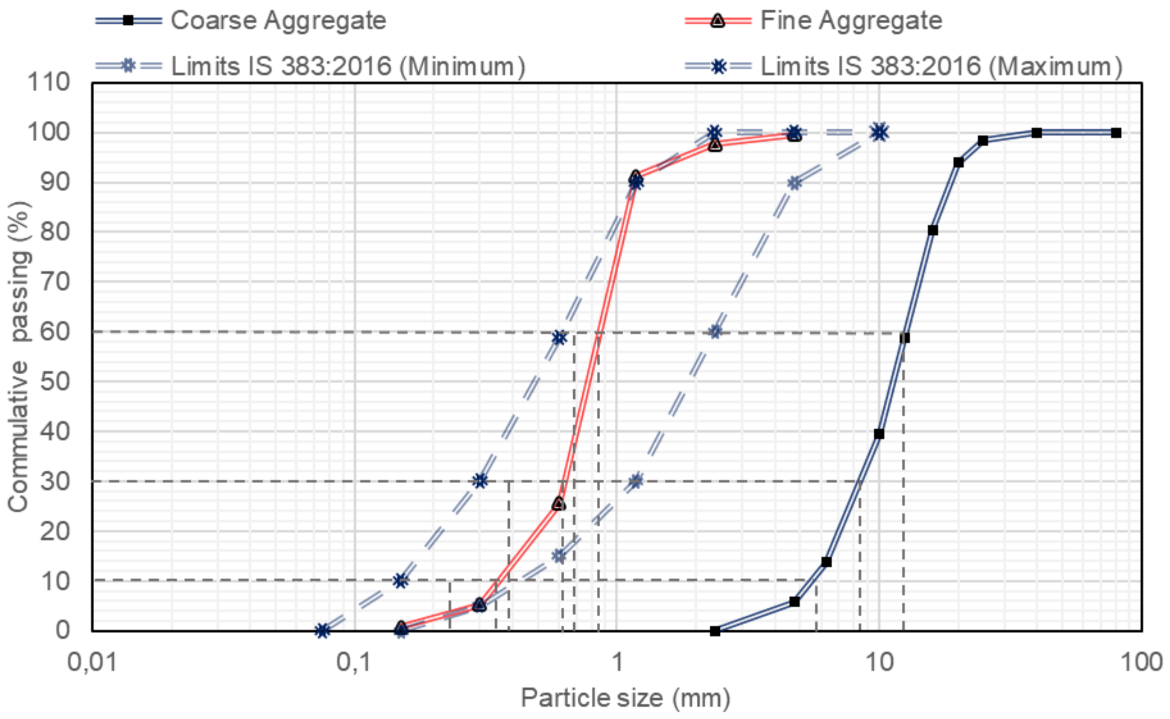

Figure 6. Particle-size distribution curve

2.2 Mix proportion

The absence of a standard mix design code for GPC poses challenges in the design of the optimal parameters. Therefore, some trials were conducted under the guidelines for fly ash-based geopolymer concretes presented by Rangan and Hardjito [44]. GPC casting trials based on these procedures showed the unsatisfactory workability and strength characteristics of the mixes. This was attributed to the inclusion of additional constituents, such as GGBFS, MK, NS, NH, and water, in the binder. The performance of these mixes is influenced by the specific sources of the materials and their manufacturing processes, which affect their interactions and chemical compositions [45]. The formation of GPC involves an iterative trial-and-error approach. The mix proportions for MK-GGBFS-based GPC involved various factors, such as the NS/NH ratio, Al/binder ratio, NH molarity, and percentage of MK and GGBFS inclusions. To formulate a mix design with high compressive strength and good workability, a test matrix was produced using a reference mix obtained from previous studies conducted in the literature. Six different mixtures were obtained by varying the proportions of the constituents, as indicated in Table 6.

Table 6. Design variables of MK and GGBFS-based geopolymer concrete

Mix ID	MK (%)	GGBFS (%)	Molarity (M)	NS/NH	Al/Binder
M_1	70	30	12	2,2	0,45
M_2	70	30	14	2,2	0,45
M_3	70	30	12	2,0	0,45
M_4	70	30	14	2,0	0,45
M_5	70	30	12	1,8	0,45
M_6	70	30	14	1,8	0,45

The percentages of MK and GGBFS were fixed at 70 % and 30 %, respectively, and the mass of Al was calculated using the ratio of Al to the binder. The masses of the NH and NS solutions were determined based on the NS-to-NH ratio, and the NH pellets were calculated using the molarity. Additional water was added to achieve workable concrete considering the water absorption of binders such as MK and GGBFS. The mix design parameters employed in the experiments are listed in Table 7.

Table 7. Mix-proportion design of different variables of MK and GGBFS-based GPC

Mix ID	**MK** (kg/m^3)	**GGBFS** (kg/m^3)	**CA** (kg/m^3)		**FA** (kg/m^3)	**Pellets of NH** (kg/m^3)	**NS** (kg/m^3)	**Water** (kg/m^3)
			20 mm	**10 mm**				
M1	315	135	406,0	609,0	563	26,00	130,20	101,5
M2	315	135	409,6	614,4	565	28,92	130,20	101,5
M3	315	135	406,0	608,0	561	24,30	135,00	101,5
M4	315	135	406,0	608,0	560	27,00	135,00	101,5
M5	315	135	406,0	608,0	561	22,78	139,22	101,5
M6	315	135	406,0	609,0	560	25,31	139,22	101,5

2.3 Testing procedure

2.3.1 Compressive strength

The compressive strength of the load on the GPC was determined to analyse the resistance to the applied compression [46]. The specimens of GPC were cast in 100 × 100 × 100 mm cubes for all the mixes. The specimens were placed in the open hall of the concrete lab for ambient curing at 27 ± 2 °C until the testing age. Under the guidelines of Indian Standard Code IS 516 Part 1, all specimens were tested after 7, 28, and 56 days of ambient curing using a compression testing machine. The specimens were placed on the disk plate of the compression testing machine, and a load was gradually applied until the specimen fractured, as shown in Figure 7.

Figure 7. Testing of compressive strength of GPC specimens on 100 mm cubes

2.3.2 Ultra-sonic pulse velocity test

The ultra-sonic pulse velocity (UPV) test was performed according to Indian standard code IS 13311:1992 Part 1 to evaluate the homogeneity of GPC and detect the presence of cracks [47]. The UPV test was performed on GPC-based samples after 28 and 56 days of ambient curing to examine the homogeneity inside the GPC, assess its quality, and identify any signs of deterioration. This nondestructive testing examination accurately determines the stress-wave pulse-propagation velocity through concrete by employing an accurate ultra-sonic electronic instrument. The refractory grease provided a proper connection between the transducers and concrete surface. The average value of multiple readings collected from various points on the concrete specimen was reported as the result of the UPV test. UPV testing of GPC was performed in a laboratory setting, as depicted in Figure 8.

Figure 8. Assessment of ultra-sonic pulse velocity GPC specimens

2.3.3 Electrical resistivity test

An ER test was performed on GPC samples to examine the probability of corrosion risk in the concrete. The ER test was conducted on cylindrical samples with a diameter of 100 mm and height of 200 mm after 28 and 56 days of ambient curing. The tests were performed using a resistivity meter consisting of four probes [48]. The testing procedure was performed according to the ASTM C1760 guidelines, as shown in Figure 9. The two outside probes of the device were used to determine the ER of the concrete, and the inside probes of the device were used to measure the potential difference between them.

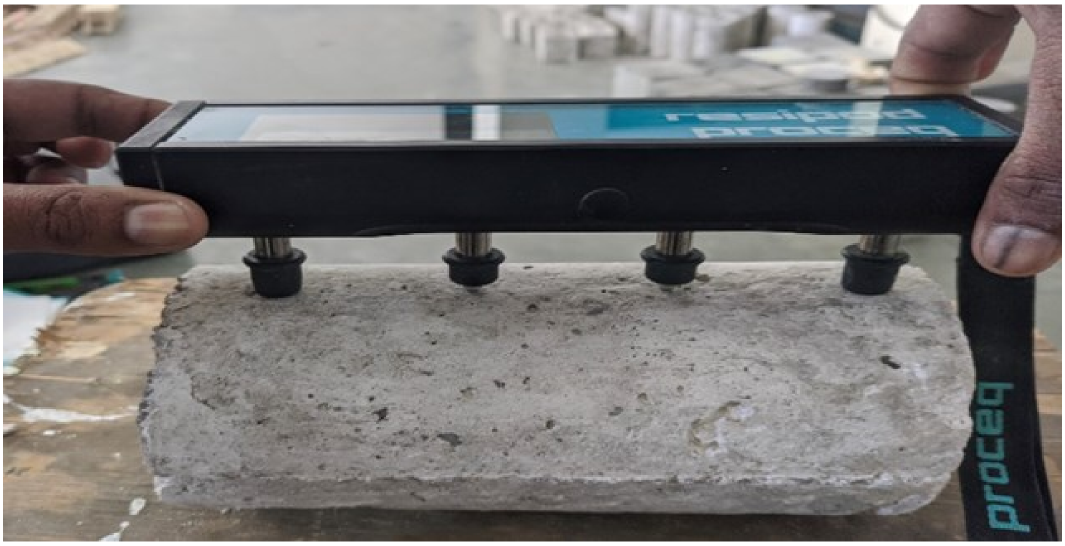

Figure 9. Testing of ER of GPC specimens

2.3.4 Resistance against acid attack

An experiment was conducted according to ASTM C 267 to investigate the effect of acid on MK-GGBFS-based GPC [49]. The changes in the compressive strength and mass were tested on 100 × 100 × 100 mm cubes, and the average result of the three samples was used for plotting the graphs. After 28 and 56 days of ambient curing, the samples were submerged in a sulphuric acid (H_2SO_4) solution for a specific exposure time. In this investigation, the standard exposure solution was a 5 % concentration of H_2SO_4. The arrangement for assessing the GPC's resistance to acid attack is shown in Figure 10.

Figure 10. Specimens exposed to a 5% concentration of H2SO4 solution

3 Results and discussion

3.1 Compressive strength

To investigate the effect of molarity on compressive strength, three mixes (M1, M3, and M5) with a molarity of 12 M and three other mixes (M2, M4, and M6) with a molarity of 14 M were prepared. The compressive strengths of MK-GGBFS-based GPC mixes at different molarities of NH with varying NS-to-NH ratios were analysed after 7, 28, and 56 days of ambient curing. The compressive strengths of the 12 M (M1, M3, and M5) and 14 M (M2, M4, and M6) mixes are shown in Figure 11.

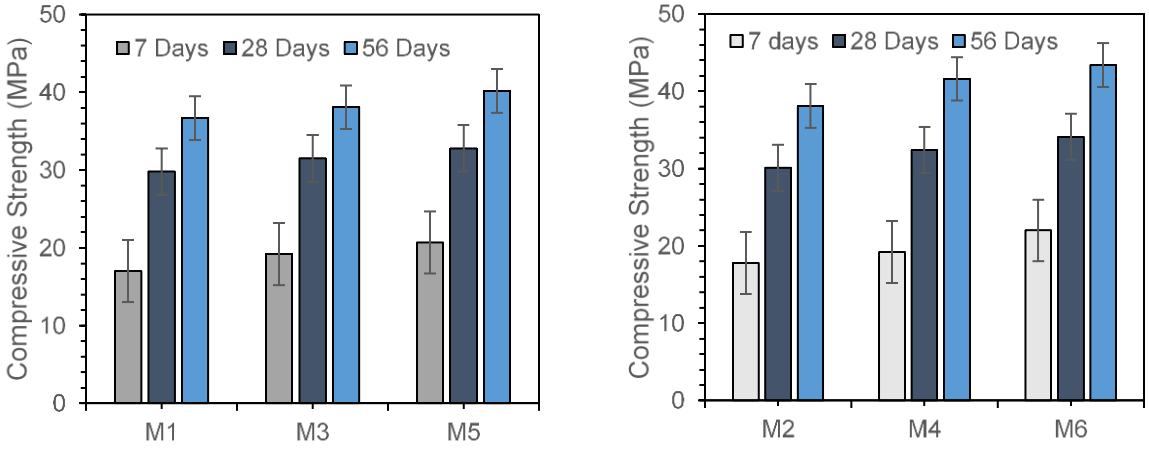

Figure 11. Compressive strength after 7, 28, and 56 days of ambient curing

As shown in Figure 11, after 7, 28, and 56 days of curing, the strength development in the MK-GGBFS-based GPC increased as the NS-to-NH ratio decreased. This phenomenon was observed for both molarity-based mixes used in the current study, that is, 12 M and 14 M. The reduction in the NS-to-NH ratio resulted in the improved activation of MK and GGBFS, leading to a higher compressive strength, which can be attributed to the increased alkalinity of the geopolymer system. Elevated alkalinity stimulated a more effective geopolymerisation reaction, facilitating the formation of a denser and stronger geopolymeric gel structure. The enhanced gel structure played a crucial role in enhancing the compressive strength of the GPC. As per the results, the optimal conditions for the MK-GGBFS-based GPC were observed to be an NS/NH ratio of 1,8 and an NH molarity of 14 M. Increasing the NH molarity in the concrete mix resulted in a higher compressive strength. This finding is consistent with previous research, which also reported that a higher NH molarity improves the compressive strength compared with a lower molarity [50]. The use of MK in GPC provided higher strength with GGBFS because MK with more fineness and a high surface area can dissolve more silica and alumina, resulting in an increase in the compressive strength and polymerisation process [51]. Additionally, the silica present in GGBFS also reacted with $Ca(OH)_2$, eventually influencing the hydration reaction and forming a strong C-S-H gel [52, 53].

3.2 Ultra-sonic pulse velocity test

The UPV data at 28 and 56 days were evaluated to understand the effects of mixture composition on the performance of the concrete. The obtained UPV values for each MK-GGBFS-based GPC mix are shown in Figure 12.

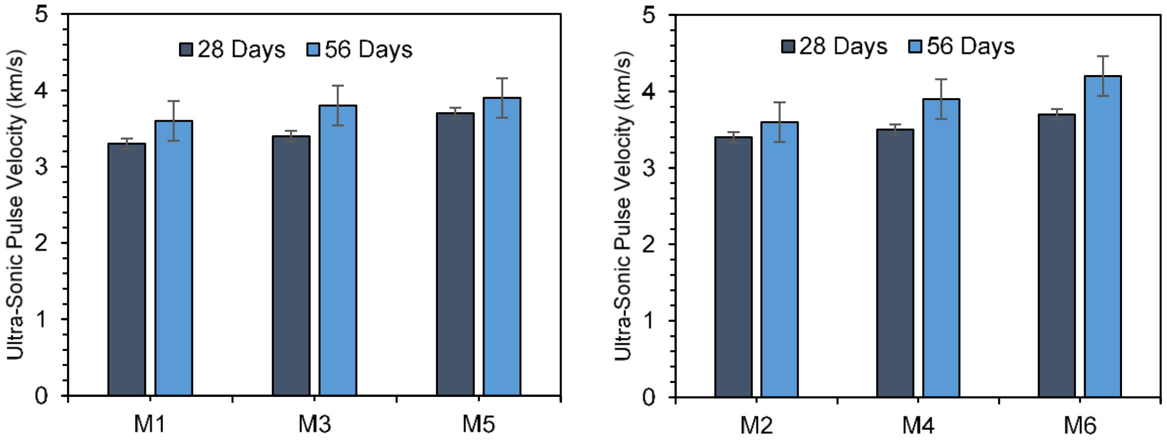

Figure 12. Ultra-sonic pulse velocity after 28 and 56 days of ambient curing at 12 and 14 molarity of NH

As shown in Figure 12, a significant improvement in the USPV of the GPC mixes prepared with MK and GGBFS at 12 M and 14 M was observed. After 28 days, the mixes prepared with 14 M showed an increasing pattern of USPV compared to those with 12 M. Previous studies have revealed that the enhancement in molarity enhances the concrete-mix quality by densifying the concrete by filling the pores [42, 54]. The use of pure NH pellets at 14 M produces an optimised alkaline environment suitable for the geopolymerisation process. Strong geopolymer interconnections result in the development of a dense and compact microstructure within the mixture, facilitating improved bonding and leading to higher pulse velocities. Moreover, the maximum USPV was observed in M6. This observation emphasises the relationship between a lower NS/NH ratio and an amplified UPV. However, at NS/NH ratios of 1,8; 2,0; and 2,2; significant reductions of 3,2 %, 4,2 %, and 6,5 % in the UPV value were observed, respectively. Previous studies confirmed the findings of the current study in the context of the USPV investigation. Beyond an NS/NH ratio of 1,8 and a UPV value beyond this ideal ratio, excessive NS can result in the formation of crystalline phases such as sodium aluminosilicate hydrates, which may have a negative impact on the UPV value [21, 24]. The geopolymer system was also enhanced when maintaining an NS-to-NH ratio of 1,8; which ensured a balanced chemical composition and favourable Si/Al ratio. Geopolymerisation kinetics are influenced by this ratio, which also affects the binder-to-activator ratio. The optimal balance between the alkaline activator and binder components was maintained by the optimised Al/binder ratio, resulting in effective geopolymer production and a consequent increase in the UPVs. This optimisation contributed to increased UPVs, indicating the improved durability and strength of the geopolymer binder.

3.3 Electrical resistivity test

The ER results of each MK-GGBFS-based GPC mix made with solutions of different molarities are shown in Figure 13.

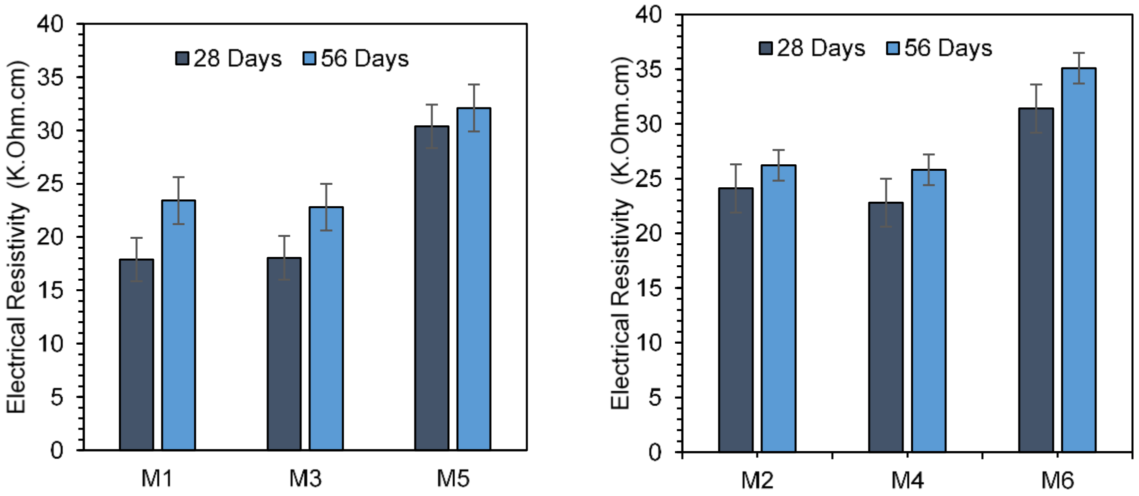

Figure 13. Electrical resistivity after 28 and 56 days of ambient curing at 12 and 14 molarity of NH

As per Figure 13, different mixes have different ER values. Mixes M1, M3, and M5 showed the lowest ER values (17,89; 18,05; and 30,37; respectively). By contrast, mixes M2, M4, and M6 demonstrated higher ER values of 23,42; 22,80; and 32,10; respectively. The mixes with an NH concentration of 12 M exhibited marginally lower ER values than those with an NH concentration of 14 M, indicating the effect of increasing the concentration of NH on the enhancement of the ER of MK-GGBFS-based GPC. Previous research obtained similar results when the alkali concentration was increased [55, 56]. Increasing the alkali concentration provided more conductive OH- and K+ ions, leading to a denser microstructure and consequently increasing the conductivity by allowing electrons and ions to move more freely [57]. In addition, a higher alkali content corresponded to increased electron and ion flexibility, which further contributed to the observed relationships between the compressive strength and other durability characteristics. Additionally, the ER of GPC mixes was increased as the specimens are subjected to prolonged curing. The findings of the current study emphasise the significance of the NS/NH ratio in determining the expansion behaviour of GPC, with lower ratios resulting in higher ER values [55, 57, 58].

3.4 Resistance against acid attack

3.4.1 Variation in mass

The effects of different molarities and NS/NH ratios on mass loss were determined by subjecting six distinct geopolymer mixtures to 28- and 56-day exposure periods, and all concrete mixtures experienced a decrease in mass, as shown in Figure 14.

As observed from Figure 14, after 28 days of exposure, mixture M1, characterised by a molarity of 12 and an NS/NH ratio of 2,2; demonstrated a reduction in mass of 2,51 %, declining from an initial weight of 2322 g to a final weight of 2254 g. Similarly, Mix M2, characterised by an equivalent molarity and NS/NH ratio, reduced mass by 1.8%, transitioning from an initial weight of 2362 g to a final weight of 2330 g. Furthermore, the mixtures M3, M4, M5, and M6 exhibited a reduction in mass by 2,38 %, 1,59 %, 1,81 %, and 1,64 %, respectively. Similarly, all mixtures consistently demonstrated a decrease in mass throughout the 56-day exposure period. The study observed that alterations in molarity and NS/NH ratios had noticeable implications for the percentage of mass loss, and the different mixtures exhibited diverse levels of degradation in response to the prevailing environmental conditions [59, 60]. The experimental findings also revealed a direct relationship between the increasing NS/NH ratios and molarity, resulting in a significant decrease in the mass of the specimens over extended exposure periods. However, additional extensive research is required to obtain a comprehensive relationship between the molarity, NS/NH ratio, and observed variations in mass. These findings suggest that the mass fluctuations observed over 28 and 56 days of prolonged exposure are intricately connected to the molarity and NS/NH ratio [52, 61, 62].

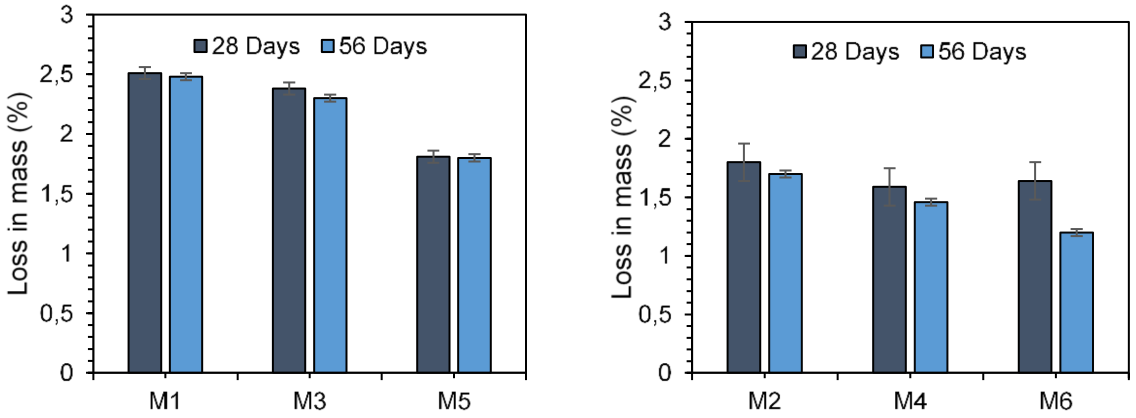

Figure 14. Mass after 28 and 56 days of exposure to 5 % concentration of the sulphuric acid solution

3.4.2 Change in compressive strength

The variations in the compressive strengths of the geopolymer concrete specimens prepared with different molarities and NS/NH ratios after 28 and 56 days of acid immersion were tested and are presented in Figure 15.

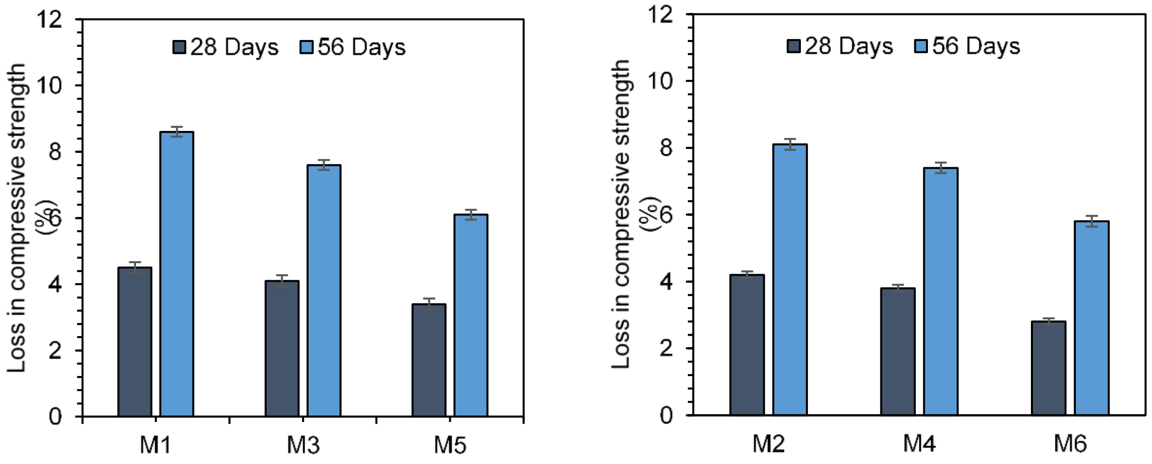

Figure 15. Loss in compressive strength after 28 and 56 days of exposure at 5 % concentration of sulphuric acid solution

Based on the data presented in Figure 15, after exposure to the acidic solution for 28 and 56 days, the compressive strength of all the mixes decreased. At 28 days, the mixes prepared with the molarity of 12 M, i.e., M1, M3, and M5, exhibited losses of approximately 2,51 %, 2,38 %, and 1,81 %, respectively, compared to their initial compressive-strength values. However, mixes M2, M4, and M6, made with a molarity of 14 M, showed significantly lower losses in compressive strength than the 12 M specimens. A similar pattern of compressive-strength reduction was observed when the specimens were tested after 56 days of exposure to the acidic solution. This decrease in strength can be attributed to the corrosive properties of sulphuric acid. The reaction between sulphuric acid and the GPC matrix resulted in the deterioration of the binding agents and disintegration of the microstructure. The aforementioned chemical reaction induced the dissolution of hydrated products present in the concrete, leading to the deterioration of interparticle bonds and a subsequent decline in the overall cohesion [52, 62]. In addition, mixes with higher molarities tended to exhibit higher compressive strengths before exposure [51, 59, 60].

4 Statistical analysis

Regression analysis was performed on the data obtained from the experiments. The results showed that several parameters had a significant impact on the compressive strength of the GPC mixtures. The linear regression between the compressive strength and other properties at different ambient curing days is presented in Figure 16.

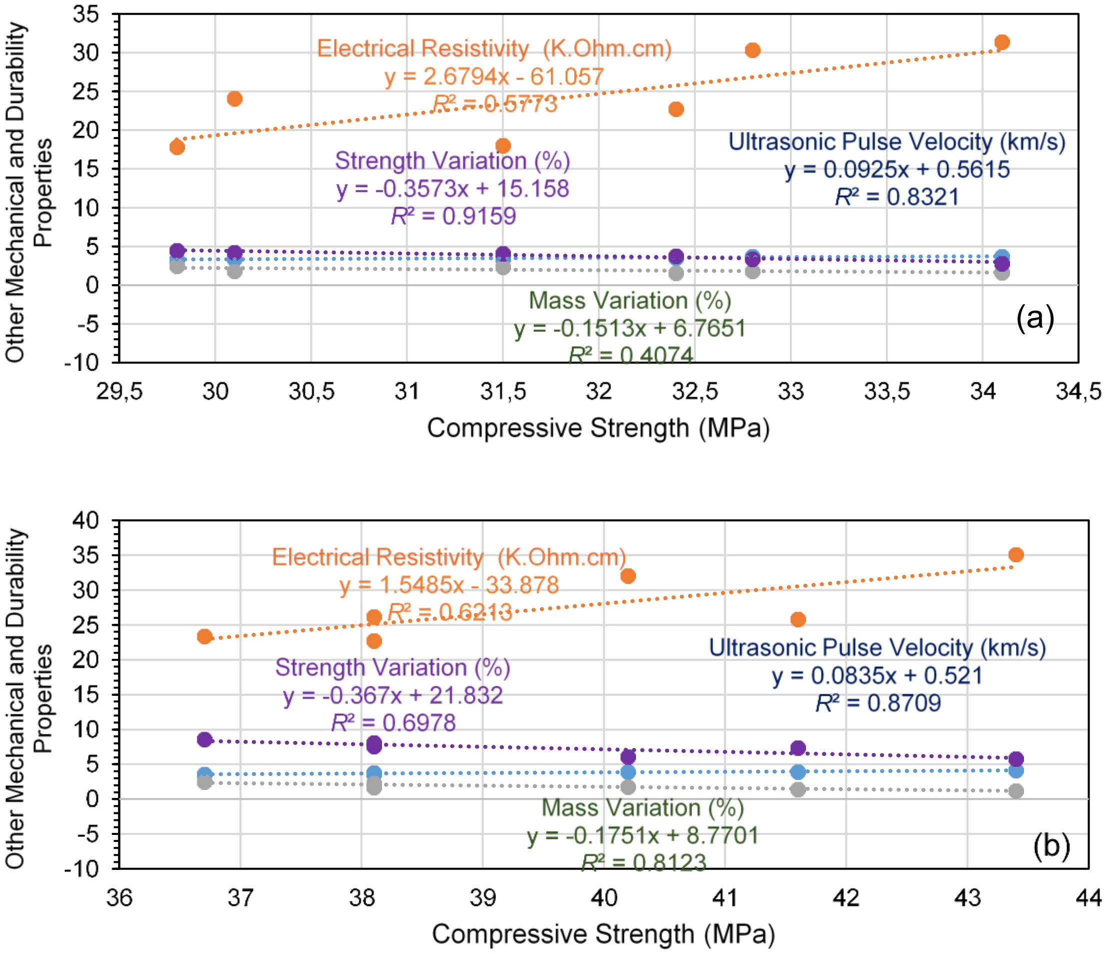

Figure 16. Statistical analysis of experimental data obtained in the current study after (a) 28 days and (b) 56 days

As per Figure 16, a strong linear regression is observed between the compressive strength and other attributes of hardened concrete evaluated in the current study. As the number of curing periods is extended from 28 to 56 days, a significant improvement in the correlation coefficient is observed. This influence was caused by the formation of a strong geopolymerisation matrix within the concrete matrix of the samples prepared with different molarities. The linear equations for each parameter are highlighted in distinct colours for differentiation. The findings of the current study are also consistent with those reported in the literature, which further indicate that these relationships contribute to the advancement of knowledge regarding the underlying factors that influence the strength of concrete and highlight the practical implications of these findings [63, 64].

5 Conclusions

The data obtained in the current study demonstrated the considerable impact of varying parameters such as NH molarity and NS/NH ratio on the mechanical strength, durability, and nondestructive properties of MK-GGBFS-based GPC. The compressive strength was examined after 3, 7, and 28 days, whereas the other durability and nondestructive attributes were determined after 28 and 56 days of ambient curing. Based on the results of tests for compressive strength, durability, nondestructive characteristics, and statistical analysis, the following major conclusions were drawn on the influence of molarity and NS/NH ratio:

- The MK-GGBFS-based GPC mix M6 (NH molarity of 14, NS/NH ratio of 1,8; and Al/B ratio of 0,45) represented the optimal results in terms of improving the mechanical properties, durability, and nondestructive parameters compared to the other concrete mixes.
- Mixes M5 and M3 also showed a similar pattern of enhancing the aforementioned characteristics of concrete after 28 and 56 days of ambient curing. However, mixes M1, M2, and M4 exhibited moderate performances.
- The UPV also improved significantly with the use of a higher molarity of NH (14 M). Geopolymerisation results in a dense packing of the ingredients within the mix, which allows the waves to pass rapidly and consequently leads to superior quality.
- The ERs of the GPC mixes with a higher concentration of alkali solution were superior to those with a lower concentration. The presence of a greater number of conductive OH- and K+ ions in the mixes promoted the movement of electrons and ions, leading to an improved ER and ingression of water within the mix.
- M6 exhibited the greatest resistance to acid attack compared with the other concrete mixes. Minimal losses in the compressive strength and mass of the samples were observed after 28 and 56 days of immersion in acidic solutions.
- Longer curing periods also affected the mechanical properties, durability, and nondestructive characteristics of GPC made with MK and GGBFS in contrast to shorter curing periods.
- The regression analyses highlight a strong relationship between the compressive strength and other properties of MK-GGBFS-based GPC. In addition, the correlation coefficient of these properties was reported to improve as the number of curing periods was extended from 28 to 56 d, validating the advancement in geopolymerisation over time.

The abovementioned observations infer that the GPC mix M6, with MK (70 %) and GGBFS (30 %) at an NH molarity of 14 M, NS/NH ratio of 1,8; and Al/B ratio of 0,45; exhibited the best results in terms of enhanced mechanical properties, durability, and resistance to aggressive environmental conditions. Considering these aspects, M6 can be considered for practical applications in the construction field depending on the type of construction required. Although the GPC M6 prepared in the current study has shown potential as a sustainable and eco-friendly alternative to traditional concrete, its application should be considered by weighing the benefits against its cost-effectiveness, the availability of raw materials, and its compatibility with existing construction practices. Additional research should be performed to determine the life-cycle assessment of MK-GGBFS-based GPC made with different concentrations of NH, varying ratios of NS/NH and Al/B, and other parameters. The application of additional supplementary cementitious materials, such as rice-husk ash, sugarcane bagasse ash, and fly ash, may also result in a considerable improvement in the characteristics of GPC. The utilisation of recycled aggregates during the production of GPC can also reveal the underlying effects on other significant environmental and cost-saving benefits. Moreover, further improvement in the attributes of GPC may lead to potential applications in the construction of infrastructure, cost-effectiveness, energy efficiency, and thermal stability.

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