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Durability study on ambient cured geopolymer concrete made with various molarities of NaOH

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Original research paper

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Geopolymer concrete is an innovative variation of the conventional construction material that reduces the environmental impact of producing Ordinary Portland Cement (OPC) while simultaneously improving the efficient use of industrial by-products. By altering the molarities of sodium hydroxide to 4M, 6M, 8M, 10M, and 12M, five combinations of geopolymer concrete were prepared for this study. After 28 days of curing at room temperature, the strength properties, viz., the compressive strength (DT and NDT), the splitting tensile strength, and the flexural strength were evaluated. Additionally, the durability properties such as the initial water absorption, saturated water absorption, sorptivity, average effective porosity, abrasion resistance, and chemical attack resistance were studied as well. All the findings of the geopolymer concrete were compared to those of the M35 grade OPC concrete. The experimental test results showed that, with the exception of GPC-4M, the other Geopolymer concrete mixtures met the target strength requirements of the M35 grade concrete. The findings revealed that the GPC-8M concrete specimens performed the best in terms of strength and durability. Consequently, widespread use of geopolymer concrete, which is prepared with fly ash (FA) and ground granulated blast-furnace slag and cured in ambient air, is recommended instead of OPC concrete.

Key words:

geopolymer concrete, alkaline solution, ambient curing, destructive test (DT), non- destructive test (NDT), durability

Izvorni znanstveni rad

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Procjena trajnosti geopolimernog betona s različitim molaritetima NaOH njegovan na temperaturi okoline

Geopolimerni beton inovativna je varijacija konvencionalnog građevnog materijala koja smanjuje utjecaj proizvodnje običnog portlandskog cementa (OPC) na okoliš, a istovremeno poboljšava učinkovitu primjenu industrijskih nusproizvoda. Promjenom molariteta natrijevog hidroksida na 4M, 6M, 8M, 10M i 12M, za ovo je istraživanje pripremljeno pet kombinacija geopolimernog betona. Nakon 28 dana njegovanja na sobnoj temperaturi, procijenjena su svojstva čvrstoće, tj. tlačna čvrstoća (DT i NDT), vlačna čvrstoća cijepanjem i čvrstoća na savijanje. Potom su ispitana i svojstva trajnosti kao što su početno upijanje vode, upijanje vode do zasićenja, sorptivnost, prosječna efektivna poroznost, otpornost na habanje i otpornost na kemijsko djelovanje. Rezultati istraživanja geopolimernog betona uspoređeni su s rezultatima istraživanja betona OPC razreda M35. Rezultati eksperimentalnog ispitivanja pokazali su da, s iznimkom GPC-4M, ostale geopolimerne mješavine betona zadovoljavaju zahtjeve ciljane čvrstoće betona razreda M35. Rezultati istraživanja otkrili su da su se GPC-8M betonski uzorci pokazali kao najbolji u smislu svojstva čvrstoće i trajnosti. Stoga se umjesto OPC betona preporučuje raširenija uporaba geopolimernog betona, koji se priprema s letećim pepelom i mljevenom granuliranom zgurom iz visokih peći te njeguje na temperaturi okoline.

Ključne riječi:
geopolimerni beton, alkalna otopina, njegovanje na temperaturi okoline, razorno ispitivanje (DT), nerazorno ispitivanje (NDT), trajnost

1. Introduction

The development of sustainable building materials has not only gained popularity but has also become necessary in the twenty-first century. Primary reason being cement, which is very widely used as a binder in the construction industry, emits 0.6 to 0.8 kg for every kg of cement produced and accounts for approximately 5 to 7 % of total worldwide CO_2 emissions [1, 2]. To counter these issues, in 1978 the French scientist Davidovits created a unique binder named "Geopolymer" wherein silica- and alumina-rich materials are activated using sodium- or potassium-based alkaline solutions. According to the study, the use of geopolymer concrete in the construction industry has the potential to eliminate nearly 80 % of the carbon emissions [3]. The development of new construction materials necessitates a thorough understanding of strength and durability standards because failure can be influenced by the application of heavy loads as well as the deterioration of structural components such as the reinforcement steel. While durability is a key parameter in the useful life of concrete structures, permeability is the primary factor that is crucial for determining durability. Permeability is not only governed by porosity, but also depends on the size and volume of pores, connectivity of pores, and pore structure [4]. Accordingly, durability characteristics, such as initial and saturated water absorption, average value of effective porosity, sorptivity, density variation, abrasion resistance, and resistance against acid and sulphate attack, were examined for geopolymer concretes treated with alkaline solutions at different molarities in this study. The test specimens were cured at room temperature and the results were compared with those of ordinary Portland cement (OPC) concrete. During the 120-day exposure period, concrete deterioration caused by sulphuric acid and sodium sulphate was tracked using measurements that included mass and compressive strength loss. The reason for selecting sulphuric acid over other acids is because in real life concrete structures are frequently subjected to sulphuric acid attack in various applications such as mining, sewage, and food processing industries [5]. In a study assessing the long-term properties of fly-ash-based geopolymers, Wallah and Rangan demonstrated that geopolymer composites have excellent durability properties [6].

Numerous researchers have examined how acids and sulphates affect geopolymer concrete and discovered that it is highly resilient to aggressive environments [7, 8]. However, it was observed that when exposed to sulphuric acid at a concentration of 5 %, the geopolymer concrete prepared with ground granulated blast-furnace slag (GGBS) as the only binder produces gypsum as a reaction product, which comprises internal voids and is subjected to much higher loss of mass than in the case of geopolymer concrete based on fly ash [9]. Wong [10] reported that the extent of acid attack on calcium silicate and calcium aluminate bonding in OPC concrete is greater than the extent to which the aluminosilicate bonding in the geopolymer concrete was destroyed. The study further confirmed that geopolymer concrete exhibited higher compressive strength at an ideal increased temperature, low to medium chloride ion penetrability, and better abrasion resistance. Valencia-Saavedra et al. [11] investigated and assessed the durability of FA/GGBS and FA/OPC concretes against acetic and sulphuric acid attacks. Alkali-activated concrete showed lower mass and compressive strength deterioration after a year, whereas OPC showed significant deterioration. Moreover, incorporation of a low volume of fibres into the geopolymer concrete mix improved the microstructural characteristics by stitching the microcracks present in the concrete matrix [12], and addition of nano-silica to geopolymer concrete created a dense structure that limited the durability, porosity, and sorptivity [13]. Kumar et al. [14] produced Ternary Blend Geopolymer Concrete (TGPC) which is a durable and environmentally friendly concrete made with a binder made from three distinct source materials. The fundamental benefit of TGPC is that it has densely packed particles with a variety of sizes and shapes which leads to better characteristics. The performance of TGPC with 1 % steel fibre and 0.15 % polypropylene fibre is superior to that of other combinations of TGPC and conventional OPC concrete. Aygörmez et al. [15] evaluated the durability of the geopolymer composites 365 days after casting. The mixture included polyamide and polyolefin fibres together with metakaolin, colemanite, slag, sand, and alkali activator. According to the results, geopolymer specimens were less affected by freeze-thaw cycles, offered endurance to the impacts of temperature changes, and degraded substantially less in HCl solutions than OPC specimens after 365 d of exposure. This resulted from the geopolymerisation process under the wet-dry curing regimes, which developed a compact microstructure. Paudal et al. [16] examined the impact of pH of the pore solution in alkali-activated fly-ash-based Geopolymer Concrete (GPC) with various silica concentrations on the alkali-silica reaction (ASR). In comparison with OPC, the results showed that GPC was more resistant to the ASR reaction and that less ASR gel was formed in the geopolymer.

Furthermore, the mechanical properties of geopolymer concrete with altered molarities, viz., the compressive strength (Destructive and Non-Destructive Test), the splitting tensile strength, and the flexural strength, were studied after completion of 28 days of curing. Presently, there are very few findings regarding the durability of geopolymer concrete prepared with various NaOH molarities. The results of five mixes of geopolymer concrete, designated as 4M, 6M, 8M, 10M & 12M, and their functional characteristics in comparison with those of OPC concrete are presented in this research paper thereby filling a gap in the literature.

2. Experimental programme

2.1. Materials

Fly ash and GGBS-based Geopolymer Concrete were prepared using silica- and alumina-rich raw materials, viz., fly ash and GGBS, in combination with sodium-based alkaline solution, which is a mixture of sodium silicate and sodium hydroxide solution. Low-calcium fly ash with specific gravity of 2.2 (dark grey colour) was obtained from the Tuticorin Thermal Power Station, India. GGBS with specific gravity of 2.8, which has an off-

Table 1. Chemical analysis of fly ash and GGBS

Source material	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	K_2O	P_2O_5	MgO	SO_3
Fly ash [%]	55.41	29.69	8.48	2.02	1.39	1.01	0.7	0.45	0.32
GGBS [%]	31.75	16.91	0.61	1.11	39.79	0.47	-	6.23	1.62

Table 2. Details of Mix identification

Sl. No.	Mix identification	Specification
1	GPC – 4M	Geopolymer concrete of 4 molarity concentration of sodium hydroxide
2	GPC – 6M	Geopolymer concrete of 6 molarity concentration of sodium hydroxide
3	GPC – 8M	Geopolymer concrete of 8 molarity concentration of sodium hydroxide
4	GPC – 10M	Geopolymer concrete of 10 molarity concentration of sodium hydroxide
5	GPC – 12M	Geopolymer concrete of 12 molarity concentration of sodium hydroxide
6	CC – M35	Ordinary portland cement concrete of M35 grade

white hue, was also utilised in the concrete production process. The chemical composition of the raw materials, i.e., fly ash and GGBS, was determined by XRF analysis and the results are shown in Table 1. Viscous sodium silicate liquid, often known as water glass, maintains the SiO_2/Na_2O ratio at 3.1, and contains mass percentages of 26.5 and 8 % of soluble silicate (SiO_2) and sodium oxide (Na_2O), respectively, while the sodium hydroxide solution was prepared using sodium hydroxide pellets with a purity of 97 %. The ratio of sodium silicate solution to sodium hydroxide solution was maintained at 2.5 for preparation of different concentrations of the alkaline solution. Both liquid sodium silicate and sodium hydroxide solution were procured from local vendors. A better packing density can be achieved by using properly graded aggregates of various sizes. Therefore, locally available blue granite metals of 20 and 12.5 mm size with specific gravities and fineness moduli of 2.8, 2.96, and 7.37, 6.97, respectively, were used as the coarse aggregates. Owing to scarcity of natural river sand, M-sand of zone II conforming to IS 383(1970):2002 [17] with specific gravity of 2.72 and fineness modulus of 2.5 was used as the fine aggregate. A polycarboxylic ether-based superplasticiser with pH and specific gravity of 7 and 1.08, respectively, was used as an additive to enhance fresh concrete characteristics. Table 2 illustrates the mix identification of geopolymer concrete and conventional concrete.

2.2. Mix design

Because there is no standard mix design for geopolymer concrete, only a few researchers have concentrated on the mix design process for different grades of geopolymer concrete and fly-ash-based geopolymer concrete [18, 19]. Assuming that concrete has a density of 2400 kg/m^3, a mix design was developed in this study by trial and error. Requirement of binder was calculated as 500 kg to produce 1 m^3 of concrete (density of both fly ash and GGBS was assumed to be 250 kg/m^3) by keeping the alkaline solution to binder ratio at 0.35, while the requirement of the aggregate materials (which makes up 70 % of the weight of concrete) was determined as 1680 kg to produce 1 m^3 of concrete. By maintaining fine aggregate to coarse aggregate ratio at 0.35 [20], requirement of fine aggregate and coarse aggregate were estimated to be 436 kg/m^3 and 1244 kg/m^3, respectively. Using the guidelines of IS10262:2009 [21], the control concrete of M35 grade was designed with OPC content and water-cement ratio of 371 kg/m^3 and 0.45, respectively. Three percent of the binder content from each mixture was considered as the quantity of superplasticiser to be used. The proportioning information for the raw materials required to produce 1 m^3 of geopolymer concrete is presented in Table 3.

Table 3. Mix proportioning for 1 m^3 of geopolymer concrete

Mix identification	Source materials [kg]		Fine aggregates [kg]	Coarse aggregates [kg]		Alkaline solution	
	Fly ash	GGBS		12.5 [mm]	20 [mm]	NaOH solution [kg]	Na_2SiO_3 solution [kg]
GPC-4M	250	250	436	498	746	50	125
GPC-6M	250	250	436	498	746	50	125
GPC-8M	250	250	436	498	746	50	125
GPC-10M	250	250	436	498	746	50	125
GPC-12M	250	250	436	498	746	50	125

*GPC - Geopolymer concrete; M - Molarity of sodium hydroxide

The quantity of fine and coarse aggregates was estimated by setting the fine aggregate to coarse aggregate ratio and aggregate volume to 0.35 and 70 % of total volume in the assumed density of concrete. For determining the quantity of binder and alkaline solution, the ratio of the alkaline solution to the binder was set at 0.35 by weight. While working out the proportioning for 1 m^3 of geopolymer concrete, the estimated requirement of alkaline solution was determined as 175 kg per cubic meter of concrete which was divided as 125 and 50 kg of Sodium Silicate and NaOH solutions, respectively, based on a Na_2SiO_3/NaOH ratio of 2.5 [22]. Furthermore, to prepare a solution of sodium hydroxide with a molarity of 4, 160 g of sodium hydroxide pellets (4 × 40) were dissolved in one litre of water, where 40 is the molecular weight of sodium hydroxide and 4 is the concentration of NaOH.

2.3. Mixing

The saturated surface dry-conditioned aggregates were first mixed with fly ash and GGBS, which is known as the dry mix. Subsequently, the alkaline solution and superplasticiser were added to the dry mix gradually and mixing was continued for an additional 4–5 minutes until a homogeneous mixture was formed. The production process for geopolymer concrete is shown in Figure 1. The alkaline solution is a mixture of sodium hydroxide and sodium silicate solutions. To make sodium hydroxide solution, the required quantity of 97 % pure sodium hydroxide pellets were dissolved in water. Preparation of the alkaline solution as per procedure described earlier was completed on the day before the concrete was mixed because this reaction is exothermic; prior preparation permits complete dissolution of sodium hydroxide pellets and sufficient time for heat release and cooling down. The sodium silicate solution was combined with the sodium hydroxide solution during concrete mixing as previously indicated.

Figure 1. Production of geopolymer concrete

2.4. Casting and curing

On completion of proper mixing by hand, the geopolymer and conventional concretes were cast into their respective moulds and vibrated for two–three minutes. The OPC and geopolymer concrete moulds were cured in a water bath for the same period until demoulding and then left to cure at room temperature for 28 days. Several sample specimens in different shapes and sizes as described hereunder were cast for various tests. To test the compressive, split tensile, and flexural strengths, specimens of size 150 mm cubes, 150 mm diameter × 300 mm height cylinders, and 100 mm breadth x 100 mm depth x 500 mm length prisms were cast. Additionally, one hundred specimens of millimetre cubes were cast to estimate the water absorption, sorptivity, density variation, and resistance against acid and sulphate attacks. Furthermore, tile-shaped specimens with 70.7 x 70.7 mm sides and 25 mm thickness were used to test abrasion resistance. Three identical specimens of each kind were tested to determine the average value of each test parameter.

3. Test results

3.1. Test for strength properties

The compressive and flexural strengths of all the geopolymer concrete combinations and the conventional concrete were determined according to IS 516 (1959):2004 [23]. The split tensile strength tests were performed as per the procedures outlined in IS 5816 (1999):2004 [24]. Table 4 presents the test results for the aforementioned mechanical parameters. It could be observed that the compressive strength of geopolymer concrete increases after 28 d of ambient curing in correspondence with the molarity of sodium hydroxide. However, in the case of specimens in which the molarity of sodium hydroxide exceeded 8M, the strength decreased marginally. The increased silica content leaching at higher sodium hydroxide concentrations, which may slow the polymerisation reaction, caused the observed decrease in strength beyond 8M [25]. The GPC-8M mix had an ultimate strength of 57.53, which was 23.72 % greater than the ultimate strength of conventional concrete. The addition of calcium to the concrete which is present in GGBS aided the increase in strength during ambient curing [26]. In addition to C-A-S-H and N-A-S-H gels, C-S-H phases were also produced as in the case of OPC concrete. Additionally, the calcium component in GGBS enables early strength development, and this increase in strength is independent of the curing period or aggregate type [27]. Findings by other investigators have also reinforced and lent credence to this hypothesis [22, 28]. Except for the GPC-

Table 4. Mechanical properties of Geopolymer and conventional concrete

Mix identification	Compressive strength at 28 days [MPa]	Compressive strength by Rebound Hammer test [MPa]	Splitting tensile strength at 28 days [MPa]	Flexural strength at 28 days [MPa]
GPC-4M	33.34	28.95	2.78	3.45
GPC-6M	49.1	39.38	3.18	4.21
GPC-8M	57.53	42.11	3.84	4.55
GPC-10M	55.14	41.04	3.51	4.43
GPC-12M	52.74	40.15	3.4	4.35
CC-M35	46.5	38.62	2.98	4.1

4M, all other geopolymer concretes achieved the desired strength of the M35 grade conventional concrete. When compared to the higher molarity geopolymer concretes, GPC-4M specimens did not contribute to higher strength development; they could only meet the M25 grade target strength requirements. As shown in Table 4, the splitting tensile and flexural strength test results maintain the trend shown in the compressive strength data. Except for GPC-4M, the other geopolymer concrete mixes displayed a greater splitting tensile strength than the OPC concrete. As evidenced from the test results, only 6–8 % of compressive resistance was achieved as splitting tensile strength, which is comparable to that of conventional concrete [29]. The flexural strength at 28 days for the GPC-6M, GPC-8M, GPC-10M, and GPC-12M concretes were higher by 3, 11, 8, and 6 %, respectively, than that of conventional concrete. However, the flexural strength of GPC-4M was 16 % lower than that of conventional concrete which is attributable to the lower concentration of the alkaline solution. The development of flexural and tensile strengths of geopolymer concrete was significantly influenced by the precipitation of alumina-silicate gel and the dissolution of alkalies on the surface of the aggregates [30]. Owing to the stronger aggregate-binder bond in geopolymer concretes, they demonstrated better flexural strength than traditional OPC concrete when cured at ambient and increased temperatures [31]. In this study, the flexural strength was approximately 8–10 % of the corresponding 28-day compressive strength of Geopolymer Concrete. Zannerni et al. [32] reported that the strength characteristics of fly-ash-based geopolymer concrete are often less favourable than those of GGBS-based Geopolymer concrete. This might be because fly ash particles have a smoother surface and are spherical in shape, whereas GGBS particles have a rough surface that forms a strong bond with aggregates. Therefore, the strength properties of geopolymer concrete made with fly ash and GGBS in combination are better than those of concrete made with fly ash alone.

3.2. Results of non-destructive tests

Non-destructive testing methods are the most effective techniques for assessing the condition of existing structures to determine their strength and durability [33]. To validate the compressive strength by non-destructive testing, the Rebound Hammer (RH) test was performed on identical specimens after 28 days of ambient curing in accordance with IS 13311 (part 2):1992 [34]. The prediction of compressive resistance by the Rebound Hammer test was lower than the destructive test results, according to statistics. This could be caused by a number of factors, viz., the type of aggregate, status of the surface, moisture content, and carbonation of the concrete [35]. The NDT results are presented in Table 4. The maximum compressive strength of the GPC-8M concrete mix was determined by the Rebound Hammer test to be 42.11 MPa, while the same GPC-8M mix achieved only marginally better results in the destructive test. The Concrete Society: 2000 [36] categorised all Geopolymer Concrete mixes including ordinary concrete as either Good (30–40 MPa) or excellent (> 40 MPa), with the exception of GPC-4M which was categorised as only fair quality (20–30MPa). The fact that there is a link between the compressive strength values determined by destructive and non-destructive tests has been established. The regression equation and the related coefficient are presented in Figure 2. It is evident that the direct compression test (DT) and Rebound Hammer (RH) test results of compressive strength were well fitted by the linear regression line, and the R^2 value was determined to be 0.9507.

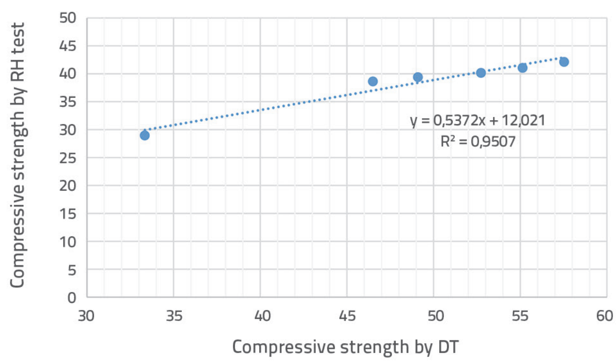

Figure 2. Correlation relation of Compressive strength by DT and NDT (RH)

3.3. Density variation

The density of concrete under different conditions can be calculated using the ratio of the weight of the concrete specimen in that condition to the volume of the concrete specimen. Figure 3 depicts the density values of the geopolymer and control concretes, and it can be observed that It fluctuated in the 2460 to 2558 kg/m³ range.

Moreover, the results establish that geopolymer concrete with sodium hydroxide concentrations of 6M, 8M, 10M, and 12M have higher density values than common OPC concrete, whereas GPC-4M mix has the lowest density of 2460 kg/m^3. The density of concrete is primarily reflected in the unit weight of aggregates used to build it; however, the creation of geopolymer gel and its link with aggregate concrete also contribute to the density of concrete. The density range of the geopolymer concrete is similar to those of Ordinary Portland cement concrete, which was also reported by Rangan [37].

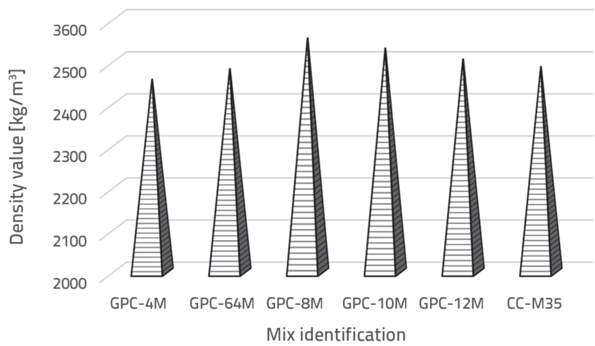

Figure 3. Density variation of Geopolymer concrete mixes

3.4. Test for water absorption and effective porosity

The initial and saturation water absorption tests were performed in accordance with ASTM C 642-82 standards [38]. Starting with oven-dried specimens of 100 mm cubes at 105 °C until the indication of constant weight (W_1), the water absorption and average effective porosity were determined. The initial and saturated water absorptions of the specimens were then measured after they were submerged in water for 30 min and 120 h, respectively. The saturated weights W_2 (30 min) and W_3 (120 h) were measured after immersion. The percentage of water absorption was calculated by dividing the difference between the saturated and oven-dried weights by the oven-dried weight. According to the guidelines provided by the Concrete Society (CEB 1989) [39], the quality of concrete is classified as good, average, or poor depending on the initial water absorption percentage at 30 min, which should be less than 3 %, between 3 % and 5 %, or greater than 5 %, respectively. Table 5 shows the initial and saturated water absorption values as well as the average effective porosity. The volume of voids was calculated by dividing the volume of voids by the overall volume of the specimen. The test findings showed that, with the exception of the GPC-4M mix, the initial and saturated water absorption rates of the geopolymer concrete were less than those of the Control Concrete. According to Ganesan et al. [12], the absorption rate of fly ash-based geopolymer concrete is lower than that of OPC concrete. These results are strongly correlated with those reported by Sathia et al. [13] as well. According to Al-Otaib [40], the slag-based Geopolymer concrete exhibited higher porosity values than the regular OPC concrete, which has a porosity range of 8–10.4 % for the same curing period, whereas slag-based geopolymer concrete has a porosity range of 10–13 %. The absorption values of fly ash and GGBS combined geopolymer concrete in this analysis ranges from 7.98 to 12.96 % for different molarities. The maximum and minimum porosities were attained in the Geopolymer concrete with GPC-4M at 12.96 % and the GPC-8M at 7.98 %. Except for the GPC-4M concrete specimens, the remaining concrete proportions were moved toward the category of good quality, as shown in Table 5. Volume of permeable voids in alkali-activated concrete is higher than that of the conventional concrete at slag contents greater than or equal to 50 % [41]. However, the use of fly ash in conjunction with GGBS in the preparation of geopolymer concrete resulted in the synthesis of N-A-S-H and C-A-S-H resulting in a denser geopolymer concrete microstructure. A strong relationship was discovered between the volume of permeable voids and the rate of water absorption. The absorption rate increased as the number of voids increased and vice versa.

3.5. Sorptivity test

Sorptivity is defined as the rate at which water penetrates the pores owing to capillarity action. The test was conducted as described by Ganesan et al. [12]. The first round of drying involved drying the 100 mm cubes in an oven at 105 °C for 24 h, and this was followed by cooling for an additional 24 h. The sides of the specimens were sealed with insulating tape to prevent water

Table 5. Immersed water absorption and effective porosity test results

Mix identification	Initial weight W_1 [kg]	Final weight after 30 min W_2 [kg]	Final weight after 120 h W_3 [kg]	Initial water absorption $(W_2-W_1)/W_1$ [%]	Saturated water absorption $(W_3-W_1)/W_1$ [%]	Average effective porosity [%]	Quality of concrete as per [39] (CEB 1989)
GPC-4M	2.45	2.532	2.58	3.33	5.29	12.96	Prosječna
GPC-6M	2.485	2.559	2.58	2.96	3.84	9.54	Dobra
GPC-8M	2.59	2.621	2.67	1.19	3.08	7.98	Dobra
GPC-10M	2.551	2.612	2.633	2.38	3.21	8.19	Dobra
GPC-12M	2.508	2.574	2.599	2.63	3.63	9.1	Dobra
CC-M35	2.468	2.542	2.567	2.98	4	9.87	Dobra

Table 6. Sorptivity test results

Mix identification	Cumulative weight of water penetrated after immersed in water level [g]				Cumulative volume of water penetrated per exposed surface area in water [cm^3/cm^2]				Sorptivity [$cm/min^{0.5}$]
	30 [min]	**60** [min]	**90** [min]	**120** [min]	**30** [min]	**60** [min]	**90** [min]	**120** [min]	
GPC-4M	27	37	41	46	0.27	0.37	0.41	0.46	3.39×10^{-2}
GPC-6M	25	33	36	40	0.25	0.33	0.36	0.4	2.67×10^{-2}
GPC-8M	23	25	29	31	0.23	0.25	0.29	0.31	1.52×10^{-2}
GPC-10M	30	35	39	42	0.3	0.35	0.39	0.42	2.2×10^{-2}
GPC-12M	23	29	34	37	0.23	0.29	0.34	0.37	2.6×10^{-2}
CC-M35	31	38	42	46	0.31	0.38	0.42	0.46	2.71×10^{-2}

from seeping from the sides of the cubes. After the initial weight of the specimen was measured, it was placed in water at a depth of 5–10 mm. A support made of fibreglass filter material was inserted to the bottom of each cube specimen to enable water penetration through the bottom surface of the cube as well, as shown in Figure 4. Weight gain was measured at 30-minute intervals over a 2-hour period. Based on these findings, the cumulative volume of water penetrating the specimen per unit contact area of the specimen was plotted against the square root of the exposure time. This plot is linearised to obtain the slope of the line which indicates the sorptivity value. Table 6 shows the sorptivity values of different geopolymer concretes and the control OPC concrete. Except for the GPC-4M, the Sorptivity of other geopolymer concrete mixes was lower than that of the conventional concrete. This can be attributed to the establishment of strong link between the aggregates and the geopolymer gel, whereas in the case the GPC-4M mix owing to its lower alkaline solution concentration the aforementioned geopolymer gel was not formed. GPC-8M had the lowest sorptivity value of 1.52×10^{-2} $cm/min^{0.5}$, while the control concrete had a value of 2.71×10^{-2} $cm/min^{0.5}$. A lower sorptivity value is preferred as it indicates lower water penetration [42]. The cumulative water penetration per unit surface area to the square root of time is shown in Figure 5 for each of the six types of concrete. The correlation co-efficient was discovered to be in the range of 0.9784–0.9996 and the linear equations were well fitted.

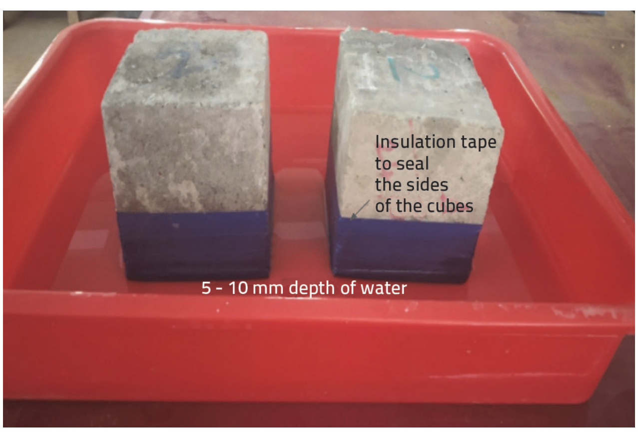

Figure 4. Sorptivity test

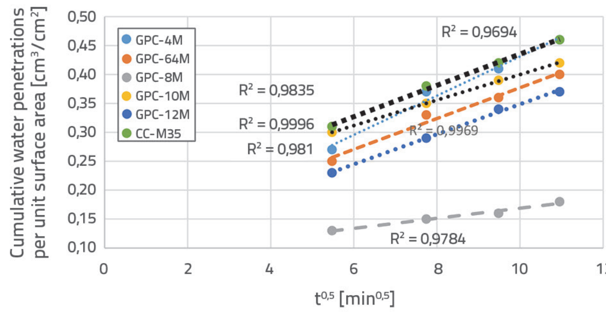

Figure 5. Cumulative water penetration vs square root of time of exposure

3.6. Abrasion resistance test

The ability of a material to resist wear or rubbing is referred to as the abrasion resistance of the concrete. In general, strong concrete is more resistant to abrasion than weak concrete. The square-tile shaped specimens prepared for this test were 25 mm thick with sides measuring 70.7 mm x 70.7 mm (5000 mm^2) in accordance with IS 1237:2012 [43]. This abrasion testing system consisted of a horizontally mounted smooth grinding disc with a diameter of 750 mm rotating at a speed of 30 rev/min. The specimens were first dried in an oven at 110 ± 5 °C for 24 h, and subsequently, the initial weight (W_1) of the specimens were measured after cooling down to ambient temperature. The specimen was then mounted on the holding device and a 300 N load was applied to the centre of the specimen, as shown in Figure 6. Fresh corundum powder with specific gravity of 3.9 and aluminium oxide content of at least 95 % by mass was employed as the abrasive agent. The rotation of the disc was stopped after every 22 revolutions to rotate the specimen 90° clockwise before proceeding with the test. Each specimen was tested over ten cycles as described above (each cycle involved 22 rotations followed by a 90° turn) with addition of a fresh dose of 20 g of the abrasive agent for each cycle. After application of total 220 revolutions to each specimen its final weight (W_2) was measured to calculate the percentage of weight loss. The average thickness loss can be obtained using Equation (1):

Table 7. Results of abrasion test

Mix identification	Initial weight [kg]	Final weight [kg]	Weight loss [%]	Average wear [mm]
GPC-4M	0.37	0.358	3.24	0.811
GPC-6M	0.377	0.371	1.51	0.398
GPC-8M	0.398	0.395	0.75	0.188
GPC-10M	0.396	0.392	1.01	0.253
GPC-12M	0.39	0.385	1.28	0.321
CC-M35	0.385	0.378	1.82	0.455

$$t = \frac{(W_1 - W_2)V}{W_1 \cdot A} \tag{1}$$

Where:

t - Average loss in thickness
W_1 - Initial weight of specimen
W_2 - Final weight of specimen
V - Initial volume of the specimen
A - Surface area of the specimen

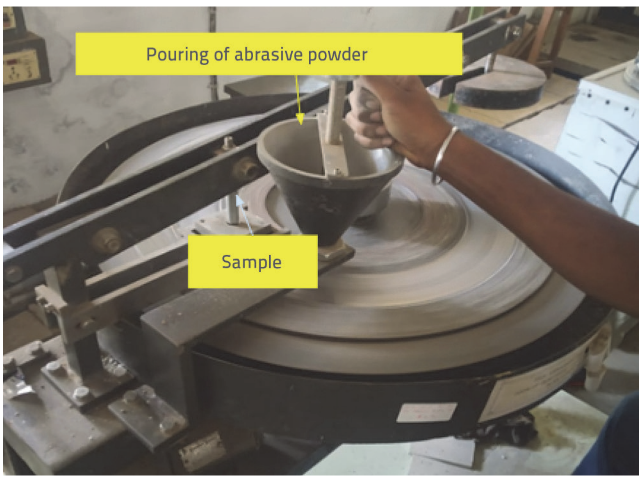

Figure 6. Abrasion test set up

The estimated initial and final weights, average thickness loss, and percentage of weight loss due to wear are listed in Table 7. For general-purpose floor tiles and heavy-duty floor tiles, the average wear should not be more than 3.5 and 2 mm, respectively. The test data revealed that the average wear rate for all concrete combinations was lower than the requirements prescribed in the Indian standards. The minimum percentage weight loss and loss of thickness due to wear were obtained in the GPC-8M mixture and the actual values are 0.75 % and 0.188 mm, respectively, which is lower than the corresponding values for OPC concrete. Overall, geopolymer concrete with sodium hydroxide concentrations of 6, 8, 10, and 12 exhibited lower wear than conventional concrete; whereas mixture with lower molarity viz., 4M, experienced more wear during the abrasion test. This demonstrates that there is a strong corelation between the geopolymer gel produced with higher molarities of NaOH and the aggregate matrix [31]. The mix with a lower sodium hydroxide content (GPC-4M) did not form strong bonds in the interfacial transition zone in contrast to other geopolymer mixes.

3.7. Resistance to acid attack

The ability of geopolymer concrete to withstand acids has been studied in the past by several researchers [44–47]. The concentration of the acidic solution and the immersion period affect the mass and strength of the geopolymer concrete. In this study, the capacity of fly ash and GGBS blended geopolymer concrete to endure sulphuric acid was tested by submerging oven-dried 100 mm cube samples for 120 days in a 3 % H_2SO_4 solution with a pH value of 0.1 after recording their initial weights. The solution was kept undisturbed and thoroughly stirred periodically to maintain its homogeneity. Besides, the acidic solution was changed every 30 days. On completion of the immersion period of 120 days, the samples were dried and their final weights were recorded. Changes in their appearance, mass, and compressive strength were examined in

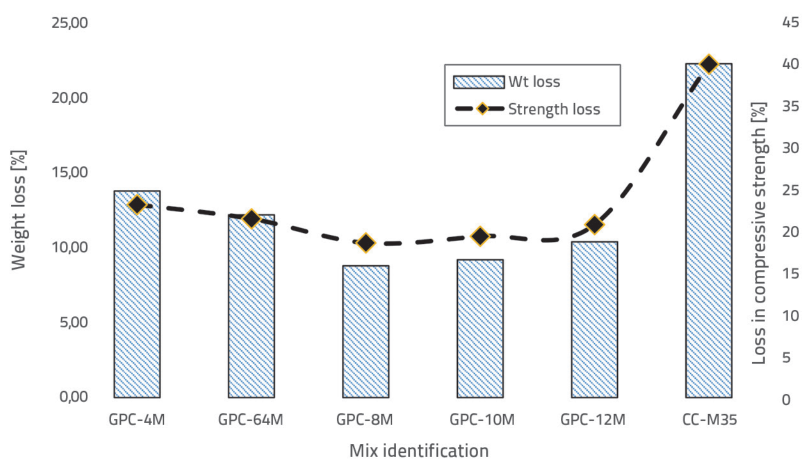

Figure 7. Loss in weight and strength of Geopolymer concrete after acid attack

Figure 8. Specimens after sulphuric acid immersion

all the geopolymer concrete specimens as well as in the control concrete specimens. Figure 7 shows the weight reduction percentage and compressive strength. A visual examination of OPC and Geopolymer concrete is shown in Figure 8.

The appearance of the geopolymer concrete specimens did not change significantly after exposure to the sulphuric acid solution. However, minor deterioration occurred and some parts of the samples were stained yellow which could be attributed to sulphur dioxide (SO_2) formation [47]. On the contrary, the conventional OPC concrete specimens were affected severely and their condition deteriorated possibly owing to the presence of high levels of calcium oxides, which ignited the reaction with sulphuric acid solution leading to the formation of calcium sulphate [47, 48]. Previous research concluded that acid attack on geopolymer concrete is a surface phenomenon [49], because deterioration begins at the surface and progresses to the interior of the concrete surface. The percentage of mass loss for geopolymer concrete with different NaOH molarities ranges was in the 8.8 to 13.8 % range, whereas the control concrete had a mass loss of 22.3 %. However, when immersed in 5 % H_2SO_4 solution for 180 days, the fly ash-based geopolymer concrete showed only 2.2 % mass reduction and 20 % strength reduction [12]. The GPC-8M mix had the lowest compressive strength loss of 18.6 %, whereas OPC concrete exhibited the highest strength reduction of 40.1 %. This significant reduction in strength of OPC concrete could be attributed to the formation of expansive gypsum and ettringite which leads to cracking and spalling of concrete [44]. Mallikarjuna et al. [9] reported that slag-based geopolymer concrete has a higher calcium content than that of fly ash-based geopolymer concrete. Consequently, the formation of calcium sulphate during sulphuric acid exposure causes internal voids, which may cause a reduction in the mass and strength of slag-based geopolymer concrete.

3.8. Resistance to sulphate attack

The resistance against sulphate attack of geopolymer concrete was evaluated with 3 % sodium sulphate solution at pH7. The initial weights of the oven-dried geopolymer and the conventional concrete specimens were recorded and then immersed in 3 % Na_2SO_4 solution. During the immersion period, the solution was stirred daily, and the solution was changed at the end of each month. On completion of immersion for 120 days, the specimens were removed and dried to calculate the weight change of the respective specimens. Their outward appearance, mass decrease, and loss of strength were observed. The visual appearances of the geopolymer and conventional concrete are shown in Figure 9. Visual inspection revealed that the geopolymer concrete specimens developed a white coating on the surface after drying; however, the OPC concrete immersed in sodium sulphate solution exhibited no symptoms of serious deterioration, but the corners were somewhat damaged. These results matched with the findings of other researchers in the past [5, 47]. Leached sodium hydroxide reacts with atmospheric carbon dioxide to produce a white coating of sodium carbonate, which causes white spots to appear on the surfaces of geopolymer concrete specimens [50]. The observed weight loss and strength loss following immersion in the sodium sulphate solution are shown in Figure 10. According to the experimental test results, the geopolymer concrete specimens exhibited negligible mass losses which ranged from 0.31 to 0.54 %, while the mass loss of conventional concrete was approximately 1.08 %. Hardjito et al. [51] discovered that when immersed in 5 % sodium sulphate solution, fly ash-based geopolymer concrete did not exhibit any significant reduction in either compressive strength or weight. The slight deterioration of OPC concrete can be attributed to the formation of gypsum which causes concrete expansion and spalling [52]. However, compared to conventional concrete, geopolymer concrete does not contain the same amount of calcium hydroxide in the concrete system to induce expansion [44]. This is the cause of the 20 % reduction in compressive strength of OPC concrete. The strength reduction of geopolymer concrete mixes, on the other hand, ranges from 10 % to 14 %. Bakharev et al. [53] evaluated the sulphate resistance of slag-based geopolymer concrete after 12 months of exposure to 5 % sodium sulphate solution. He reported that the strength of the OPC concrete was reduced by 25 %, while the strength of the slag-based geopolymer concrete was reduced by 17 %. The chemical resistance to sodium sulphate solution was higher in alkali-activated slag mortars, fly ash/slag mortars, and slag-activated concrete [54, 55]. Geopolymer concrete has the best sulphate resistance owing to the neutralised cross-links of the alumina-silicate polymer structure compared to the hydration structure of conventional OPC concrete.

Figure 9. Specimen after sodium sulphate immersion

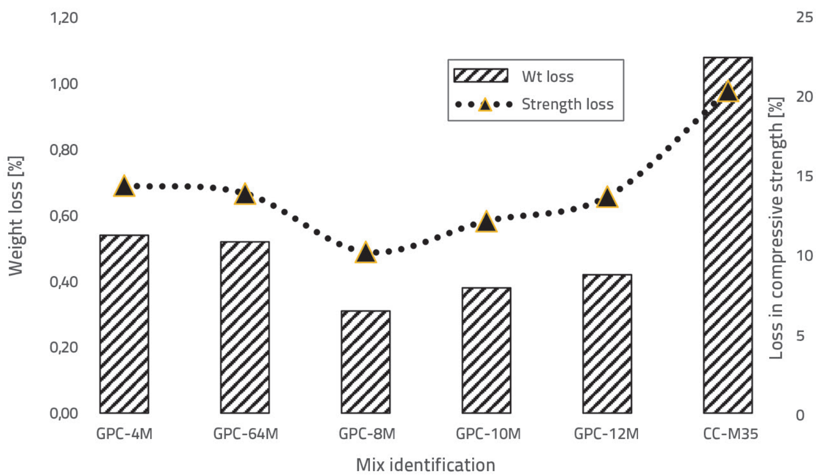

Figure 10. Loss in weight and strength of Geopolymer concrete after sulphate attack

4. Conclusion

The strength and durability of geopolymer concrete at molarities of 4M, 6M, 8M, 10M, and 12M, as well as conventional concrete, were evaluated. The following conclusions were drawn from the experimental test results.

- Based on the compressive strength results, GPC-8M concrete achieved an optimum strength of 57.53 MPa, which is 23.72 % higher than control concrete of M35 grade.
- An increase in the molarity of sodium hydroxide enhanced the splitting tensile strength of geopolymer concrete up to a sodium hydroxide molarity of eight, and a similar trend was observed in the flexural strength.
- The results of the destructive tests were compared with the results of the non-destructive tests (Rebound Hammer). The NDT results for both the geopolymer and the conventional concrete were inferior to the destructive test results.
- The geopolymer concrete mixes of GPC-6M, GPC-8M, GPC-10M, and GPC-12M have lower saturated and initial water absorption values than the control concrete.
- According to the Concrete Society, 1989, all geopolymer concrete mixes, with the exception of GPC-4M, are rated as good quality because the initial water absorption percentage at 30 min is less than 3 %.
- Apart from the GPC-4M mix, the other geopolymer concrete mixtures had a lower average effective porosity than the OPC concrete which could be attributed to the differences in the microstructure.
- Conventional cement concrete had a sorptivity of 2.71 x 10^{-2} cm/min$^{0.5}$. In contrast, the lowest value of 1.52 x 10^{-2} cm/min$^{0.5}$ was predicted in the geopolymer concrete mix of GPC-8M.
- The GPC-8M specimen exhibited excellent resistance against wear. This led to average loss in thickness of 0.188 mm, which is 58.68 % less than control concrete. Hence, this mix is recommended for use to produce concrete floor tiles as per IS 1237:2012.
- Geopolymer concrete based on fly ash and GGBS has excellent resistance to acid and sulphate attack.
- When immersed in 3 % sulphuric acid solution for 120 days, the geopolymer specimens lost 8–14 % of their weight and 18–23 % of their strength, whereas conventional concrete lost 22 % and 40 % of its weight and strength, respectively.
- When exposed to 3 % sodium sulphate solution for 120 days, both Geopolymer and OPC concrete suffered less than 2 % weight loss. However, the extent of strength reduction was 10–14 % and 20 % for geopolymer and conventional concrete, respectively.
- The study found that fly ash and GGBS-combined geopolymer concrete with sodium hydroxide concentrations of 6, 8, 10, and 12 had outstanding mechanical and durability qualities. Furthermore, using industrial by-products, geopolymer concrete can be utilised as a supplement to OPC concrete to reduce CO_2 emissions.

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