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Behavior and Correlations between different Mechanical Properties of Fly Ash-based Geopolymer Concrete

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Abstract Undoubtedly, the interest in using Geopolymer Concrete (GPC) recently speared. Hence, it's essential to study the behavior of GPC. In the current research, the mechanical properties of GPC were studied to investigate the performance at the time interval of 28 days to 90 days. The study extended to include water absorption, water permeability, and sulfate attack tests. The experimental work program was conducted to cover the effect of the curing method (steamer with 60°C or warm air) in addition to the curing period (seven days or three days). Also, the bond strength was investigated between steel reinforcement bars and concrete. Furthermore, the GPC ingredients were captured internally using a scanning electron microscope (SEM) to analyze their integrity. The results showed that the recorded slump value of the GPC mixture was more than the conventional concrete (CC) mixture by 130%, afterward the GPC mixture became stickier, and hardening happened. The GPC mixtures achieved significant enhancement, and the strength was highly developed after 28 days more than CC, especially for GPC cured in a steamer at 60°C for seven days, which reached the limits of high-strength Geopolymer Concrete (HSGPC) after 90 days.

Keywords: Fresh Properties, Mechanical Properties, High Strength Geopolymer Concrete, Fly Ash (Class F), Sulfate Attack, Durability, SEM.

1 Introduction

Portland cement (PC) is the preferred binder for conventional concrete (CC) that provides the desired mechanical properties and is the essential primary cementitious material. Whereas, one factor of climate change is the production of PC which lead to the emission of approximately 8% of global CO_2. According to **[1]**, the production amount of the PC produces approximately the same amount of CO_2 in the atmosphere field. As a result, developing environmentally sustainable alternative cementitious material is crucial. In this regard, Geopolymer holds much promise for use as an alternative to PC in the concrete industry. Concerning global warning, Geopolymer Concrete (GPC) has the benefit of significantly reducing CO_2 emissions in the atmosphere and was first coined by **[2]**.

Geopolymer is an alternative cementitious material formed through the chemical reaction of silica and alumina-rich industrial waste products such as Fly Ash (FA), metakaolin (MK), palm oil fuel ash (POFA), ground granulated blast furnace slags (GGBFS), or rice husk ash (RHA) with alkaline solutions such as alkali hydroxide solutions (sodium hydroxide, potassium hydroxide), soluble silicates (potassium and sodium silicate), at room temperature or high temperatures. In general, Al_2O_3 and SiO_2 minerals are dissolved in highly alkaline solutions to form Geopolymer binders. The geopolymerization process involves transporting and orienting the dissolved oxides, followed by coagulation to form gel and poly-condensation to form a three-dimensional network of silico-aluminate structures. Alumino-silicate oxides (Si_2O_5, Al_2O_2) and alkali poly-silicates interact chemically to form polymeric Si-O-Al linkages during geopolymerization. Hence, the formed GPC mixture is denser. In general, the GPC is eco-friendly, low energy consumption, and cementless with superior properties suitable for precast concrete.

Using low calcium FA and GGBFS to produce high-strength Geopolymer concrete (HSGPC) with ambient curing was studied by **[3]**. The authors investigate experimentally the factors affecting the properties of HSGPC, as well as studying the fresh and hardened properties of produced concrete. While, the effect of GGBFS (which varied in content from 0% to 40% of the total cementitious material), alkaline liquid (sodium silicate to sodium hydroxide ratio 2.5), water-cementitious material ratio (30%, 35%, and 40%), and molarity of

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NaOH (14M and 16M) were also studied on the workability and strength of GPC by the authors. The results showed increases in strength were observed in GPC mixture with a higher GGBFS ratio and if the FA was replaced by 40% of GGBFS the compressive strength reached 77 MPa. FA is available widely across the globe and capable of producing a new generation of green concrete that may be used to produce a thorough understanding of the prospective uses of environmentally friendly structures **[4]**. Also, **[5]** provided an elaborative discussion of the durability properties of the GPC mixture and explained the progress and perspective results for the literature review. While, **[6]** studied how the FA's properties, composition, and mix proportions affected the bonding strength between GPC and steel reinforcement bars. Five dissimilar sources of FA were used to produce GPC with varying FA contents (300, 400, and 500 kg/m^3). Alkaline activators in various ratios were also used. The distribution of particle sizes and the concentrations of SiO_2, Al_2O_3, and CaO in the FA significantly affect the bond strength of the GPC, and the bond strength increased with increasing FA content.

Therefore, **[7]** investigated the formulation of FA (Class F) with varying parameters, ratios, and compositions for oil well cementing applications. 12M molarity of NaOH, FA to alkali binder ratio of 60:30, Na_2SiO_3 to NaOH ratio of 0.5, the total water content of 10% of the total slurry mass, and 10 ml of dispersant is the optimum composition for oil well cementing applications. That further suggests FA (Class F) is a better replacement for the PC for oil well cementing applications at high pressure and temperature conditions.

A trial-and-error process for GPC mix design was adopted to study the effect of changes in various parameters **[8]**. The results recommended that compressive strength was significantly increased in the case of alkaline liquid to FA ratio of 0.35, sodium silicate to sodium hydroxide ratio of 2.5, sodium concentration of 16M, the addition of superplasticizer with 3% of FA, and heat cured in an oven for 48hrs at 60ºC. According to **[9],** manufacturing GPC with silicates to aluminate ratios between 1.5 and 2.0 provides a significant improvement in the compressive strength of the studied mixes. Therefore, by increasing the elevated temperature between 80°C and 90°C, the geopolymerization process was catalyzed, then the compressive strength improved. Furthermore, temperature and curing period are crucial to the successful curing of the GPC. Wherefore, higher temperatures and longer curing times encourage the production of the N-A-S-H gel, which in turn causes the Geopolymer to harden and acquire strength.

The impact of sulfate attack on the compressive strength of the GPC mixture was assessed by **[10]**. The cubic samples of the cured in a steamer at an elevated temperature of 60°C for three days GPC mixture were submerged in a 10% magnesium sulfate solution for 90 days. The experimental results for the compressive strength of the GPC mixture reflect the GPC mixture's noteworthy efficacy in resisting sulfate attack up to 90 days. Otherwise, **[11]** reported that the immersed GPC in sulfuric acid within 12 weeks almost lost its alkalinity and weight loss in the range from 0.81% to 1.64%. Therefore, the compressive strength decreased by 44% to 71%. The effect of using steel fiber for GPC was investigated. As the indirect tensile strength performance of fibrous GPC was studied by **[12]**. The relevant results showed significant enhancement in the performance of GPC by increasing the FA content in the mixture, and the indirect tensile strength increased. In the end, the percentage of 1% steel fiber content achieved the highest performance in comparison to 2% steel fiber content. Also, **[13]** discovered that steel fibre led to low water absorption, significant resistance to alternate wetting and drying cycles, in addition to abrasion resistance. From the economic view, **[14]** verified the cost of the GPC, and the results relevant that the cost of GPC at the bulk level was reduced by 40% of the CC.

The researchers are still working on designing a GPC mixture with well-known specific properties from the beginning. Further, the results and recommendations of the previous literature differ due to the influencing factors of the studied parameters. Also, the previous studies lacked in; covering the short-term durability of GPC in the interval period of 28 days to 90 days; evident correlations between different mechanical properties; keeping the coarse and fine aggregate contents constant for the studied mixtures (CC and GPC).

To this ends, the main objective of the research is to investigate the fresh and mechanical properties of the GPC based on abundantly available FA (Class F), in addition to conducting durability tests for a certain period up to 90 days. To achieve this study, one CC and three GPC mixtures were cast to cover the studied parameters. The studied parameter, such as the effect of using a steamer with 60ºC as a GPC mixture curing enhancer for seven or three days was investigated and compared relevant results with the case of curing in warm air and CC mixture. In detail, the experimental work program included the studying of fresh properties (slump test), and mechanical properties (compressive strength, indirect tensile strength, flexural strength, and bond strength), in addition to water absorption, water permeability, and sulfate attack to verify the durability of the GPC. Ultimately, the correlations between compressive strength and the other mechanical properties were investigated. It is worth mentioning that, microstructures of the GPC were captured to verify the internal integrity of the GPC.

2 Experimental Work Program

Four concrete mixes were cast (CC mix and three GPC mixtures), and the ingredients materials of concrete mixtures, such as. PC, CEM-I/42.5 N was tested according to **[15]**. Therefore, crushed stone and siliceous sand were tested according to **[16]**. The test results for used materials are summarized in **Tables 1 to 4**. On the other hand, the CC mix was designed and produced according to the procedure outlined in **[17]**. The GPC mixture was produced by mixing FA (Class F, comply with **[18],** see **Table 5** for chemical composition determined by X-Ray diffraction analysis - XRD), coarse aggregate, fine aggregate, sodium silicate solution (SiO_2=29.4%, Na_2O=14.7%, and water=55.9%), and sodium hydroxide solution (Molarity:12, 480-grams sodium hydroxide 98-99% purity to 1000 ml water).

The GPC mixture was cast and cured by two methods (a steamer with 60°C or warm air), the curing period (seven days or three days), and other parameters were kept constants for all concrete mixtures (coarse and fine aggregate, and w/c). The cured in a warm air GPC mixture (cast in summer weather) was subjected to daily temperature measurement by a digital temperature gauge, and the recorded temperature around samples ranged from (32°C to 42°C). **Table 6** shows the proportions of concrete ingredients for CC and GPC mixtures.

The mechanical properties of the concrete mixtures were conducted after 28, 56, and 90 days by testing cubes for compressive strength, cylinders for indirect tensile strength and bond strength (after embedding steel reinforcement bars), and prisms for flexural strength. However, cubes were tested for water absorption, water permeability, and sulfate resistance tests after 28, 56, and 90 days. The dimensions of cubic molds are 100×100×100mm, cylindrical molds are 100×200mm, and prismatic molds are 100×100×500mm. The pull-out test (bond strength) samples were prepared by embedding a steel bar with a 12mm diameter inside the cylindrical molds with dimensions of 150×300mm filled with concrete. It is worth mentioning that for each test, three samples were tested each time (28, 56, and 90 days).

Table 1 Physical and Mechanical Properties of the Used Cement

Property	Result	Acceptable Limit [15]
Cement Fineness by Blaine Test Specific Surface Area (cm^2/gm)	3753	-
Initial Setting Time (minutes)	180	not less than 60minutes
Final Setting Time (minutes)	220	-
Cement Soundness (Le Chatelier) in (mm)	4	not more than 10mm
Compressive Strength 2 Days (MPa)	28.9	not less than 10.0MPa
Compressive Strength 28 Days (MPa)	58.8	not less than 42.5MPa and not more than 62.5MPa

Table 2 Chemical Analysis of Portland Cement - CEM-I/42.5 N

Oxide	(%) by Mass
Silicon dioxide (SiO_2)	22
Aluminum oxide (Al_2O_3)	5.4
Ferric oxide (Fe_2O_3)	3.2
Calcium oxide (CaO)	60
Phosphorus pent oxide (P_2O_5)	-
Sulphur trioxide (SO_3)	3.03
Potassium oxide (K_2O)	0.16
Titanium dioxide (TiO_2)	-
Sodium oxide (Na_2O)	0.45
Magnesium oxide (MgO)	-

Table 3 Physical and Mechanical Properties of the Used Crushed Stone

Property	Result	Acceptable Limit [16]
Specific Gravity	2.75	-
Unit Weight (t/m^3)	1.72	-
Materials Passing No. 200 Sieve (%)	1.55	Less than 3%
Absorption (%)	1.66	Less than 2.5%
Abrasion (Los Anglos) (%)	12.94	Less than 30%
Crushing Factor (%)	15.82	Less than 30%
Impact (%)	16.93	Less than 45%
Maximum Aggregate Size (mm)	10	-

Table 4 Physical Properties of the Used Sand

Property	Result	Acceptable Limit [16]
Specific Gravity	2.77	-
Unit Weight (t/m^3)	1.77	-
Materials Finer than No. 200 Sieve (%)	1.85	Less than 3%
Absorption (%)	1.25	Less than 2%
Zone	1	-

Table 5 Chemical composition of Fly Ash as determined by XRD

Oxide	(%) by Mass	Acceptable Limit [18]
Silicon dioxide (SiO_2)	60.28	-
Aluminum oxide (Al_2O_3)	28.59	-
Ferric oxide (Fe_2O_3)	4.99	-
Total SiO_2 + Al_2O_3 + Fe_2O_3	93.86	70% min
Calcium oxide (CaO)	1.19	No specified
Phosphorus pent oxide (P_2O_5)	0.52	No specified
Sulphur trioxide (SO_3)	0.06	5.0% max
Potassium oxide (K_2O)	1.09	No specified
Titanium dioxide (TiO_2)	2.42	No specified
Sodium oxide (Na_2O)	0.01	1.50% max
Magnesium oxide (MgO)	0.27	No specified
Loss on Ignition (LOI%)	0.58	6.0% max

Table 6 The Ingredients of Concrete Proportions for the Studied Concrete Mixtures

Mixture	Coarse Aggregate (Kg/m³)	Fine Aggregate (Kg/m³)	Cementitious Material (Kg/m³)		Water Content (Kg/m³)	Sodium Hydroxide NaOH (Kg/m³)	Sodium Silicate Na_2SiO_3 (Kg/m³)	Remarks
			Cement	Fly Ash				
CC	1200	600	400	-	180	-	-	Cured in Water Tank (25ºC)
GPC-S7	1200	600	-	400	-	51.4	128.5	Cured for Seven Days in a Steamer (60ºC)
GPC-S3	1200	600	-	400	-	51.4	128.5	Cured for Three Days in a Steamer (60ºC)
GPC-A	1200	600	-	400	-	51.4	128.5	Cured in Warm Air (32ºC-42ºC)

3 Results, Analysis, and Discussion

3.1 Fresh Properties of Concrete Mixtures

Immediately, after concrete mixing, a slump test was performed to estimate the consistency of fresh CC and GPC mixtures. Often, the average time for proceeding slump test is almost 150 seconds. Although the GPC mixture is usually more cohesive and stickier than the CC mixture due to the addition of sodium silicate and sodium hydroxide solutions (both of which have a viscosity greater than water) but the CC and GPC mixtures recorded slump values of 100 mm and 230 mm, respectively. In general, the higher slump of the GPC mixture suggests that the concrete mixture is less sticky and more workable. The recorded slump value for the GPC mixture was valid for a brief time then the GPC mixture became more cohesive than the CC mixture after the hardening. Aside from that, the concrete mixtures showed no signs of segregation or bleeding during the mixing, compaction, and finishing. The consistency of the concrete mixtures of CC and GPC, in terms of the slump value, is shown in **Fig. 1**.

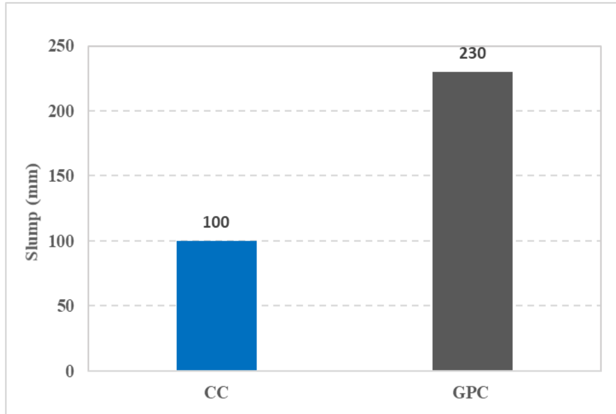

Fig. 1 Slump values for CC and GPC Concrete Mixtures

3.2 Mechanical Properties of Concrete Mixtures

Testing of the concrete samples was carried out according to **[19]**. It appeared that changes in the curing method and period significantly affect the mechanical properties of GPC mixtures. The following **Table 7** shows the test results for compressive, indirect tensile, flexural, and bond strengths after correcting the calculated values according to the standard dimensions of concrete samples **[19]** and **[20]**. It was relevant that the GPC-S7 mixture achieved high-performance hardened properties compared with the other mixtures of all ages. That confirms the proper method of curing by using a steamer with 60ºC for seven days which almost achieved the HSGPC limits of compressive strength after 90 days (57.9MPa).

Table 7 Compressive Strength, Indirect Tensile Strength, Flexural Strength, and Bond Strength

Mixture	Compressive Strength (MPa)			Indirect Tensile Strength (MPa)			Flexural Strength (MPa)			Bond Strength (MPa)		
	28 Days	56 Days	90 Days	28 Days	56 Days	90 Days	28 Days	56 Days	90 Days	28 Days	56 Days	90 Days
CC	42.5	45.0	50.5	2.4	2.9	3.5	7.8	8.2	9.7	5.2	5.7	6.5
GPC-S7	43.6	47.8	57.9	2.8	3.3	3.8	8.5	9.6	10.8	5.5	6.2	7.0
GPC-S3	38.2	43.8	51.0	2.1	2.6	3.0	6.8	7.6	8.8	4.8	5.2	5.7
GPC-A	36.5	40.5	45.5	1.8	2.2	2.6	5.5	6.3	7.7	4.3	4.7	5.0

As shown in **Table 7** and **Fig. 2**, compressive strength continuously develops at different testing times (from 28 days to 90 days) for all concrete mixtures. After 28 days, the lowest and highest compressive strength appeared in the GPC-A mixture and the GPC-S7 mixture with values of 36.5 MPa, and 43.6 MPa, respectively. The compressive strength of the CC mixture increased by 5.88% and 18.82% after 56 days and 90 days, respectively compared with 28 days' compressive strength. Also, the compressive strength increased by 12.22% after 90 days compared with the compressive strength of 56 days' age. On the other hand, the compressive strength results of the GPC-S7 mixture evidence an increase. At the testing time of 56 days, the compressive strength increased by 9.63% and increased by 32.79% at 90 days compared with compressive strength after 28 days and increased by 21.13% after 90 days in comparison to the compressive strength of 56 days' age. For the GPC-S3 mixture, it seems at the testing time of 56 days, the compressive strength increased by 14.66% compared with the compressive strength after 28 days. Therefore, the compressive strength after 90 days increased by 33.50% compared with the compressive strength after 28 days. Also, the compressive strength increased by 16.44% after 90 days compared with the compressive strength at 56 days' age. However, the relevant results of the compressive strength for the GPC-A mixture increased by 10.96% and 24.66% after 56 and 90 days, respectively in comparison to the compressive strength after 28 days. An increase in compressive strength was gained by 12.34% after 90 days in comparison to the compressive strength after 56 days.

The compressive strength of the GPC-S7 mixture after 28 days was more than CC, GPC-S3, and GPC-A mixtures by 2.59%, 14.14%, and 19.45%, respectively but after 56 days increased by 6.22%, 9.13%, and 18.02% in comparison to CC, GPC-S3, and GPC-A mixtures, respectively. After 90 days, the compressive strength for the GPC-S7 mixture increased by 14.65%, 13.53%, and 27.25% in comparison to CC, GPC-S3, and GPC-A mixtures, respectively. The rate of compressive strength development increased in GPC mixtures in comparison to the CC mixture even though it's cured in warm air. Whilst, the increasing rate was recorded as 18.82%, 32.79%, 33.50%, and 24.66% for CC, GPC-S7, GPC-S3, and GPC-A mixtures, respectively according to the time interval from 28 days to 90 days.

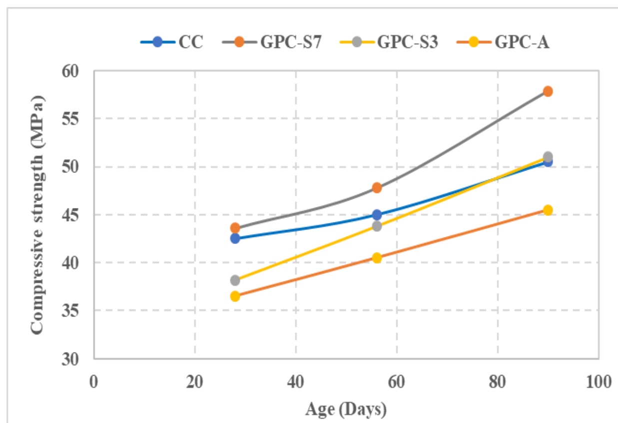

Fig. 2 Compressive Strength for CC and GPC Concrete Mixtures

It was noted from **Table 7** and **Fig. 3** that the minimum and maximum indirect tensile strength was found at 28 days in the GPC-A mixture with a value of 1.8 MPa and in the GPC-S7 mixture with a value of 2.8 MPa. The indirect tensile strength of the CC mixture increased by 20.83% and 45.83% after 56 days and 90 days, respectively compared with the indirect tensile strength after 28 days. Also, the indirect tensile strength increased by 20.69% after 90 days compared with the indirect tensile strength after 56 days. The GPC-S7 mixture has a significant evident increase. At the testing time of 56 days, the indirect tensile strength increased by 17.86% and increased by 35.71% after 90 days compared with the indirect tensile strength after 28 days. Also, the indirect tensile strength increased by 15.15% after 90 days compared with the indirect tensile strength after 56 days. For the GPC-S3 mixture, the indirect tensile strength increased by 23.81% after 56 days and increased by

42.86% after 90 days compared with 28 days' indirect tensile strength and with an increase of 15.38% after 90 days compared with the indirect tensile strength of 56 days. However, the indirect tensile strength of the GPC-A mixture increased by 22.22% and 44.44% after 56 and 90 days, respectively compared with 28 days' indirect tensile strength and with an increase of 18.18% after 90 days compared with the indirect tensile strength of 56 days' age. The rate of indirect tensile strength development increased in GPC mixtures in comparison to the CC mixture even though it is cured in warm air.

After 28 days, the indirect tensile strength of the GPC-S7 mixture was more than CC, GPC-S3, and GPC-A mixtures by 16.67%, 33.33%, and 55.55%, respectively but after 56 days increased by 13.79%, 26.92%, and 50.00% in comparison to CC, GPC-S3, and GPC-A mixtures, respectively. After 90 days, the indirect tensile strength for the GPC-S7 mixture increased by 8.57%, 26.67%, and 46.15% in comparison to CC, GPC-S3, and GPC-A mixtures, respectively. Whilst, the increasing development in indirect tensile strength rate was recorded as 45.83%, 35.71%, 42.86%, and 44.44% for CC, GPC-S7, GPC-S3, and GPC-A mixtures, respectively according to the time interval from 28 days to 90 days.

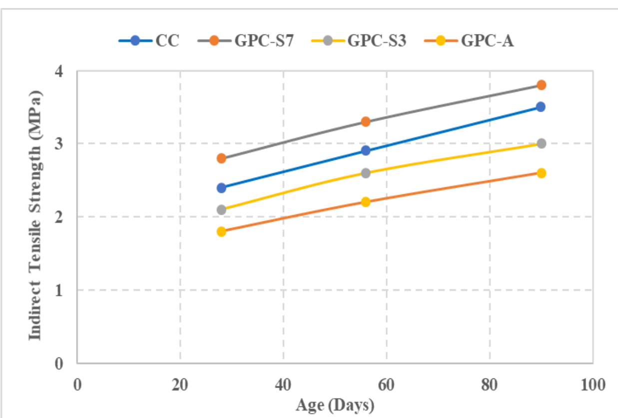

Fig. 3 Indirect Tensile Strength for CC and GPC Concrete Mixtures

It was observed from **Table 7** and **Fig. 4** that the minimum flexural strength was recorded at 28 days' age in the GPC-A mixture with a value of 5.5 MPa, and the maximum flexural strength was observed in the GPC-S7 mixture with a value of 8.5 MPa. For the CC mixture, the flexural strength increased by 5.13% after 56 days and increased by 24.36% after 90 days compared with 28 days' flexural tensile strength and an increase of 18.29% after 90 days compared with the flexural strength after 56 days. whereas, the flexural strength of the GPC-S7 mixture increased by 12.94% and 27.06% in comparison to 28 days' flexural strength after 56 days and 90 days, respectively, and with an increase of 12.50% after 90 days compared with the flexural strength of 56 days. The flexural strength of the GPC-S3 mixture increased by 11.76% after 56 days and increased by 29.41% after 90 days compared with flexural strength after 28 days. Moreover, the flexural strength increased by 15.78% after 90 days compared with the flexural strength after 56 days. Furthermore, for the GPC-A mixture, the flexural strength increased by 14.55% after 56 days and increased by 40.00% after 90 days compared with flexural strength after 28 days. Also, the flexural strength increased by 22.22% after 90 days compared with flexural strength after 56 days.

After 28 days, the flexural strength of the GPC-S7 mixture was more than CC, GPC-S3, and GPC-A mixtures by 8.97%, 25.00%, and 54.54%, respectively but after 56 days increased by 17.07%, 26.32%, and 52.38% in comparison to CC, GPC-S3, and GPC-A mixtures, respectively. Therefore, after 90 days, the flexural strength for the GPC-S7 mixture increased by 11.34%, 22.73%, and 40.26% compared with CC, GPC-S3, and GPC-A mixtures, respectively. Whilst, the increasing rate of flexural strength was recorded as 24.36%, 27.06%, 29.41%, and 40.00% for CC, GPC-S7, GPC-S3, and GPC-A mixtures, respectively, according to the time interval from 28 days to 90 days.

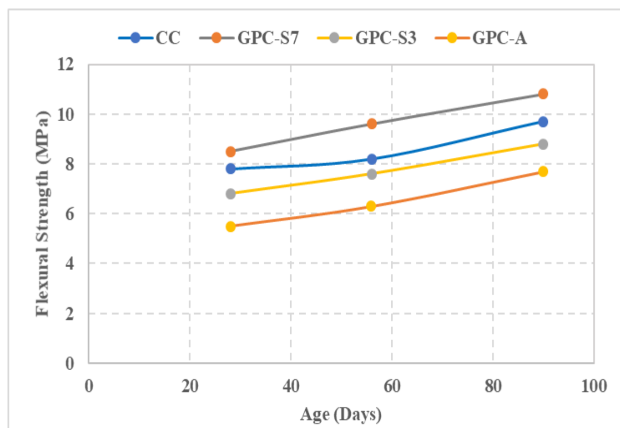

Fig. 4 Flexural Strength for CC and GPC Concrete Mixtures

Table 7 and **Fig. 5** represent the minimum and maximum bond strength values after 28 days in the GPC-A mixture with a value of 4.3 MPa and in the GPC-S7 mixture with a value of 5.5 MPa. While, the bond strength of the CC mixture increased by 9.61% and 25.00% after 56 days and 90 days, respectively compared with 28 days' bond strength and with an increase of 14.03% after 90 days compared with a bond strength of 56 days' age. For the GPC-S7 mixture, the bond strength increased by 12.73% after 56 days and increased by 27.27% after 90 days in comparison to bond strength after 28 days and with an increase of 12.90% after 90 days compared with a bond strength of 56 days' age. However, the bond strength of the GPC-S3 mixture increased by 8.33% after 56 days and increased by 18.75% after 90 days compared with 28 days' bond strength and with an increase of 9.62% after 90 days in comparison to bond strength after 56 days' age. Furthermore, the bond strength of the GPC-A mixture increased by 9.30% and 16.28% after 56 days and 90 days, respectively compared with 28 days' bond strength. Also, the bond strength increased by 6.38% after 90 days compared with bond strength after 56 days.

At 28 days' age, the bond strength of the GPC-S7 mixture was more than CC, GPC-S3, and GPC-A mixtures by 5.77%, 14.58%, and 27.91%, respectively, and after 56 days increased by 8.77%, 19.23%, and 31.91% in comparison to CC, GPC-S3, and GPC-A mixtures, respectively. After 90 days, the bond strength for the GPC-S7 mixture increased by 7.69%, 22.81%, and 40.00% compared with CC, GPC-S3, and GPC-A mixtures, respectively. Whilst, the increasing rate of bond strength was recorded as 25.00%, 27.27%, 18.75%, and 16.28% for CC, GPC-S7, GPC-S3, and GPC-A mixtures, respectively, according to the time interval from 28 days to 90 days.

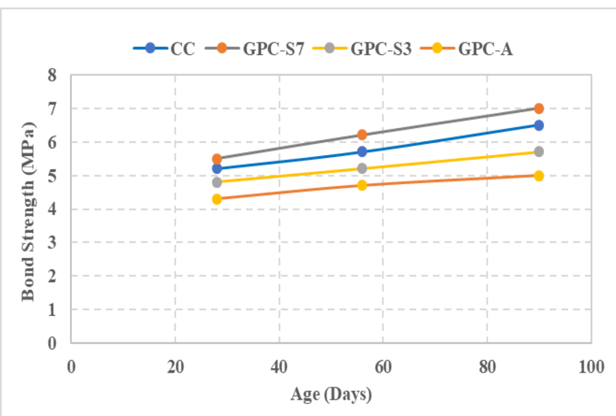

Fig. 5 Bond Strength for CC and GPC Concrete Mixtures

4 Durability Properties

4.1 Water Absorption and Water Permeability of the Concrete Mixtures

The durability tests of the studied concrete, such as water absorption, water permeability, and sulfate resistance were conducted after 28, 56, and 90 days according to **[19]**. As mentioned before, the changes in the curing method and period affect the strength of GPC mixtures, which was confirmed here by durability testing indicators. The following **Table 8** shows the test results for water absorption and permeability.

Table 8 Water Absorption and Water Permeability of the Tested Concrete Mixtures

Mixture	Water Absorption (%)			Water Permeability (mm)		
	28 Days	56 Days	90 Days	28 Days	56 Days	90 Days
CC	7.6	7.3	6.4	0.18	0.15	0.11
GPC-S7	7.5	7.2	6.1	0.16	0.13	0.09
GPC-S3	7.8	7.5	6.7	0.23	0.18	0.15
GPC-A	8.2	7.7	7.2	0.25	0.20	0.17

Table 8 and **Fig. 6** show that the minimum and maximum water absorption percentages appeared in the GPC-S7 mixture with a percentage of 7.5% and in the GPC-A mixture with a percentage of 8.2%, respectively. It was observed that the water absorption of all tested mixtures decreased at different testing times. For the CC mixture, the percentage of water absorption after 56 days decreased by 3.95% compared with the water absorption percentage after 28 days. Moreover, the percentage after 90 days decreased by 15.79% compared with the water absorption percentage of 28 days. Also, the water absorption percentage after 90 days decreased by 12.33% compared with the percentage after 56 days. The water absorption for the GPC-S7 mixture decreased by 4.00% and 18.67% after 56 and 90 days compared with the water absorption percentage after 28 days. Also, the water absorption percentage after 90 days decreased by 15.27% compared with the percentage after 56 days. For the GPC-S3 mixture, the water absorption decreased by 3.85% and 14.10% in comparison to 28 days' water absorption percentage after 56 and 90 days, respectively. Also, the water absorption percentage after 90 days decreased by 10.67% in comparison to 56 days' water absorption percentage. The water absorption of the GPC-A mixture decreased by 6.09% after 56 days and decreased by 12.19% after 90 days compared with 28 days' water absorption, respectively. The percentage of water absorption after 90 days decreased by 6.49% compared with the percentage after 56 days.

After 28 days, the water absorption of the GPC-S7 mixture was less than CC, GPC-S3, and GPC-A mixtures by 1.32%, 3.85%, and 8.54%, respectively, but after 56 days decreased by 1.37%, 4.00%, and 6.49% in comparison to CC, GPC-S3, and GPC-A mixtures, respectively. After 90 days, the water absorption for the GPC-S7 mixture decreased by 4.69%, 8.96%, and 15.28% compared with CC, GPC-S3, and GPC-A mixtures, respectively. However, the decreasing rate of water absorption was recorded as 15.79%, 18.67%, 14.10%, and 12.19% for CC, GPC-S7, GPC-S3, and GPC-A mixtures, respectively, according to the time interval from 28 days to 90 days.

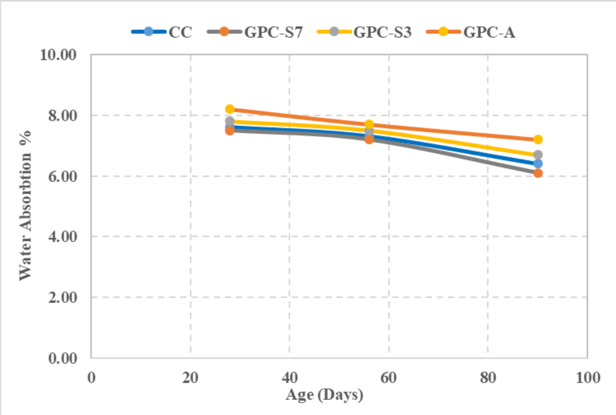

Fig. 6 Water Absorption for CC and GPC Mixtures

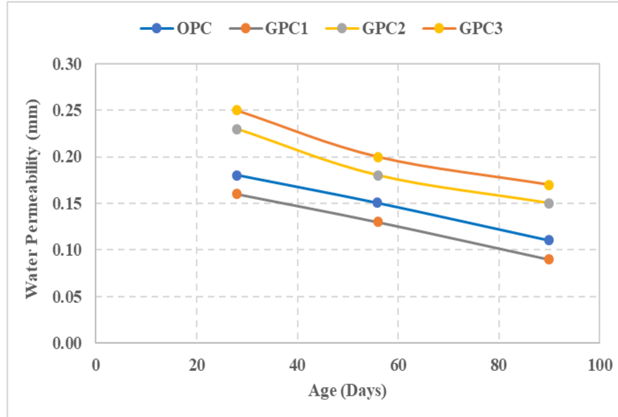

Fig. 7 Water Permeability for CC and GPC Mixtures

Table 8 and **Fig. 7** show that minimum water permeability occurs after 28 days in the GPC-S7 mixture and is equal to 0.16 mm, but the maximum value of water permeability occurs in the GPC-A mixture is equal to 0.25 mm. The water permeability of the CC mixture decreases by 16.67% and 38.89% after 56 and 90 days, respectively compared with water permeability after 28 days. After 90 days, the water permeability decreased by 26.67% in comparison to 56 days' water permeability. For the GPC-S7 mixture, the water permeability after 56 days decreased by 18.75% compared with the water permeability after 28 days. Also, the water permeability after 90 days decreased by 43.75% compared with 28 days' water permeability. Further, the water permeability after 90 days decreased by 30.77% compared with the water permeability after 56 days. In the case of the GPC-S3 mixture, the water permeability decreased by 21.74% and 34.78% after 56 and 90 days, respectively compared with 28 days' water permeability. Also, the water permeability decreased by 16.67% after 90 days compared with 56 days' water permeability. The water permeability of the GPC-A mixture decreased by 20.00% compared with the water permeability of 28 days, and the value after 90 days decreased by 32.00% compared with the water permeability after 28 days. Also, the water absorption after 90 days decreased by 15.00% compared with 56 days' water permeability.

After 28 days, the water permeability of the GPC-S7 mixture was less than CC, GPC-S3, and GPC-A mixtures by 11.11%, 30.43%, and 36.00%, respectively, and after 56 days decreased by 13.33%, 27.78%, and 35.00% in comparison to CC, GPC-S3, and GPC-A mixtures, respectively. After 90 days, the water permeability for the GPC-S7 mixture decreased by 18.18%, 40.00%, and 47.06% compared with CC, GPC-S3, and GPC-A mixtures, respectively. While, the decreasing rate of water permeability was recorded as 38.89%, 43.75%, 34.78%, and 32.00% for CC, GPC-S7, GPC-S3, and GPC-A mixtures, respectively, according to the time interval from 28 days to 90 days.

4.2 Compressive Strength and Unit Weight Loss after Sulfate Attack Effect for Concrete Mixtures

Cubic samples were soaked in high-dose magnesium sulfate solution (10% concentration) to study the effect of sulfate attack on the concrete mixtures after 28 days from casting. The soaked cubic samples were tested under the effect of axial compression load after 28, 56, and 90 days. **Table 9** shows the observed compressive strengths of the studied concrete samples after soaking in a magnesium sulfate solution. It was relevant that the exposure period of up to 90 days does not represent any considerable negative effect on the compressive strength of GPC mixtures. Further, the compressive strength of the GPC mixtures increased over time for the cubic samples immersed in the sulfate solution (10% concentration).

Table 9 Compressive Strength of Studied Mixtures after Exposure to Sulfate Attack

Testing Time	CC		GPC-S7		GPC-S3		GPC-A	
	without Sulfate Attack	with Sulfate Attack	without Sulfate Attack	with Sulfate Attack	without Sulfate Attack	with Sulfate Attack	without Sulfate Attack	with Sulfate Attack
28 Days (MPa)	42.5	42.7	43.6	43.9	38.2	38.5	36.5	36.7
56 Days (MPa)	45.0	48.0	47.8	50.0	43.8	45.0	40.5	43.0
90 Days (MPa)	50.5	49.0	57.9	59.0	51.0	53.0	45.5	47.0

The compressive strength of the CC mixture increased by 12.41% after 56 days of immersion, and a steady decline occurred, but GPC mixtures continued with the increase. Whereas, after 90 days of immersion, the compressive strength lost up to 2.97% for the CC mixture compared with the CC mixture without the effect of sulfate attack. While the CC mixture lost compressive strength, the GPC mixtures gained strength in the magnesium sulfate solution. After 90 days of immersion, the compressive strength for all studied GPC mixtures increased. The compressive strength for the GPC-S7 mixture increased by 19.62%, 16.28%, and 25.53% compared with the GPC-A mixture after 28 days, 56 days, and 90 days, respectively. For the GPC-S3 mixture, the compressive strength increased by 4.90%, 4.65%, and 12.77% compared with the GPC-A mixture after 28 days, 56 days, and 90 days, respectively. Hence, the mechanism of GPC based on FA differs from that of CC, and the products of geopolymerization and hydration are distinct. The main geopolymerization product is not sulfate attacked in contrast to hydration products. Because of this, the GPC samples remained unharmed despite being immersed in a sulfate solution for up to 90 days. In the end, studying intervals above 90 days is highly recommended to cover the rate of increase or deterioration that may happen for GPC.

In contrast to the cubic samples of the CC mixture, the GPC mixtures GPC-S7, GPC-S3, and GPC-A did not appear to have lost any mass or experienced any degradation during the exposure to the sulfate solution (10% concentration). The results thus demonstrate the substantial stability of the GPC mixes in sulfate solution for 90 days. Also, due to curing in a steamer, which gives greater ingredient integrity, the unit weight of the GPC-S7 and GPC-S3 mixtures stays constant at 56 and 90 days of age but the CC mixture lost unit weight due to abrasion, see **Fig. 8**.

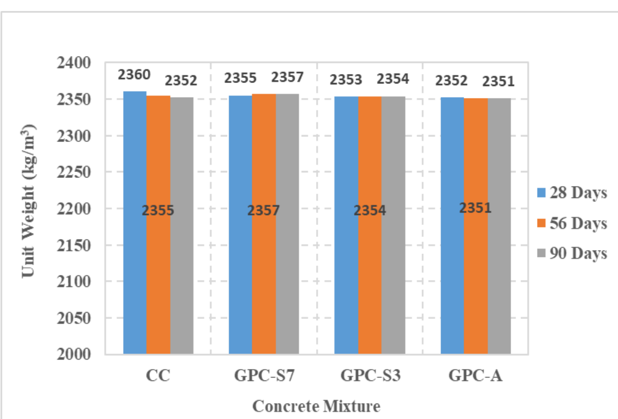

Fig. 8 Unit Weight of CC and GPC Mixtures

The GPC samples immersed in the sulfate solution revealed no evidence of exterior changes, such as cracking or disintegration. Moreover, after 90 days of exposure, the surfaces of the CC samples started to diminish, and cracks appeared from sulfate exposure. **Fig. 9** shows the captured visual condition of CC and GPC samples after 90 days.

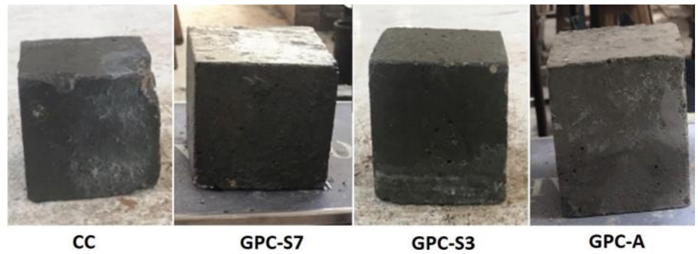

Fig. 9 Visual Appearance of Samples Immersed in sulfate Solution (10% concentration)

5 Microstructure of GPC Mixtures

In order to investigate the microstructure of GPC mixtures after 90 days, a scanning electron microscope (SEM) was utilized. The required samples were prepared by cutting from GPC using a diamond saw sized 3 to 6 mm in height and diameter of about 10 mm. Furthermore, the samples were left to dry in the oven for 24 hours to remove moisture before being gold-plated for imaging.

The GPC-S7 microstructure was identified as non-porous with small low micropores, non-microcracks, and low unreacted FA, which lead to cause low permeability properties. This microstructure is also responsible for the high strength of the GPC mixture shown in **Fig. 10**. On the other hand, the microstructure for the GPC-A identified as porous microstructure with higher micropores, identical large microcracks and higher unreacted FA, which leads to high permeability properties. The porous microstructure is also responsible for the low strength of the GPC mixture, see **Fig. 11**. Microstructure analysis of the GPC confirmed the obtained results from water absorption and water permeability in addition to the mechanical properties such as compressive strength, indirect tensile strength, flexural strength, and bond strength which agreed that GPC cured in a steamer with 60ºC for seven days better than other GPC or CC.

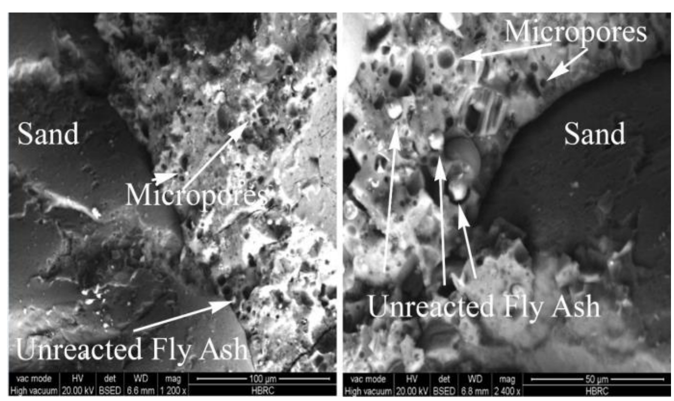

Fig. 10 SEM Images of the GPC-S7 Mixture

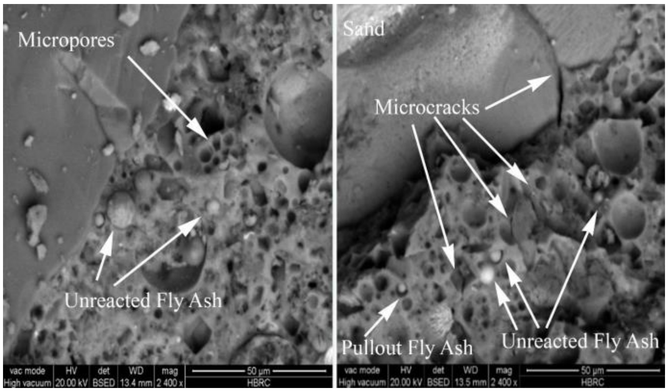

Fig. 11 SEM Images of the GPC-A Mixture

6 Correlations between Compressive Strength and Other Mechanical Properties

Table 10 shows the relationship between compressive strength and other mechanical properties such as indirect tensile strength, flexural strength, and bond strength. According to **[20]**, the direct tensile strength values are taken as $0.85f_s$ or $0.6f_f$. Those values were obtained from experimental results of the indirect tensile strength (f_s) and flexural strength (f_f).

Table 10 Correlations between Compressive Strength, Indirect Tensile Strength, Flexural Strength and Bond Strength for different Concrete Mixtures

Mixture	Testing Time	f_{cu} (MPa)	f_s (MPa)	f_f (MPa)	f_b (MPa)	f_s/f_{cu} (%)	f_f/f_{cu} (%)	f_b/f_{cu} (%)	$0.85f_s$ (MPa)	$0.6f_f$ (MPa)	$0.85f_s/f_{cu}$ (%)	$0.6f_f/f_{cu}$ (%)
CC	28 Days	42.50	2.40	7.80	5.20	5.65	18.35	12.24	2.04	4.68	4.80	11.01
	56 Days	45.00	2.90	8.20	5.70	6.44	18.22	12.67	2.47	4.92	5.48	10.93
	90 Days	50.50	3.50	9.70	6.50	6.93	19.21	12.87	2.98	5.82	5.89	11.52
GPC-S7	28 Days	43.60	2.80	8.50	5.50	6.42	19.50	12.61	2.38	5.10	5.46	11.70
	56 Days	47.80	3.30	9.60	6.20	6.90	20.08	12.97	2.81	5.76	5.87	12.05
	90 Days	57.90	3.80	10.80	7.00	6.56	18.65	12.09	3.23	6.48	5.58	11.19
GPC-S3	28 Days	38.20	2.10	6.80	4.80	5.50	17.80	12.57	1.79	4.08	4.67	10.68
	56 Days	43.80	2.60	7.60	5.20	5.94	17.35	11.87	2.21	4.56	5.05	10.41
	90 Days	51.00	3.00	8.80	5.70	5.88	17.25	11.18	2.55	5.28	5.00	10.35
GPC-A	28 Days	36.50	1.80	5.50	4.30	4.93	15.07	11.78	1.53	3.30	4.19	9.04
	56 Days	40.50	2.20	6.30	4.70	5.43	15.56	11.60	1.87	3.78	4.62	9.33
	90 Days	45.50	2.60	7.70	5.00	5.71	16.92	10.99	2.21	4.62	4.86	10.15

However, the results for the CC mixture show that the direct tensile strength to compressive strength (f_{cu}) ranged from 4.80% to 11.52%, but the flexural strength ranged from 18.22% to 19.21% of f_{cu}. Also, the bond strength was equal to 12.24% to 12.87% of f_{cu}. On the other hand, for the GPC mixture, the direct tensile strength ranged from 4.19% to 12.05% of f_{cu}, but flexural strength was 15.07% to 20.08% of f_{cu}. Moreover, the bond strength was 10.99% to 12.97% of f_{cu}. Wherefore, it was noted that the GPC mixtures are similar to the CC mixture in the correlations of mechanical properties to compressive strength.

7 Conclusions

From the previously discussed experimental work, the relevant conclusions can be summarized as follows

- The recorded slump value for the GPC mixture was more than the CC mixture by 130%, valid for a brief time then the GPC mixture became more cohesive than the CC mixture after the hardening.
- For the GPC mixture cured in a steamer with 60ºC for seven days, the compressive strength increased by (2.59%, 14.14%, and 19.45%) after 28 days, increased by (6.22%, 9.13%, and 18.02%) after 56 days, and increased by (14.65%, 13.53%, and 27.25%) after 90 days compared with CC, GPC cured in a steamer with 60ºC for three days and GPC cured in warm air mixtures, respectively. Also, the GPC mixture cured in a steamer with 60ºC for seven days recorded compressive strength of 43.6 MPa after 28 days and reached high-strength concrete limits (57.9 MPa) after 90 days.
- The indirect tensile strength of the GPC mixture cured in a steamer with 60ºC for seven days increased by (16.67%, 33.33%, and 55.55%) after 28 days, but after 56 days increased by (13.79%, 26.92%, and 50.00%), furthermore,

after 90 days increased by (8.57%, 26.67%, and 46.15%) in comparison to CC, GPC cured in a steamer with 60ºC for three days and GPC cured in warm air mixtures, respectively.

- The flexural strength of the GPC mixture cured in a steamer with 60ºC for seven days increased by (8.97%, 25.00%, and 54.54%) after 28 days, but after 56 days increased by (17.07%, 26.32%, and 52.38%), moreover, after 90 days increased by (11.34%, 22.73%, and 40.26%) in comparison to CC, GPC cured in a steamer with 60ºC for three days and GPC cured in warm air mixtures, respectively.
- The bond strength of the GPC mixture cured in a steamer with 60ºC for seven days increased by (5.77%, 14.58%, and 27.91%) after 28 days, but after 56 days increased by (8.77%, 19.23%, and 31.91%) While after 90 days increased by (7.69%, 22.81%, and 40.00%) in comparison to CC, GPC cured in a steamer with 60ºC for three days and GPC cured in warm air mixtures, respectively.
- The strength development rate increased in GPC mixtures compared with the CC mixture even though cured in warm air. Therefore, the compressive strength development rates were (18.82%, 32.79%, 33.50%, and 24.66%), the indirect tensile strength development rates were (45.83%, 35.71%, 42.86%, and 44.44%), the flexural strength development rates were (24.36%, 27.06%, 29.41%, and 40.00%), and the bond strength development rates were (25.00%, 27.27%, 18.75%, and 16.28%) for CC, GPC cured in a steamer with 60ºC for seven days, GPC cured in a steamer with 60ºC for three days, and GPC cured in warm air mixtures, respectively according to the time interval from 28 days to 90 days.
- The water absorption of the GPC mixture cured in a steamer with 60ºC for seven days was less than CC, GPC cured in a steamer with 60ºC for three days, and GPC cured in warm air mixtures by (1.32%, 3.85%, and 8.54%, respectively) after 28 days, and decreased by (1.37%, 4.00%, and 6.49%, respectively) after 56 days, and decreased by (4.69%, 8.96%, and 15.28%, respectively) after 90 days.
- The GPC mixture cured in a steamer with 60ºC for seven days recorded water permeability less than CC, GPC cured in a steamer with 60ºC for three days, and GPC cured in warm air mixtures by (11.11%, 30.43%, and 36.00%, respectively) after 28 days, but decreased by (13.33%, 27.78%, and 35.00%, respectively) after 56 days and decreased by (18.18%, 40.00%, and 47.06%, respectively) after 90 days.
- The decreasing rates of water absorption were (15.79%, 18.67%, 14.10%, and 12.19%), but the decreasing rates of water permeability were (38.89%, 43.75%, 34.78%, and 32.00%) for CC, GPC cured in a steamer with 60ºC for seven days, GPC cured in a steamer with 60ºC for three days, and GPC cured in warm air mixtures, respectively according to the time interval from 28 days to 90 days.
- The compressive strength of GPC mixtures increased over time whether or not the samples were immersed in the over-dose sulfate solution (10%). Therefore, the compressive strength of the CC mixture soaked in sulfate solution (10%) lost up to 2.97% after 90 days. However, the compressive strength of GPC mixtures did not have any significant predatory effect after 90 days.
- The GPC submerged in the sulfate solution revealed no signs of cracking, disintegration, or changes in the exterior appearance, whereas the surfaces of the CC samples started to break down after 90 days and formed cracks because of the sulfate exposure.
- For the GPC mixture cured in a steamer at 60ºC for seven days, the microstructure was identified as non-porous with small low micropores, non-microcracks, and low unreacted FA leads to low permeability properties. Therefore, the microstructure for the GPC mixture cured in warm air was identified as a porous microstructure with higher micropores, identical large microcracks, and higher unreacted FA leads to high permeability properties.
- The results for the CC mixture show that the direct tensile strength to compressive strength (f_{cu}) ranged from 4.80% to 11.52%, but the flexural strength ranged from 18.22% to 19.21% of f_{cu}. Also, the bond strength was equal to 12.24% to 12.87% of f_{cu}. Whereas, for the GPC mixture, the direct tensile strength ranged from 4.19% to 12.05% of f_{cu}, but flexural strength was 15.07% to 20.08% of f_{cu}. Furthermore, the bond strength was 10.99% to 12.97% of f_{cu}. Ultimately, it's noted that the GPC mixtures are similar to the CC mixture in the correlations of mechanical properties to compressive strength.

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