

Durability properties of blended fly ash- slag geopolymer concrete as a repairing and strengthening materials

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Abstract

Repair materials with low carbon footprints that are environmentally friendly have become very popular in the global construction industry. Concrete made with significant quantities of Portland cement will gradually deteriorate over time and will need to be repaired or replaced. The developing of sustainable concrete repair materials is necessary.

This study aims to investigate the characterization of ambient cured blended geopolymer concrete (GPC) as a repairing and strengthening materials in comparison with Portland cement concrete (PCC). Four GPC mixes were prepared with various percentages of fly ash (FA): ground granulated blast furnace slag (GGBFS) with (100%:0, 50%:50%, 25%:75%, and 0%:100%). The alkaline solution employed for the polymerization process in this study is a combination of sodium hydroxide solution (16M) and potassium silicate solution. Parallel to the investigated GPC mix, a PCC mix was prepared for the pull-off test and comparison. The compressive strength for all mixes was evaluated at different ages (7 and 28 days). The bond strength was evaluated using pull-off test. Furthermore, durability properties of all concrete mixtures were conducted as abrasion resistance, rate of water absorption, rapid chloride penetration Test (RCPT), sulphate resistance, and resistance to elevated temperature up to 800 °C.

The results depicted that using 50% GGBFS lead to high early strength at 7days 49 MPa and 52.7 MPa at 28 days. The pull-off test results shown that the blended GPC with 50% GGBFS exhibited good bond strength to the cementitious concrete. In addition to GPC showing superior resistance to abrasion, sulfate and high temperature resistance compared to PCC, there is also a reduction in chloride ion penetrability and absorption rate. Moreover, GPC showed a 9.6% loss in its compressive strength with respect to 42% for PCC after 120 days exposure to 5% sodium sulphate solution. In addition, the blended GPC developed more stability than PCC after being exposed to a temperature of 800 °C. Due to their high strength, good bond with the subsurface and superior durability properties, GPC can be considered as a suitable option for repairing worn structures, infrastructure and road pavements.

Keywords: Geopolymer concrete, Durability, Abrasion resistance, Sulphate resistance, Rate of absorption, Elevated temperature.

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I. Introduction

In general, reinforced concrete structures offer excellent structural strength and long-term durability, making them suitable for use in infrastructure applications. However, reinforced concrete structures quickly deteriorate if they are subjected to severe environments like the maritime environment or are directly exposed to harmful substances [1]. Portland cement (PC) has been utilized for the construction of numerous infrastructures such as road construction, buildings,...etc [2]. However, the simultaneous action of mechanical and thermal loads causes OPC concrete to deteriorate [3]. The main signs of concrete deterioration are cracking, spalling, surface degradation, seepage of concrete, and de bonding of rebars [3,4]. Consequently, to ensure their continued serviceability, deteriorated structural components need effective and successful repair materials [3, 5]. Due to the enormous costs involved in the prevention, repair, and rehabilitation of these defects, the deterioration of PC-based structures in ageing infrastructure continues to be a cause of concern worldwide [4, 6]. Due to this, researchers are vying with one another to develop a more practical, affordable, and environmentally acceptable material to solve this issue. One current solution is geopolymer binders.

Alkali-activated binders, also known as geopolymer, have been identified by researchers as a new binder that significantly reduces CO₂ emissions and emits six times less of it than PC [7], It results in less global

warming. In most cases, cement hydration results in an improvement in concrete strength [8]. Hydration does not occur in geopolymer concrete (GPC) because water does not react with the cementitious materials [9, 10]. It was discovered that the cementitious materials rich in Si and Al perform a chemical reaction known as polymerization in order to get the strength required in concrete. In the process of polymerization, monomer molecules interact with one another to create three-dimensional polymeric chains [11-13]. The alkaline liquid that serves as a catalyst and cementitious materials are the two major components of GPC [14]. The cementitious materials may be naturally occurring, such as kaolinite, clay, etc., or they may be wastes from other industries, such as silica fume, granulated blast furnace slag (GGBFS), and fly ash (FA) [15-17]. It is crucial to realise, however, that published data have demonstrated that the strength performance of GPC is dependent on the chemical composition of the source materials, curing method, alkaline liquid ratios, and the molarity of NaOH (NH) [18–20].

In structural applications, compressive strength typically attracts the most attention. Similar to PCC, GPC strengthens over time in ambient environmental conditions [21, 22]. However, heat curing from 0° C to 150° C considerably increases compressive strength [23] where, depending on the curing temperature, complete compressive strength could be attained in a short period of time [21,22,24]. Many researchers were attracted by the geopolymer composites' durability performance. In terms of durability, GGBFS combined with FA geopolymer shown good resistance to permeability [25], high temperature [26], and attack by sodium sulphate [27]. Researchers [28-30] also came to the conclusion that geopolymer composites had an intrinsic fire resistance advantage over composites made of PC. Additionally, according to several research studies, FA-based GPC has a good resistance to chloride ingress and a low permeability to chloride ions [31-35]. Research on the substitution of GGBFS in the development of strength and durability properties of FA-based GPC was conducted by Hardjito et al. [36] and Venu and Gunneswara Rao [37].

Despite the geopolymer's benefits in terms of mechanical and durability, its cost and cast-in-situ deployment made it impossible for it to replace PC concrete [38]. Therefore, it is more practical to use geopolymer in restricted quantities for repair and strengthening applications. For the retrofitting and restoration of the damaged reinforced concrete elements, some researchers introduced the geopolymer materials [39–41]. The results showed that the used geopolymer materials adhered well and could withstand ultimate stresses that were at least as great as those of the control specimen. The geopolymer is applied as a protective coating in addition to repair applications for reinforced concrete elements [42-45]. In order to overcome the issue of shrinking that may occur when utilizing geopolymers for repair applications, incorporating internal short fibers has been suggested [43,44,46,47]. Good binding strength and compatibility between the existing and repair materials are necessary for a repair material [48]. The adhesion and friction between two surfaces determines the bond strength [49]. Additionally, because each bond assessment testing method places a different type of stress on the interface surfaces (slant shear, splitting tensile, and pull-off), the results of those tests produce various bond strength values [50].

Although the research and studies previously given demonstrated intriguing benefits of geopolymer as a sustainable building material and geopolymer as a repairing and strengthening materials, they are insufficient to take the GPC into consideration as a prospective repairing product.

More durability studies are needed to be examined because limited studies are available on abrasion resistance, rapid chloride penetration and rate of absorption tests on FA and GGBFS-based GPC. In this study, the authors aimed to create blended fly ash- slag GPC with properties that are suitable for usage as a concrete repairing and strengthening agent in both fresh and hardened states including bond strength.

II. Experimental program

Material properties

Geopolymer concrete in this study was made up with aluminosilicate materials include FA and/or GGBFS. Low-calcium FA (class F) according to **ASTM C 618-012a** [51] with specific gravity 2.4 and GGBFS according to **ASTM C989-94** [52] which was collected from local distributor with specific gravity 2.9 were selected to make the GPC mixes. PC CEMI 42.5N was used for the preparation of the control cement mix to compare with GP concrete. The chemical composition of the used FA, GGBFS and PC as determined by (XRD) analysis, is given in Table 1. River siliceous medium well-graded sand (S) was used as a fine aggregate in the experimental program for all concrete mixes according to **ECP 203/2019-part 3** [53] and **ASTM C33/C33M** [54] with a specific gravity of 2.6, a fineness modulus of 2.33 and water absorption 0.9%. Whereas the crushed limestone was used as a coarse aggregate (CA) for all concrete mixes with maximum size 10 mm and specific gravity 2.55. The usage of an alkaline solution was decided upon based on its findings, and it was a combination of NH and potassium silicate K_2SiO_3 (KS) since KS is less viscous than sodium and will thus aid in

achieving good workability in addition to concentration and molarity, according to Ghazy et al., 2022 [55]. The alkaline solution (A) used with a ratio 2.5 was a combination of NH pellet form with 98-99% purity and KS which chemical composition was provided by the manufacturer is as follows: (Molar ratio $\text{SiO}_2/\text{K}_2\text{O} = 2$, $\text{K}_2\text{O} = 14\text{-}15\%$, $\text{SiO}_2 = 29\text{-}30\%$ and water = 58% by mass), the solution viscosity is equal to 450 MPa.s, and its specific gravity is 1.4 g/ML. The dissolved mass of NH depending on the concentration of solution expressed in terms of Molar (M). In this study NH solution with a concentration of 16 M was used, which consist of ($16 \times 40 = 640$ gm) of NH solids per liter of the solution, where 40 is the molecular weight of NH. The tap water contributed in accordance with the specifications of ECP 203-2019 [53] was used to prepare the alkaline solution and for curing the PC concrete. Superplasticizer (SP) of modified polycarboxylates in the form of a clear liquid and having a density of approximately 1.08 kg/liter at room temperature was used as meeting the requirements of ASTM C494 type G and F to improve the workability of the geopolymer mixes. Polypropylene fibers (PP) have been used at a fixed ratio to all geopolymer mixes and the mechanical properties of this PP are presented in Table 2 as given by the manufacturer.

Table 1: Chemical compositions of the used FA, GGBFS and PC

Oxide %	FA	GGBFS	PC
SiO ₂	61	41.66	20
Al ₂ O ₃	18	13.96	5.20
Fe ₂ O ₃	5.2	1.49	3.10
TiO ₂	-	0.58	-
MnO	-	0.35	-
MgO	1	5.35	-
CaO	6	34.53	63
Na ₂ O	0.7	0.49	0.44
K ₂ O	0.8	0.97	0.15
SO ₃	2.3	-	3.01
P ₂ O ₅	-	0.01	-
LOI	0.2	0.05	5.10

Table 2: The mechanical properties of polypropylene fiber used

Fiber type	Diameter (mm)	Length (mm)	Aspect ratio	Density (kg/m ³)	Elastic modulus (MPa)	Tensile strength (MPa)
PP	0.02	12	750	900	3500	550

Mix proportions and specimens preparations

Five mixes were made, divided into four GPC mixes with different percentages of FA: GGBFS (100%: 0%, 50%:50%, 25%:75%, 0%:100%) as the main binder, and the fifth mix was PCC as a control mix. The proportions of the studied mixes are displayed in Table 3. The binder represented by FA or GGBFS individually or both combined in the aforementioned quantities was used to prepare the GPC mixtures.

For all GPC mixes, The NH solution was prepared 24 h before mixing with molarity of 16. The solution made up of NH was added to KS solution around an hour before mixing to make the alkaline solution. The solution and binder materials were first mixed together for 2 minutes using drum mixer with capacity of 100 L. After that sand and coarse aggregate were added and continue mixing for another 2 minutes, then SP and extra water were added to the mix. Finally, PP fibers were manually added and the mixing is continuous with the mixer until the components of the mix are encapsulated and homogeneous to make fresh GPC.

For PCC mix, coarse aggregate was added with cement in Drum mixer and then mixed in dry state for 2 minutes. water and sand were then alternately added to the cement and coarse aggregate mix for additional 5 minutes to ensure the consistency of the mix. The fresh concrete was placed in the prepared molds as displayed in Fig. 1, and the fresh GPC and PCC were compacted using a mechanical vibrator for 10 s to remove any trapped air.

PCC samples were kept in their molds for 24 hours as a rest period at temperature 20 ± 2 °C and 50% RH, then the samples were removed from the molds and the curing process took place. Curing in PCC is carried out by covering the sample with wet burlap until the test ages at 7 and 28 days. GPC samples containing FA+ GGBFS were kept in their molds for 24 hrs. However, FA-based GPC samples were kept in their molds for 72

hrs. Samples were removed from the molds and cured with heat in a chamber by putting the samples at a temperature 40 °C for 48 hours as recommended by [56]. After the samples have cooled to room temperature, they are placed outdoor in ambient conditions. The samples were kept until they were used in the specific test for each sample. The outdoor temperatures of the curing period were between February and March in 2022 as shown in Fig. 2.

Table 3: Mix proportions of different concrete mixes

NO	MIX ID	proportions (kg/m ³)										Slump (mm)
		C	FA	GGBFS	S	CA	A		PP	SP	EX	
							KS	NH				
1	F100S0	-	400	-	689	1033	171.429	68.57	0.9	-	-	230
2	F50S50	-	200	200	702	1053	171.429	68.57	0.9	2	8	230
3	F25S75	-	100	300	709	1063	171.429	68.57	0.9	6	40	230
4	F0S100	-	-	400	716	1074	171.429	68.57	0.9	12	40	230
5	PCC	400	-	-	642.4	964	-	-	-	-	240	80

Note: C: Cement, FA: Fly ash, GGBFS: Ground granulated blast furnace slag, S: Sand, CA: Coarse aggregate, A: Alkaline solution, KS: Potassium silicate, NH: Sodium hydroxide, PP: Polypropylene fibers, SP: Superplasticizer, EX: Extra water.

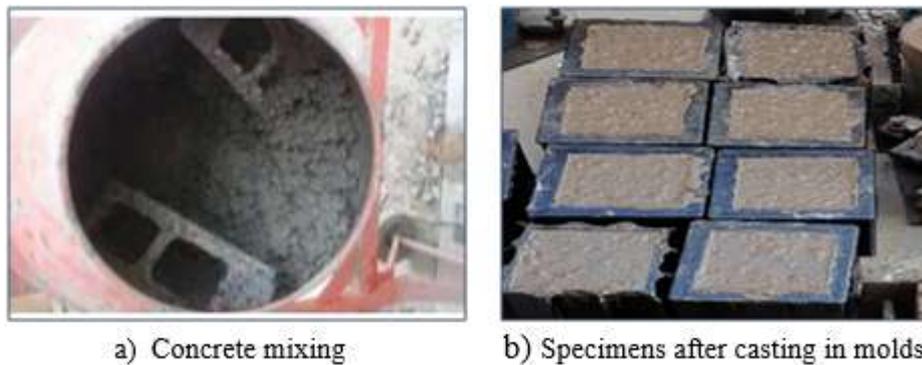


Fig. 1: Mixing and casting of concrete mixes

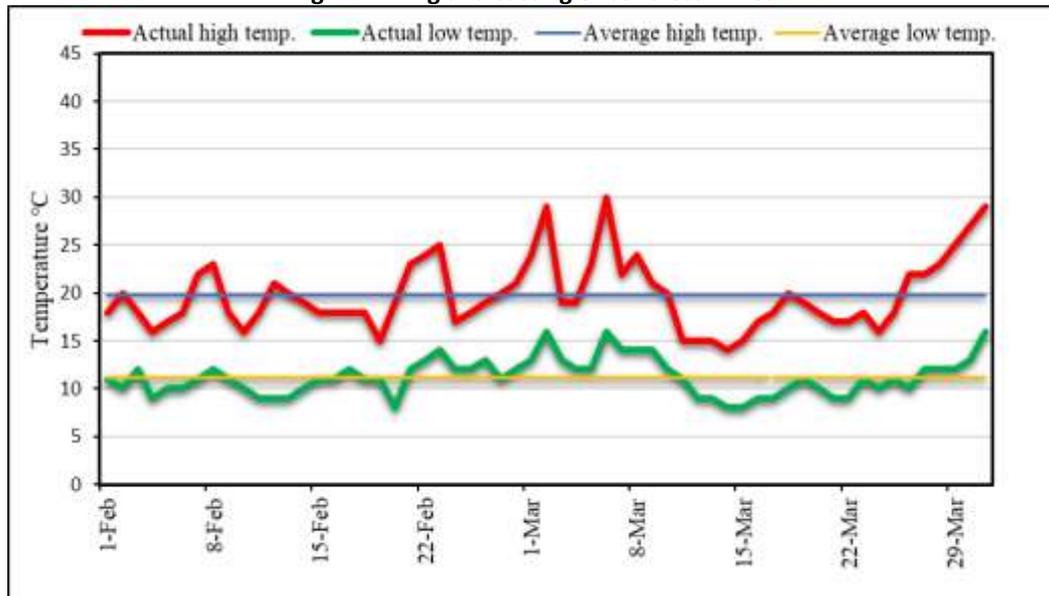


Fig. 2: The outdoor temperature of the GPC curing along February- March in 2022

Test procedures

Fresh properties of concrete mixes

According to **ASTM C143** [57], the workability of the freshly mixed concrete was tested immediately after the process of mixing.

Compressive strength of concrete mixes

In this investigation, compressive strength was measured at different ages (7 and 28 days). Compressive strength was determined in accordance with **BS EN 12390-3:2019** [58] using cubic specimens of size (100 ×100 ×100) mm. For testing, a digital hydraulic compression testing machine with a capacity of 2000 kN was used.

Bond strength (pull-off test)

The pull-off test was intended to investigate the bond between the repair material and the substrate one according to **ASTM C1059-13** [59] at the age of 28 days. The active load in this test is provided immediately perpendicular to the surface where the materials for the repair and substrate materials come into contact. As a result, the measured values were regarded as accurate and actual. The substrate material for this test was PCC beam of (150× 150 ×75) mm. Thereafter, a layer of each repair concrete was added with thickness of 75 mm at the top of the substrate concrete. The beam specimens were cured, and then wet-drilled cores of 45 mm in diameter and 112.5 mm in depth were inserted. The cores were drilled using discs measuring 50 mm, with a minimum centerline spacing of 100 mm and a minimum distance of 50 mm from the centre of a disc to the free edge, these distances comply with the specifications of **ASTM C1583-13** [60]. After that, each core was attached to an aluminium disk using a fast setting epoxy. The epoxy was allowed to cure for 24 hours in the lab at room temperature, and then pull-off device was used to manually pull off the disk until failure occurred as shown in **Fig. 3**.



Fig. 3: Pull-off test setup

Durability properties of concrete mixes

Abrasion resistance test

Abrasion resistance is the ability of a material to withstand surface wear carried out by flat rubbing contact with another material. According to **ASTM C779** [61], the sample is made with size (70×70×30) mm and place in oven for 24 hours at 110 °C, and initial weight is measured. The test is constrained and positioned in the Bohme circular processor's path, which offers a consistent wearing drive on its surface as shown in **Fig. 4**. It must submit to a wearing stack of 294 N after 16 cycles of pivoting. There are 22 revolutions in each cycle. Abrasion loss can be expressed in terms of average depth of wear. The average depth of loss, determined by the measuring of the specimen's dimensions following the test and the loss of the specimen's mass.



Fig. 4: Abrasion resistance test machine

Rate of water absorption test

The term "water absorption" refers to the transposal of water through capillary action, and it is determined by the increase in specimen weight over time. This investigation was conducted in accordance with **ASTM C 1585-04** [62]. Four covers of tightly applied "tape" were placed on each specimen's surface to make the sides impermeable. The specimen's bottom face was set up in a small water bath. One centimeter of water's surface was visible above the sample's base. The sorptivity coefficient of the sample, "S" was determined by using Eq.1.

$$S = (Q/A) / (t)^{0.5} \quad (1)$$

Where:

S = Sorptivity in (mm/s^{0.5}).

Q = The vol of water absorbed in (mm³).

A = The exposed area of the specimen in (mm²).

T = The time in (s).

Rapid chloride penetration test

According to **ASTM C1202-07** [63], the rapid chloride ion penetration into concrete samples was measured using ARF-2568 RCPT equipment as depicted in **Fig. 5**. The test was conducted using cylindrical mould with size (100×50) mm. A sample was placed in a cell that was surrounded on one side by a solution of 0.3 N NaOH and on the other by a solution of 3% NaCl and subjected to 60 V applied DC voltage for 6 h. The charge passed through each test sample can be determined using the following Eq. 2.



Fig. 5. Rapid chloride penetration test setup

$$Q = 900(I_0 + 2I_{30} + 2I_{60} + \dots + 2I_{330} + I_{360}), \quad (2)$$

Where, Q = Charge passed (Coulombs).

I₀, I₃₀, I₆₀, ..., I₃₃₀, I₃₆₀ = current at 0, 30, 60, ..., 330, 360 min.

Sulphate resistance test

The test was conducted to examine sulphate's impact on concrete. Sulphate may be present in soil or groundwater, which can harm concrete when it comes into contact with it. Test specimens were (100×100×100) mm cubes of PCC and GPC for compressive strength and change in mass test. The sulphate resistance of PCC and GPC was assessed by determining the residual compressive strength and change in mass after sulphate exposure according to the instructions in **ASTM C 642** [64]. After a 28-day curing period, the cubes were immersed in a sodium sulphate (Na₂SO₄) solution with a 5% concentration for a particular exposure period (28, 56, 90, and 120 days). To reduce evaporation and dust particle fallout, the containers were closed. Every month, new solutions were maintained to preserve the solution's pH value. In order to avoid deposits at the base of the containers, the solutions were stirred once a week. After 28 days, 56 days, 90 days and 120 days, three samples were removed from the containers to be tested. Mass and compressive strength changes were seen both before and after immersion. The cube samples were examined in a compression testing machine with a capacity of 2000 kN.

Resistance to elevated temperature test

All specimens of PCC and GPC were exposed to elevated temperatures at the age of 28 days. Specimens were exposed to elevated temperatures using an electrical heater furnace with a capacity up to 1200 °C. For each mix, three cubes with dimensions (100×100×100) mm were exposed to 200 °C, 400 °C, 600 °C, and 800 °C according to the rate shown in Fig. 6-a. The specimens were then given time to naturally cool inside the furnace to room temperature after the temperature was maintained at the target level for 2 hours as depicted in Fig. 6-b. The resistance to elevated temperatures of concrete mixes is measured using residual compressive strength, visual appearance and the change in weight.



Fig.6: a) Fire curves, b) Concrete specimens in electrical furnace

III. Test results and discussions

Table 4, presents the results of testing for compressive strength, pull-off, abrasion resistance, rate of water absorption and rapid chloride penetration.

Table 4: Results of compressive strength, pull-off, abrasion resistance, rate of water absorption and rapid chloride penetration tests

Mix ID	Compressive strength (MPa)		Bond strength (MPa) at 28 days	Depth of wear (mm)	Sorptivity coefficient (mm/s ^{0.5})	Charge passed (coulombs)
	At 7 days	At 28 days	Dry surface			
F100S0	21.3	31.2	0.6	1.5	1.31	29343.6
F50S50	49	52.7	1.8	0.7	1.01	22014.9
F25S75	37.9	39	1.2	0.9	1.2	8474.4
F0S100	38.1	39	0.8	1	1.3	3019.5
PCC	26.7	29.8	0	1.9	1.4	29854

Fresh test results

All of the mixes employed in the current experimental program were subjected to a slump test. Despite using the same proportion of liquid in PCC and GPC mixes, the control mix, PCC, had a slump value of 80 mm, while FA-based GPC had a slump value of 230 mm. For other GPC mixes that contain GGBFS, extra water and SP in various proportions were added to each mix as listed in Table 3, to achieve a constant slump value of 230 mm for the repair applications. In addition, it was discovered that adding more GGBFS into GPC mixes reduced the workability and resulted in a stiffer mix [65,66]; as a result, more water and superplasticizer were employed.

Compressive strength results of concrete mixes

Results of compressive strength for various concrete mixes are shown in Fig. 7 and Table 4. At 7 days, addition of GGBFS leads to early strength gain in GPC. High early age strength is a desired characteristic of concrete repair materials. 7 days strength F50S50, F25S75 and F0S100 was found to be about 93%, 97% and 97.8% of that at 28 days, respectively.

At the age of 28 days, the compressive strength of F100S0 is lesser than the compressive strength of F50S50, F25S75 and F0S100 by percentages of 68.75%, 24.84% and 24.84%, respectively. Comparing with a PCC mix, it is found to have compressive strength that is lower by percentages of 4.73%, 76.74%, 30.75%, and

30.75%, respectively, than F100S0, F50S50, F25S75, and F0S100. The maximum compressive strength is 52.65 MPa with 50% GGBFS content, and the lowest is 31.2 MPa when using 100% FA. So when using 50% GGBFS instead of FA, the percentage increase in compressive, this finding is in line with the result obtained by [66].

The 'Ca' components in GGBFS reacted and created more C-S-H and C-A-S-H, which coexisted with geopolymer products [67] and supported the strength development of geopolymer concrete as a repair material. This agrees with a different study that found a high rate of strength development was influenced by high pozzolanic activity and calcium content. Additionally, this is because the presence of C-S-H gel will increase the alkalinity, accelerating the geopolymerization and dissolution of aluminosilicate [68-71]. Due to the reduced calcium content in FA, the strength of the FA-based geopolymer repairing material is lower than that of the GGBFS-based geopolymer [72,73]. However, higher GGBFS content led to the presence of extra water and an increase in superplasticizer for workability, which resulted in a reduction in compressive strength [74]. In this investigation the increase in GGBFS content from 50% to 100% (F25S75 and F0S100) resulted in decrease in compressive strength at different ages but still higher than PCC.

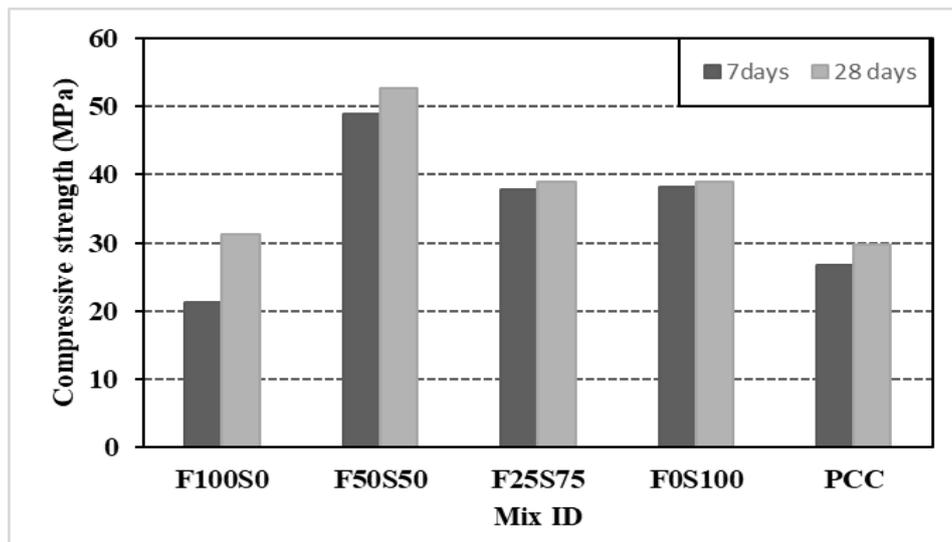


Fig. 7: Compressive strength for different concrete mixes

Bond strength (pull-off)

Figure 8, presents the failure modes of pull-off specimens. It was noticed that failure at the contact surface between the repair materials and the aluminium disk revealed poor epoxy, and the test was deemed unsuccessful, as shown in **Fig. 8-a**, for F100S0. Besides, F0S100 and F25S75 specimens failed in the repair material, as depicted in **Fig. 8(b, c)** in the case of dry surface. On the other hand, F50S50 specimens failed at substrate concrete, as shown in **Fig. 8-d**. This may be explained by the fact that the bond strength in the interfacial zone is greater than the tensile strength of the substrate. While PCC specimens broke before testing.



Fig. 8: Failure of the pull-off specimens in a) top surface of repair material, b and c) repair material, d) substrate concrete

The results of bond strength for different repair materials in case dry surface shown in Table 4 and Fig. 9. The results indicate that blended GPC with 50% GGBFS as a repair material exhibited good bond strength to the cement-based substrate. The findings of Pull-off test were found to be more or less identical to that reported by different individuals [75] who investigated the pull-off bonding strength of the FA/GGBFS-based GPC to PC substrate.

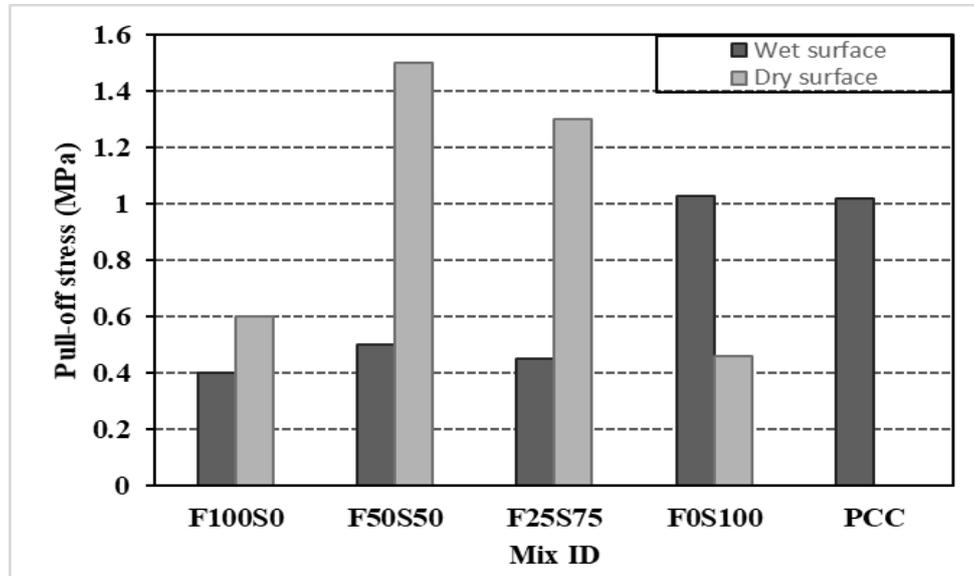


Fig. 9: Bond strength between substrate concrete and different repair materials

Durability properties test results

Abrasion resistance

Abrasion loss can be expressed in terms of average depth of wear as shown in Fig. 10. It was evident from the result that the depth of wear decreased with using GGBFS in GPC mixes, the best percentage of GGBFS was 50% which was achieved depth of wear 0.7 mm. However, **Hu et al.** [76] studied abrasion resistance of geopolymer mortar as repair material with using of 20% GGBFS as a replacement and this led to reduce the depth of wear by 44.4% compared with PCC. Comparing GPC mixes with PCC mix the depth of wear reduced by 22.04%, 62.4%, 51.6% and 46.3% respectively, for F100S0, F50S50, F25S75 and F0S100, which means that the increasing in GGBFS content from 20% to 50% resulted in decrease in depth of wear. The performance of abrasion resistance is similar to the relation between their compressive strengths. It was primarily because geopolymeric repair materials could produce a dense structure earlier than cement, and the abrasion resistance of repair materials was dependent on the density of the structure. for this is that the structure's density affects the abrasion resistance. Earlier than PCC, GPC was able to create a dense structure, which means that the abrasion resistance for GPC was better.

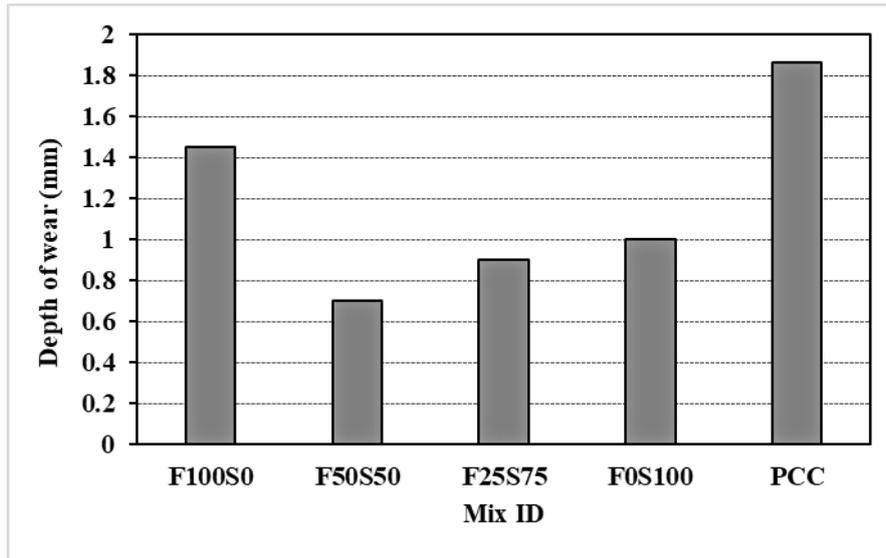


Fig. 10: Average depth of abrasion for different concrete mixes at 28 days

Rate of water absorption

Figure. 11, indicates the test results of the sorptivity coefficient values of GPC and PCC mixes. The findings indicate that GPC mixes created with 50% GGBFS had better sorptivity values than other GPC mixes. Using GGBFS with percentage of 50% reduced the sorptivity coefficient by 23% compared to 100% FA based GPC mix. For PCC mix, it is found to have sorptivity coefficient that's higher by percentages of 6.02%, 37.7%, 14.3% and 7.2%, respectively, than F100S0, F50S50, F25S75 and F0S100. This demonstrable truth shows that GPC is more sustaining in terms of having access to water. As a repair and strengthening material this is good property. The addition of GGBFS to FA-based GPC appears to have improved the microstructure performance, which in turn improved porosity, water absorption, and sorptivity, these finding are in line with **Bellum et al., 2022** [77].

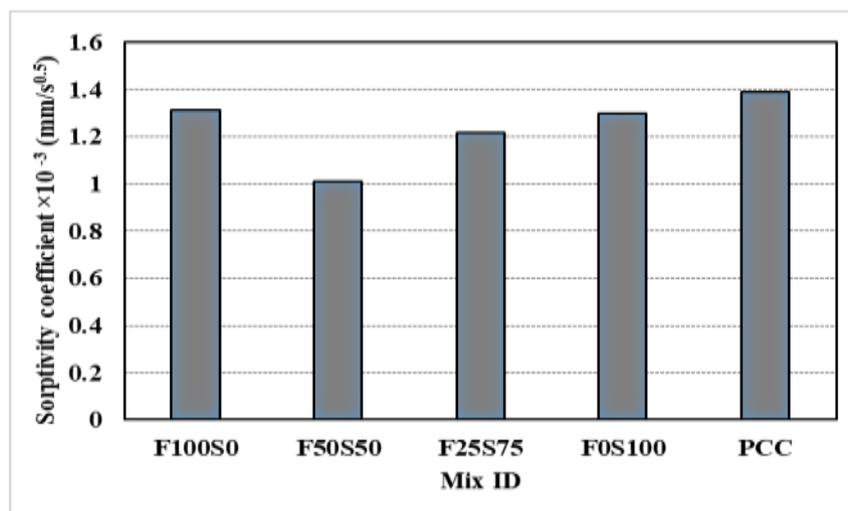


Fig. 11: Sorptivity coefficient of different concrete mixes at 28 days

Rapid chloride penetration test

Figure. 12, illustrates the RCPT test results of GPC and PCC samples. The results showed that using of GGBFS with FA or GGBFS only has greater influence on the reduction of chloride ion penetration through GPC samples. However, in terms of charge passed higher chloride ion penetration was seen for 100% FA-based GPC samples. The charge passed into GPC mixes like F100S0, F50S50, F25S75 and F0S100 are 29343.6, 22014.9, 8474.4 and 3019.5 Coulomb, respectively.

It is established that GPC samples showed higher resistance to chloride ion penetration than PCC mix, giving GPC with chloride the superior durability properties. Such findings are in line with the results obtained by references [78-80].

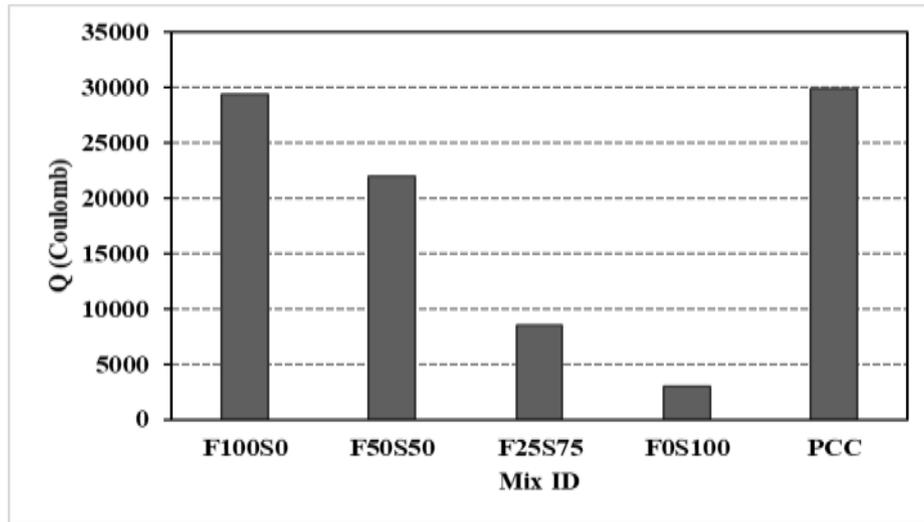


Fig. 12: Charge passed for GPC and PCC mixes

Sulphate resistance

Figure.13 and Table 5 show the compressive strength and weight loss in percentage for concrete mixes F100S0, F50S50, F25S75, F0S100, and PCC at 28 days, 56 days, 90 days, and 120 days.

Table 5: Compressive strength and loss of weight values of GPC and PCC mixes after exposed to 5% sodium sulphate solution at different ages

Mix ID	Loss of weight % (after exposure)				Compressive strength (MPa)				
	28 days	56 days	90 days	120 days	Before exposure	After exposure			
						28 days	56 days	90 days	120 days
F100S0	0.97	1.24	1.45	1.7	31.2	28.9	26.5	23.3	20.1
F50S50	0.6	0.94	1.11	1.4	52.7	52.4	51.9	49.4	47.6
F25S75	0.9	1.2	1.4	1.6	39	38.7	37.4	35.3	32.8
F0S100	0.93	1.1	1.3	1.7	39	38.6	37.01	34.6	31.1
PCC	1.03	1.3	1.61	2	29.8	27.6	23.4	20.3	17.2

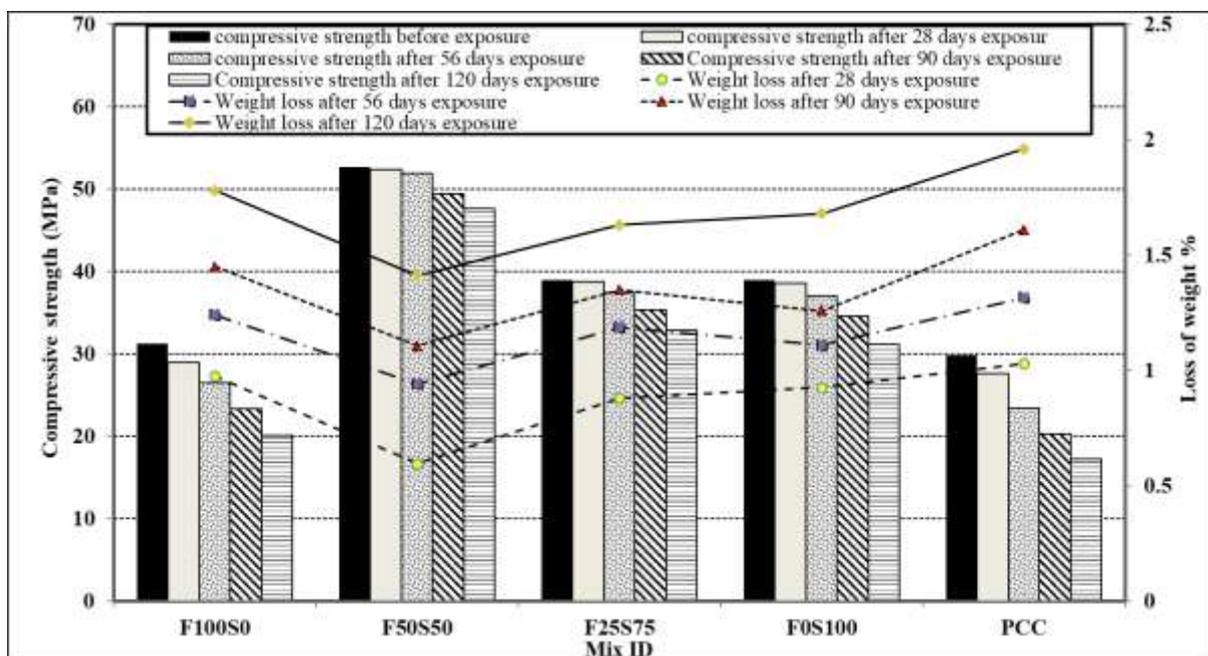


Fig. 13: Loss of weight and residual compressive strength for specimens exposed to 5% sodium sulphate at different ages

Regarding to the change in compressive strength from Fig. 13, it is observed that compressive strength of F100S0, F50S50, F25S75, F0S100 and PCC mixes decreased gradually to 7.3%, 0.45%, 0.62%, 0.9%, 7.4%, respectively after exposure for 28 days and decreased to 15%, 1.42%, 3.9%, 4.98%, and 21.45%, respectively after exposure for 56 days and decreased to 25%, 6.11%, 9.3%, 11.2%, and 31.9%, respectively after exposure for 90 days compared to unexposed specimen. The highest residual compressive strength during 120 days was noted for F50S50 mix which contained 50% GGBFS. According to the test results, F100S0, F50S50, F25S75, and F0S100 suffered a minimum of strength loss, whereas PCC experienced the most. Additionally, it was reported that GPC concrete has better sulphate resistance than PCC [81]. Sulphate ions $(SO_4)^{2-}$ had a minimally detrimental impact on the compressive strength of geopolymer concrete [81]. In comparison to PCC, it could be seen that FA-based GPC suffered the least strength loss when 50% GGBFS additions were included and has good resistance to the aggressive environment.

Regarding to the change in weight from Fig. 13, It should be noted that the percentage weight loss of each mix rises with the duration of immersion. During 28 days, 56 days, 90 days, and 120 days of immersion in a 5% sulphate solution, the percentage of weight loss is higher in PCC than in GPC. The results of weight loss due to the leaching of Si in the geopolymer gel structure and the transfer of sulphate ions caused by the dissolution of siloxane linkages (-Si-O-Si-bonds) may be what happened when geopolymer concrete samples were submerged in sulphate solution. This agree with findings that reporter by **Nagajothi, et al,2022** [79].

Resistance to elevated temperature

The effect of elevated temperatures on compressive strength and weight of different concrete mixes at various temperatures is tabulated in **Table 6** and displayed in Fig. 14.

Table 6: Influence of elevated temperatures on compressive strength and weight of different concrete mixes

Mix ID	Compressive strength (MPa)					Loss of weight%			
	20 ± 2 °C	200 °C	400 °C	600 °C	800 °C	200 °C	400 °C	600 °C	800 °C
F100S0	31.2	34.1	31.8	28.6	19.2	0.25	1.1	4.34	11.4
F50S50	52.7	56.8	54.6	48.4	38.4	0.25	1.06	2.23	2.5
F25S75	39	41.4	38.2	33.8	23.7	0.25	7.13	9.6	10.4
F0S100	39	41	37.6	32.7	22.4	0.25	1.7	3.8	9.3
PCC	29.8	26.3	22.6	13.7	8.6	0.87	5.4	9.2	13.8

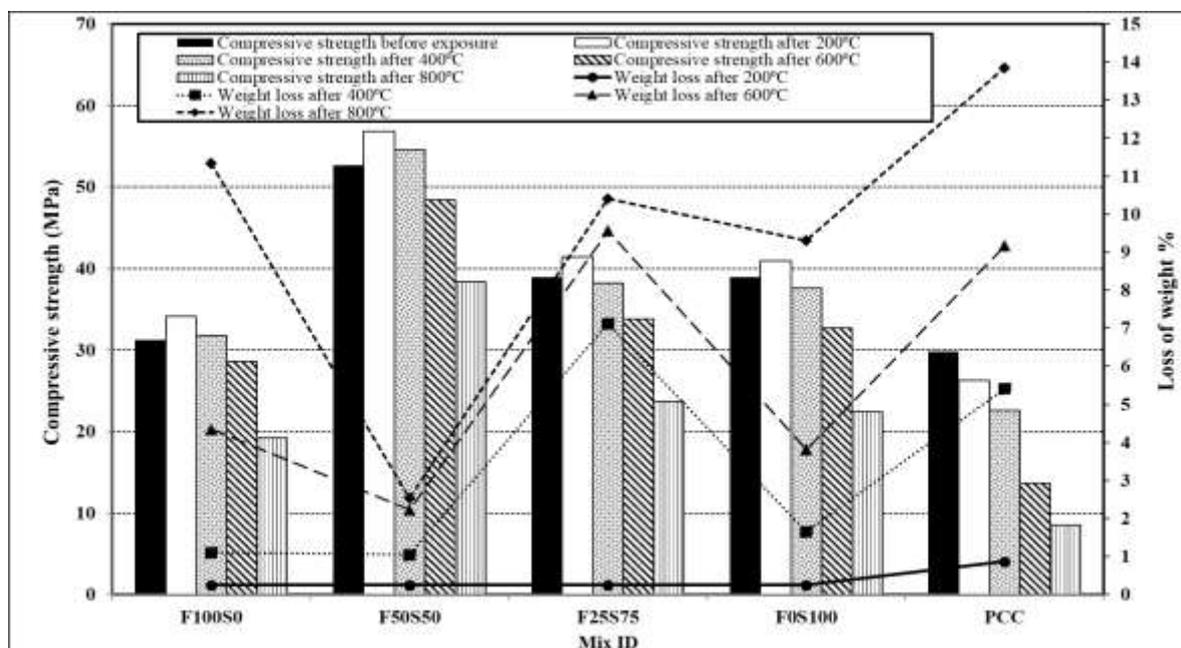


Fig. 14: Residual compressive strength and loss of weight caused by exposure to elevated temperatures

As seen in (Fig. 14), the compressive strength of the GPC samples dramatically increased after being exposed to a temperature of 200 °C. As contrasted to that unexposed samples, the compressive strength of F100S0, F50S50, F25S75, and F0S100 increased by approximately 9.3%, 7.9%, 6.3%, and 5.2%, respectively. For GPC mixes, full geopolymerization in the matrix may be responsible for the increase in compressive strength at 200 °C. However compressive strength of PCC sample decreased after exposing to a temperature of 200 °C by percentage 11.71%.

On the other hand, heating to 400 °C and 600 °C resulted to compressive strength reduction of about 6.7%, 3.9%, 7.7%, and 8.3% after exposed to 400 °C and 8.3%, 8%, 13.2%, and 16.1%

for F100S0, F50S50, F25S75, and F0S100, respectively. The decrease in compressive strength could be a result of the thermal discordance between the geopolymer matrix and the aggregates, which caused internal stresses to build before cracks began to degrade the concrete [83, 84].

As well as, the compressive strength of GPC samples decreased after exposed to 800 °C by percentage 38.5%, 27.1%, 39.15%, and 42.5% for F100S0, F50S50, F25S75, and F0S100 respectively. According to Guerrieri and Sanjayan (2010) [85], this reduction is caused by the chemically bound water being released, and the binding between hydrated water is completely destroyed at 800 °C.

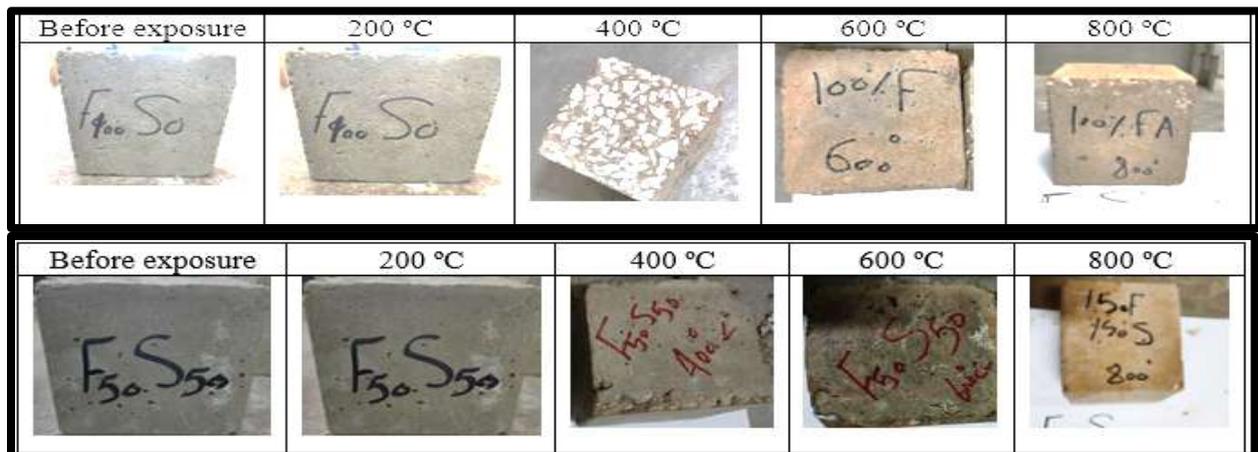
Moreover, The PCC mix suffered a significant decrease of strength after exposed to 400 °C and 600 °C can be linked to calcium hydroxide's $[Ca(OH)_2]$ dissociation, one of the primary products of the hydration of Portland Cement [86]. Ionic compounds dissociate, or break up into tiny pieces, between 300 °C and 400 °C, while $[Ca(OH)_2]$ dehydrates, or loses water, between 500 °C and 600 °C [81], which also reduces the strength of PCC concrete.

Additionally, the percentage of weight loss after exposure to elevated temperatures is presented in Table 6 and is plotted in Fig.14. For samples of GPC and PCC, the weight change at 200 °C was negligible and undetectable. When the temperature rises to 400 °C, 600 °C, and 800 °C all specimens progressively lose weight. The most significant weight decrease occurred in the PCC mix but the weight loss was about 13.84% at 800 °C. On the other hand, the lowest percentage of weight loss was in the F50S50 mix by 2.5% Compared to the samples before exposure.

Damage and colour changes of concrete mixes at different temperature levels

As demonstrated in Fig. 15, in response to exposure to elevated temperatures, colour of geopolymer concrete changed. At 800 °C, the geopolymer concrete turns from a normal dark grey to a salmon pink colour. From 400 °C and above, this colour change is also accompanied by an increase in the amount of surface cracks on the geopolymer concrete specimens. This is because of the significant increase in iron oxide in FA and GGBFS and the oxidation of the iron particles in FA and GGBS at high temperatures, which are the sources of the apparent colour change in geopolymer [87].

On the other hand, in the PCC samples colour changed from dark gray to light gray at 800 °C, while no cracks appeared at 400 °C, and cracks already appeared at 600 °C. According to various research, the chemical composition of PC and FA, reveals that the FA contain around five times as much iron oxide as cement [86].



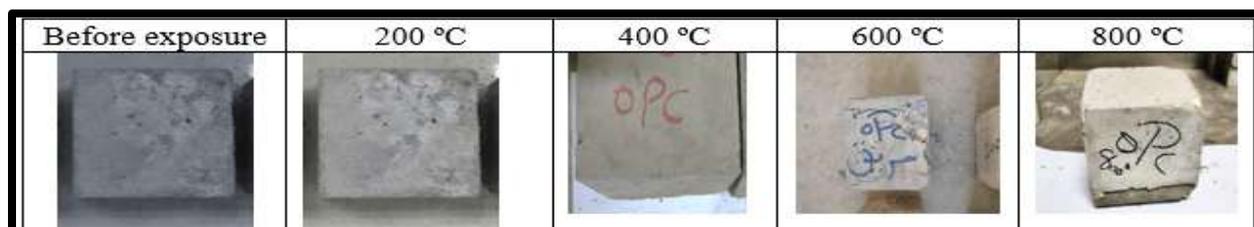


Fig. 15: The physical effects of elevated temperatures on different concrete mixes a) F100S0, b) F50S0, c) PCC

IV. Conclusions

New commercial repair materials are created and used worldwide every year, but not all of them improve the sustainability of the environment. When a repairing material is inexpensive, eco-friendly, and has good mechanical and durability properties, it is regarded as being of high quality. A geopolymer is the ideal option for such applications. This research aimed to create blended FA- GGBFS GPC that has qualities that make it useful for worn structures, infrastructure and road pavements in both the fresh and hardened properties and compared with Portland cement concrete as a repair material. The findings of the experimental test revealed the following:

1. From the investigation of the mechanical properties, it was observed that a GPC mix with 50% GGBFS achieves the best compressive strength and can be used as a substitute for conventional concrete as a repair material.
2. The blended GPC with 50% GGBFS exhibited good bond strength in pull-off test to the cementitious concrete for dry interface surface condition.
3. The geopolymeric repair materials outperform cement repair in terms of abrasion resistance. The best percentage of GGBFS was 50% which achieved depth of wear 0.7 mm. Comparing with PCC mix the depth of wear reduced by 62.4%.
4. Geopolymer concrete has a slightly lower rate of water absorption than Portland cement concrete. GPC mixes with 50% GGBFS showed better sorptivity coefficient compared to 100% FA-based GPC mixes. PCC mix had higher sorptivity coefficients, indicating GPC's more sustainable water access.
5. Geopolymer concrete exhibits a lower percentage loss in compressive strength owing to sulphate attack at different ages. As well as, the percentage of weight loss is higher in PCC mix by 39% than in GPC mixes due to sulphate attacks.
6. Using of 50% GGBFS contribute the best performance in elevated temperature compared with other mixes. After being exposed to 800 °C, GPC concrete developed more structural stability than Portland cement concrete. GPC concrete began to show surface cracks between 600 and 800 °C, but OPC concrete started to show cracks significantly earlier at 200 °C.
7. Due to its sustainable and diversified components and superior properties to ordinary concrete, geopolymer concrete based on FA and GGBFS is one of the reliable substitutes for conventional concrete as repairing material.
8. Further studies are required to promote the use of geopolymers for various applications as repairing materials. The studies must be performed in other durability properties such as freezing- thawing, and carbonation. On the other hand, the cost of manufacturing process of geopolymer concrete as a repair material need to be investigate.

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