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Durability Performance of One-Part Geopolymer Versus Two-Part Geopolymer and Portland Cement Mortar

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Abstract- **The investigations in the field of geopolymer binders indicated that this new material has a great potential to be an alternative to cement to reduce the carbon dioxide emissions. On the other hand, it was found that the traditional geopolymer has multiple defects, including the presence of viscous corrosive solutions. Researchers were interested in solving this problem and the traditional type was developed into one-part geopolymer and the need for solutions became in its composition and it became possible for this material to be an alternative to cement. But until now there are unexplained issues about one part geopolymers. In this instance, this study aims towards the investigated the fresh and hardened properties of one-part geopolymer mortar versus two-part geopolymer mortar and PC. The fresh and hardened properties that include workability, compressive strength, sulfate resistance, acid resistance and heat resistance were studied for samples cured at 30 OC and compared to PC samples cured by immersing in water. Moreover scanning electron microscopy (SEM) was investigated to support the test results. The results showed that, workability of one-part geopolymer mortar was enhanced by adding fly ash (FA). Moreover, the results revealed that higher compressive strength was achieved by adding ground granulated blast furnace slag (GGBS) and one-part geopolymer mortar exhibited superior resistance to sulfate, acid and heat by compared to PC. According to a SEM test one-part geopolymer mixes including GGBS were found to be more homogenous and dense than those containing FA.**

Keywords- **Geopolymer, One-part geopolymer, Two-part geopolymer, Durability performance, Sulfate resistance, Acid resistance, Heat resistance.**

I. INTRODUCTION

In recent years, with the increase in population, the demand for the use of portland cement (PC) as one of the basic building materials has become very large. PC contributes to the emission of 5 to 8% of global dioxide emissions for the year 2006 [1]. There are many attempts by researchers to find alternative materials to PC for example, the effect of adding rice straw ash (RSA) and cotton stalk ash (CSA) as replacement of cement in self-compacting concrete was studied by Agwa et al. [2], and the results showed that it is possible to add CSA as partial replacement of cement in construction materials. Amin et al. [3] studied the effect of adding many admixtures and also used ceramic wastes as a coarse aggregate to improve the performance of concrete.

Geopolymeric mortar was one of the prospective partial replacement materials for PC, because geopolymer has low permeability and a good fire resistance [4]. Geopolymer consists of a combination of aluminosilicate materials and a high concentration of alkali solutions [5]. Geopolymer is classified as an environmentally eco-friendly material, and thus because it produces less carbon dioxide and has high mechanical properties which were studied by many researchers [6-11]. Despite the great effort exerted by researchers to develop geopolymer, they have insurmountable drawbacks such that the solutions used in their formation are corrosive and viscous. Consequently, The discovery of a one-part geopolymer “just add water” is a step forward in the field of manufacturing geopolymer mixtures, and it consists of aluminosilicate sources and powder solid activators that directly mixed with water when the usage [12-14].

According to one-part geopolymer mortars, GGBS, which has been the primary binder in alkali-activated materials, has a high potential, according to many studies [15]. The created alkali-activated slag binders have a high calcium content [16], which could result in a rapid setting time [17], a low hydration heat [18], and acceptable mechanical and durability characteristics [18-20]. It was reported by Askarian et al. that the 28-day compressive strength of one-part geopolymer mortar reached to 38.8 MPa at ambient curing [21]. The plain alkali-activated slag binders exhibit brittleness under flexural and tensile tests, much like other cementitious compositions. Additionally, drying shrinkage for alkali-activated slag binders is much higher than for PC-based compositions [22].

On the other hand, many investigations were conducted recently in order to clarify the role of calcium during the geopolymerization process and the structure of one and two-part geopolymers in the presence of various calcium sources [23-27]. It was reported that the basic molecular unit is said to have a negative charge because of the AlO4 tetrahedral groups, which are charge-balanced by alkali metal cations like K+ or Na+. When the synthesis is conducted in the presence of a reactive calcium source, the Ca2+ ion has a chance to neutralize the negative charge instead of K+ or Na+ ions [28].

Moreover, it was reported that geopolymers that harden at ambient temperature or higher have durable and stable high-temperature characteristics and can be used since protective insulation components have garnered a lot of interest [29,30]. Another research by Djobo et al. (2016) [27] examined geopolymer materials with various activator

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concentrations and curing temperatures, and they observed that the change in curing temperature from 60 °C to 80 °C had no effect on the composition of the geopolymer. Additionally, according to Ranjbar et al. (2014) [31], when exposed to temperatures as high as 500 °C, geopolymer mixtures grew stronger than comparable examples that were not subjected to elevated temperatures.

Due to the extent of the concrete's application area, it is difficult to completely avoid being exposed to issues with durability like sulfate resistance, acid resistance and high temperatures. Therefore, the service life of concrete will be longer the greater its resistance to outside influences. Several affect, including sulfate resistance, acid resistance and fire could happen in the environment where the concrete is used, depending on the type of reinforced concrete building. These are the factors that have a detrimental impact on the strength and durability of concrete. Besides evaluating the durability performance of one-part geopolymer has become critical, but there is limit studies addressing this issue [32]. To overcome this problem, it will be helpful to evaluate the durability of one-part geopolymer mortars as an alternative of cement against these negative effects. This study was conducted to contribute to the literature because there have been a few differences in the durability findings obtained from one-part geopolymer mortars. The experimental durability results from FA, GGBS, or FA-GGBS composite mortars activated by NSP, NC, and CH are therefore covered in this article.

II. EXPERIMENTAL WORK

2.1. Materials

In this study, fly ash (FA) and/or ground granulated blast furnace slag (GGBS) were used as aluminosilicate materials. According to ASTM C618-12 [33], FA (class F) (low calcium) was acquired by a Sika Company for Construction in Egypt. GGBS was gathered from the Helwan steel factory in Cairo, Egypt. Table 1 lists the chemical compositions of FA and GGBS as determined by X-Ray Fluorescence (XRF) analysis according to suppliers. A control mixture that complied with the specifications of (EN 196-1:2016) [34] was prepared using Portland cement (PC) (CEMI 42.5N) for the comparison. Table 1 displays the characteristics of the used PC.

Sodium metasilicate pentahydrate (Na2SiO3.5H2O) (NSP), calcium hydroxide (Ca(OH)2) (CH), and sodium carbonate (Na2CO3) (NC) were the solid activators (powder) used for one-part geopolymer mortars. Table 2 lists the properties of the used solid activators for one-part geopolymer mortars. 99% pure NC powder, 95% pure CH, and NSP were purchased from Al-Radwan Chemical Company in Tanta, Egypt. For two-part geopolymer, the liquid activator is a mixture of sodium hydroxide (NaOH) (NH) pellets with 98–99% purity and sodium silicate (Na2SiO3) (NS) solution with a chemical composition of (Na2O = 14.7%, SiO2 = 29.4%, and water by mass = 55.9%), as determined by the manufacturer, and a density of 1480 kg/m3. The NH solution is made by dissolving it in water that is palatable, which is then allowed to stand for 24 hours.

According to ECP 203-2019 [35], the fine aggregate employed was medium well graded silicious sand that was sieved over sieve size 4.75 mm. The limits of ECP 203-2019 [35] and the grading of the used sand are depicted in (Fig. 1). In addition, Table 3 gives the properties of the used sand.

Table 1. The chemical compositions, physical and mechanical properties of used FA, GGBS and PC

Chemical compositions				
Oxide %		FA	GGBS	PC
SiO_2		61	41.66	20.39
Al_2O_3		18	13.96	5.6
Fe_2O_3		5.2	1.49	3.43
TiO_2		2.08	0.58	-
MnO		0.01	0.35	-
MgO		1	5.53	2.91
CaO		6	34.53	63.07
Na_2O		0.7	0.49	0.38
K_2O		0.8	0.97	0.35
SO_3		-	-	0.7
P_2O_5		0.41	0.01	-
LOI		0.2	0.05	2.06
Physical and mechanical properties				
Specific gravity		2.4	2.9	3.15
Soundness (mm)		-	-	2
Specific surface area (cm^2/g)		4500	5000	3300
Initial setting time (min)		-	-	150
Final setting time (min)			-	240
Standard consistency (W/C %)		-	-	28
Compressive strength (MPa)	3 days	-	-	17
	28 days	-	-	45

Table 2. The properties of the used solid activators for one-part geopolymer mortars as given by the suppliers

Property	Value		
	NSP	CH	NC
Na_2O %	29	-	-
SiO_2 %	28.5	-	-
pH (1% solution in water)	12.5	12	11.5
Specific gravity	2.61	2.21	2.54
Appearance	White powder	White powder	White powder

Table 3. The properties of the used sand

Property	Value
Specific gravity	2.55
Unit weight (t/m^3)	1.72
Void ratio (%)	32.55
Fineness modulus	2.46
% clay and fine matter (by weight)	2
Water absorption %	0.9

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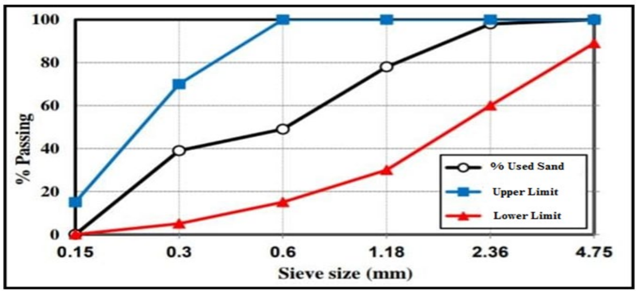

Figure 1. The grading curve of the used sand.

2.2. Methods of curing

For curing samples in this study, two methods were used. All one-part geopolymer samples after pouring were placed at thermal curing (TC) (30 oC) until the day of testing at ages 7, and 28 days similarly for the geopolymer sample. For PC samples, after casting, the samples were left outdoor for 24 hours under 17 ± 5 oC, 55% RH, and then demolded and immersed in water tank for curing (WC).

2.3. The Proportions and Preparation of Specimens

One-part geopolymer is made similarly to traditional Portland cement. Sand, solid powder activators and source materials were mixed together in a pan with a capacity of 60 litres for 2 minutes as the initial stage. The second step, which took more than five minutes, was to add water to the dry mixture.

For two-part geopolymer, before beginning the mixing process, the NH solution was made 24 hours in advance. It was then combined with the NS solution and left for an additional 2 hours. In the next phase, the FA and/or GGBS were added to the mixer and mixed for 5 minutes with the alkaline solution before sand was gradually added and stirred for a further 5 minutes. After mixing, the new mixture was put into the moulds, and it was compacted for 30 seconds on a vibrating table to release any trapped air and to guarantee the homogeneity of the mixture.

To prepare the PC mixture mortar, after combining PC and sand for two minutes, water was added, and the mixture continued to mix for an additional three minutes, until it was glossy and completely combined. All specimens were demolded and cured by WC after 24 hours of casting.

The proportions of geopolymer mortars are given in Table 4, the solid activator was prepared by incorporating 16% NSP, 4% NC and 4% CH by weight of binder. Mix 2GM composed up of a solution of NS and NH (10M) and (NS/NH= 1.5). Sand to binder was always used in a 3:1 ratio. However, the amount of GGBS and FA varied while the binder content was kept constant at 450 g.

Table 4. The proportions of main mortar mixes

Mix No.	Mix ID	W/b	Proportion of mortar, (g)								
			FA	GGBS	NSP	NC	CH	Sand	Water	Liquid Activator	PC
1	S100W40	0.40	0	450	72	18	18	1350	180	0	0
2	S50W35	0.35	225	225	72	18	18	1350	157.5	0	0
3	S30W28	0.28	315	135	72	18	18	1350	126	0	0
4	F100W35	0.35	450	0	72	18	18	1350	157.5	0	0
5	F100W26	0.26	450	0	72	18	18	1350	117	0	0
6	2GM	-	0	450	0	0	0	1350	-	288	0
7	CM	0.46	0	0	0	0	0	1350	207	0	450

Note; NSP: Sodium metasilicate pentahydrate, NC: Sodium carbonate, CH: Calcium hydroxide, W/b= water/binder, PC: Portland cement, 2GM: two-part geopolymer mortar, CM: cement mortar, Mix ID (S50W35) refers to: (S) GGBS with ratio 50% of binder, (W) water with ratio 35% of binder.

III. TESTS CONDUCTED

3.1. Fresh Tests

The fluidity of mixtures was measured in order to study their fresh properties. A flow table and a truncated die were used to determine the flowability according to standard ASTM C 1437-07 [36].

3.2. Mechanical Tests

On the other hand, the compressive strength test was carried out at the age of 28 and 56 days to measure the hardening properties. Prisms with dimensions (40 × 40 × 160 mm) were prepared to measure compressive strength according to EN 196-1:2016 [37] using digital hydraulic compression testing machine with 300 kN capacities.

3.3. Durability Tests

The following tests were conducted on geopolymer mortar mixes and control mix of PC to study the durability performance of geopolymer mortar mixes and compared results with the control mix of PC according to [38,39].

3.3.1 Sulfate Resistance

The resistance of different mortar mixtures against sulfate was measured through the change in the weight and the compressive strength. In order to measure the change of weight and the remaining compressive strength cubes of 50 × 50 × 50 mm were cast. After 28 days of curing, each specimen was weighted to know the initial weight. The specimens were submerged in a 5% concentration of sodium sulfate (Na_2SO_4) solution. To prepare the solution of 5% concentration, for each 100 gm. solution; 95 gm. of water and 5 gm. of Sodium sulfate powder (by weight) is added. For the purpose of keeping the concentration, the solution is changed every 14 days [38].

The change in weight and compressive strength was measured after the samples were exposed to the solution for 28, 56 and 90 days. The samples were weighed before immersing them in the solution and after the test period the samples were extracted and dried in the laboratory for a week, then weighed again to determine the change in weight. Moreover, to measure the residual compressive strength, the

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specimens were removed from the sulfate solution, left it to dry and then tested in compressive test machine according to EN 196-1:2016 [37].

3.3.2 Acid Resistance

The resistance of different mortar mixtures against acid was investigated through the change in the weight and the compressive strength. Cubes of 50 × 50 × 50 mm were cast to measure the loss of weight and the residual compressive strength. After 28 day of curing, each specimen was weighted to know the initial weight.

Subsequently, the specimens were submerged in a 5% concentration of sulfuric acid (H_2SO_4) solution. For each 100 gm. of the solution, 95 gm. of water and 5 gm. of acid sulfate powder (by weight) were added to create the 5% solution. Also, the solution is changed every 14 days to maintain its PH. The specimens were exposed to the solution for 28, 56 and 90 days, and at each period the remaining compressive strength and change in weight were checked [38].

To measure the change of weight, the specimen were taken out and left to air dry in the laboratory condition for a week. Then weights of the specimens were measure during the weighing scale available in laboratory and from that change in weight was calculated. Compressive strength was measured according to EN 196-1:2016 [37].

3.3.3 Heat Resistance

An electric furnace having a heating capacity of 1250 ºC was used to determine the resistance of different mortar mixtures against high temperatures according to ASTM E831 (2014) [40]. After 28 days of curing for all one and two part geopolymer samples at 30 ^{O}C and PC that cured in water, all samples were placed in the laboratory until the time of testing at 17 ± 5 ºC, 55% RH. Cubes of 50 × 50 × 50 mm were cast to measure the residual compressive strength. Three cube specimens from each mortar mix were exposed to 200 ºC, 400 ºC, 600 ºC and 800 ºC temperature for 2 hours in the furnace. The rate of heating was 5 ºC / min for obtaining a constant relation between heating times and growing temperature. Then the samples were left in this furnace and it was switched off to cool the samples slowly for 24 h and the compressive strength was measured according to EN 196-1:2016 [37].

3.4 Scanning Electron Microscopy (SEM)

An electron beam-based microscope known as a scanning electron microscope (SEM) was utilized at the faculty of Science at Kfr-Elshiekh University in Egypt to study the surface structure of prepared specimens using a high resolution SEM. The samples that will be examined with SEM are first dried at 60 °C until the constant weight is attained. Following that, test samples of 10 × 10 mm^2 surface area and 3 mm thickness were cut from the 50 × 50 × 50 mm mortar specimens that had completed their curing period. The samples are then subjected to microscopic SEM observations of the final products morphologies.

IV. RESULTS AND DISCUSSION

4.1 Fresh and Mechanical Properties

4.1.1 Flow

The flowability values of different mixtures are plotted in Fig. 2. By replacing GGBS with FA, it is observed that the flowability values increased. Replacing GGBS content by 50% and 100% with FA for the mixtures S50W35 and F100W35 caused increasing in flowability value by 28.57% and 157.14 % respectively; over the mixture S100W40. This may refer to the fine spherical particles of FA [41]. Also, the increasing of water content resulted in an increase the flowability values and this observed for the mixtures F100W35 and F100W26 that the flow% was 90% and 35 %, respectively; at 0.35 and 0.26 w/b content.

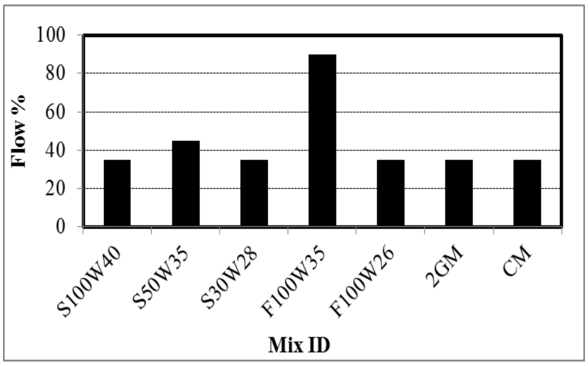

Figure 2. The flowability of different mortar mixes.

4.1.2. Compressive Strength

The compressive strength of different mortar mixes are shown in Fig. 3. The mixture S100W40 which curing at 30 ºC for 28 days had the greatest compressive strength, which was around 43.17 MPa followed by the 2GM mixture that achieved 41.67 MPa, while the mixture F100W35 had the lowest value, 9.83 MPa that curing with the same method. At 28th day, the compressive strength for mix S100W40 that cured at 30 ºC was 43.17 MPa, whereas the compressive strengths for mixes F50S50W35, S30W28 and S0W26 which cured by the same method were 34.21 MPa, 28.33 MPa and 16.70 MPa, respectively; the decreases were 79.24%, 65.62% and 38.68% with respect to the mix S100W40, respectively. Moreover, for the control mix CM which was subjected to WC, the compressive strength was 29.51 MPa after 28 days. Hence, the compressive strength of single GGBS based geopolymer is higher than that of FA. This refers to the lower calcium content in FA [42].

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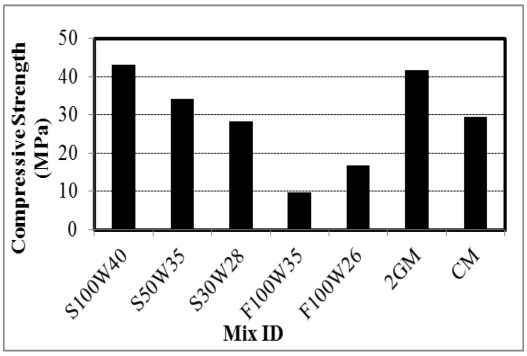

Figure 3. The compressive strength for different mortar mixes at 28 days.

4.2. Durability Test Results

4.2.1. Effect of Exposure to 5% Sodium Sulfate Solution

The sulfate resistance was evaluated based on changes in the physical appearance, weight and compressive strength after exposure periods of 28, 56 and 90 days.

After exposure to 5% Na2SO4 solution, no changes were found in one and two part geopolymer and PC samples.

In addition to, the change of weight is plotted in (Fig. 4) and presented in Table 5 after 28, 56 and 90 days of exposure.

Table 5. The Effect of Exposure to 5% Sodium Sulfate Solution on weight and Compressive Strength

Mix No.	Mix ID	Change of weight (g)				Compressive strength (MPa)			
		Before exposure	After 28 days exposure	After 56 days exposure	After 90 days exposure	Before exposure	After 28 days exposure	After 56 days exposure	After 90 days exposure
1	S100W40	270	271.50	272.70	274.86	43.17	40.15	36.70	34.83
2	S50W35	269.80	271.89	273.37	276.21	34.21	30.79	27.37	24.40
3	S30W28	269.93	272.43	274	277.20	28.33	24.36	21.53	19.76
4	F100W26	269.50	272.70	275.4	278.67	16.70	11.52	9.80	7.76
5	F100W35	269	272.53	275.10	278.40	9.83	6.59	5.60	4.10
6	2GM	269.90	271.22	272.43	274	41.67	39.58	36.67	35.30
7	CM	270	274.86	277.56	280	29.51	17.71	15.94	12.65

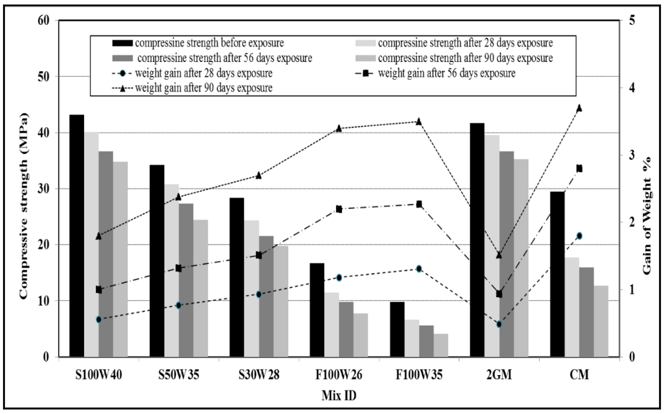

Figure 4. The change of weight and compressive strength due to 5% sodium sulfate exposure for different periods.

It was observed that the weight of both one and two part geopolymer and the PC samples significantly increased after being exposed to Na_2SO_4 solution after 28, 56 and 90 days. In contrast to the unexposed samples, S100W40, S50W35, S30W28, F100W26, F100W35, 2GM, and CM experienced weight increases of approximately 0.56%, 0.77%, 0.93%, 1.18%, 1.31%, 0.49%, and 1.80%, respectively; after 28 days of exposure and increased by 1%, 1.32%, 1.51%, 2.18%, 2.27%, 0.94%, and 2.80%, respectively; after 56 days.

The CM samples had the largest increase in weight, followed by F100W35samples after 90 days of exposure, whereas the percentage increase for CM and F100W35 samples was 1.87% and 1.29%, respectively, compared to the S100W40 samples. This may refer to the sulfate attack is dependent on the solubility of the calcium salt formed. As a result, the reaction products may be less stable than the reactants they are replacing, but they do so by occupying spaces (like holes or pores) in the material's structure, which causes an increase in weight during the exposure period.

Moreover, the change of compressive strength is given in Table 5 and plotted in (Fig. 4). The compressive strength was tested after 28, 56 and 90 days of sulfate solution exposure. For each type of mortar, the reference compressive strength was determined using the 28-day of curing compressive strength of mortar specimens without any exposure.

After exposure, the compressive strength of one and two part geopolymer and PC samples was measured. Through the results given in (Fig. 4), it was observed that the compressive strength of the samples S100W40, S50W35, S30W28, F100W26, F100W35, 2GM, and CM decreased gradually to 7%, 10%, 14%, 31%, 32.96%, 5% and 40%, respectively; after 28 days and decreased to 15%, 20%, 24%, 41.32%, 43%, 12% and 46%, respectively; after 56 days, compared to unexposed samples. This agree with results that reported by (Kumar and Ramesh 2017) [43].

The largest residual compressive strength after 90 days was recorded for 2GM followed by S100W40 samples due to higher alkaline concentration leads to better resistance of geopolymers upon sulfate exposure, as was reported by (Rangan et al. 2006) [44].

Hence, even after exposure up to 90 days, there was no significant decrease in compressive strength of one-part geopolymer samples. In addition, when exposed to sulfate solution for different time periods up to 90 days, the decreased in one-part geopolymer samples was less than that in PC samples; which indicates that the geopolymers have an excellent resistance to sulfate attack. This may refer to the much denser microstructure and the more stable polymerization of geopolymers [45].

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4.2.2. Effect of Exposure to 5% Sulfuric Acid Solution

By immersing one and two part geopolymer and PC samples in 5% sulfuric acid for 28, 56 and 90 days, the acid resistance assessment of each was evaluated.

The physical appearance, change in weight, and change in compressive strength of PC mortar and geopolymers mortar were displayed following exposure to sulfuric acid.

After being exposed to acid, the specimens of all mixtures erode with different ratios. It was observed that the surface damage to the samples increased with increasing the exposure time to the solution. Moreover, one-part geopolymer samples are less erosive than PC samples. (Fig. 5) demonstrates the physical appearance after 90 days of exposure to geopolymer and PC samples.

Figure 5. The physical appearance of geopolymer and PC samples after the exposure to 5% sulfuric acid.

Moreover, the loss of weight is plotted in (Fig. 6) and given in Table 6 after 28, 56 and 90 days of exposure.

Table 6. The Effect of Exposure to 5% sulfuric acid exposure on weight and compressive strength

Mix No.	Mix ID	Change of weight (g)				Compressive strength (MPa)			
		Before exposure	After 28 days of exposure	After 56 days of exposure	After 90 days of exposure	Before exposure	After 28 days of exposure	After 56 days of exposure	After 90 days of exposure
1	S100W40	269.93	267.30	265.80	263.38	43.17	37.87	34.53	29.13
2	S50W35	270	265.95	264.60	261.58	34.21	29.40	26	19.33
3	S30W28	269.80	265.40	263.52	259.63	28.33	21.93	20.11	12.96
4	F100W26	269.73	264.60	262.71	256.18	16.70	12.53	10.69	4.21
5	F100W35	269.55	264	262	255.43	9.83	7.37	6.20	2.33
6	2GM	269.87	267.30	265.86	264	41.67	38.17	34.60	30.22
7	CM	269.25	263.25	259.20	250.51	29.51	21.56	16.23	9.45

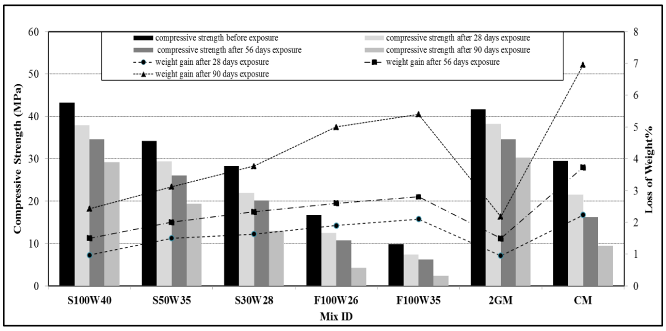

Figure 6. The change of weight and compressive strength due to 5% sulfuric acid exposure at different ages.

It was observed from (Fig. 6) that one-part geopolymer samples had a loss in weight, and also the longer the exposure time to the solution, the greater the percentage of loss in weight. The PC samples had the largest decrease in weight compared to the one and two parts geopolymer samples. The primary potential cause of geopolymers superior performance versus PC under sulfuric acid resistance is the lower calcium content of the source material. This due to the calcium content in PC is much higher due to lime being one of source material [46].

Moreover, compared with the samples that were not immersed in the H_2SO_4 solution, the weight loss percentage after 28 days of exposure of the samples S100W40, S50W35, S30W28, F100W26, F100W35, 2GM, and CM is about 0.97%, 1.50%, 1.63%, 1.90%, 2.10%, 0.95%, and 2.23%, respectively; and also it decreased by 1.5%, 2%, 2.33%, 2.60%, 2.80%, 1.49%, and 3.73%, respectively; after 56 days. After 90 days of exposure, it was observed that the largest weight loss percentage was for the CM sample compared to one-part geopolymer samples.

This may refer to the direct attack on the aluminosilicate structure and delamination is the causes of the weight loss of alkali-activated mortars in the presence of acids. This attack causes the Si-OAl bonds to be broken, which increases the amount of Si-OH and Al-OH groups in the alkali-activated systems and generates more silicic acid ions and dimers that migrate to the solution, causing a loss of weight in the materials [47].

In addition to, the change of compressive strength is given in Table 6 and plotted in (Fig. 6). The 28-day curing compressive strength of mortar specimens without any exposure was used as the reference compressive strength for all types of mortar. It was observed that the compressive strength of all mixes decreases upon exposure to the acid

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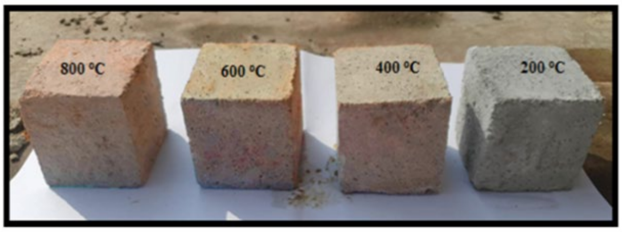
solution, as the resistance decreases with increasing exposure duration. The CM samples were the least resistant to acid solutions compared to one-part geopolymer sample (S100W40) and 2GM, whereas, the compressive strength of S100W40, 2GM and CM after 56 days of exposure was 34.53 MPa, 34.60 MPa and 16.23 MPa, respectively; the decreases values of compressive strength were about 20%, 16.97 and 44.93% respectively; compared to unexposed samples. After 90 days of exposure, the lowest residual value of compressive strength was 2.33 MPa for one-part geopolymer sample (F100W35).

Hence, this reveals that one-part geopolymer is more resistant to sulfuric acid than PC. The source material for geopolymer concrete includes calcium, which is an essential element in improving acid resistance. In addition to, using GGBS in the matrix results in a compact matrix with fine pore structure, which reduces acid penetration into the binder [48].

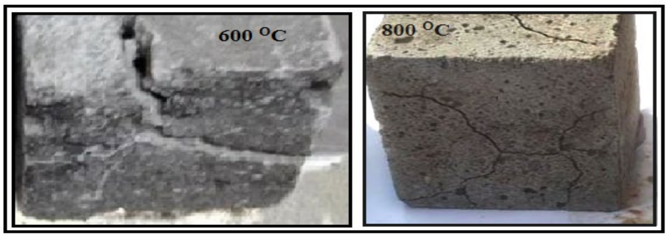
4.2.3. Effect of Exposure to Elevated Temperature

The effect of high temperature on different one and two part geopolymer specimens and PC samples was also studied. All one and two part samples have the same change in colour. Fig. 7-A depicts the color changes that happened in one-part geopolymer samples after being exposed to high temperatures from a normal dark grey to salmon pink at 800 ^{O}C. This due to the substantial increase in iron oxide in FA and GGBS and the oxidation of the iron particles in FA and GGBS at high temperatures are the causes for the visible colour change in geopolymer [30]. Moreover, it is clearly apparent that the surface of the geopolymer samples did not crack up to 600 ^{O}C.

On the other hand, in the PC samples, at 800 ^{O}C, colour changed from a typical dark grey to a light grey after being exposed to high temperatures. It is clear that up to 400 ^{O}C, the PC specimen's surface exhibited no signs of cracking. However, at 600 ^{O}C, PC specimens began to crack more noticeably, and at 800 ^{O}C, they were completely damaged as shown in (Fig. 7-B). In some studies, when looking at the chemical composition of PC, FA and GGBS, it can be seen that the FA or GGBS contain about five times more iron oxide than cement [49].



A: The effect of high temperatures on color of one-part geopolymer specimens



B: Damage of PC specimens at high temperature

Figure 7. The effect of exposure to elevated temperature on one-part geopolymer sample.

In addition to, the change of weight after 28 days of curing is shown in (Fig. 8). The change in weight at 200 ^{O}C for one and two part geopolymer samples was small and unnoticeable, as shown in (Fig. 8) and given in Table 7.

When elevated temperatures reach 400 ^{O}C, 600 ^{O}C, and 800 ^{O}C, all specimens gradually lose weight. The largest weight loss was for the CM specimen, whereas the loss of weight was about 10.20% at 600 ^{O}C compared to the specimen before the exposure (17 ± 5 °C, 55% RH).

Table 7. The investigated mortars exposed to elevated temperature.

Mix No.	Mix ID	The change of weight				
		Before exposure	After exposure			
		17 ± 5 ^{O}C , 55% RH	200 ^{O}C	400 ^{O}C	600 ^{O}C	800 ^{O}C
1	S100W40	269.67	268.15	267.30	265	263
2	S50W35	269.56	267.30	265.41	263	261.50
3	S30W28	269.73	266.50	264.60	261.90	260.60
4	F100W26	269.95	265.68	263.52	260	253.80
5	F100W35	269.83	265.18	263.30	259.33	253.40
6	2GM	269.78	268.38	268.15	266.22	264
7	CM	270	264.60	261.90	245	Failed completely

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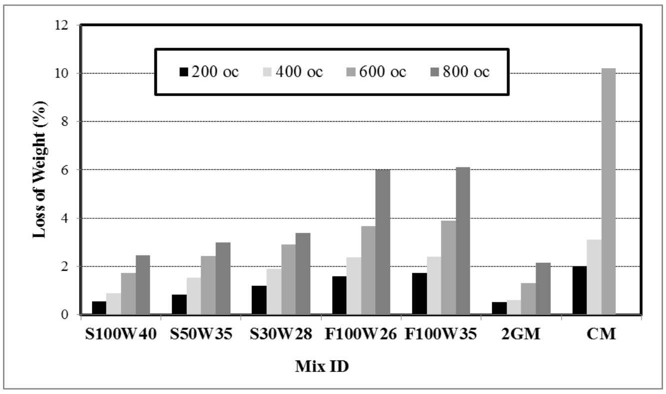

Figure 8. The loss of weight due to elevated temperature exposure at different temperature (%).

Moreover, the change of compressive strength is given in Table 8 and plotted in (Fig. 9). The compressive strength of both one and two part geopolymer and PC samples significantly increased after being exposed to a temperature of 200 ^{O}C, as can be observed in (Fig. 9), whereas S100W40, S50W35, S30W28, F100W26, F100W35, 2GM and CM recorded an increase in compressive strength about 47%, 35%, 33%, 31%, 30.21%, 55.60% and 29.11%, respectively; compared to that unexposed samples at 17 ± 5 ^{o}C, 55% RH.

The compressive strength of the CM samples began to decrease at a high temperature of 400 ^{O}C and 600 ^{O}C and recorded a 20.89% and 185.95%, respectively; reduction in compressive strength compared to unexposed samples, this agree with results that was reported by (Bingol et al., 2020) [50].

Moreover, The significant loss of strength experienced in the PC after 400 °C can be attributed to the dissociation of calcium hydroxide [$Ca(OH)_2$], which is one of the main products of the hydration of PC [51]. Dissociation is the process in which ionic compounds split into smaller particles and occurs between 300 and 400 ^{O}C, with the dehydration of [$Ca(OH)_2$] occurring between 500 ^{O}C and 600 ^{O}C [51], which also leads to strength reduction in PC concrete.

Table 8. The test results of residual compressive strength of mortar mixes exposed to elevated temperature after 28 days

Mix No.	Mix ID	Compressive strength (MPa)				
		17 ± 5 ^{o}C	200 ^{o}C	400 ^{o}C	600 ^{o}C	800 ^{o}C
1	S100W40	43.17	63.47	57.20	38.85	22.88
2	S50W35	34.21	46.18	42.76	29.42	17.29
3	S30W28	28.33	37.68	34.56	22.66	12.75
4	F100W26	16.70	21.88	20.37	12.55	6.51
5	F100W35	9.83	12.80	11.60	7.27	3.74
6	2GM	41.67	64.84	55.90	39.45	23.75
7	CM	29.51	38.10	24.41	10.32	Failed completely

Guerrieri and Sanjayan (2010) [52] reported that this reduction is caused by the chemically bound water being released, and that this bond of hydrated water is totally broken at 800 ^{O}C (Zero compressive strength recorded).

The compressive strengths of geopolymer specimens increased gradually with increasing elevated temperatures from 200 ^{O}C to 400 ^{O}C and began to decrease at 600 ^{O}C and 800 ^{O}C by reference to unexposed sample, as shown in (Fig. 9).

Hence, this may be relevant to the denser microstructure of the binding paste that resulted from the acceleration of chemical reactions between the GGBS and alkali activator by heating mortars to high temperatures. Additionally, after the free water is vaporized, the hydrate binder matrix is in a closer configuration, which results in stronger van der Waals forces because the gel layers are moving closer to one another. This strength increase of up to 400 ^{O}C is the result of this closer configuration. As of 600 ^{O}C, mortar compressive strengths started to decrease and as the temperature reached 800 ^{O}C these losses reached significant levels [53-55].

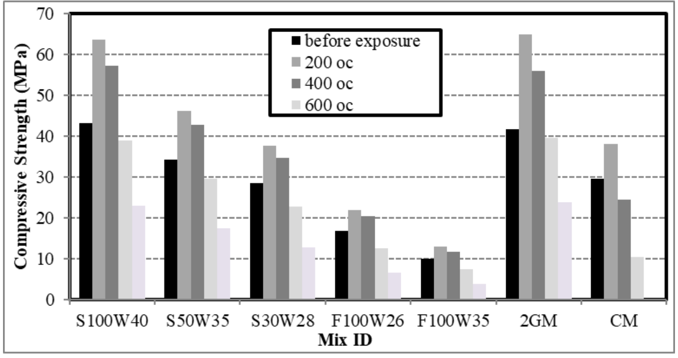

Figure 9. The residual compressive strength due to elevated temperature exposure at different temperature.

4.3. SEM Analysis

The SEM images of the one-part geopolymer samples and 2GM sample that all cured at 30 ^{O}C in addition to CM sample that cured by water for 28 days are shown in Fig. 10 at two different magnifications to clarify voids and cracks, if any. Images are more accurate the greater the magnification ratio.

It can be seen from Fig. 10 (A, D, C and F) that the microstructures of one-part geopolymer S100W40 samples are more homogenous than those of F100W35 samples which explain the higher compressive strength of S100W40 samples. Because the geopolymer gel produced by GGBS activation showed a more substantial space-filling feature than systems using FA, it was found that the gel area in the GGBS-based geopolymer mortar was significantly denser and had a more homogeneous microstructure. Therefore, mixture S100W40 had the maximum strength out of all the one part geopolymer mixtures [56].

Fig. 10 (B, C, E and F) display microstructures containing unreacted FA particles of different sizes. The reduced strength of CM and F100W35 samples was caused by pores and micro-cracks, which can be seen in Fig. 10 (F and I).

The F100W35 samples exhibit less compressive strength than the S50W35 samples because they include a larger amount of unreacted FA particles, resulting in a less dense matrix, which caused its compressive strength to be low at 28 day, 16.70 MPa. This agrees with the results of investigation conducted by Hongen et al., 2020 [57].

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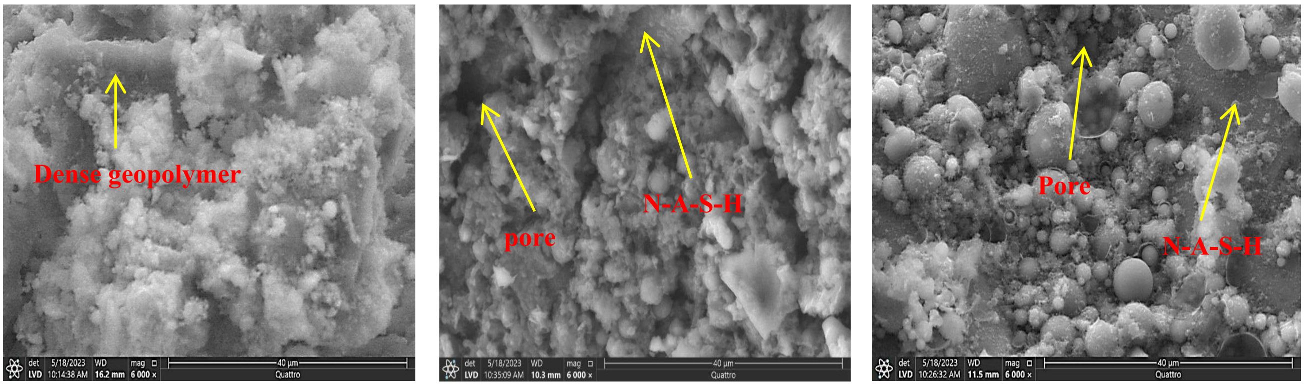
When liquid alkali activator was used, the process of alkali particle dissolution was sped up; preventing the particles from remaining un-dissolved or only partially dissolved, and the geopolymeric product could form shells around the metasilicate particles. This resulted in the mix 2GM having a dense surface morphology similar to S100W40 as shown in Fig. 10 (G and H) [58].

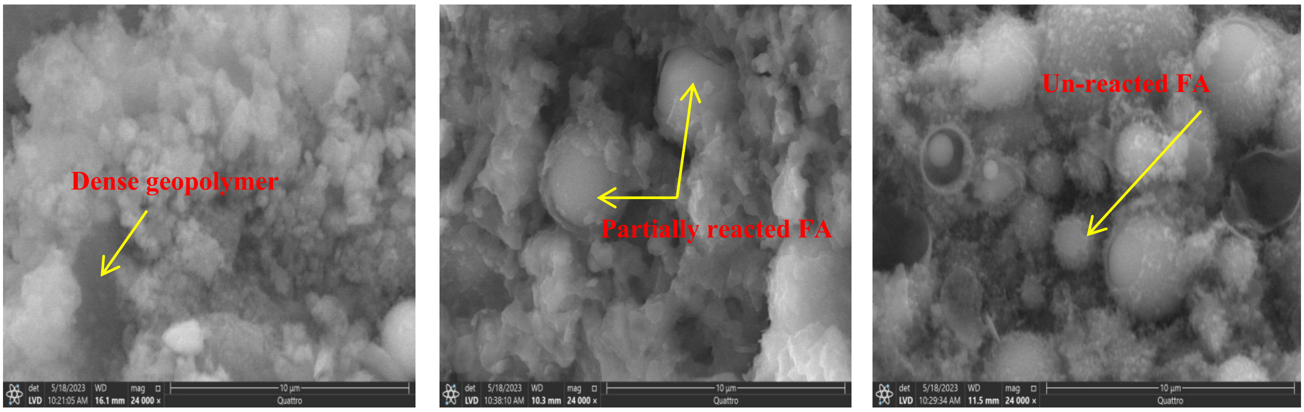
As can be seen from Fig 10 (I) the control mix CM has a poor microstructure that is less dense and less homogeneous than the microstructure of the geopolymer samples. Additional holes and calcium hydroxide (CH) crystals are seen with a reduction in the calcium silicate hydrate C-S-H [58].

SEM images of S100W40 and S50W35 samples at 600 ^{O}C are presented in Fig. 11. It can be seen several thermal microcracks and pores in the samples after exposure to 600 ^{O}C. Moreover, there was a significant reduction in the amounts of unreacted fly ash particles in S50W35 samples. The pores may have resulted from the matrix collapse caused by phase transitions and geopolymer degradation [59,60].

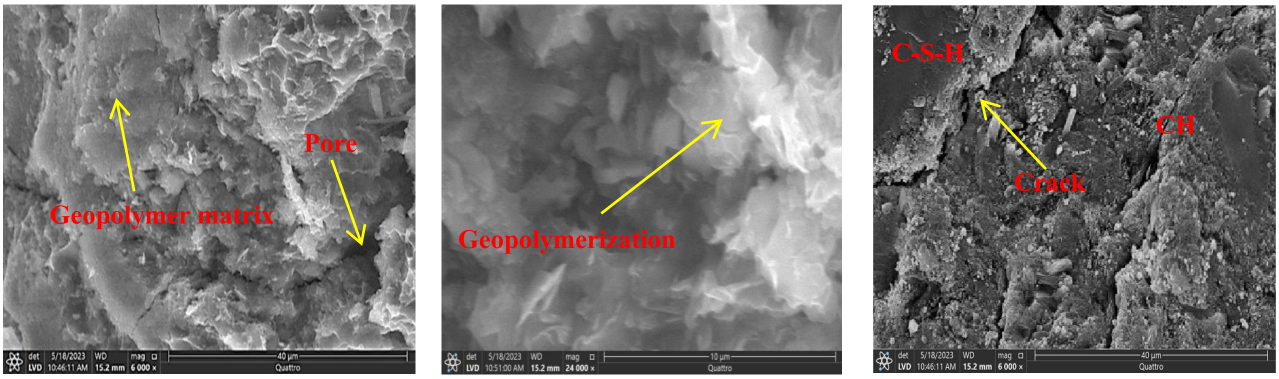
SEM was used to characterize one-part geopolymer S50W35 sample exposed to 5% of sulfuric acid after 90 days of exposure and this shown in Fig. 12. It can be observed a dense surface morphology but the samples have more pores and cracks. This agrees with Fernandez-Jimenez [61], who reported that alkali-activated specimens do not exhibit considerable changes in the structure after the exposure to acids.



A- S100W40 at 6000x B- S50W35 at 6000x C- F100W35 at 6000x



D- S100W40 at 24000x E- S50W35 at 24000x F- F100W35 at 24000x



G- 2GM at 6000x H- 2GM at 24000x I- CM at 6000x

Figure 10. SEM micrographs of geopolymer and PC mortars zoomed at 6000x and 24000x.

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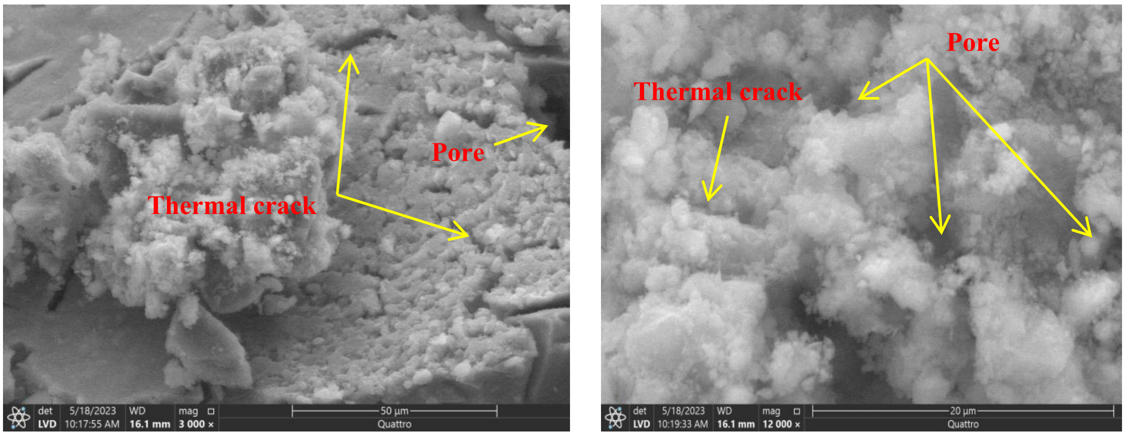
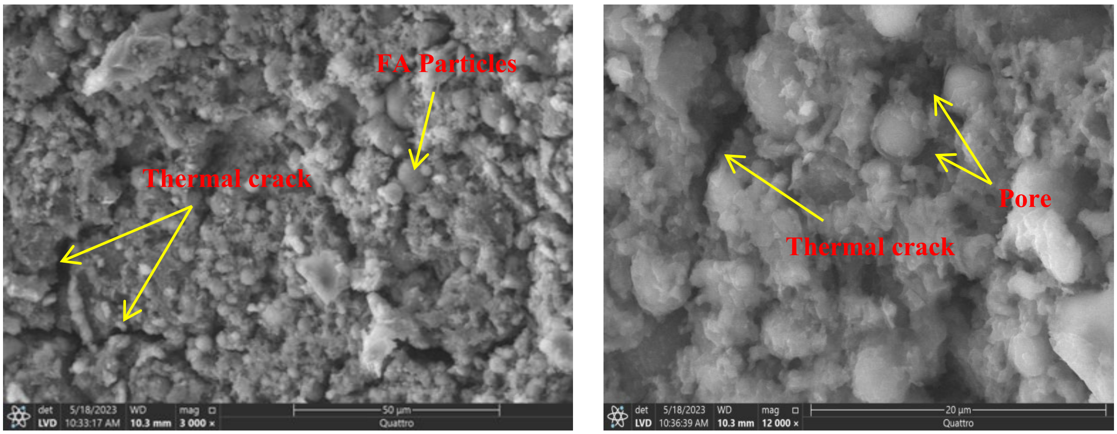
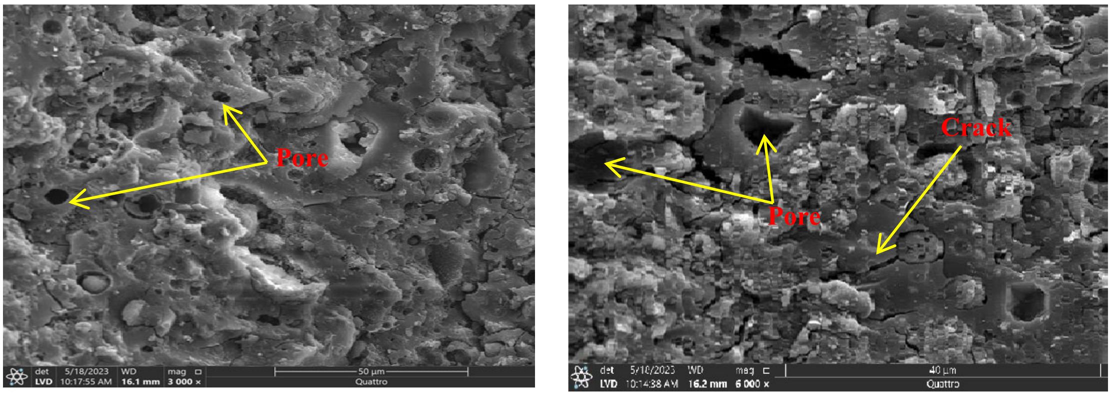


A- S100W40 600 ^{O}C at 3000x B- S100W40 600 ^{O}C at 12000x



C- S50W35 600 ^{O}C at 3000x D- S50W35 600 ^{O}C at 12000x

Fig. 11: SEM micrographs of one-part geopolymer mortars at 600 OC



A- S50W35 at 3000x B- S50W35 at 6000x

Figure 12. SEM of one part geopolymer mortar after 90 days of the exposure to 5% sulfuric acid.

V. CONCLUSIONS

This study amid at developing and investigating the durability performance of one-part geopolymer mortar versus two part geopolymer and Portland cement ones by performing various tests such the flow and compressive strength tests in addition to sulfate resistance, acid resistance and the exposure to high temperature. According to the tests carried out within the scope of this paper, one-part geopolymer mortars generally demonstrated better performance than PC mortar, and as a result. The paragraphs that follow summarize and highlight the explanation of the experimental study.

1. The flowability of one-part geopolymer mortar decreased with increasing in GGBS content. In addition to, one- part geopolymer mortars achieved high compressive strength after 28 days of curing by compared to PC samples, which compressive strength of one-part geopolymer mortar that contains 100% of GGBS reached to 43.17 MPa.

2. Based on the test results, one-part geopolymer mortars had a good resistance to sulfate attack. After being exposed to sodium sulfate solution for up to 90 days, the surface of test specimens appears undamaged. Moreover, after exposure to sodium sulfate solution, geopolymer and PC specimens experience a rise in weight and a decrease in compressive strength. However, one-part geopolymer specimens had the least loss in compressive strength and weight gain compared to PC.
3. Exposure to sulfuric acid solution damages the surface of all specimens and results in loss of weight following the exposure in addition to decreasing the compressive strength. However, one-part geopolymer specimens were better in sulfuric acid resistance than PC specimens.
4. The resistance of one-part geopolymer specimens to high temperatures was better than PC specimens, however, at 800 ^{O}C the compressive strength of one and two part geopolymer samples reached 22.88 MPa and 23.75 MPa, respectively; whereas the percentage of heat resistance for two-part geopolymer samples was slightly better than that of one Part geopolymer that consists of GGBS only, as the percentage of increase was 3.8% compared to one Part geopolymer samples
5. SEM test showed that the one-part geopolymer mixtures that contain GGBS are more homogeneous and denser than those that contain FA, and it showed that exposure to high temperatures causes a lot of thermal cracks, which leads to deterioration of the sample at different rates, in addition to that the samples when exposed to acids do not change their microstructure.
6. Further studies focusing on durability are still required.

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