A STUDY ON THE DURABILITY OF THE SLAG-BASED GEOPOLYMER CONCRETES CONTAINING BINARY SOLID MIXTURES IN CORROSIVE ENVIRONMENTS

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As a novel solution, to reduce or even eliminate the dependence on the ordinary Portland cement (OPC) which as an energy-intensive and highly polluting production, and simultaneously, for effectively using waste materials, Geopolymer concrete (GPC) has emerged. GPC is manufactured by using alkali-activated binders instead of OPC. In this study, the differences and impacts of the partial replacement of the Slag by the most common pozzolans such as Rice Husk Ash (RHA), Fly Ash (FA), Metakaolin (MK), Silica Fume (SF), and Zeolite on the durability of the Slag-based GPC are investigated. To evaluate the durability performance of the specimens, a series of tests including compressive strength (7, 28 and 90-days), Rapid Chloride Permeability Test (RCPT), Rapid Chloride Migration Test (RCMT) and Accelerated Corrosion Test (ACT) were performed. Also, the samples were exposed to Sulfuric acid solution in order to investigate the effect of this corrosive environment on the weight reduction and compressive strength changes of the mix designs. The results indicated that using up to 10% replacement of Slag in GPC with FA, SF and MK can improve the durability in RCPT, RCMT, and ACT and also can cause significant improvements in durability against Sulfuric acid in all replacement ratios.

Keywords: *geopolymer concrete, slag, durability, binder solid replacements*

1. Introduction

In recent decades, an abundance of efforts has been made in order to achieve practical solutions for efficiently recycling waste materials. Based on the recent studies, the wastes could be effectively utilized for industrial applications and by which the technical, environmental and economic challenges could be overcome. Today, the fast development of the construction industry has emphasized demands for energy production and subsequently, the environmental issues have risen alarmingly. Among all of the construction materials, cement needs prominent attention because its production is energy-intensive and highly polluting. A great amount of CO_2 is released into the atmosphere during the cement manufacturing process [1].

Accordingly, to prevent depletion of the natural aggregates and adoption of environmental sustainability, waste materials could be recycled and reused. Also, extensive attention has been paid to the by-product waste materials such as Fly ash (FA), Rice husk ash (RHA), granulated blast-furnace slag (GBFS) etc. to be partially replacements for cement in concrete [2-5]. As a novel solution, in order to reduce or even eliminate the dependence on the ordinary Portland cement (OPC) and simultaneously, effectively utilize the waste materials, geopolymer concrete (GPC) has emerged [6,7]. In general, geopolymers are introduced as alternative binders by that the OPC is fully replaced with materials that are rich in aluminosilicates such as GBFS [8]. Industrial wastes such as FA or GBFS are typically mixed with alkaline activating solutions such as potassium hydroxide, sodium silicate, sodium hydroxide and the mixture of sodium silicate and sodium hydroxide to produce a fly ash-based or slag-based GPC which shows mechanical properties equal or greater than that of the OPC concrete [9]. Moreover, the use of slag in the GPC can cause a further increment in durability properties while other pozzolans were not effective at that level. On the other hand, the presence of slag makes the mortar set more slowly compared to the OPC concrete and causes the mixture to gain strength in a longer period of time which leads to lower heat generation during the process of hydration [10]. Admittedly, the additives such as GBFS helps to reduce demands for the energy-intensive heat-curing processes and make it possible to achieve high strengths (28-day compressive strength up to 108MPa) [11]. In contrast to the OPC concrete which suffers from low resistance in corrosive environments, because of its alkaline nature, the GPC exhibits a great performance during encountering the corrosive conditions such as sulfate attacks, due to its more stable and robust cross-linked alumina-silicate polymer structure [12-15]. To enhance the durability of the GPC exposed to the aggressive environmental conditions, efforts have been made by adding the pozzolanic materials to the binder. For instance, in some of the studies, it was illustrated that the presence of the silica fume (SF) in the mortar, manages to markedly ameliorate the durability of the GPC exposed to the acid environments [16]. Xiao et al. [17] concluded that variation of silica to alumina ratio (Si/Al) and alkali solutions result in affecting the structure of the GPC and ionic transports. They reported that porosity affects migration of the alkali from the FA-based

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GPC to the ionic solutions and moisture plays an important role in the improvement of mechanical strength and durability. It was also depicted that as the structure of the FA-based GPC becomes denser, resistance against chloride, sulfate and acidic solutions is enhanced. Okoye et al. [18] evaluated the effect of SF on the long term durability of the FA-based GPC exposed to a corrosive condition containing 2% H_2SO_4 and 5% NaCl solutions. It was observed that in the case of the GPC containing 20% SF, the porosity of the binder decreased which led to a reduction in chloride penetration and thus, durability properties are significantly enhanced. Moreover, Lee et al. [19] reported that in slag-based GPC, the reactivity of the SF and aluminum particles of GBFS increased and consequently the process of polymerization was enriched which caused improvement in durability and resistance to the chloride penetration. The rice husk, as another waste material, contains 50% cellulose, 25-30% lignin and 15-20% silica [20]. After burning it in specific conditions, the remnant material which is known as Rice Husk Ash (RHA) consists of an abundance amount of silica and its behavior is similar to the pozzolans which can be utilized in the GPC [21]. Das et al. [22] carried out a study on the capability of the RHA as a potential natural material for the production of the GPC. They concluded that usage of the RHA improves both corrosion and sulfate resistance. Ramani and Chinnaraj [23] investigated the performance of the GPC contained GBFS and black rice husk ash (BRHA). They reported that the onset of corrosion for the specimens containing 10 and 20% BRHA occurred at 34 and 36 days, respectively, while it takes only 23 days for the control specimen without BRHA. Based on the statistics, 500 million tons of ash are annually produced, of which 75-80% are comprised of the FA [24]. The studies indicate that the FA-based geopolymer binder can provide improved properties when the fineness of the fly ash increased and by which the level of polymerization is promoted due to its greatly reactive surface [25, 26]. The Metakaolin (MK) is a mineral additive consists of both silica and alumina, which has been applied in the production process of the OPC concrete for years. It has been observed that mechanical properties and durability of concrete are ameliorated by using the MK due to its excellent pozzolanic activity and filling effects [27, 28]. Nuaklong et al. [29] studied the effect of replacing the FA with MK in the geopolymer binders. They concluded that this replacement could significantly improve the mechanical properties, abrasion resistance, transport properties and resistance against acid attacks. Quantitatively, it was observed that the replacement of 30% MK remarkably enhanced the compressive strength, porosity and water absorption of the recycled aggregate GPC with corresponding values of 134, 69 and 89% in comparison with the specimens without MK. One of the other feasible materials that can be potentially used in a binder, is the natural zeolite which consists of silicon and aluminum tetrahydrate which is linked by one oxygen atom [30]. Accordingly, Nikolov et al. [31] evaluated the possibility of zeolite using as a solid material in geopolymer and found that the obtained product had ample adhesion characteristics that can make the zeolite-based geopolymer an appropriate choice for plasters and coating. Based on the literature review, the GPC is capable of being successfully used in the construction industry as it reduces the need for cement production and also it showed improvements in strength and durability [32]. Moreover, the deterioration of urban and coastal concrete structures exposed to corrosive environments demonstrates the significance of concrete durability [33].

In this study, for the first time, a thorough comparison and investigation on the impacts of using the Rice Husk Ash (RHA), Fly Ash (FA), Metakaolin (MK), Silica Fume (SF), and Zeolite as alternative replacements on the durability of a Slag-based GPC is done. For this purpose, the slag was partially replaced with the RHA, FA, MK, SF and Zeolite with ratios of 10, 20 and 30%. To evaluate the durability performance of the specimens, a series of tests including compressive strength, rapid chloride permeability (RCPT), rapid chloride migration tests (RCMT) and accelerated corrosion test (ACT) were performed. Also, the samples were exposed to Sulfuric acid solution with PH=1 in order to investigate the effect of this corrosive environment on the weight and strength of the mix designs.

2 Materials and Methods

2.1 Materials

Coarse aggregates with maximum size of 12.5 mm, density of 2640 Kg/m^3 and water absorption of 1.5%, exploited from river deposits are used for mixes. The density and water absorption of the fine aggregates were 2620 Kg/m^3 and 2.5%, respectively. The coarse aggregates were graded in compliance with ASTM C33 [34]. For the sake of preparing the geopolymer, laboratory grade sodium silicate with specific gravity of 1.52 Kg/m^3 and SiO_2/ Na_2O ratio of 2, was used. The sodium hydroxide flakes with purity of 96% was added to distilled water and a solution with 10M (M=molarity) concentration was prepared. The compositions of the materials are presented in Table 1.

The materials used as replacements of Slag were silica fume (SF), fly ash (FA), metakaolin (MK), Zeolite and Rice Husk Ash (RHA) with density of 2200, 1450, 2600, 1100 and 2100 Kg/m^3, respectively. These materials are manufactured

Table 1

Materials composition

Composition (%)	Fly Ash	Slag	Metakaolin	Zeolite	Silica Fume	Rice Husk Ash
SiO_2	55.9	37.4	52.9	68.2	92.2	88.8
Al_2O_3	24.3	7.4	43.8	21.8	0.8	3.4
Fe_2O_3	7.7	27.6	0.5	1.3	1.9	1.3
CaO	8	20.5	0.3	4.3	1.8	2.7
MgO	1.6	2.8	1.2	1.4	1.5	1.4
TiO_2	1.3	3	0.6	0.1	0	0
Na_2O	0.3	0.5	0.3	1.5	0.9	0.8
K_2O	0.9	0.8	0.4	1.4	0.9	1.6

Table 2

Mix Design Proportions

Mix	Slag (Kg/m³)	RHA (Kg/m³)	Fly Ash (Kg/m³)	Meta-kaolin (Kg/m³)	Silica Fume (Kg/m³)	Zeolite (Kg/m³)	Na_2SiO_3 (Kg/m³)	NaOH (Kg/m³)	(SS+SH)/BS*	Fine aggregate (Kg/m³)	Coarse aggregate (Kg/m³)
SL100	350	-	-	-	-	-	125	50	0.5	997	1008
SL90-RHA10	315	35	-	-	-	-	125	50	0.5	997	1008
SL80-RHA20	280	70	-	-	-	-	125	50	0.5	997	1008
SL70-RHA30	245	105	-	-	-	-	125	50	0.5	997	1008
SL90-FA10	315	-	35	-	-	-	125	50	0.5	997	1008
SL80-FA20	280	-	70	-	-	-	125	50	0.5	997	1008
SL70-FA30	245	-	105	-	-	-	125	50	0.5	997	1008
SL90-MK10	315	-	-	35	-	-	125	50	0.5	997	1008
SL80-MK20	280	-	-	70	-	-	125	50	0.5	997	1008
SL70-MK30	245	-	-	105	-	-	125	50	0.5	997	1008
SL90-SF10	315	-	-	-	35	-	125	50	0.5	997	1008
SL80-SF20	280	-	-	-	70	-	125	50	0.5	997	1008
SL70-SF30	245	-	-	-	105	-	125	50	0.5	997	1008
SL90-ZE10	315	-	-	-	-	35	125	50	0.5	997	1008
SL80-ZE20	280	-	-	-	-	70	125	50	0.5	997	1008
SL70-ZE30	245	-	-	-	-	105	125	50	0.5	997	1008

*SH: Sodium Hydroxide (NaOH), SS: Sodium Silicate (Na_2SiO_3), BS: Binder Solid

in Iran by companies of Ferrosilice, ClinicBeton, Esfahan Steel, Kavian and Sanjesh Bonyan Sazeh. A polycarboxylates-based superplasticizer was used in the mixing process (with commercial name of FARCO PLAST P103R).

2.2 Specimen Preparation

The sodium hydroxide and sodium silicate were mixed for production of alkaline solution. Accordingly, the ratio of Na_2SiO_3 to NaOH, and alkaline solution to solid phase of the geopolymer paste were kept equal to 2.5 and 0.5, respectively. Moreover, the slag was replaced with the Rice Husk Ash (RHA), Fly Ash (FA), Metakaolin (MK), Silica Fume (SF) and Zeolite at replacement ratios of 10, 20 and 30% by slag weight. 16 concrete mix designs were manufactured and the mix designs details are given in Table 2.

To produce the concrete specimens, 10M NaOH solution and Na_2SiO_3 were mixed together and then remained in ambient condition for 24 hours before being used in the mixtures. The fine and coarse aggregates were prepared to satisfy the saturated surface-dry (SSD) condition. The aggregates and solid phase of geopolymer paste were mixed for about 2-3 minutes and then the superplasticizer and alkali activator solution were added. The process of mixing continued for 6 minutes before casting the mixtures into the molds. Then, all specimens were kept in the controlled-humidity room to be cured at the humidity and temperature of 96% and 21^{0}C, respectively. To ensure that the process of hardening had completely occurred, after 48 hours, the specimens were demolded and left in the ambient temperature until the testing time.

2.3 Testing Procedure

For the compressive strength test, the 10 cm cubic specimens were prepared and the compressive strengths were assessed after 7, 28 and 90 days the age of specimens. For the sake of evaluating the durability of specimens against chloride ingression, the rapid chloride permeability test (RCPT) was conducted at the age of 28 days according to ASTM C1202 [35]. In RCPT, the electrical charge passing through a concrete disc specimen with a thickness of 50mm is measured within 6 hours under the electrical potential of 60V [36]. The RCPT apparatus setup is shown in Figure 1.

Fig. 1- RCPT and RCMT apparatus setup.

There are many testing methods for evaluation of the chloride permeability in cement-based materials such as Bulk diffusion test, Electrical Migration techniques, rapid migration test, electrical resistivity test, water penetration under pressure test and etc. [35-44]. In this study, to measure resistance against the chloride penetration, the non-steady-state chloride migration coefficient was utilized by using rapid chloride migration test (RCMT) according to Nord Test BUILD 492 [45]. Table 3 presents correlation between the applied initial current and duration of test.

As illustrated in Figure 1, the 10% sodium chloride (NaCl) and 0.3M sodium hydroxide (NaOH) were used to form the cathode and anode, respectively. It should be mentioned that during the process of testing, the temperature has to be in the range of 20 to 25°C. In order to move the chloride ions from the NaCl solution into the specimen, an external electrical potential was applied to the specimen.

After the testing process, the specimens were split along their cross-sections. Then, the split surfaces were sprayed with 0.1M silver nitrate ($AgNO_3$) solution by which, the chloride penetration could be measured based on formed precipitates of silver chloride. If chloride increases on the surface after spraying the solution, it will create a whitish color, otherwise, it will be observed as brown color. As a result, the border of the area with changed color specifies the depth of chloride penetration. Subsequently, the depth of the chloride penetration was measured which was used to specify the diffusion coefficient using the following equation [45]:

$$D_{nssm} = \frac{RT}{zFE} \cdot \frac{X_d - \alpha\sqrt{X_d}}{t}. \quad (1)$$

Where:

$$E = \frac{U-2}{L}. \quad (2)$$

$$\alpha = 2\sqrt{\frac{RT}{zFE}} \cdot erf^{-1}\left(1 - \frac{2c_d}{c_0}\right). \quad (3)$$

In these equations, used parameters are defined as follow:

D_{nssm}: non-steady-state migration coefficient (m^2/s)
z: absolute value of ion valence for chloride z=1
F: Faraday constant (9.648×10^4 J/(V.mol))
U: absolute value of applied voltage (V)
R: gas constant (8.314 J/(K.mol))
T: average value of the initial and final temperatures in the Anolyte solution (K)
L: thickness of the specimen (m)
X_d: average value of the penetration depth (m)
t: test duration (s)
erf^{-1}: inverse of error function
C_d: chloride concentration at which the color changes, C_d=0.07 N
C_0: chloride concentration in the catholyte solution, C_0=2N

Table 3

Voltage and test duration for concrete specimen (NT BUILD 492) [45]

Initial current I_{30V} (with 30 V) (mA)	Applied voltage U (after adjustment) (V)	Possible new initial Current I_0 (mA)	Test duration t (hour)
I_0<5	60	I_0<10	96
5≤I_0<10	60	10≤I_0<20	48
10≤I_0<15	60	20≤I_0<30	24
15≤I_0<20	50	25≤I_0<35	24
20≤I_0<30	40	25≤I_0<40	24
30≤I_0<40	35	35≤I_0<50	24
40≤I_0<60	30	40≤I_0<60	24
60≤I_0<90	25	50≤I_0<75	24
90≤I_0<120	20	60≤I_0<80	24
120≤I_0<180	15	60≤I_0<90	24
180≤I_0<360	10	60≤I_0<120	24
I_0≥360	10	I_0≥120	6

Since $erf^{-1}\left(1-\frac{2\times0.07}{2}\right)=1.28$, the following simplified equation can be used:

$$D_{nssm}=\frac{0.0239(273+T)}{(U-2)t}\left(X_d-0.0238\sqrt{\frac{(273+T)L\,X_d}{U-2}}\right). (4)$$

Where:
D_{nssm}: non-steady-state migration coefficient ($\times10^{-12}$ m^2/s)
U: absolutevalue of the applied voltage(V)
T: average initial and final temperaturein the anolyte solution (°C)
L: thickness of the specimen(mm)
X_d: averagevalue of the penetration depths (mm)
T: test duration (h)

The accelerated corrosion test (ACT) is a rapid corrosion testing method. Based on the literature, it is an accepted effective method for the rapid evaluation of the corrosion resistance in concrete specimens and has been used in many investigations [46-51]. In ACT test, a 4% sodium chloride solution was prepared and in which the reinforced cylindrical concrete specimens were immersed and a steel bar acting as the electrode was connected to the positive terminal of the DC power source. The steel plates were connected to the negative terminal (counter electrode) beside the specimens in the solution. In this circuit, the steel bar, plates, and sodium chloride solution act as the anode, cathode, and electrolyte, respectively. The process of corrosion was triggered by applying an anode potential equal to 30V. For the sake of accelerating the process of corrosion, a high applied voltage was applied. Figure 2 schematically represents the test setup considered for the ACT [46] and Figure 3 shows the specimens and DC power supply in current study. The time duration for observing the corrosion cracks on the surface was measured. A data logger was used to record the variation of current versus time. As the cracks emerged, the current intensified abruptly. The current variation versus time and also the needed time for failure of reinforced concrete specimens were measured for all mix designs. Figure 4 shows a tested specimen after the corrosion crack occurrence.

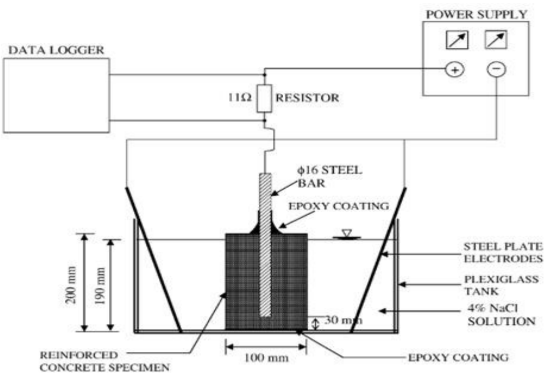


Fig. 2 - Schematic representation of the setup for the accelerated corrosion test (ACT) [46]

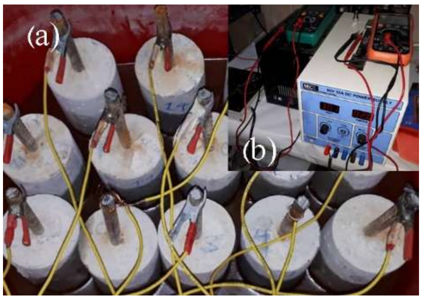


Fig. 3 - (a) Specimens in ACT (b) DC power supply.

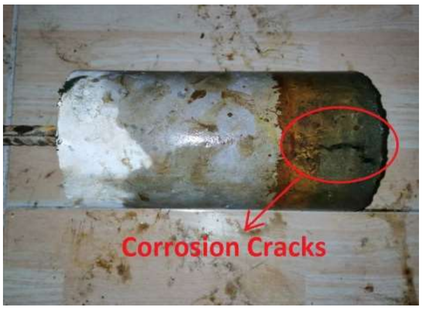


Fig.4 - A tested specimen after corrosion crack occurrence.

Fig. 5 - Specimens after 28 days of exposure to Sulfuric acid.

For further investigation on the durability of mix designs in corrosive environments, the hardened specimens for 28 dayswere placed in Sulfuric acid solution with PH=1 and the weight loss and also reductions of compressive strengths were measured after 28 days of exposure to the corrosive environment. Figure 5 shows some of the specimens after exposure to Sulfuric acid.

3. **Results and discussion**

3.1 Compressive strength

The comparison of compressive strengths at the ages of 7, 28 and 90 days is demonstrated in Figure 6. As it can be observed, the concrete of SL90-MK10 containing 10% MK, showed the maximum strength compared to other concretes. This value was 14.18% higher than that of the control specimen. The mix designs with 10% FA and SF, had an improvement in their 7-day strength. As the ratio of replacement increased, the strength followed a decreasing trend.

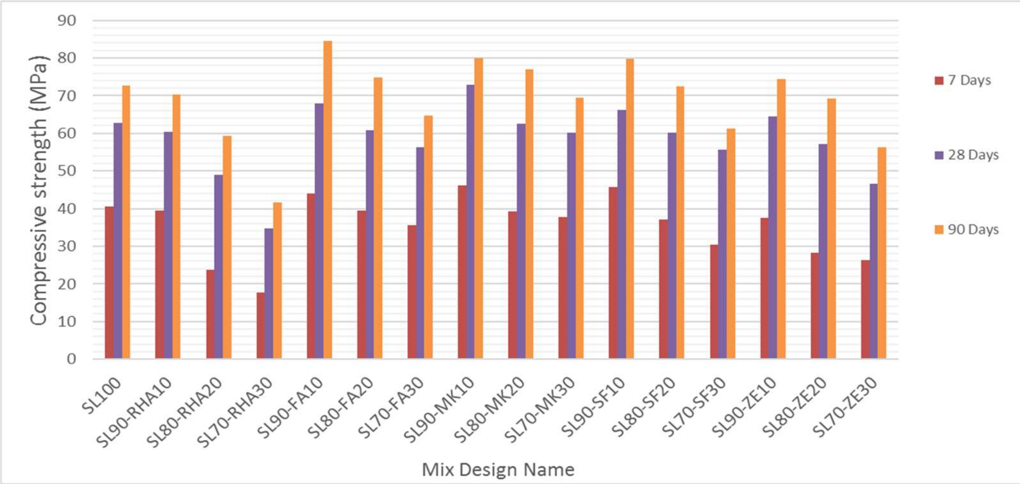


Fig. 6 - Compressive strengths of Concrete Mixes.

Similar to the 7-day compressive strength, in the 28-day compressive strengths, the SL90-MK10 concrete in which 10% slag has been replaced with the MK, showed the highest amount of compressive strength which was 72.96MPa (16.23% higher than that of the control specimen). As it was mentioned in other researches, the inclusion of metakaolin in geopolymers significantly affects the rate of polymerization and compressive strength. The amount of increment in compressive strength depends on metakaolin content, curing temperature and curing duration. Due to fine particle size of metakaolin, it decreases the porosity and consequently densifies the microstructure [52].

The lowest compressive strength was observed for the concretes containing the RHA. In the case of 10% replacement of Slag with FA and SF, the strength enhanced by 8.32% and 5.62%, respectively. The results indicate that the SL90-FA10 concrete containing 10% FA as the replacement, showed the maximum 90 days compressive strength among all of the mix designs with 84.46 MPa that was 16.35% higher than that of the control specimen. This result was in compliance with the results of other researches on substitution of Slag by FA in GPCs [53-55]. In addition, the other mixes containing 10% MK, SF and Zeolite showed improvements in compressive strengths that were 10.11, 9.78 and 2.41%, respectively.

3.2. RCPT, RCMT and ACT

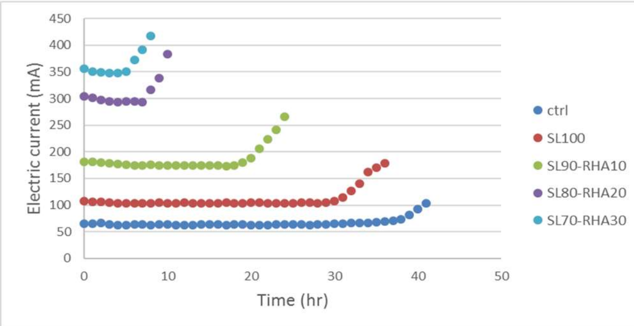
The results of accelerated corrosion test (ACT) in mix designs containing RHA are shown in Figure 7(a). The results indicate that using RHA decreased the durability of the GPC and even at replacement ratio of 10%, negative effects are observed on the rate of corrosion. There is a contradiction in performance of this pozzolan in GPC and what occurs in OPC. The results of Chindaprasirt et al. [56] indicated that in OPC using RHA effectively increased the time of first crack in ACT test.

Figure 7(b) illustrates the results of ACT for concretes containing FA. Based on the results, the presence of FA negatively affected the onset of corrosion. The 10% replacement of FA slightly slowed down the corrosion rate but in higher replacement ratios it decreased the durability. Higher early electric currents indicate higher electric conductivity and this phenomenon illustrates higher porosity, so the results indicate that among considered mix designs, maximum safe replacement ratio of Slag with FA in this GPC was 10%. Similar results were also observed by Ismail et al. [57]. Their results illustrated that replacing Slag by FA in 25%, 50% and 100% of weight caused increment of porosity and sorptivity and consequently increased the choloride diffusion coefficient in GPCs. The results of Tennakoon et al. [58] also showed FA replacement in Slag-based GPCs caused higher corrosion current in samples.

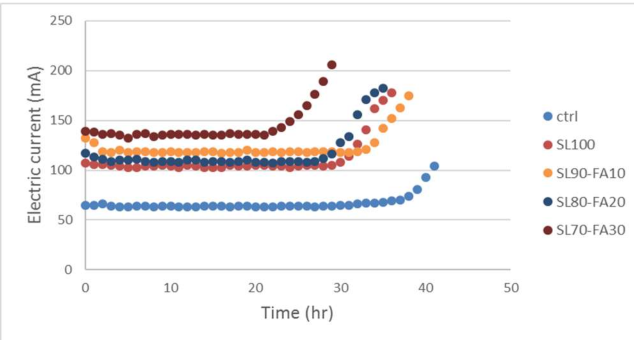
Moreover, Figure 7(c) depicts the results of ACT in mixes containing MK. These results indicate that replacement of MK up to 10%, slightly improves the performance, and similar to FA, as the replacement ratio increases to 20%, the corrosion intensified. This result could relate to this fact that the optimal amount of the MK is in a range between 10 to 20%. Parande et al. [59] obtained similar results in their study on OPCs and reported that 15% replacement of MK is the optimal ratio. The results of Bernal et al. [60] also presented that the inclusion of MK as a secondary alumino-silicate precursor in low replacement ratios can results in the refinement of the pore network and consequently decreasing the sorptivity and the ingress of aggressive agents into the GPCs.

Figure 7(d) shows the results of ACT for concretes containing SF. Using SF considerably improves the GPC performance even at the replacement ratios of up to 30%. This effect can be related to significant reduction of short-term and total water absorption in Slag-based GPCs by SF replacement as it was also mentioned in the results of Rostami et al. [61], However, the use of high replacement ratios is not justifiable from the economic and technical standpoints because it increases the paste adherence and decreases the pumping ability, but based on the previous researches, durability is ameliorated while high ratios of the SF are used in OPCs [62].

Few studies have been carried out concerning the use of natural Zeolite and its effects on the durability of GPCs. In this study, for the first time, the effects of replacing Slag by Zeolite on chloride penetration of GPCs is investigated. Figure 7(e) illustrates the results of ACT in mix designs containing Zeolite. According to results, the optimal ratio for Zeolite replacement is equal to 10% because the ratios of 20 and 30%, significantly increased the rate of electric current.



(a)



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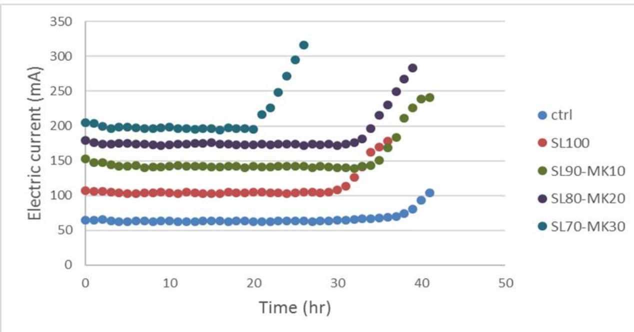

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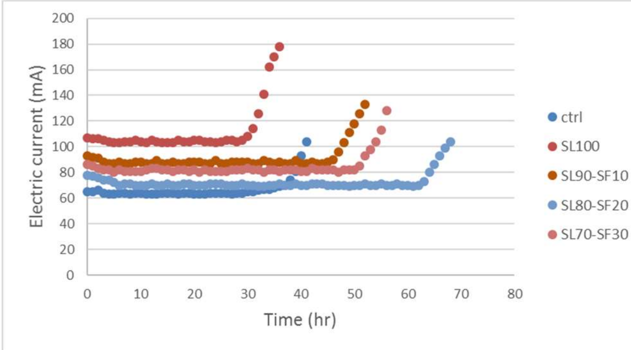

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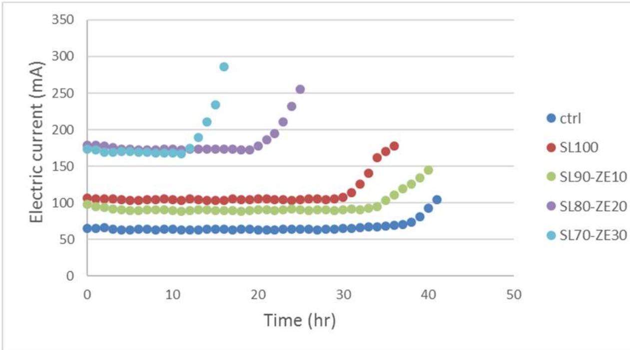

(e)

Fig. 7 - Results of ACT in mixes containing: (a): RHA, (b): FA, (c): MK, (d): SF and (e): Zeolite

Similar to FA, low admixtures of Zeolite improved the durability of GPC which can be correlated to the mechanism of pozzolans' effects on corrosion protection. Zeolite is a source of active Al_2O_3 and SiO_2, and it can provide the formation of additional quantities of silicate hydrates in low ratios of substitution. This results in the colmatation of pores and growth in the strength of the paste. A high amount of clinoptilolite as well as major alkali cations content in Zeolite compositions cause a significant pozzolanic activity [63]. But because of its porous microstructure and natural high water absorbtion, in higher replacement ratios, it increases the water absorption of concrete and consequently exacerbates the chloride penetration. [64, 65].

Results derived from the Rapid Chloride Permeability Test (RCPT) are shown in Figure 8. Similar to ACT, severe increase in rate of permeability at the ratios of 20 and 30% for the RHA, reveals its negative effect in high replacement ratios in GPC. Furthermore, the same trend in ratios more than 10% of MK illustrates their unsatisfactory effects on chloride permeability durability The positive impacts can be observed in the case of SF and FA replacements up to 20% and regard to the results of ACT, the significant improvement of durability against chloride penetration can be

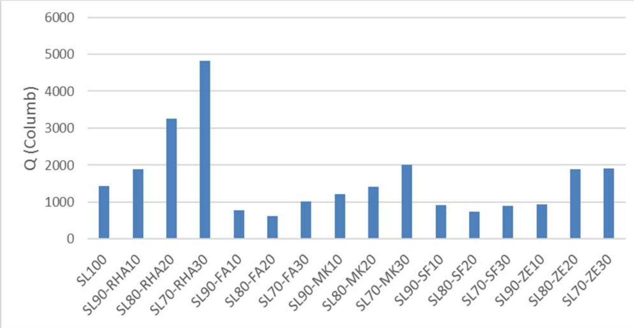

Fig. 8 - Results of Rapid Chloride Permeability Test (RCPT).

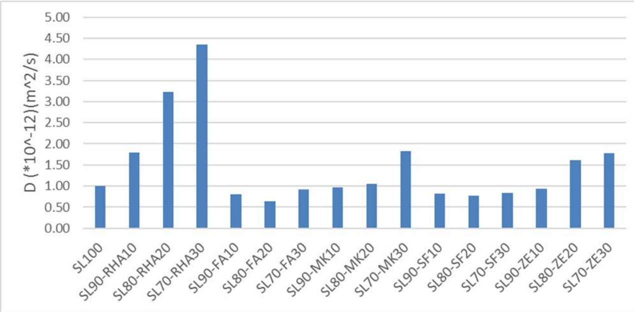

Fig. 9 - Rapid Chloride Migration Test (RCMT).

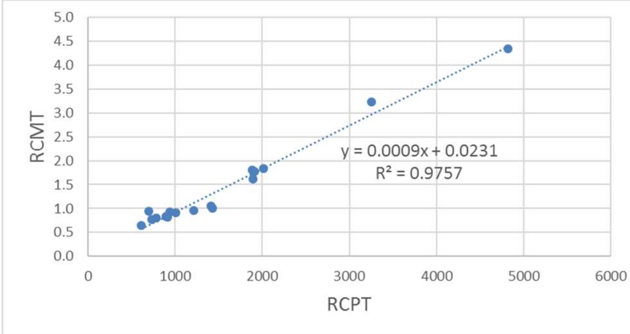

Fig. 10 - The relation between RCPT and RCMT results.

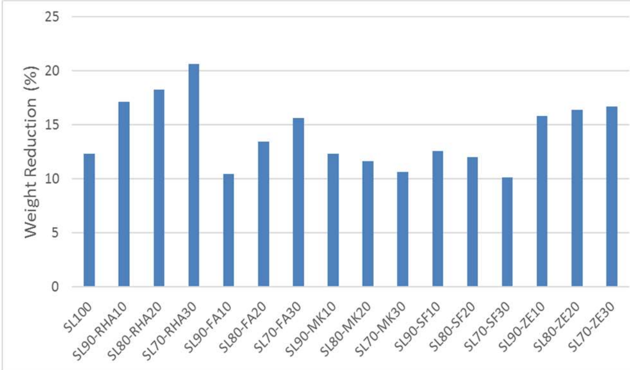

Fig. 11 - Results of the weight reduction after 28 days of exposure to Sulfuric acid solution.

achieved in the case of replacement of Slag with these pozzolans. 10% and 20% replacement of Slag with FA decreased the chloride permeability about 45% and 57%, respectively. Ismail et al. [57] reported that the degree of chloride penetration increased with the inclusion of higher than 25% replacement of fly ash in the binder of Slag-based GPCs which was in accordance with the results of the current research. In this research for the first time it has been revealed that there could be a significant improvement in chloride penetration resistance of Slag-based GPCs with up to 20% replacement of Slag by FA. Moreover, 10% and 20% replacement of Slag with SF decreased the chloride penetration in RCPT about 35% and 48%, respectively. In the research of Rostami et al. [61] it has been mentioned that increasing the percentage of SF in Slag-based GPCs up to 15%, diminished the rate of passing electric charge, which represents increase of resistance against the penetration of chloride ions. This increased resistance against penetration of chloride ion could be related to formation of C-S-H gel and filling of the pores by silica fume in low rates of Slag replacement by SF [61].

In addition, similar results were acquired by the Rapid Chloride Migration Test (RCMT) that demonstrates depth of chloride penetration by changing the color of the broken section (chemical reaction of silver nitrate with salt). Although there are fundamental differences between the RCMT and RCPT, there is a great conformation between their results as is shown in the Figures 9 and 10.

The results indicated that the replacement of Slag with 10% of MK and Zeolite can decrease slightly the non-steady-state migration coefficient (D). There were salient improvements in reduction of (D) coefficient for SF and FA replacements up to 20%. 10% and 20% replacement of Slag with FA decreased the (D) coefficient about 19% and 36%, respectively. Also, 10% and 20% replacement of Slag with SF diminished the (D) coefficient about 18% and 23%, respectively.

The negative effects at high ratios of the Slag replacement with other pozzolans such as Zeolite and RHA on the GPC durability, can be attributed to the permeability as well as level of capillary water absorption. The RHA for instance has ahigh water absorption. Conversely, the SF and FA behave differently due to their spherical shape and high pozzolanic potential which makes them act as effective pozzolanic materials. Regarding their filler performance, formation of geopolymer around the spherical particles, apparently leads to a better compaction which conforms with obtained results.

3.3 Exposure to Sulfuric Acid Solution

Results of the weight loss of the specimens after 28-day exposure to the sulfuric acid solution with PH=1, are presented in Figure 11. The results indicate that maximum weight reduction is observed in the case of mix designs containing RHA. In general, the mixes containing SF and FA have experiences less weight reduction compared to the control specimen what is mainly attributed to the greater compaction, proper filling characteristics and reduction in water absorption of these specimens. Moreover, it is observed that the specimens containing RHA and Zeolite have substantially lost their weight which can be related to high water absorption of these two materials and consequently, deep penetration of acid solution into the structure of these specimens.

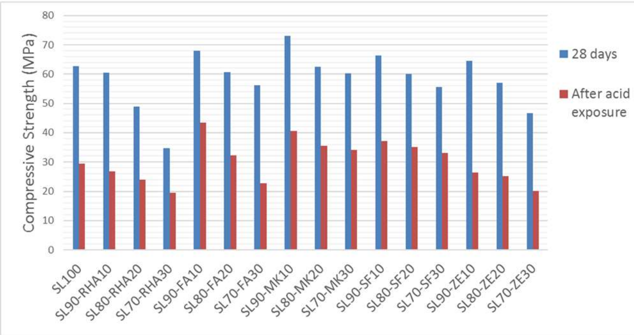

Fig.12 - Compressive strength (MPa) before and after 28 days of exposure to Sulfuric acid solution.

Figure 12 illustrates the results of the compressive strength of the specimens before and after 28 days of exposure to Sulfuric acid solution. As it can be observed, the specimens containing FA, MK and SF showed higher compressive strength in comparison with control Slag-based GPC in all replacement ratios. The highest improvements were observed in 10% of replacement of Slag with FA, MK, and SF that were 47.6%, 37.9%, and 26.7%, respectively. In spite of the fact that the increment of replacement ratios of MK, SF, and FA more that 10% decreases the compressive strength, it diminishes the decrement rate. For instance, the specimen containing 30% replacement with SF showed the lowest loss of compressive strength which was 40.57%. This reduction in the case of control specimen and the mixes containing 10% replacements of SF and MK, was 53.21, 43.86 and 44.47%, respectively. The improvement of GPC durability against sulfuric attack by inclusion of MK was previously observed in other researches. As it has been illustrated in many researches [66-69], aluminosilicate gel is the prominent binding phase that provides interparticle bonding, which cause enhancement of the macroscopic strength and strength gain behavior of geopolymer pastes. FA and MK comprise of significant amounts of reactive SiO_2 and Al_2O_3 and partial replacement of main solid binder in GPC by them can result in a higher initial reaction rate and provide longer reaction duration [70,72]. Therefore, addition of them in Slag-based GPC improves the strength and leads to enhanced sulfate attack resistance. Similar to the previous tests, replacement of Slag with Zeolite and RHA waned the durability of the specimens in exposure to sulfuric acid solution which is related, at it has been mentioned, to the more porous structure of fabricated GPCs containing them.

4. Conclusions

In this research, the effects of Slag replacement by the most common pozzolans such as Rice Husk Ash (RHA), Fly Ash (FA), Metakaolin (MK), Silica Fume (SF), and Zeolite on the durability of the Slag-based GPC are investigated. For this purpose, the Slag was partially replaced with the RHA, FA, MK, SF, and Zeolite. To evaluate the durability performance of the specimens, a series of tests including compressive, Rapid Chloride Permeability Test (RCPT), Rapid Chloride Migration Test (RCMT) and Accelerated Corrosion Test (ACT) were performed. Also, the samples were exposed to Sulfuric acid solution to investigate the effect of this corrosive environment on the weight and compressive strength of the mix designs. The most significant results are:

- In 28-day compressive strength, the mix with 10% replacement of Slag by MK, showed the highest compressive strength. It was 72.96MPa which was 16.23% higher than control mix and the mix design contained 10% of FA showed the maximum 90-day strength among all of the mix designs with 84.46 MPa which was 16.35% higher than control specimen.

-The replacement of Slag with SF considerably improves the GPC performance in ACT even at the replacement ratios of up to 30%. But in the case of FA, MK and Zeolite, replacement up to10% improved the durability in the ACT.

-The positive impacts were observed in the case of SF and FA replacements up to 20% in RCPT and RCMT. Regard to RCPT, RCMT, and ACT results, the improvement of durability against Chloride permeability can be achieved in the case of replacement of Slag with these pozzolans.

-After exposure to Sulfuric acid, the specimens containing MK and SF showed higher compressive strength in comparison with control Slag-based GPC in all replacement ratios. The highest improvements were observed for 10% of replacement of Slag with FA, MK, and SF that were 47.6%, 37.9%, and 26.7%, respectively.

- In the case of Sulfuric acid corrosion durability, despite the fact that the increment of replacement ratios of MK, SF, and FA more that 10% decreases the compressive strength, it diminishes the decrement rate.

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