

Corrosion Resistance of Geopolymer Based Materials

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ABSTRACT

Concrete is considered the backbone material in the construction field. Cement manufacturing emits huge amounts of CO₂ into the atmosphere. Also, the concrete deterioration in aggressive environments is one of its disadvantages. Thus, finding new eco-friendly construction materials for green and sustainable construction is very essential. The geopolymer (GP) based materials can be employed as eco-friendly sustainable construction materials. Many research works studied the fresh and the mechanical properties of the GP based systems but its durability has not been covered well. This paper studies the corrosion resistance of the GP mortars. The following parameters have been studied: the molarity of NaOH (6, 10, 16 and 20); the Na₂SiO₃ to NaOH ratio (1, 2.5 and 4.5); the alkaline solution to fly ash ratio (0.4, 0.5 and 0.6); the curing temperature (25°C, 60°C and 90°C); the rest period (0, 24 and 48 hours) and finally the extra water as a percentage of fly ash (10%, 12.5% and 15%). The results showed that there are optimum conditions for the investigated parameters to achieve the highest values for the desired mechanical properties of the considered GP mortar mixes. The corrosion resistance evaluated by half-cell, current intensity readings and periods to the first crack are affected by the investigated parameters. Increasing the molarity of the used solution, reducing the solution to fly ash ratio and reducing the percentage of extra water enhanced the corrosion resistance.

Keywords: Geopolymer, Fly ash, Alkaline solution, Corrosion, Durability.

1. Introduction

Concrete is the cheapest and most widely used construction material. The manufacturing of its main binder, which is Portland cement emits approximately between 5% and 7% of the total global CO₂ emissions into the atmosphere. In addition, the concrete industry consumes the natural resources of the coarse and fine aggregate. Lately the term sustainability appeared on the scientific arena. It means the saving of the natural resources in addition to minimum energy consumption during the construction process. Sustainability could be achieved by one of the following approaches: increasing the use of supplementary cementitious material (e.g. fly ash, slag and silica fume.... etc.), utilization of recycled aggregate from the demolition and construction wastes (Topc, and Sengel 2004) and searching for new construction materials which mainly do not depend on Portland cement as a binder. Geopolymeric binder is a new type of inorganic cementing binder which was developed and introduced firstly by Davidovits (1979). Geopolymer (GP) binder is a new material which does not use Portland cement and its ingredients are pozzolanic material (e.g. low calcium fly ash), which is rich in silicon (Si) and aluminium (Al), and alkaline solutions (Na₂SiO₃ and NaOH) (Duxson et al., 2007). Davidovits (1994) and Van Deventer et al. (2010) found that the production of GP binder emits about 80% less CO₂ than the manufacture of ordinary Portland cement (OPC). Many research works have been conducted on the parameters affecting the production of GP based materials and its influence on their fresh and hardened properties.

Hardjito et al (2004) found that higher concentration (in terms of molarity) of sodium hydroxide solution and higher mass ratio of sodium silicate-to-sodium hydroxide liquid result in a higher compressive strength of GP concrete. The results of Hardjito and Rangan (2005) showed that the higher curing temperature in addition to longer curing times resulted in larger compressive strength for GP concrete. The extra water remains outside of the geopolymeric network and acts as a lubricating element (Hardjito and Rangan, 2005, and Davidovits, 2011). Shaikh and Afshang (2013) mentioned that the different ratios of NS to NH play an important role in the corrosion resistance of GP mortars and that sodium silicate is also believed to act as a corrosion inhibitor in GP mortars. Hardjito and Rangan (2005) proved that a rest period (sufficient time) should be provided between the casting and the curing process. The calcium content in the OPC matrix is the main factor governing its durability. On the other hand the GP systems possess low calcium containing materials which led to less such negative effects. The results obtained by Reddy et al (2013) showed high resistance to chloride attack relative to OPC concrete. Many publications studied the advantages of GP systems subjected to elevated temperature and the results showed its ability to have high residual compressive strengths after exposure to 800°C. On the other hand OPC concrete degrades at lower temperature than that of GP concrete Daniel & Jay G., (2010). D. V. Reddy et al. (2013) investigated the corrosion resistance of fly ash GP concrete and the test results indicated excellent resistance of the GP concrete with a longer time to corrosion cracking relative to ordinary Portland cement concrete. On the other hand, Badar et al. (2014) investigated the GP concrete under accelerated corrosion induced by accelerated carbonation.

Considering the good fresh and mechanical properties of the GP systems beside their eco-friendly impact, the durability of the GP systems has not been investigated sufficiently. Thus, this experimental study will clarify the influence of each parameter involved in its manufacturing on its corrosion resistance using accelerated corrosion testing. The obtained results will be compared with those of OPC systems. This study is conducted on the mortar scale.

2. EXPERIMENTAL PROGRAM

The considered mixtures formed six groups. The first group investigated the effect of concentration of NaOH, while the second group studied the effect of sodium silicate to sodium hydroxide ratio, whereas the third group investigated the effect of alkaline liquid to fly ash ratio by mass and the fourth group explored the effect of extra water to GP solids ratio by mass. On the other hand, the fifth group investigated the effect of the heat-curing temperature and the sixth group studied the effect of the curing time.

2.1 Materials

Fly ash; low-calcium fly ash (FA) class F satisfying the requirements of [ASTM C618 \(2008\)](#) and produced in a coal-fired power plant was used as the pozzolanic material. The specific gravity and the specific surface area of the used FA were 2.31 and 5000 cm²/gm, respectively. The chemical composition as determined by X-Ray Fluorescence (XRF) analysis is listed in Table 1. **Alkaline solution;** the used alkaline solution was a combination of a sodium silicate Na₂SiO₃ (NS) and sodium hydroxide NaOH (NH). The Sodium silicate solution was used as the alkaline activator (SiO₂=29.4%, Na₂O=14.7% and water=55.9%). The sodium hydroxide was in pellets form with 98% purity and a molecular weight of 40. In the present work four different molarities were used (6M, 10M, 16M and 20M). Both of the liquid solutions were mixed together at the proposed ratios to prepare the alkaline solution. **Fine aggregate;** river siliceous sand with specific gravity of 2.55, fineness modulus of 2.36 and water absorption of 0.90% was used. The clay and fine matter was 2% by weight. **Ordinary Portland cement;** CEM-1 42.5N ordinary Portland cement (OPC) with initial and final setting times 75 and 220 mins, respectively was used. The used cement complied with the requirements of [\(EN 196-1:2005\)](#). OPC was used for the preparation of the control mixture to be used for comparison purposes. The chemical, physical and mechanical properties of the used cement are listed in Table 3. **Water;** Potable water with pH value of 7.5 was used as extra water (EW) for GP mixtures to enhance the flowability in the fresh state. On the other hand, it was used for mixing and curing the OPC mortar specimens.

2.2 Mixing procedure and casting

The compositions of GP mortar mixes containing fly ash, fine aggregate, sodium silicate solution, NaOH solution and extra water are listed in Table 4. The fine aggregate and the fly ash were first mixed together in dry state. The alkaline solution was mixed with the extra water. The liquid component of the mixture was then added to the dry materials and the mixing continued for another 8 minutes. After mixing, the flow test was conducted to evaluate its percentage flow in fresh state according to [ASTM C1437 \(2015\)](#). After conducting the flow test, the fresh mortar was cast in the moulds and compacted by manual strokes. The GP specimens were left open to air temperature for 24 hours then were heat cured in an oven at different temperatures. After that, the specimens were removed from the moulds and taken out from the oven and were left at laboratory temperature up to testing. The mixing process used for OPC mortar (Table 5) was similar to that for GP mortar. The control mortar mix (OPC) was removed from its moulds and was cured using tap water for 28 days.

2.3 Mechanical Properties of the GP mortar

The flexural and compressive strength were determined using prismatic specimens of size 40x40x160 mm which were prepared according to [EN 196-1:2005](#). The strength of the OPC and GP mortar mixes were measured at 28 and 60 days age and according to the proportions mentioned in Table 4 and 5. Each prism was tested using three-point load bending setup to obtain flexural strength then the compressive strength test was carried out on each of the two halves.

Table 1: Chemical Composition of fly ash as determined by XRF

Oxide	(%) by mass
Silicon dioxide (SiO₂)	60.28
Aluminum oxide (Al₂O₃)	28.59
Ferric oxide (Fe₂O₃)	4.99
Total SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	93.86
Calcium oxide (CaO)	1.19
Phosphorus pent oxide (P₂O₅)	0.52
Sulphur trioxide (SO₃)	0.06
Potassium oxide (K₂O)	1.09
Titanium dioxide (TiO₂)	2.42
Sodium oxide (Na₂O)	0.01
Magnesium oxide (MgO)	0.27
Loss on Ignition (LOI)	0.58

Table 2: Chemical analysis of the used cement

Oxide	(%) by mass
Silicon dioxide (SiO₂)	20
Aluminum oxide (Al₂O₃)	5.20
Ferric oxide (Fe₂O₃)	3.10
Calcium oxide (CaO)	63
Phosphorus pent oxide (P₂O₅)	-
Sulphur trioxide (SO₃)	3.01
Potassium oxide (K₂O)	0.15
Titanium dioxide (TiO₂)	-
Sodium oxide (Na₂O)	0.44
Magnesium oxide (MgO)	-
Loss on Ignition (LOI)	5.10

Table 3: Physical and mechanical properties of the used cement

Property	Value	(BS EN196-1:2005)
Specific gravity	3.15	—
Soundness, (mm)	3	< 10
Fineness, (%)	7	< 10
Initial setting time, (min)	75	> 60
Final setting time, (min)	220	< 600
Compressive strength, (MPa)	43.2	42.5
Standard consistency, (%)	28	—

Table 4: Experimental program and mix proportions of GP mixtures

Groups	Mix ID	Molarity	NS/NH	S/FA	FA/Sand.	RP (hour)	CP (hour)	EW/F	CT (°C)
G1 Molarity	6M	6M	2.5	0.40	0.50	24	48	0.10	60
	10M	10M	2.5	0.40	0.50	24	48	0.10	60
	20M	20M	2.5	0.40	0.50	24	48	0.10	60
G2 Na ₂ SiO ₃ / NaOH (NS/NH)	NS/NH 1	16M	1	0.40	0.50	24	48	0.10	60
	GP control	16M	2.5	0.40	0.50	24	48	0.10	60
	NS/NH 4.5	16M	4.5	0.40	0.50	24	48	0.10	60
G3 Activators/ Fly ash (S/FA)	S/FA 0.5	16M	2.5	0.50	0.50	24	48	0.10	60
	S/FA 0.6	16M	2.5	0.60	0.50	24	48	0.10	60
G4 Curing Temperature (CT)	C 25°C	16M	2.5	0.40	0.50	-	-	0.10	Air cured
	C 90°C	16M	2.5	0.40	0.50	24	48	0.10	90
G5 Rest period (RP)	RP 0	16M	2.5	0.40	0.50	0	48	0.10	60
	RP 2	16M	2.5	0.40	0.50	48	48	0.10	60
G6 Extra water (EW)	EW 12.5%	16M	2.5	0.40	0.50	24	48	0.125	60
	EW 15%	16M	2.5	0.40	0.50	24	48	0.15	60

Table 5: Mix proportions for ordinary Portland cement mixture

Mix ID	Cement	Fine aggregate	Water	Curing Temperature (°C)
M-Cement	1	2	0.5	(25 ± 2 °C)

2.4 Accelerated corrosion test

Accelerated corrosion test was performed on mortar samples according to (Wootton, 2001 and Sharkawi, et al. 2010). This approach accelerates the corrosion process experimentally by making the steel reinforcement become anodic by impressing a DC current, thus enhancing the corrosion cell. Accelerated corrosion test is applied on concrete lollipop specimens by partially immersing them in a tank containing 5 % NaCl by weight (approximately double that of typical seawater) at room temperature and connecting the outstanding reinforcing bars to a constant 12-volt DC power source in a configuration inducing an impressed current. Comparing the period, after which the first crack occurs as a result of rust and measuring the corrosion activity by a half cell and measuring the intensity of current flowing through each sample, corrosion resistivity could be compared. Lollipop specimens were cylinders of 100 mm diameter and 200 mm height with cylinders with a single 16 mm diameter centrally embedded steel reinforcing bar. Details of the lollipop samples and the test setup are shown in Figs.1-2. The corrosion activity was measured using half-cell apparatus and according to ASTM C876-09 as shown in Fig.3.

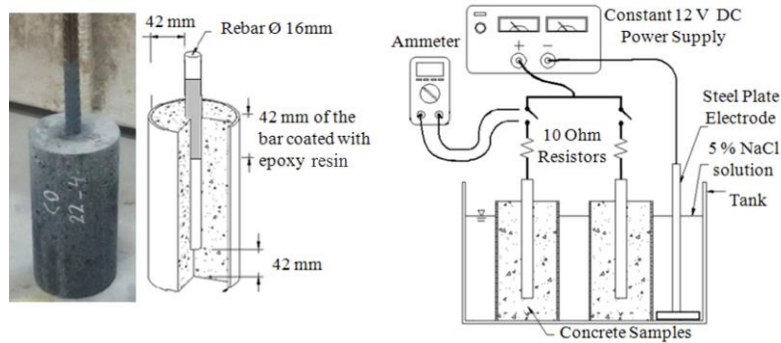


Fig. 1: Details of Accelerated Corrosion Test specimens and test setup



Fig. 2: Accelerated corrosion test setup



Fig. 3: Setup of half-cell apparatus for measuring the corrosion activity

3. Results and discussions

3.1 Hardened properties of GP mixes

3.1.1 Compressive strength

Compressive strengths at different ages as affected by different parameters are presented in Fig. 4. The influence of molarity of NH on compressive strength was studied through mixes M6, M10, GP control and M20. It can be clearly noticed that increasing the molarity of NH increased the compressive strength at all ages, up to GP control (M16), at which the compressive strength values were 35.38 and 55.2 MPa at 28 and 60 days age, respectively. Beyond this molarity level, a reduction in the compressive strength was recorded. Moreover, it can be noticed that a remarkable development in the compressive strength was recorded for the investigated mixes. On the other hand, the effect of NS/NH ratio indicated enhancement in the compressive strength with increasing of NS/NH ratio at all tested ages. The compressive strength values were 43.6, 55.2 and 48.73 MPa at 60 days age for mixes NS/NH1, GP control and NS/NH4.5, respectively. The effect of alkaline solution to fly ash ratio was studied by investigating mixes GP control, S/FA 0.5 and S/FA 0.6. A noticeable development in the compressive strength was noticed with age. Moreover, increasing alkaline solution to fly ash ratio remarkably reduced the compressive strength at all ages. The compressive strength values were 55.2, 52.6 and 48.25 MPa at 60 days age for mixes GP control, S/FA 0.5 and S/FA 0.6, respectively. The influence of rest period (RP) on the compressive strength was also investigated through mixes RP0, GP control and RP2. The results showed an improvement in the compressive strength for mix RP2 compared to mix RP0 and GP control. The compressive strength values were 52.1, 55.2 and 62.12 MPa at 60 days age for mixes RP0, GP control and RP2, respectively.

The influence of the curing at ambient temperature compared with thermal curing was investigated using mixes C25°C, GP control and C90°C. It can be noticed that thermal curing played an important role in the rate of strength gain, especially at early ages. The compressive strength values were 32.32, 35.38 and 48.63 MPa at 28 days for mixes C25°C, GP control and C90°C, respectively, whereas, the compressive strength values at 60 days were 41.3, 55.2 and 61.11 MPa for the mentioned mixes, respectively. Mixes EW 12.5% and EW15% detected the effect of using extra water beside the alkaline solution in mixing GP mortar mixes. It can be noticed that using extra water reduced the compressive strength. The compressive strength values were 55.2, 51.24 and 48.11 MPa at 60 days age for mixes GP control (EW10%), EW12.5% and EW15%, respectively. It can be noticed that the added water played a vital role only in enhancing the workability by reducing the viscous nature of mixture but showed an adverse effect on strength which is in accordance with findings of [SUBHASH et al \(2013\)](#). For achieving relatively high early compressive strength GP mortar, mixes should be prepared with low alkaline solution to fly ash ratio, NS/NH achieving 2.5, molarity of 16 and to be cured at 90°C as noticed with mix C90°C. This mix yielded 48.63 and 61.11 MPa compressive strength at 28 and 60 days age, respectively, whereas, the mortar mix prepared with ordinary Portland cement (M-cement) gave 39.3 and 47.4 MPa compressive strength at 28 and 60 days age, respectively.

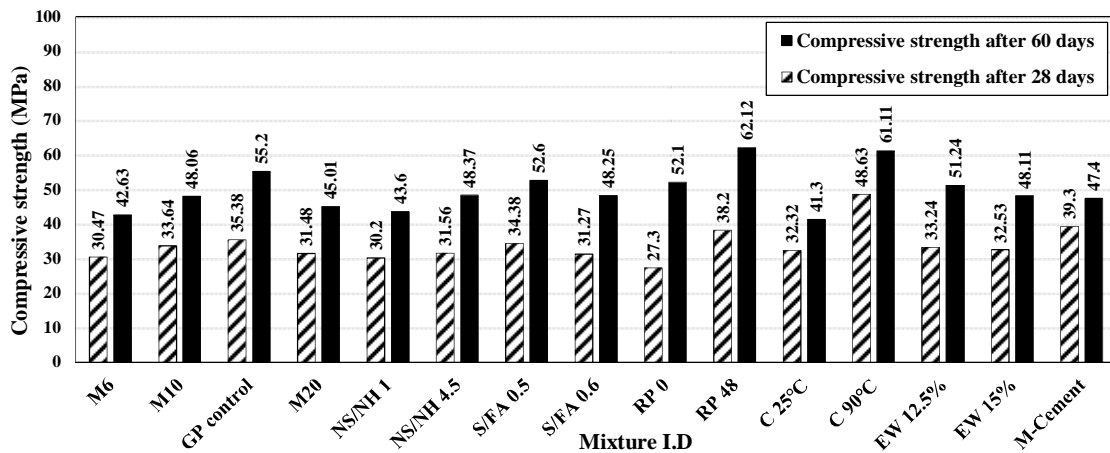


Fig. 4: Compressive strength for GP specimen and cement specimens

3.1.2 Flexural strength

Flexural strength at different ages as affected by different parameters are presented in Fig. 5. The influence of molarity of NH on flexural strength was studied through mixes M6, M10, GP control and M20. It can be clearly noticed that increasing the molarity of NH increased the flexural strength at all ages up to GP control (M16) at which the flexural strength values were 9.32 and 13.2 MPa at 28 and 60 days age, respectively. Beyond this molarity level, a reduction in the flexural strength was recorded. Moreover, it can be noticed that a remarkable development in the flexural strength was recorded for the investigated mixes. On the other hand, the effect of NS/NH ratios indicated enhancement in the flexural strength with increasing NS/NH ratio at all tested ages. The flexural strength values were 8.89, 13.2 and 9.58 MPa at 60 days age for mixes NS/NH1, GP control and NS/NH4.5, respectively. The effect of alkaline solution to fly ash ratio was studied by investigating mixes GP control, S/FA 0.5 and S/FA 0.6. A noticeable development in the flexural strength was noticed with age. Moreover, increasing alkaline solution to fly ash ratio reduced remarkably the flexural strength at all ages. The flexural strength values were 13.2, 11.2 and 10.4 MPa at 60 days age for mixes GP control, S/FA 0.5 and S/FA 0.6, respectively.

The influence of rest period (RP) on the flexural strength was also investigated using mixes RP0, GP control and RP2. The results showed an improvement in the flexural strength for mix RP2 compared to mix RP0 and GP control. The flexural strength values were 11.65, 13.2 and 15.63 MPa at 60 days age for mixes RP0, GP control and RP2, respectively. The influence of the curing at ambient temperature compared with thermal curing was investigated using mixes C25°C, GP control and C90°C. It can be noticed that thermal curing played an important role in the rate of strength gain especially at early ages. The flexural strength values were 7.5, 9.32 and 9.73 MPa at 28 days for mixes C25°C, GP control and C90°C, respectively, whereas, the flexural strength values at 60 days were 10.8, 13.2 and 13.71 MPa for the mentioned mixes, respectively. Mixes EW 10%, EW12.5% and EW15% detected the effect of using extra water beside the alkaline solution in mixing GP mortar mixes. It is can be noticed that using extra water reduced the flexural strength. The flexural strength values were 13.2, 12.83 and 11.67 MPa at 60 days age for mixes GP control (EW10%), EW12.5% and EW15%, respectively.

For achieving relatively high early strength GP mortar mixes should be prepared with low alkaline solution to fly ash ratio, NS/NH achieving 2.5, molarity of 16 and to be cured after 48 hours rest period as noticed with mix RP2. This mix gave 10.31 and 15.63 MPa flexural strength at 28 and 60 days age, respectively, whereas, the mortar mix prepared with ordinary Portland cement (M-cement) gave 8.42 and 12.1 MPa flexural strength at 28 and 60 days age, respectively.

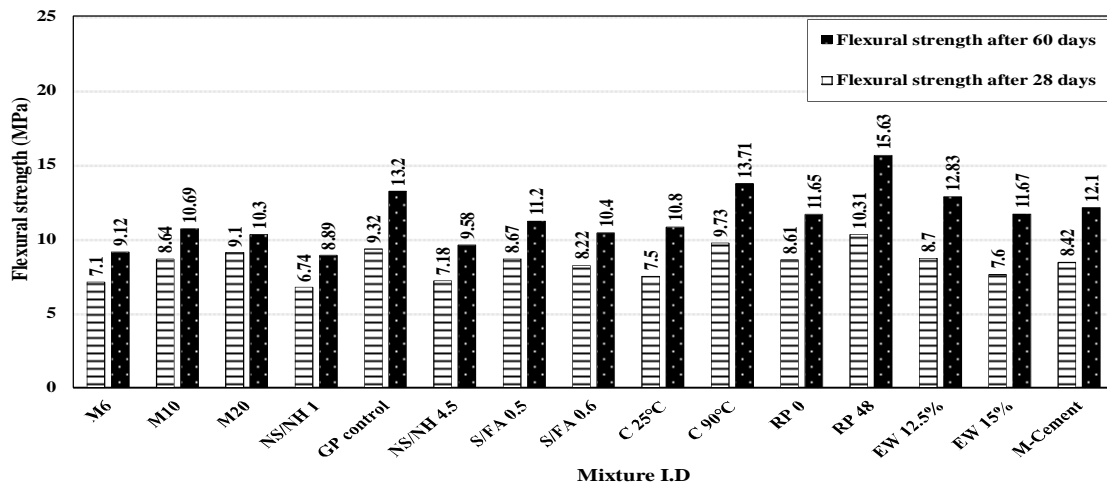


Fig. 5: Flexural strength for GP specimen and cement specimens

3.2 Corrosion Resistance

Corrosion resistance of GP mortar mixes as affected by molarity of NH, NS to NH ratio, solution to FA ratio, curing temperature, rest period as well as extra water were studied. The results of corrosion resistance are presented as current intensity passing through steel bars and the half-cell potential readings with time. Moreover, the period elapsed until first cracking and the mass loss of the corroded bars were determined. The results are presented as following.

3.2.1 Effect of molarity of NH on corrosion resistance

Increasing the concentration of sodium hydroxide solution in GP mortars resulted in better resistance against chloride penetration, and better corrosion resistance in terms of lower negative potential readings and decreasing the current intensity as presented in Figs. 6-7. According to ASTM C876 (2000), the corrosion rate for higher concentration of NH 20M is much slower than for low concentration. For example, after 40 days exposure, the half-cell reading and the current for GP specimens at 6M, 10 M, 16M and 20M were -542, -485, -433 and -430 mV and 0.195, 0.07, 0.045 and 0.043A, respectively. The GP specimens with concentrations 6M, 10M, 16M and 20 M recorded periods to first crack of 16, 23, 69 and 71 days and had a damaging failure after 50, 52, 100 and 104 days, respectively.

3.2.2 Effect of NS to NH ratio on corrosion resistance

The results of the used three different ratios of NS to NH by mass (1, 2.5 and 4.5) are presented in Figs. 8-9. It is observed that the negative potential readings and the current intensity values decreased due to the increase in the NS/NH ratios. The rate of decrease of negative potential values and the current intensity of GP mortar with NS/NH ratio of 2.5 is the slowest. For example after 30 days exposure the half-cell readings for GP specimens recorded in case 1, 2.5 and 4.5 were -510, -433 and -490 mV and the current intensity readings were 0.046, 0.035 and 0.01 A, respectively. The GP specimens with NS/NH ratio equal to 1, 2.5 and 4.5 NS/NH ratios recorded a first crack after 19, 69 and 27days, and had a damaging failure after 40, 100 and 52 days, respectively.

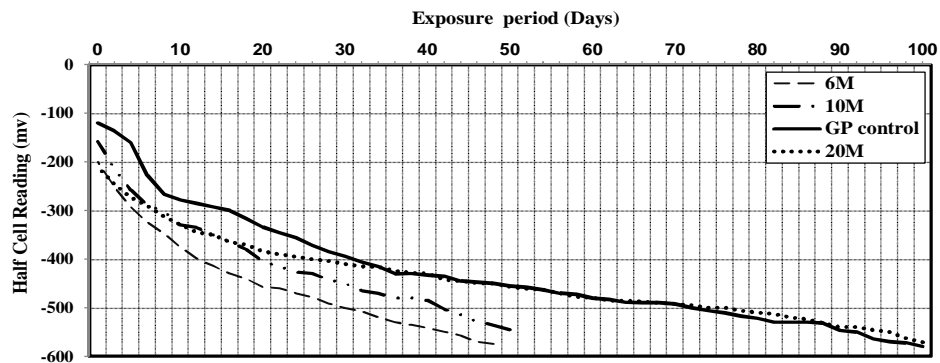


Fig. 6: Effect of concentration of sodium hydroxide solution on half-cell readings of GP specimens

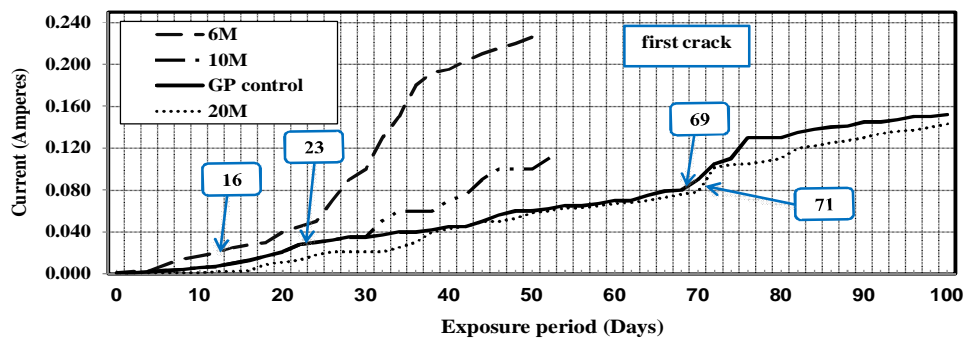


Fig. 7: Effect of concentration of sodium hydroxide solution on the current intensity readings of GP specimens

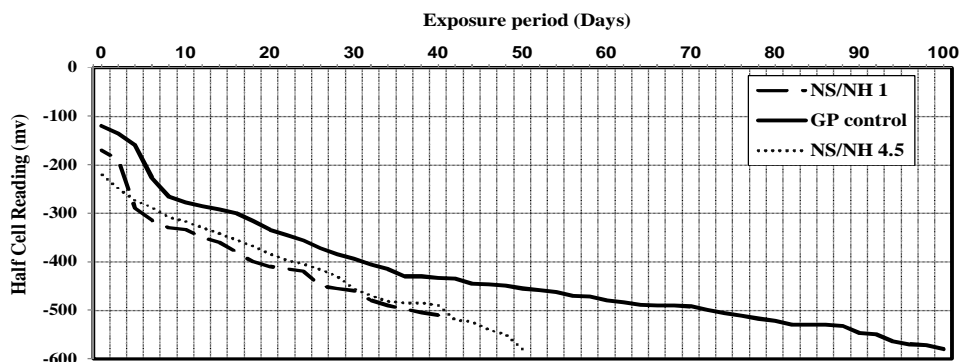


Fig. 8: Effect of NS to NH ratio on the half-cell readings of GP specimens

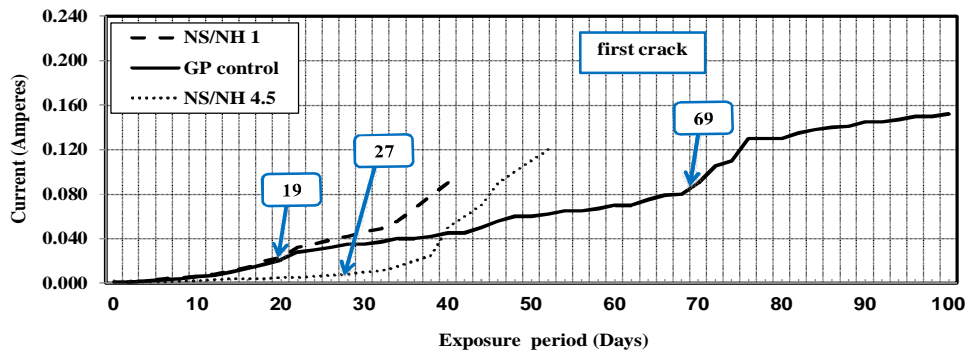


Fig. 9: Effect of NS to NH ratio at the current intensity reading of GP specimens

3.2.3 Effect of solution to FA ratio on corrosion resistance

Regarding the effect of alkaline liquid to fly ash ratio, the negative potential readings were increasing and a significant increase in the current intensity resulted from increasing the alkaline liquid to fly ash ratio. For example, as shown in Fig. 10, after 46 days exposure, the half-cell readings of the GP were -447, -460 and -524 mV, and the current intensity readings in Fig. 11 were 0.056, 0.1 and 0.15 A for the investigated mixes with 0.4, 0.5 and 0.6 S/FA ratios, respectively. The rate of increase of negative potential values and the current intensity of GP mortar specimens in case of 0.4 S/FA ratio was the slowest. The GP specimens in case of 0.4, 0.5 and 0.6 S/FA ratios recorded the first crack after 69, 31 and 28 days, and had a damaging failure after 100, 66 and 56 days for the tested specimens, respectively.

3.2.4 Effect of curing temperature on corrosion resistance

The obtained results given in Figs. 12-13 revealed that the negative potential readings decreased and a significant decrease in the current intensity value occurred for GP specimens cured in hot air oven compared to the ambient air cured specimens. For the endothermic condensation polymerization to take place, the supply of heat needs to be uniform. The half-cell readings after 20 days exposure of GP specimens cured at 30, 60 and 90°C, as shown in Fig. 12, recorded negative potential readings of -380, -334 and -295 mV, respectively. As shown in Fig. 13 the corresponding current intensity readings recorded after 20 days were 0.031, 0.021 and 0.011 A, respectively. The GP specimens in the case of 25, 60 and 90°C recorded the first crack after 25, 69 and 43 days, and had a damaging failure after 40, 100 and 64 days, respectively.

3.2.5 Effect of rest period on corrosion resistance

Figs. 14-15 present the influence of rest period on corrosion resistance. Increasing the rest period exhibited better corrosion resistance, due to significant decrease in the current intensity value, and decrease of the negative potential readings. The rate of decrease in negative potential values and the current intensity for zero rest period was the fastest. After 30 days exposure the half-cell readings for GP specimens in the case of 0, 1 and 2 days rest period, were -505, -394 and -390 mV. In Fig. 15 the current readings were recorded after 30 days as 0.036, 0.035 and 0.008 A for 0, 1 and 2 days rest period, respectively. The GP specimens in case of rest period of 0, 1 and 2 days recorded the first-crack after 25, 69 and 62 days, and had a damaging failure after 46, 100 and 70 days, respectively.

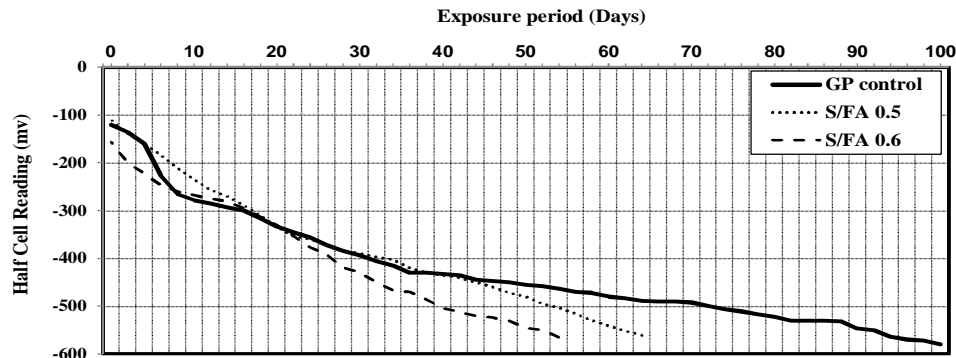


Fig. 10: Effect of alkaline liquid to fly ash ratio on the half-cell reading of GP specimens

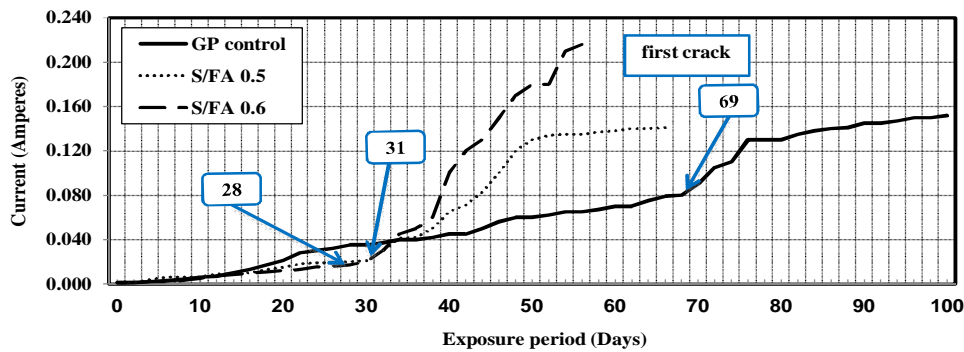


Fig. 11: Effect of alkaline liquid to fly ash ratio on the current intensity readings of GP specimens

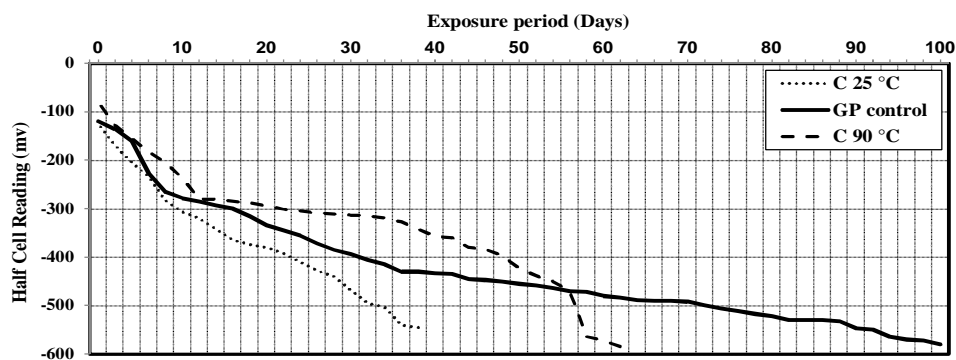


Fig. 12: Effect of curing temperature on the half-cell readings of GP specimens

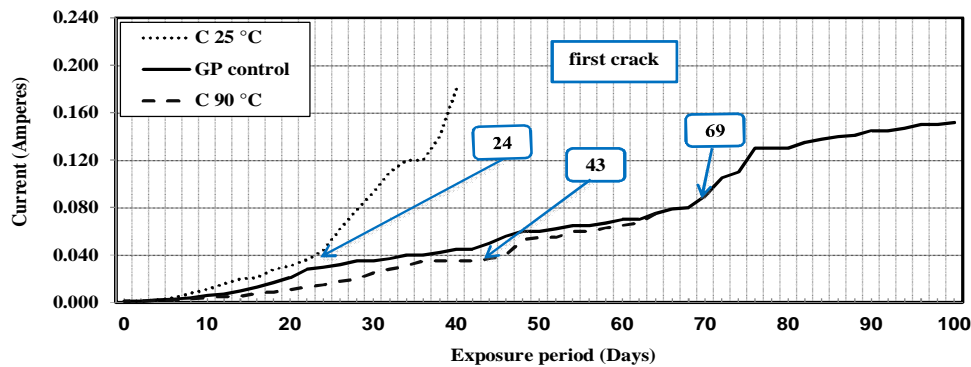


Fig. 13: Effect of curing temperature on the current intensity readings of GP specimens

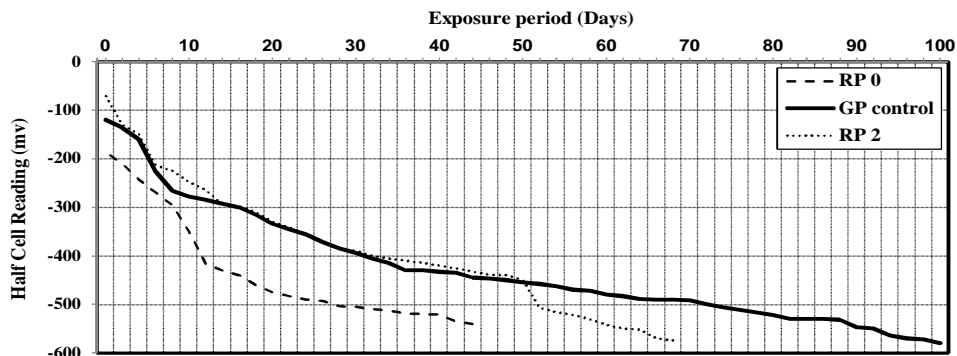


Fig. 14: Effect of rest period on the half-cell reading of GP specimens

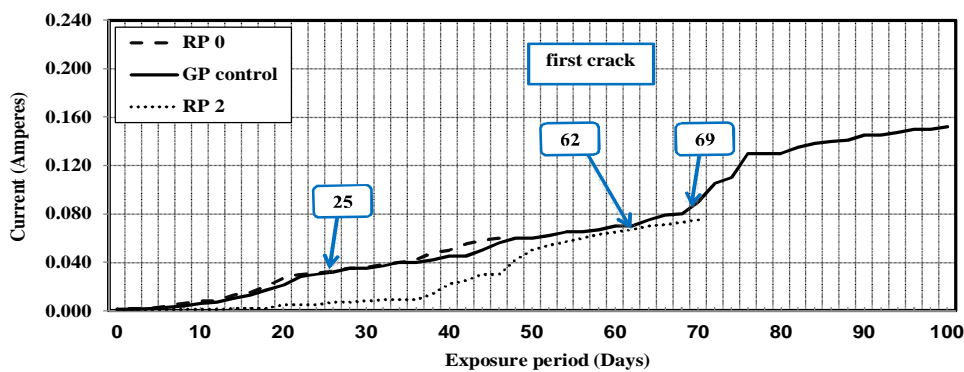


Fig. 15: Effect of rest period on the current intensity reading of GP specimens

3.2.6 Effect of extra water on corrosion resistance

The findings in Figs. 16-17 indicated that there was an inverse relationship between extra water and corrosion resistance. The negative potential and the current intensity values significantly increased with the increase of extra water. For example after 40 days exposure, the half-cell readings for GP specimens with 0.1, 0.125 and 0.15 extra water ratios were -433, -514 and -570

mV, respectively. Moreover, the corresponding current intensity readings were 0.045, 0.06 and 0.087 A at 0.1, 0.125 and 0.15 extra water ratios, respectively. The rate of increase of negative potential values and the current intensity for GP mortars in the case of extra water ratio 0.1 is the slowest. The GP specimens in case of 0.1, 0.125 and 0.15 extra water ratios recorded the first crack after 69, 19 and 17 days, and had a damaging failure after 100, 44 and 42 days, extra water ratios, respectively.

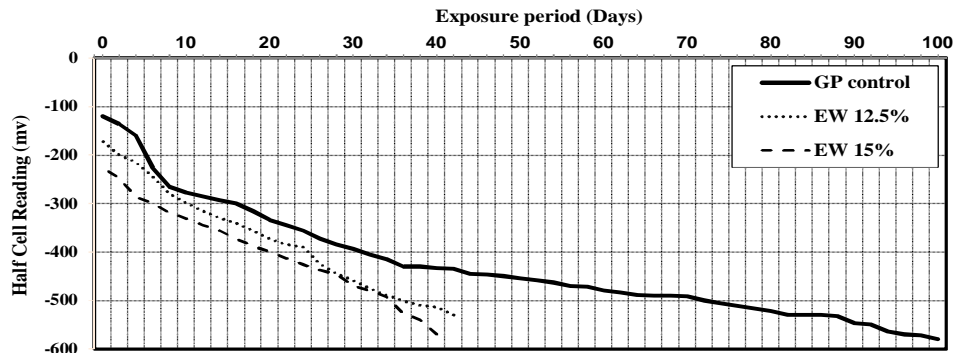


Fig. 16: Effect of extra water on the half-cell readings of GP specimens

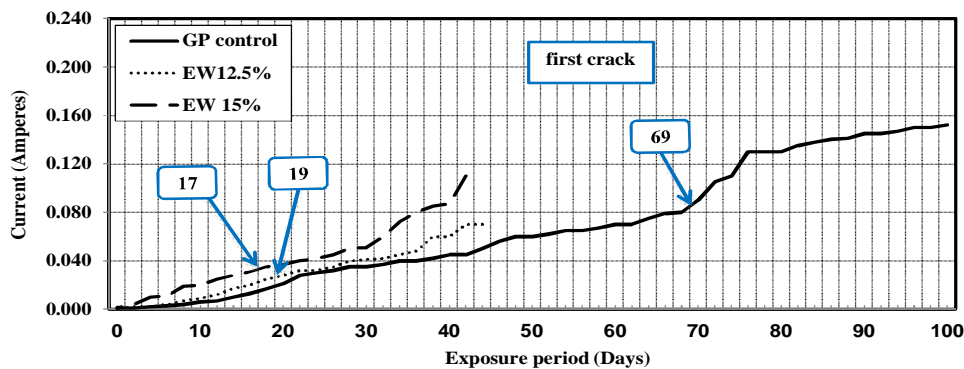


Fig. 17: Effect of extra water on the current intensity readings of GP specimens

3.2.7 Mass loss and visual inspection

At the end of corrosion tests, the actual steel mass loss of reinforcing bars for both OPC and GP mortars were determined according to ASTM G1-03 (2011). The rebars retrieved after accelerated corrosion testing are presented in Fig. 18, which shows severe corrosion damage of the rebars from the OPC mortars, while the rebars from the GP mortars were “healthy”, with relatively low corrosion effects on their surfaces. The percentage of mass losses of reinforcing bars for GP and OPC specimens are shown in Fig.19. The percentage mass loss of the bars in the OPC specimen, after accelerated corrosion testing, was 21%. In the case of GP mortar, the reinforcing bars lost approximately between 2 to 6 % by mass of steel.

3.2.8 Comparison between corrosion resistance of GP and OPC mixes

The results of the half-cell potential readings and the variation of current intensity with time in the steel of the reinforced GP mortars are shown in Figs. 20-21. The results of GP mixes demonstrated better resistance against chloride penetration than the OPC specimens. The GP specimens exhibited better corrosion resistance in terms of lower negative potential readings

and reducing of the current intensity than the cement specimens. Moreover, the corrosion rate in the GP specimens is much slower in the cement specimens. For example, after 16 days exposure, the half-cell readings and the current intensity for cement specimens were -463 mV and 0.083 A, respectively. On the other hand, the half-cell readings and the current intensity for GP specimens were -300 mV and 0.013 A, respectively. The cement specimens recorded the first crack after 6 days and had a damaging failure after 20 days. Moreover, the period to first crack as well as the period to damaging failure of the GP specimens were 69 and 100 days, respectively.



Fig. 18: Retrieved rebars after accelerated corrosion testing

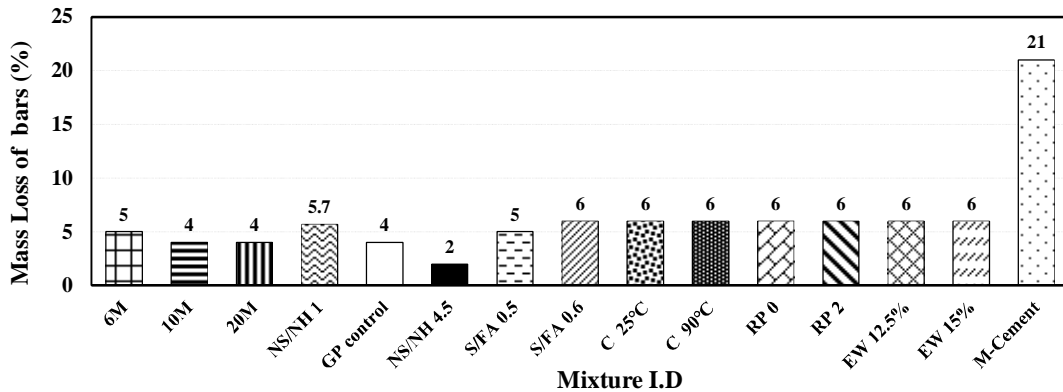


Fig. 19: Percentage mass losses of reinforcing bars after accelerated corrosion exposure of specimens

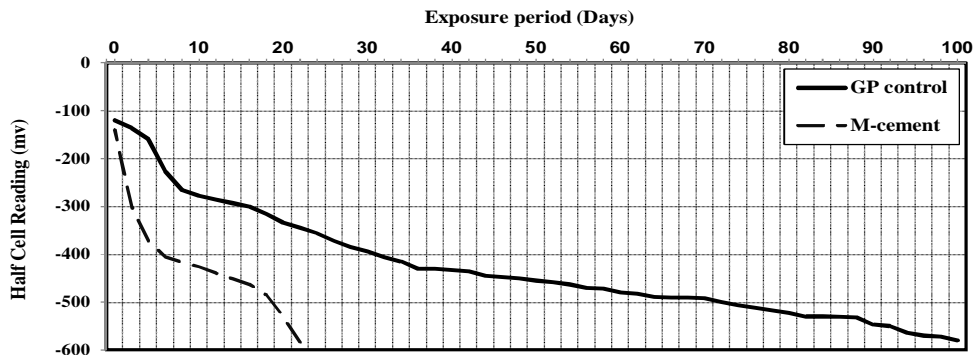


Fig. 20: Half-cell readings for GP and OPC specimens

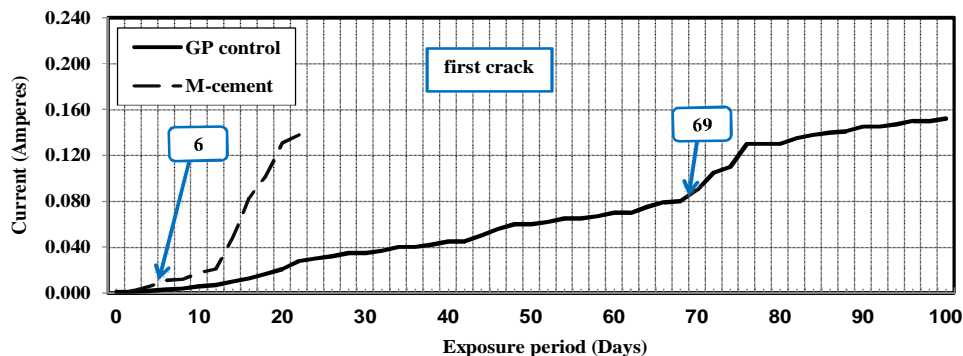


Fig. 21: The current intensity readings for GP and OPC specimens

3.3 Water absorption

The water absorption values at different ages as affected by different parameters are presented in Fig. 22. The influence of molarity of NH on the water absorption was studied using mixes M6, M10, GP control and M20. It can be seen that the water absorption of GP mortars with concentrations of 6M, 10M, 16M and 20M 8.13%, 7.26%, 5.8% and 5.1 %, respectively. This could be attributed to the better voids filling in mixes with higher molaries resulting in decreasing the water absorption percentages. On the other hand, the effect of NS/NH ratios indicated inverse relationship between the NS/NH ratio and the water absorption. The water absorption values were 6.7%, 5.8% and 5.3% for mixes NS/NH 1, GP control and NS/NH 4.5, respectively. The effect of alkaline solution to fly ash ratio was studied by investigating mixes GP control, S/FA 0.5 and S/FA 0.6. A noticeable development in the water absorption was noticed. Moreover, increasing alkaline solution to fly ash ratio increased remarkably the water absorption. The water absorption values were 5.8%, 6% and 6.3% for mixes GP control, S/FA 0.5 and S/FA 0.6, respectively. The influence of rest period (RP) on the water absorption was investigated using mixes RP0, GP control and RP2. The results showed a reduction in the water absorption for mix RP2 compared to mix RP0 and GP control. The water absorption values were 6.24%, 5.8% and 5.4% for mixes RP0, GP control and RP2, respectively.

The influence of the curing at ambient temperature compared with thermal curing was investigated using mixes C25°C, GP control and C90°C. It can be noticed that thermal curing played an important role in the rate of water absorption. The water absorption value were 6.95%, 5.8% and 5.5% for mixes C25°C, GP control and C90°C, respectively. Moreover, mixes EW12.5% and EW15% detected the effect of using extra water beside the alkaline solution in mixing GP mortar mixes. It is can be noticed that using extra water increased the water absorption. The water absorption values were 5.8%, 6.4% and 7.3% for mixes GP control (EW10%), EW12.5% and EW15%, respectively. For achieving relatively low absorption strength GP mortar mixes should be prepared with low alkaline solution to fly ash ratio, NS/NH achieving 2.5, molarity of 20 and to be cured at 60 °C with 24 hours rest period as noticed with mix M20. This mix gave 5.1% water absorption, whereas; the mortar mix prepared with ordinary Portland cement (M-cement) gave 8.33% water absorption.

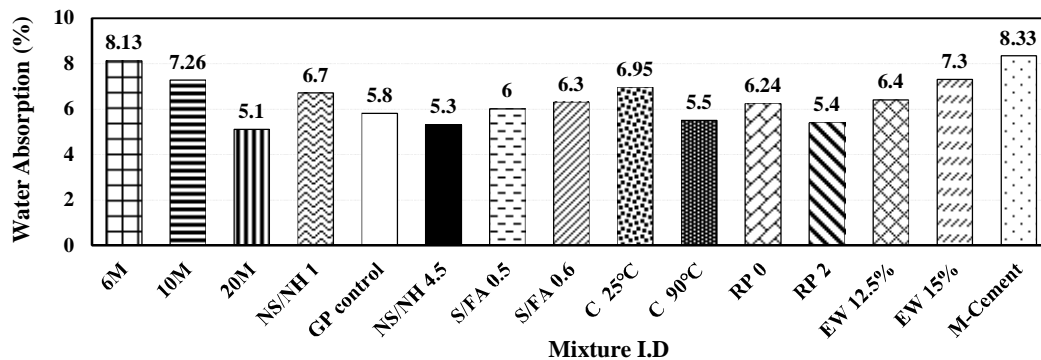


Fig. 22: The water absorptions for GP and OPC specimens

4. Conclusions and recommendations

Based on the results of the experimental work and the analysis presented in this paper, the following conclusions could be drawn:

1- There are optimum conditions for the investigated parameters to achieve the highest values for the desired mechanical properties of the considered GP mortar mixes. Keeping molarity at 16, NS/NH at 2.5, reducing alkaline solution to fly ash ratio, providing 48 hours rest period, curing at 90°C as curing temperature and reducing extra water assures achieving the best mechanical properties (compressive and flexural strengths).

2- GP mortar mixes showed superior mechanical properties compared with mortars made using ordinary Portland cement. GP mortars showed enhancements in compressive strengths up to 23.74 and 31.05% over the Portland cement mix at 28 and 60 days, respectively. Moreover, for flexural strength, the improvements were up to 22.4 and 29.2% over Portland cement mix at 28 and 60 days age, respectively.

3- Increasing molarity of the used solution enhanced the corrosion resistance of GP mortar mixes. The negative potential as well as current intensity values were remarkably reduced with increasing the molarity. Moreover, the periods to first crack were 16, 23, 69 and 71 days for M6, M10, M16 and M20 molarities, respectively.

4- NS to NH ratio influenced the corrosion resistance and the ratio of 2.5 showed the best corrosion resistance. The periods up to first crack were 19, 69 and 27 days for NS/NH ratios of 1, 2.5 and 4.5, respectively.

5- An inverse relationship between the solution to fly ash ratio and the corrosion resistance was observed. The periods to first crack were 69, 31 and 28 days for 0.4, 0.5 and 0.6 S/FA ratios, respectively.

6- Curing at 60°C showed the best corrosion resistance evaluated by half-cell, current intensity as well as periods to first crack.

7- Rest period for 24 hours seemed sufficient to enhance the corrosion resistance compared to no rest period.

8- Negative potential reading, periods to first crack as well as current intensity readings proved an inverse relationship between extra water and corrosion resistance. The periods to first crack were 69, 19 and 17 for 10%, 12.5% and 15% extra water, respectively.

9- The GP mortars mixes, showed relatively low mass loss of steel bars compared with relatively higher values for OPC mix. The enhancements in corrosion resistance ranged between 3.5 and 10.5 times the control values.

5. References

1. ASTM C618-08 (2008): Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete, American Society for Testing and Materials, Philadelphia, DOI: 10.1520/C0618-08.
2. ASTM C876-09 (2000), Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete.
3. ASTM G1-03(2011), Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens.
4. ASTM Standard. (2000): Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete, (ASTM C618-2000).
5. ASTM Standard. (2015). Standard Test Method for Flow of Hydraulic Cement Mortar. (ASTM Standard 1437-2015).
6. Badar M. S, Kupwade-Patil K., Bernal S. A, Provis J.L and, Allouche E.N, (2014), "Corrosion of steel bars induced by accelerated carbonation in low and high calcium fly ash geopolymer concretes", *Construction and Building Materials* 61, pp.79–89.
7. BS EN 196-1:2005: Methods of testing cement. Determination of strength.
8. Daniel L.Y. K. and, Jay G.S. (2010), "Effect of elevated temperatures on geopolymer paste, mortar and concrete", *Cement and Concrete Research*, pp.334–339.
9. Davidovits J. (1994), "High-Alkali Cements for 21st Century Concretes", In *Concrete Technology*, Past, Present and Future, Proceedings of V. Mohan Malhotra Symposium, Editor, P. Kumar Metha.
10. Davidovits J. (2011), "Geopolymer chemistry & applications", 3rd edition. Saint-Quentin", France, Institut Geopolymere.
11. Davidovits, J., (1979). "SPE PACTEC'79". Society of Plastic Engineers, Brookfield Center, USA, 151.
12. Duxson P., Lukey G., and Van D. J. (2007), " Physical evolution of geopolymer derived from metakaolin up to 1000 °C", *Journal of Materials Science* 42(9), pp.3044 -3054.
13. Hardjito D. and, Rangan B.V. (2005), "Development and properties of low-calcium fly ash-based geopolymer concrete", Research report GC1, Faculty of Engineering Curtin University of Technology, Perth, Australia.
14. Hardjito.D., Wallah S.E., Sumajouw D.M.J. and Rangan B.V. (2004), "On the development of fly ash-based geopolymer concrete", *ACI Materials Journal* 101, no. 6.
15. Reddy D. V., Edouard JB. and Sobhan K., (2013), "Durability of Fly Ash Based Geopolymer Structural Concrete in the Marine Environment", 2013, American Society of Civil Engineers.
16. Shaikh F. U.A. and Afshang A., (2013), "Corrosion Durability of Geopolymer Concretes Containing Different Concentrations of Alkaline Solution" Curtin University, Perth, Australia1, pp. 1–10.
17. Sharkawi, A., Rizkalla, S. and Zia, P. (2010): Corrosion activity of steel bars embedded in magnesium phosphate fiber reinforced cementitious material "PCW Grancrete". American society of civil engineers.



18. Subhash V.P. and, Sanjay S. J., Yuwaraj M. G. (2013), "Effect of water-to-geopolymer binder ratio on the production of fly ash based geopolymer concrete", International Journal of Advanced Technology in Civil Engineering, ISSN: 2231 –5721, Vol.2, Issue-1, pp. 79–83.
19. Topc U. IB. and, Sengel S. (2004), "Properties of Concretes Produced With Waste Concrete Aggregate", Cement and Concrete Research, Vol.34, NO. 8, pp.1307–12.
20. Van Deventer J.S.J, Provis J.L, Duxson P and Brice D.G. (2010), "Chemical research and climate change as drivers in the commercial adoption of alkali activated materials", Waste Biomass Valor 1 ,pp. 145-155.20.
21. Wallah S.E. and, Rangan B.V. (2006), "Low Calcium Fly Ash Based Geopolymer Concrete: Long Term Properties. Research Report GC2", Faculty of Engineering, Curtin University of Technology, Perth, Australia, pp. 01-97.
22. Wootton, I. (2001), "Confinement of steel reinforced concrete by externally applied fiber reinforced polymer wraps", The Florida state university.