

## Effects of alkali solutions on corrosion durability of geopolymer concrete

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**Abstract.** This paper presents chloride induced corrosion durability of reinforcing steel in geopolymer concretes containing different contents of sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) and molarities of NaOH solutions. Seven series of mixes are considered in this study. The first series is ordinary Portland cement (OPC) concrete and is considered as the control mix. The rest six series are geopolymer concretes containing 14 and 16 molar NaOH and  $\text{Na}_2\text{SiO}_3$  to NaOH ratios of 2.5, 3.0 and 3.5. In each series three lollypop specimens of 100 mm in diameter and 200 mm in length, each having one 12 mm diameter steel bar are considered for chloride induced corrosion study. The specimens are subjected to cyclic wetting and drying regime for two months. In wet cycle the specimens are immersed in water containing 3.5% (by wt.) NaCl salt for 4 days, while in dry cycle the specimens are placed in open air for three days. The corrosion activity is monitored by measuring the copper/copper sulphate ( $\text{Cu}/\text{CuSO}_4$ ) half-cell potential according to ASTM C-876. The chloride penetration depth and sorptivity of all seven concretes are also measured. Results show that the geopolymer concretes exhibited better corrosion resistance than OPC concrete. The higher the amount of  $\text{Na}_2\text{SiO}_3$  and higher the concentration of NaOH solutions the better the corrosion resistance of geopolymer concrete is. Similar behaviour is also observed in sorptivity and chloride penetration depth measurements. Generally, the geopolymer concretes exhibited lower sorptivity and chloride penetration depth than that of OPC concrete. Correlation between the sorptivity and the chloride penetration of geopolymer concretes is established. Correlations are also established between 28 days compressive strength and sorptivity and between 28 days compressive strength and chloride penetration of geopolymer concretes.

**Keywords:** geopolymer; concrete; durability; sorptivity; corrosion; chloride permeability

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### 1. Introduction

Concrete is one of the most widely used construction materials in the world and Portland cement is its main binder. However, the cement industry contributes between 5 and 7% of total global  $\text{CO}_2$  emission into atmosphere. Research efforts are continuing to make the concrete more sustainable by reducing the amount of cement. Partial replacement of cement by various cementitious materials such as, fly ash, slag, silica fume, etc. in concrete is now common practice in industry as their use in the concrete improves the mechanical and durability properties. However, their use as partial replacement of cement in concrete is limited to small amount

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typically up to 25-30% for fly ash and slag and up to 5-10% for silica fume.

The development of a new type of inorganic cementitious binder called “geopolymeric binder” is introduced in recent years. Geopolymer binder is a ‘new’ material that does not use Portland cement. Instead, a source of material such as fly ash, that is rich in silicon (Si) and aluminium (Al), is reacted by alkaline solutions (Duxton *et al.* 2007). It has been estimated that the manufacture of geopolymeric cement emits about 80% less CO<sub>2</sub> than the manufacture of OPC (Davidovits 1994 and Tempest *et al.* 2009), primarily because the limestone does not need to be calcined to produce the geopolymeric binder. Fly ash based geopolymers have extremely low embodied energies. In geopolymer-based concrete (produced from fly ash and a soluble silica-like activator, and cured under mild heating), Tempest *et al.* (2009) estimated that 70% less energy is consumed when compared with OPC-based concrete of similar strength.

Considerable research has been conducted on the mechanical properties of fly ash based geopolymer concrete. Geopolymer concrete exhibits superior mechanical properties than ordinary concrete. It also exhibits superior durability properties in terms of acid, sulphate, fire and corrosion resistance. Chloride induced corrosion of reinforcing steel in concrete is an important durability issue for reinforced concrete (RC). Superior corrosion resistance of concrete is always a sought after property in RC. Different techniques have been used to protect the reinforcing steel against corrosion in the concrete. One of the most commonly used techniques is epoxy coating of the reinforcing steel (Erdogdu *et al.* 2001; Hartley 1996; Salparanta 1988, Liisa 1988, Manning 1996, ACI Committee 222 1991). However, several field problems associated with field handling of epoxy-coated steel reinforcement have been reported (ACI 1988; Manning 1996; Erdogdu *et al.* 2001). Another widely used technique is cathodic protection, which requires modification of electrochemical nature of surface of the steel reinforcement by impressed current (Page and Sergi, 2000; Ahmad *et al.* 2000; Roberts, 2002; Chung, 2000; Bennett and Broomfield 1997). In addition, other techniques utilizing corrosion inhibiting admixtures (Saricimen *et al.* 2002; Slater 1983; Tullmin *et al.* 1995; Miller and Fielding 1997; Nami *et al.* 1994), nonmetallic reinforcements (Tannous and Saadatmanesh 1999; Gentry and Husain 1999) and supplementary cementing materials (SCM) in concrete (Ahmed *et al.* 2006; Mehta 1998, 1999; Malhotra 1987) are being developed. Their limitations, long-term performances and cost effectiveness have yet to be established.

Corrosion durability of geopolymer concrete is studied by a number of researchers (Miranda *et al.*, 2005, Bastidas *et al.* 2008, Oliva and Nikraz 2011, Reddy *et al.* 2011, Patil and Allouche, 2012, Fansuri *et al.* 2012). Miranda *et al.* (2005) studied the corrosion resistance of fly ash based geopolymer mortar and reported similar corrosion resistance of geopolymer mortar to cement mortar. The molarities of sodium hydroxide (NaOH) alkali solution used in their study were 8M and 12.5M. Bastidas *et al.* (2008) also reported similar corrosion resistance of fly ash based geopolymer mortars to ordinary cement mortars and the molarity of NaOH solution was 12.5M. Oliva and Nikraz (2011) studied the corrosion resistance of two geopolymer concrete mixes containing 14M NaOH solution in accelerated corrosion environment. Superior corrosion resistance of both geopolymer concretes are reported compared to ordinary Portland cement concrete of similar compressive strength in their study. Reddy *et al.* (2011) also studied the corrosion resistance of geopolymer concretes containing 8M and 14M NaOH solution under accelerated corrosion environment at very high external DC potential of 30V applied to a 13 mm diameter bar of 500 mm in length. Better corrosion resistance of geopolymer concretes in terms of lower corrosion current than ordinary Portland cement concrete is also reported in their study. Superior corrosion resistance of geopolymer concrete is also reported recently by Patil and

Allouche (2012). The molarity of NaOH solution in their study was also 14M.

It can be seen that in all of the above studies that the highest molarity of NaOH solution was 14M and the ratio of sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) to NaOH was as high as 2.5. NaOH and  $\text{Na}_2\text{SiO}_3$  alkali solution are commonly used in blended form to activate the fly ash in geopolymer concretes. The concentrations of NaOH solution and the amounts of  $\text{Na}_2\text{SiO}_3$  affect the properties of geopolymer concrete (Fansuri *et al.* 2012). It is generally believed that the higher the molarity of NaOH solution for a given amount of  $\text{Na}_2\text{SiO}_3$  the faster the geopolymerisation process and higher the compressive strength of concrete. The same is also valid for the  $\text{Na}_2\text{SiO}_3$ , where higher compressive strength of geopolymer concrete can be achieved by increasing its content in the mix. The passivity of geopolymer concrete is also affected by the high molar NaOH solution and high  $\text{Na}_2\text{SiO}_3$  content as it affected the alkalinity of the geopolymer concrete (Thompson *et al.* 1997). However, no such study on the effect of high molar NaOH solution and the high contents of  $\text{Na}_2\text{SiO}_3$  on the corrosion durability of reinforcing steel in geopolymer concrete is reported. Moreover, no study on the associated durability properties such as chloride penetration and sorptivity of such geopolymer concretes is also reported in the literature. Therefore, this study is designed to evaluate the effects of high molar NaOH solutions such as 14M and 16M and  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratios of 2.5, 3 and 3.5 on the corrosion durability of geopolymer concretes. The effects of above parameters on two associated durability tests such as chloride penetration and sorptivity that directly relates to the chloride induced corrosion resistance of concrete are also evaluated in this study.

## 2. Materials

Ordinary Portland cement (OPC) was used in the control mix and class F fly ash was used in the geopolymer mixes. Chemical compositions and properties of OPC and class F fly ash are shown in Table 1. The activating solutions for geopolymer were sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) with a chemical

Table 1 Chemical analysis and physical properties of portland cement and fly ash

Chemical analysis	Cement (%)	Class F fly ash (%)
$\text{SiO}_2$	20.2	51.80
$\text{Al}_2\text{O}_3$	4.9	26.40
$\text{Fe}_2\text{O}_3$	2.8	13.20
CaO	63.9	1.61
MgO	2.0	1.17
MnO	-	0.10
$\text{K}_2\text{O}$	-	0.68
$\text{Na}_2\text{O}$	-	0.31
$\text{P}_2\text{O}_5$	-	1.39
$\text{TiO}_2$	-	1.44
$\text{SO}_3$	2.4	0.21
Physical properties		
Particle size	25 - 40% $\leq 7 \mu\text{m}$	40% of 10 $\mu\text{m}$
Specific gravity	2.7 to 3.2	2.6
Surface area ( $\text{m}^2/\text{g}$ )	-	-
Loss on ignition (%)	2.4	0.5

composition of (wt.%):  $\text{Na}_2\text{O} = 14.7$ ,  $\text{SiO}_2 = 29.4$  and water = 55.9. The other characteristics of the sodium silicate solution are specific gravity of 1.53 g/cc and viscosity at  $20^\circ\text{C}$  of 400 cp. The sodium hydroxide (NaOH) solution was prepared from analytical grade sodium hydroxide pellets. The mass of the NaOH solids in the solution varied depending on the concentration of the solution expressed in terms of molar, M. In this study, the NaOH solution with concentrations of 14M and 16M were considered. The NaOH was first mixed with de-ionized water. During the mixing of sodium hydroxide solution, the white sodium hydroxide pellets were slowly dissolved by the addition of de-ionized water. The sodium hydroxide solution was then mixed with  $\text{Na}_2\text{SiO}_3$  (Sodium Silicate) at desired ratios and produced the alkali activator solution. The alkali activator solutions were then used in the mixing of geopolymer concretes.

### 3. Experimental program and mix proportions

In this study, seven series of mixes are considered. Table 2 shows the detail experimental program and mix proportions of all seven series. The first series is the control series where ordinary concrete is used and is designated as OPC mix. The rest six series are geopolymer concretes and contained different concentrations of NaOH solution and ratios of  $\text{Na}_2\text{SiO}_3/\text{NaOH}$ . The second, third and fourth series contain three different  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratios of 2.5, 3 and 3.5, respectively. A 14M NaOH solution is used in above three series. They are designated as GP-14-2.5, GP-14-3 and GP-14-3.5, respectively. The fifth, sixth and seventh series are similar to the second, third and fourth series in every aspect except the concentration of NaOH solution, where 16M NaOH solution is used. They are designated as GP-16-2.5, GP-16-3 and GP-16-3.5, respectively. The alkali activator solution to fly ash ratio of geopolymer concretes is kept similar to water/cement ratio of OPC mix. The water to geopolymer solid ratios of all geopolymer concretes are also shown in Table 2.

Table 2 Mix proportions and properties of geopolymer concretes

Series	Mix type/ Designation	Fly ash ( $\text{kg}/\text{m}^3$ )	Cement ( $\text{kg}/\text{m}^3$ )	Aggregate ( $\text{kg}/\text{m}^3$ )	Alkaline activator solution ( $\text{kg}/\text{m}^3$ )		Water ( $\text{kg}/\text{m}^3$ )	Water/ geopolymer solid ratio	Slump (mm)	28 days compressive strength (MPa)
					Sodium silicate, ( $\text{Na}_2\text{SiO}_3$ )	Sodium hydroxide (NaOH)				
1	OPC	-	422	1788	--	-	190	-	105	40
2	GP-14-2.5	422	-	1788	135.7	54.3	-	0.195	280	31
3	GP-14-3	422	-	1788	142.5	47.5	-	0.196	280	35
4	GP-14-3.5	422	-	1788	147.7	42.2	-	0.198	270	38
5	GP-16-2.5	422	-	1788	135.7	54.3	-	0.174	250	33
6	GP-16-3	422	-	1788	142.5	47.5	-	0.188	250	37
7	GP-16-3.5	422	-	1788	147.7	42.2	-	0.190	240	50

Conventional mixing is used to prepare both OPC and geopolymer concretes. The geopolymer concretes are subjected to steam curing at 60°C for 24 hours immediately after casting. The specimens are then demolded and cured in the laboratory in open air until the date of testing. The OPC concrete specimens are demolded after 24 hours and stored in the curing tanks where they are subjected to standard wet curing conditions. Concrete cylinders having 100 mm in diameter and 200 mm in height are cast to measure the 28 days compressive strength. At least three cylinders are cast and tested for each mix. Lollypop specimens of 100 mm (diameter)X 200 mm (height) cylinder with a 16 mm diameter steel bar at the centre of each cylinder is prepared for the corrosion test.

## 4. Testing methods

### 4.1 Monitoring of corrosion of reinforcing steel in concrete

The corrosion of reinforcing steel in geopolymer and ordinary concretes was evaluated by half-cell potential measurements according to ASTM C876 standard (2000). It is a non-destructive electro-chemical method used to find out the probability of corrosion tendency of rebar in the concrete. This technique directly measures the potential of rebar using a high-impedance voltmeter as shown in Fig. 1. The voltmeter was consisted of two terminals, one of which was connected to the rebar in concrete, while the other was connected to a copper/copper sulphate reference cell with a porous sponge at the end. During the measurement process, the sponge is guided to slide over the surface of the concrete, and readings from the voltmeter are recorded. ASTM C 876 has provided guidelines on the relationship between half-cell potential and the tendency of rebar corrosion as follows (ASTM C876-09 2000 and Srimahajariyaphong and Niltawach 2011):

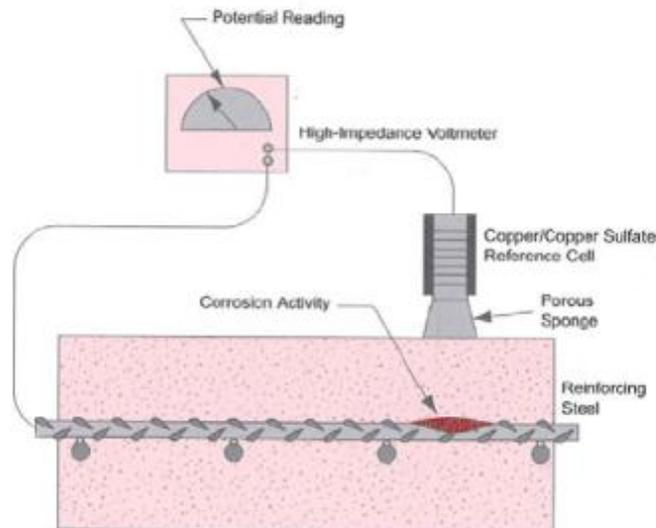


Fig. 1 Half-cell potential measurement setup

1. If potentials over an area are more positive than -200 mV, there is greater than 90% probability that no reinforcing steel corrosion occurs in that area at the time of measurement.
2. If potentials over an area are in the range of -200 mV to -350 mV, corrosion activity of the reinforcing steel in that area is uncertain.
3. If potentials over an area are more negative than -350 mV, there is greater than 90% probability that reinforcing steel corrosion occurs in that area at the time of measurement.

#### 4.2 Sorptivity of concrete

Sorptivity of both ordinary and geopolymer concretes was measured according to ASTM C1585 standard (2013). In this test 50 mm thick and 100 mm diameter discs were used. Curved surface and one flat surface of each disc were epoxy coated for this test.

#### 4.3 Chloride penetration test

Chloride penetration of ordinary and geopolymer concretes was determined according to the ASTM C1543 (2010). In this test the sample dimensions were similar to that used in sorptivity test. Epoxy was also used to coat the curved surface and one plain surface. This was done in order to restrict the chloride ion flow in one direction only. The epoxy coated samples were then immersed in water containing 3.5% sodium chloride for 4 days and then allowed to dry for 3 days. This wetting-drying cycle was applied for eight weeks. After the wetting-drying cycles the specimens were broken into two pieces and 0.1N AgNO<sub>3</sub> solution was sprayed on the broken surface in order to observe the chloride penetration depth. The change in colour on the broken concrete surface indicates the chloride penetration depth in the specimen. In all of the above durability tests at least three specimens were used for each mix and averaged.

### 5. Results and discussion

#### 5.1 Workability and compressive strength of geopolymer concretes:

The effects of two different molarities of NaOH solution and three different ratios of Na<sub>2</sub>SiO<sub>3</sub>/NaOH on workability and 28 days compressive strength of geopolymer concretes are shown in Table 2. It can be seen that the compressive strength of geopolymer concrete increases with increase in Na<sub>2</sub>SiO<sub>3</sub> contents for a given concentration of NaOH solution. The rate is much higher in the geopolymer concretes containing 16M NaOH solution. The higher compressive strength of geopolymer concrete containing 16MNaOH compared to that containing 14MNaOH is due to faster and higher dissolution rate of silicate and aluminate in fly ash (Fansuri *et al.* 2012). During geopolymerisation process the silicate and aluminate in fly ash is dissolved by the NaOH and form sodium-alumina-silicate geopolymerisation product which contributed to the strength of geopolymer matrix. Similar results are also reported by other researchers (Olivia and Nikraz 2011).

#### 5.2 Effect of molarity of NaOH and amount of Na<sub>2</sub>SiO<sub>3</sub> on water sorptivity

The water sorptivity values of different geopolymer concretes and ordinary concrete are shown in Fig. 2. It can be seen that the water sorptivity of geopolymer concretes is lower than that of

ordinary concrete. Results also show that the water sorptivity of geopolymer concrete decreases with increase in  $\text{Na}_2\text{SiO}_3$  contents for a given concentration of NaOH solution. The rate of decrease of sorptivity is even higher for higher concentrations of NaOH in geopolymer concretes. The significant reduction of sorptivity of geopolymer concretes containing high molar NaOH and higher amount of  $\text{Na}_2\text{SiO}_3$  solutions can be attributed to the formation of increasing amount of dense sodium-aluminasilicate gel in the matrix. Past research shows that the concentration of sodium hydroxide is the most important factor for geopolymer synthesis (Puertas *et al.* 2000). The solubility of aluminosilicate increases with increase in hydroxide concentration (Gasteiger *et al.* 1992). Sodium silicate also helps in solubility of fly ash particles during geopolymerisation process and if less sodium silicate is available in the mixture empty space between fly ash particles in the geopolymer matrix results. Therefore, by increasing the sodium silicate content the empty spaces can be reduced. The low sorptivity value of geopolymer concrete is also an indication of disconnected fine pore structures in the matrix. Research shows that the water absorption and sorptivity of concrete significantly reduced in disconnected pore system (He *et al.* 2012). The lower sorptivity of geopolymer concretes than ordinary concrete can also be attributed to the higher slump and hence better compaction of former than the latter. The positive effect of low sorptivity is also observed on chloride penetration and corrosion resistance of geopolymer concretes and is discussed in the following sections.

### 5.3 Effect of molarity of NaOH and amount of $\text{Na}_2\text{SiO}_3$ on chloride penetration

The effects of different molarities of NaOH and  $\text{Na}_2\text{SiO}_3$  contents on chloride penetration of geopolymer concretes are shown in Fig. 3. A linear decreasing trend of chloride penetration in geopolymer concretes can be seen with increasing concentrations of NaOH solution and amount of  $\text{Na}_2\text{SiO}_3$  contents. The results are consistent with those of water sorptivity values. As discussed before the low water sorptivity of geopolymer concrete might contributed to the better chloride penetration resistance.

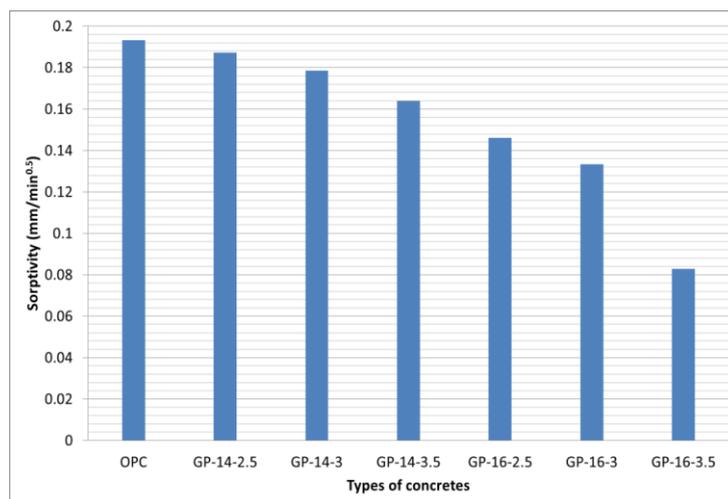


Fig. 2 Effects of molarity of NaOH and amount of  $\text{Na}_2\text{SiO}_3$  on water sorptivity

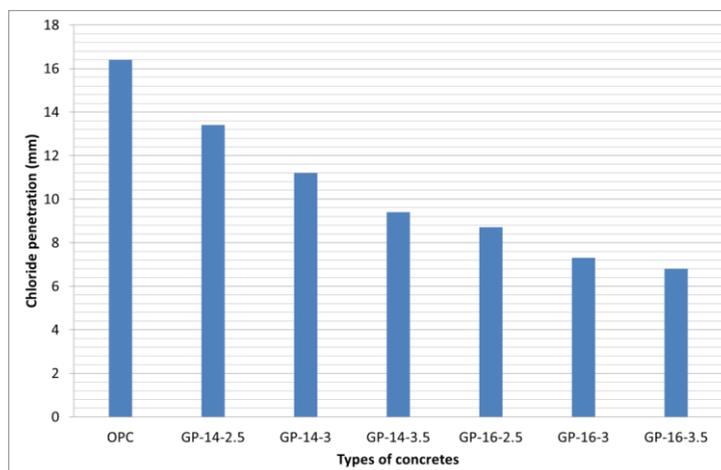


Fig. 3 Effects of molarity of NaOH and amount of  $\text{Na}_2\text{SiO}_3$  on chloride penetration

#### 5.4 Effect of molarity of NaOH and amount of $\text{Na}_2\text{SiO}_3$ on chloride induced corrosion resistance:

Among many corrosion monitoring and measuring techniques, half-cell potential measurement method is the most convenient and quickest method of monitoring the corrosion of reinforcing steel in the concrete. However, this method only provides the probability of corrosion activity of steel bar in the concrete. The half-cell potential readings shown in Figs. 4 and 5 are based on copper/copper sulphate reference electrode. The effects of two different molarities of NaOH solution on the corrosion resistance of geopolymer concretes in terms of half-cell potential readings are shown in Figs. 4-5 and compared with that of ordinary concrete. The half-cell potential readings shown in the figures are average of three specimens. It can be seen that all geopolymer concretes exhibited better corrosion resistance in terms of lower negative potential readings than their counter part ordinary concrete. The potential reading of all geopolymer concretes increases to more negative readings with progress of time. However, the rate of increase of negative readings and hence the corrosion rate of geopolymer concretes is slower than that of ordinary concrete. The geopolymer concrete made with 16M NaOH solution exhibited better corrosion resistance in terms lower negative potential values than that containing 14M NaOH solution. According to ASTM C876 (2000) the smaller the negative potential readings the lower the probability of corrosion of steel in the concrete. The better corrosion resistance of geopolymer concretes containing 16M NaOH solution is also consistency with the sorptivity and chloride penetration resistance results observed in this study.

The effects of different quantities of  $\text{Na}_2\text{SiO}_3$  on the corrosion resistance of geopolymer concrete can also be seen in Figs.4-5. It is observed that the negative potential readings are decreased due to increase in the  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratios. The rate of increase of negative potential values of geopolymer concrete with  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio of 3.5 is very slow and reached towards a constant rate at 16M NaOH. This is believed to be due to simultaneous increase of molarity of NaOH and quantity of  $\text{Na}_2\text{SiO}_3$  solutions in geopolymer concrete. The superior corrosion resistance of geopolymer concretes over ordinary concrete can also be seen in Fig. 6.

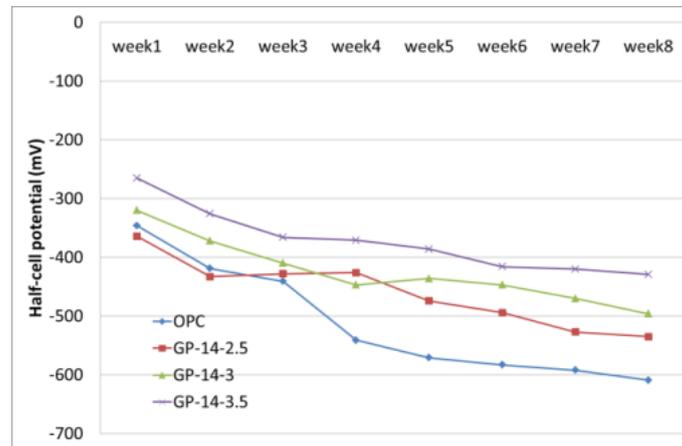


Fig. 4 Effect of different ratios of sodium silicate to sodium hydroxide on corrosion resistance of geopolymer concrete containing 14M sodium hydroxide solution

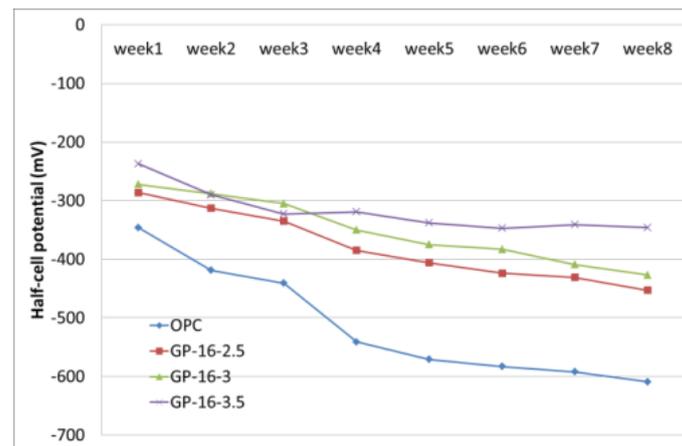


Fig. 5 Effect of different ratios of sodium silicate to sodium hydroxide on corrosion resistance of geopolymer concrete containing 16M sodium hydroxide solution

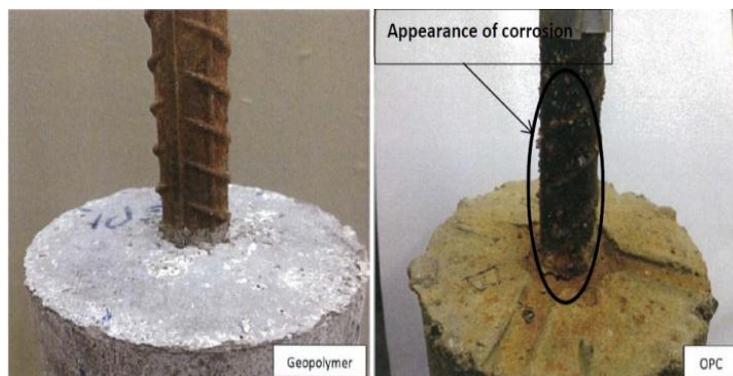


Fig. 6 Corrosion of steel bar in geopolymer concrete and ordinary concrete

The sodium silicate is also believed to be acted as corrosion inhibitor in geopolymer concrete. Research shows that sodium silicate is used as corrosion inhibitor in many applications e.g., in metallic water pipe protection (Asrar *et al.* 1998). Silicate inhibits the corrosion of steel bar in geopolymer concrete by forming a thin silicate film on the surface of steel bar (Asrar *et al.* 1998).

### 5.5 Actual mass loss calculation and visual inspection

At the end of corrosion tests, the actual steel loss of reinforcing bars in OPC concrete and geopolymer concretes are evaluated according to ASTM G1-03 (2011). Standard procedure of cleaning of reinforcing bars according to ASTM G1-03 is followed. In the case of OPC concrete, the reinforcing bar lost approximately 0.05% by mass of steel, whereas in geopolymer concretes the no mass loss of steel bar is observed even though the half-cell potential values indicated some probability of corrosion. The small amount of steel loss observed in this study is due to the application of natural corrosion regime in relatively small period of time of 8 weeks. The conditions of steel bar in both concretes after the corrosion test are shown in Figs. 6 and 7. The appearance of corrosion can be seen in the steel bar in the OPC concrete specimen, on the other hand no such corrosion can be observed in the steel bar in the geopolymer concrete specimens (Fig. 7). The surface appearance of steel bars after corrosion tests in both concretes is shown in Fig. 8.



Fig. 7 Condition of reinforcing bar in OPC and geopolymer concrete after splitting the specimen

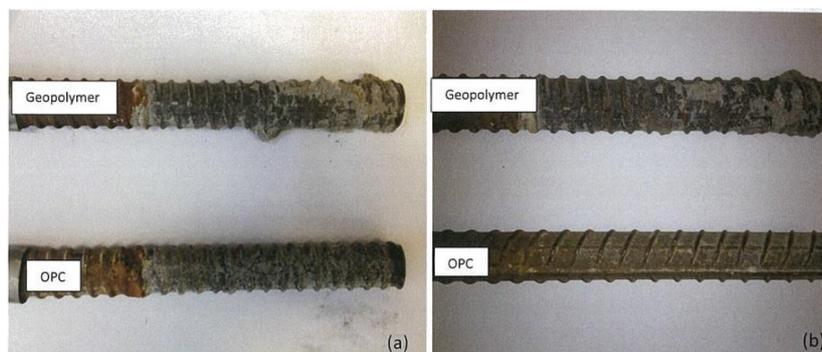


Fig. 8 Surface appearance of reinforcing bar in OPC and geopolymer concrete before (a) and after (b) mechanical/chemical cleaning according to ASTM G1

Fig. 8a shows the sticking of geopolymer matrix on the surface of the steel bar, whereas no trace of cement matrix can be seen on the steel bar in the OPC specimen. The sticking of geopolymer matrix on steel clearly indicates the absence of corrosion on the steel bar in the geopolymer concrete and it also indicates good bond between the steel bar and the geopolymer concrete. After mechanical/chemical cleaning, the geopolymer matrix still stucked on the steel surface, whereas the steel bar in OPC concrete showed no sign of matrix on its surface. This again proved the absence of corrosion and better bond between geopolymer concrete and steel bar in geopolymer concretes.

5.6 Relationship of compressive strength with sorptivity and chloride penetration of geopolymer concretes

Figs. 9 and 10 show the correlations between compressive strength and sorptivity and between compressive strength and chloride penetration of geopolymer concretes. A linear decreasing trend of sorptivity with increase in compressive strength of geopolymer concretes is observed. Similar relationship is also observed between the compressive strength and the chloride penetration.

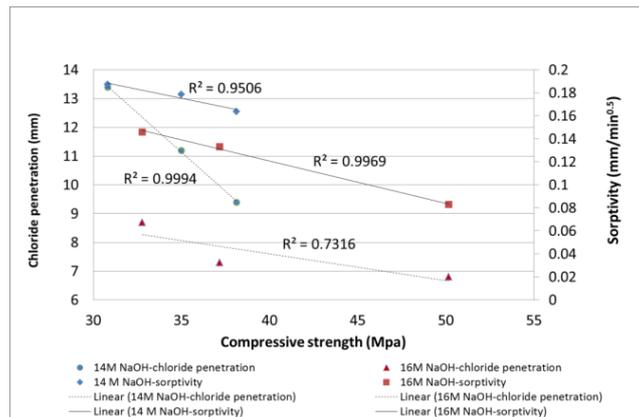


Fig. 9 Relationships among compressive strength, sorptivity and chloride penetration of geopolymer concretes

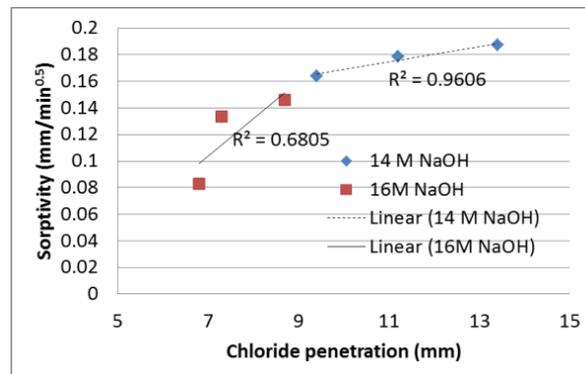


Fig. 10 Correlation between chloride penetration and sorptivity of geopolymer concretes

Correlation between the sorptivity and the chloride penetration of geopolymer concretes is also established where decrease in chloride penetration is observed with decrease in sorptivity values. It can also be seen that the rate of decrease of sorptivity with decrease in chloride penetration of geopolymer concretes containing 16M NaOH solution is much higher than that containing 14M NaOH.

## 6. Conclusions

In this study the effects of molarities of NaOH and different contents of  $\text{Na}_2\text{SiO}_3$  on chloride induced corrosion of geopolymer concrete are evaluated. With limited variables the following conclusions are made:

1. The geopolymer concretes exhibited better corrosion resistance than ordinary concrete, which is evidenced from half-cell potential readings.
2. The higher the amount of  $\text{Na}_2\text{SiO}_3$  and the concentration of NaOH solutions the better the corrosion resistance of geopolymer concrete is.
3. Similar behaviour is also observed in sorptivity and chloride penetration depth measurements.
4. The geopolymer concretes exhibited lower sorptivity and chloride penetration depth than that of ordinary concrete.
5. Correlation between the sorptivity and the chloride penetration of geopolymer concretes is established.
6. Correlations are also established between 28 days compressive strength and sorptivity and between 28 days compressive strength and chloride penetration of geopolymer concretes.

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## References

- ACI Committee 222 (1991), "Corrosion of metals in concrete", ACI Manual of Concrete Practice Part 1-1991: Materials and General Properties of Concrete, *American Concrete Institute*, Detroit, USA.
- Ahmad, S., Basavaraja, L.R. and Bhattacharjee, B., (2000), "Design procedures for cathodic protection systems for RC members", *Indian Concrete J.*, 74(4), 208-213.
- Ahmed, S.F.U., Maalej, M., Paramasivam, P. and Mihashi, H. (2006), "Assessment of corrosion-induced damage and its effect on the structural behavior of RC beams containing supplementary cementitious materials", *J. Progress Struct. Eng. Mater.*, 8(2), 69-77.
- Asrar, N., Malik, A.U. and Ahmed, S. (1998), *Corrosion Prevention with Sodium Silicate*, Technical Report N0.TR3804/EVP95013.
- ASTM C1543-10a (2010), Standard Test Method for Determining the Penetration of Chloride Ions into concrete by ponding.
- ASTM C1585-13 (2013), Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic

- Cement Concrete.
- ASTM C876-09 (2000), Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete.
- ASTM G1-03(2011), Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens.
- Bastidas, D.M., Jimenez, A.F., Palomo, A. and Gonzalez, J.A. (2008), "study on the passive state stability of steel embedded in activated fly ash" *Corros. Sci.*, **50**, 1058-1065.
- Bennett, J. and Broomfield, J.P. (1997), "Analysis of studies on cathodic protection criteria for steel in concrete", *Mater. Perform.*, **36**(12), 16-21.
- Chung, D.D.L. (2000), "Corrosion control of steel reinforced concrete", *J. Mater. Eng. Perform.*, **9**(5), 585-588.
- Davidovits, J. (1994), "Global warming impact on the cement and aggregates industries", *World Resource Review*, **6**(2), 263-278.
- Duxson, P., Fernández-Jiménez, A., Provis, J.L., Lukey G.C., Palomo, A. and Van Deventer, J.S.J. (2007), "Geopolymer technology: the current state of the art", *J. Mater. Sci.*, **42**, 917-33.
- Erdogdu, S., Bremner, T.W. and Kondratova, I.L., (2001), "Accelerated testing of plain and epoxy coated reinforcement in simulated seawater and chloride solutions", *Cement Concrete Res.*, **31**, 861-867.
- Fansuri, H., Prasetyoko, D., Zhang, Z. and Zhang, D. (2012), "The effect of sodium silicate and sodium hydroxide on the strength of aggregates made from coal fly ash using the geopolymerisation method", *Asia-Pacific J. Chem. Eng.*, **7**, 73-79.
- Gasteiger, H.A., Frederick, W.J. and Streisel, R.C. (1992), "Solubility of aluminosilicates in alkaline solutions and a thermodynamic equilibrium model", *Ind. Eng. Chem. Res.*, **31**(4), 1183-1190.
- Gentry, T.R. and Husain, M. (1999), "Thermal compatibility of concrete and composite reinforcements", *ASCE, J. Compos. Construct.*, **3**(2), 82-86.
- Hartley, J. (1996), "Corrosion protection with epoxy coated reinforcement", *Steel Times*, **224**(1), 23-24.
- He Z.M., Long G.C. and Xie Y.J. (2012), "Influence of subsequent curing on water sorptivity and pore structure of steam-cured concrete", *J. Central South Univ.*, **19**, 1155-1162.
- Liisa, S. (1988), "Corrosion prevention of concrete reinforcement by epoxy coating", *Nordic Concrete Res.*, 250-258.
- Malhotra, V.M. (1987), "Supplementary cementing materials for concrete", *CANMET*, Canada.
- Manning, D.G. (1996) "Corrosion performance of epoxy-coated reinforcing steel: North American experience", *Construct. Build. Mater.*, **10**(5), 349-365.
- Mehta, P.K. (1998), "Role of pozzolanic and cementitious materials in sustainable development of the concrete industry", *Sixth CANMET/ACI conference*, Ed. V.M Malhotra, ACI special publication, SP-178, 1-20.
- Mehta, P.K. (1999), "Advancements in concrete technology", *Concrete Int.*, **21**(6), 69-75.
- Miller, J.R. and Fielding, D.J. (1997), "Durability by admixture", *Concrete Int.*, **19**(4), 29-34.
- Miranda, J.M., Jimenez, A.F., Gonzalez, J.A. and Palomo, A. (2005), "Corrosion resistance in activated fly ash mortars", *Cement Concrete Res.*, **35**, 1210-1217.
- Nami, C.K., Bury, M.A. and Farzam, H. (1994) "Corrosion evaluation of a sodium thiocyanate based admixture", *Concrete Int.*, **16**(4), 22-25.
- Olivia, M. and Nikraz, H.R. (2011), Corrosion performance of embedded steel in fly ash geopolymer concrete by impressed voltage method. In incorporating sustainable practice in mechanics of structures and materials, Taylor and Francis group, London.
- Olivia, M. and Nikraz, H.R. (2011), "Strength and water permeability of fly ash geopolymer concrete", *ARPJ. Eng. Appl. Sci.*, **6**(7), 70-78.
- Page, C.L. and Sergi, G. (2000), "Developments in cathodic protection applied to reinforced concrete", *ASCE J. Mater. Civil Eng.*, **12**(1), 8-15.
- Patil, K.K. and Allouche, E.N. (2012), Examination of chloride induced corrosion of reinforced geopolymer concrete, *J. Mater. Civil Eng.*, doi:10.1061/(ASCE)MT.1943-5533.0000672
- Puertas, F., Martinez-Ramirez, S., Alonso, S. and Vazquez, T. (2000), "Alkali activated fly ash/slag cements: Strength behaviour and hydration products", *Cement Concrete Res.*, **30**(10), 1625-1632.

- Reddy, D.V., Edouard, J.B., Sohban, K. and Rajpathak, S.S. (2011), Durability of reinforced fly ash based geopolymer concrete in the marine environment, In proceedings of 36<sup>th</sup> conference on our world in concrete and structures, Singapore, 10.
- Roberts, D.G. (2002), "Corrosion control in reinforced concrete", *Struct. Eng.*, **80**(23/24), 18-20.
- Saricimen, H., Mohammed, M., Quddus, A., Shameem, M. and Barry, M.S. (2002), "Effectiveness of concrete inhibitors in retarding rebar corrosion", *Cement Concrete Compos.*, **24**, 89-100.
- Slater, J.E. (1983), "Corrosion of metals in association with concrete", *ASTM STP 818*.
- Srimahajariyaphong, Y. and Niltawach, T. (2011), "Corrosion prevention of rebar in concrete due to chloride. Journal of metals, materials and minerals", **21**(1), 57-66.
- Tannous, F.E. and Saadatmanesh, H. (1999), "Durability of AR glass fiber reinforced plastic bars", *J. Compos. Construct.*, **3**(1), 12-19.
- Tempest, B., Sanusi, O., Gergely, J., Ogunro, V. and Weggel, D. (2009), Compressive strength and embodied energy optimization of fly ash based geopolymer concrete. In: world of coal ash (WOCA) conference.
- Thompson, J.L., Scheetz, B.E., Schock, M.R., Lytle, D.A. and Delaney, P.J. (1997), Sodium silicate corrosion inhibitors: issues of effectiveness and mechanisms, Water Quality Technology Conference, November 9-12, 1997, Denver, CO.
- Tullmin, M., Mammoliti, L., Sohdi, R., Hansson, C.M. and Hope, B.B. (1995), "The passivation of reinforcing steel exposed to synthetic pore solution and the effect of calcium-nitrite inhibitor", *Cement Concrete Aggr.*, **17**(2), 134-144.

**APPENDIX**

$$M_n = A_s f_y \left( d - \frac{a}{2} \right) + A_p f_{yp} \left( d_p - \frac{a}{2} \right) \quad (\text{SI Units}) \quad (1)$$

$$K = \frac{2 + \lambda}{2\lambda + 1} \quad (\text{SI Units}) \quad (2)$$

$$\tan \beta = \frac{3(\lambda - 1)}{\lambda + 2} \quad (\text{SI Units}) \quad (3)$$