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Durability performance of concrete containing Saudi natural pozzolans as supplementary cementitious material

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Abstract. This paper reports an experimental investigation conducted to evaluate the durability performance of concrete mixtures prepared utilizing blends of Type I Portland cement (OPC) and natural pozzolans (NPs) obtained from three different sources in Saudi Arabia. The control concrete mixture containing OPC alone as the binder and three concrete mixtures incorporating NPs were prepared keeping water/binder ratio of 0.4 (by weight), binder content of 370 kg/m^3, and fine/total aggregate ratio of 0.38 (by weight) invariant. The compressive strength and durability properties that included depth of water penetration, depth of carbonation, chloride diffusion coefficient, and resistance to reinforcement corrosion and sulfate attack were determined. Results of this study indicate that at all ages, the compressive strength of NP-admixed concrete mixtures was slightly less than that of the concrete containing OPC alone. However, the concrete mixtures containing NP exhibited lower depth of water penetration and chloride diffusion coefficient and more resistance to reinforcement corrosion and sulfate attack as compared to OPC. NP-admixed concrete showed relatively more depth of carbonation than OPC when subjected to accelerated carbonation. The results of this investigation indicates the viability of utilizing of Saudi natural pozzolans for improving the durability characteristics of concrete subjected to chloride and sulfate exposures.

Keywords: Saudi natural pozzolan; cement replacement; concrete; compressive strength; durability characteristics

1. Introduction

Deterioration of concrete structures under aggressive exposure conditions, such as those encountered in the coastal areas, has been a challenging durability problem that makes it difficult to achieve the targeted service life. For example, the harsh environmental conditions in the Arabian Gulf include fluctuating temperatures rising to 50°C in summer and dropping to as low as 2°C in winter, widely fluctuating relative humidity, and the presence of soils containing high concentrations of chloride and sulfate salts (Al-Amoudi 1995). Efforts have been made worldwide including Saudi Arabia to produce durable concrete mixtures that can withstand the aggressive exposure conditions that prevail in the marine regions. Pozzolanic materials such as silica fume, fly ash, granulated blast furnace slag, metakaolin, and natural pozzolan, etc., are widely used as supplementary cementitious materials to produce concrete with high durability performance (Al-Amoudi *et al.* 2006, Ashish *et al*. 2016, Lenkaa and Panda 2017, Yahiaoui *et al*. 2017, Djamila *et al*. 2018, Jenaa and Panda 2018, Nas and Kurbetc 2018).

Natural pozzolan (NP) has been utilized in many countries throughout the world where it is available as a local material. Some other countries have imported this material for its technical advantage. Potential use of NP as a partial replacement of ordinary Portland cement (OPC) has been the focus of a number of researchers (Rodriguez and Uribe-Afif 2002, Pekmezci and Akyuz 2004, Mouli and Khelafi 2008, Najimi *et al*. 2008, Kaid *et al*. 2009, Najimi *et al*. 2012, Yu *et al*. 2015). It has been reported that at early ages, the compressive strength of concrete mixtures prepared with the blends of OPC and NP was less than that prepared using OPC alone as the binder (Shannag and Asim 1995, Colak 2003, Uzal and Turanli 2003, Mouli and Khelafi 2008, Najimi *et al*. 2008, Najimi *et al*. 2012). However, after extended curing, the strength of NP-admixed concrete is reported to be higher than the concrete containing OPC alone (Ghrici *et al*. 2007). Almost all the studies showed that the concrete mixtures prepared with NP as supplementary cementitious material exhibit better durability properties than OPC alone. With the partial replacement of OPC with NP, the pores in concrete get refined resulting into reduction of the penetration of aggressive species in concrete such as water, chloride, sulfate, etc., thereby, enhancing the durability of concrete against deterioration caused by reinforcement corrosion and sulfate attack (Shannag and Asim 1995, Uzal and Turanli 2003). Shrinkage of concrete is also reported to decrease with the addition of NP (Ghrici *et al*. 2007). Furthermore, some studies reported that the concrete mixtures prepared by incorporating NP showed a higher resistance against acid attack as compared to that of the concrete mixtures containing OPC alone as binder (Rehmani and Ramzanianpour 2008, Siad *et al*. 2010).

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In Saudi Arabia, imported NP has been used by the concrete industry as one of the pozzolanic admixtures to achieve the durability requirements despite the fact that large reserves of NP do exist in the western region of the country and ready to be used (Moufti *et al*. 2000, Roobol *et al*. 2002). In an effort to produce concrete mixtures using NP as a locally available supplementary cementitious material, several companies in Saudi Arabia have recently started producing different grades of NP commercially by crushing volcanic tuff collected from basalt plateaus, called Herrat in Arabic, in the western region of Saudi Arabia. To produce different grades of the natural pozzolan, crushing of the raw materials is carried out differently to achieve different particle size distributions and degrees of fineness. Several studies pertaining to the physical and chemical characteristics of the Saudi natural pozzolans are reported (Sabtan and Shehata 2000, Khan and Alhozaimy 2011, Celik *et al.* 2014, Moon *et al.* 2014). As indicated by these researchers, the physical and chemical characteristics of the Saudi natural pozzolans vary slightly due to different locations of the source of volcanic tuff and different levels of crushing the raw materials. The variations in the physical and chemical characteristics are attributed also to the differences in sampling and testing methods. The Saudi natural pozzolan is reported to marginally satisfy the requirements of a supplementary cementitious material in accordance with ASTM C618 (2017) for Class N natural pozzolan (Khan 2013), which is solely based on strength requirement.

The main objective of the present work is to study the beneficial effects of the Saudi NPs (sourced from three different local producers) on the durability performance of concrete mixtures subjected to the simulated aggressive exposure conditions. The other significance of this investigation emerges from the fact that the utilization of indigenous Saudi NP as an alternate supplementary cementing material would be highly beneficial to the Kingdom of Saudi Arabia. It would result in a significant saving in the cost of concrete, compared to that prepared utilizing imported pozzolanic materials, such as silica fume and fly ash. Furthermore, the utilization of local pozzolanic material would eliminate the dependency on the external sources as well as reduce the consumption of Portland cement. Since the production of Portland cement is a highly energy intensive process and releases significant quantity of greenhouse gases, a reduction in its usage will certainly lead to a decrease in the carbon footprint.

2. Experimental Investigation

Four different concrete mixtures were considered in this investigation, one mixture contained OPC alone as the binder (considered as the control mixture) and in the other three mixtures, binary binders (three blends of OPC and natural pozzolan from each of the three sources) were used. For each of the four concrete mixtures, the water/binder ratio, total binder content, and fine/total aggregate ratio were kept invariant. The performance of these concrete mixtures was evaluated in terms of strength and durability indicators that included compressive strength, depth of water penetration, depth of carbonation, chloride diffusion coefficient, and resistance against reinforcement corrosion and sulfate attacks. The details of materials, concrete mixtures, preparation and curing of test specimens, and brief description of each test conducted in the present work are presented in the following sub-sections.

Table 1 Chemical compositions of cementitious materials

Constituent	OPC	NP-1	NP-2	NP-3
CaO (%)	64.4	8.8	7.4	9.4
SiO_2 (%)	22.0	41.5	40.2	43.9
Al_2O_3 (%)	5.6	12.8	14.5	16.2
Fe_2O_3 (%)	3.8	17.5	18.0	11.6
K_2O (%)	0.4	0.8	0.9	0.8
MgO (%)	2.1	8.9	8.3	8.8
Na_2O (%)	0.2	3.4	3.6	3.1
Loss on ignition (%)	0.7	1.5	1.6	1.4

Table 2 Fineness and average particle diameter of Saudi natural pozzolans

Property	NP-1	NP-2	NP-3
Specific surface area (cm^2/g)	4260	4420	3940
average particle diameter (μm)	35.4	32.6	37.0
Specific gravity	2.66	2.64	2.60

2.1 Materials

Ordinary Portland cement (OPC), Type I, conforming to ASTM C 150 (2018) and natural pozzolans (NPs) from three different sources in western Saudi Arabia were used as the cementitious materials in this study. The NPs obtained from the three sources are abbreviated as: natural pozzolan 1 (NP-1), natural pozzolan 2 (NP-2), and natural pozzolan 3 (NP-3). The chemical compositions of these cementitious materials (OPC and NPs) are given in Table 1. Referring to Table 1, the sums of the percentages of the pozzolanic oxides (SiO_2, Al_2O_3 and Fe_2O_3) of NP-1, NP-2, and NP-3 are in the range of 71.7 to 72.7% that marginally satisfy the requirements of the minimum limit of 70% for class N natural pozzolan in accordance with ASTM C618 (2017). The OPC had a fineness of 3700 cm^2/g and a specific gravity of 3.15. The fineness and average particle diameters of NP-1, NP-2 and NP-3 are shown in Table 2. The average specific gravity of the Saudi natural pozzolans used was 2.63.

Locally available crushed limestone and dune sand were used as fine and coarse aggregates, respectively. The specific gravity and water absorption of coarse aggregate were 2.6 and 1.1%, respectively. The maximum normal size of coarse aggregate was 12 mm and was graded according to size number 57 of ASTM C 33 (2018). The specific gravity of dune sand was 2.56 with a water absorption of 0.6%.

SP-420 was used as a superplasticizer for achieving a slump of the concrete mixtures in the range of 100 ±25 mm.

2.2 Concrete mixtures

Table 3 Quantities of ingredients for producing 1 m^3 of concrete mixtures

Mixture ID	Water (kg)	Binder (kg)		FA (kg)	CA (kg)	SP (% by wt. of binder)
		OPC	NP			
OPC	148	370	0	721	1177	0.85 (3.2 kg)
NP-1	148	296	74	720	1175	1.10 (4.1 kg)
NP-2	148	296	74	720	1175	1.10 (4.1 kg)
NP-3	148	296	74	720	1175	1.10 (4.1 kg)

FA: Fine Aggregate, CA: Coarse Aggregate, SP: Superplasticizer

Four concrete mixtures using four combinations of binder (cementitious materials) were considered in the present work. The first concrete mixture (designated as OPC) contained Portland cement alone as the binder and considered as the referenced mixture. In the second, third, and fourth concrete mixtures (designated as NP-1, NP-2, and NP-3), the blends of Portland cement and natural pozzolans (NP-1, NP-2, and NP-3) were used as binary binders (80% OPC plus 20% NP by weight of total binder content). For each of the four mixtures, w/b ratio, total binder content, and fine/total aggregate ratio were kept invariant at 0.4 (by weight), 370 kg/m^3, and 0.38 (by weight), respectively. The details of the proportioning of all the four concrete mixtures are summarized in Table 3.

2.3 Preparation and curing of specimens

The concrete mixtures were prepared using a tilting drum type mixer. Cubes of 100×100×100 mm in dimensions were cast in steel molds and compacted on a vibrating table. These specimens were used to test compressive strength of concrete. Similarly, 150×150×150 mm cubes of concrete were prepared to determine the depth of water penetration. Cylindrical specimens of 75 mm diameter and 150 mm height were prepared to test the chloride diffusion and resistance to sulfate attack. Some of the cylinders with the same dimensions were prepared with a 12-mm steel reinforcement bar, centrally placed, to monitor reinforcement corrosion in terms of the corrosion current density. After finishing the fresh concrete surface, the specimens were covered with plastic sheet. All the specimens were removed from the molds after 24 hours of casting and were submerged under water for 27 days for curing except for the 100-mm cubes, which were cured until 180 days. For determining the depth of carbonation, cubical mortar specimens of 50 mm size were cast and water cured for a period of 28 days. These mortar specimens were prepared with a water to binder ratio of 0.45 and sand to cementitious materials ratio of 2.75.

2.4 Compression test

The 100-mm cubes were tested to determine the compressive strength of concrete at 7, 14, 28, 90 and 180 days in accordance with ASTM C 39 (2018). The compressive load was applied using Matest Compression Testing Machine at a rate of 0.1 N/mm^2. Three specimens were tested at each age and the average values of the three replicate specimens were reported as the representative values.

2.5 Depth of water penetration

The depth of water penetration was determined according to the European standard, BS EN 12390 (2009). The 150-mm cube specimens were water cured for 28, 90 and 180 days, thereafter; they were dried under laboratory condition for 24 hours. They were then oven-dried in oven for 72 hours at a temperature of 70°C and, thereafter, cooled for 1 day in the laboratory conditions. Water was forced to penetrate the specimen through one of its the faces under a pressure head of five bars (500 kPa). This pressure was maintained for a period of 3 days and, thereafter, the specimens were split open into two halves using a wedge and compression-testing machine. The water penetration profile was marked and the maximum depth of water penetration was recorded. The average of the maximum depth of water penetration in three replicate specimens was reported as the representative value.

2.6 Chloride diffusion coefficient

At the end of 28 days of curing period, the specimens were taken out of the water tank and allowed to dry for a week. They were then coated with an epoxy resin all over leaving only the top surface uncoated. These specimens were then immersed in a 5% sodium chloride solution. After six months of exposure to the chloride solution, the specimens were taken out from the exposure tank, dried, and then 5-mm thick slices were obtained from them. Six slices were cut from each of the specimens exposed to chloride, using the dry cutting technique to reach a depth of 75 mm. These slices were crushed and ground to a fine powder passing through ASTM No. 100 sieve. This powder was then soaked in concentrated nitric acid for 24 hours and afterwards diluted with distilled water. Mercuric theocynite and ferric aminosulfate were also added and then the sample mixture was analyzed in spectrophotometer. The chloride concentrations at the surface and at the depth of 10 mm were used to determine the chloride diffusion coefficient according to Fick's second law of diffusion (Crank 1975).

2.7 Resistance to reinforcement corrosion

Cylindrical concrete specimens with centrally placed reinforcing steel bars were cured in water for 28 days. Thereafter, they were partially submerged in 5% NaCl solution and corrosion current density was monitored for 300 days using the linear polarization resistance method (Ahmad and Bhattacharjee 1995). Saturated calomel electrode (SCE) was used as the reference electrode, stainless steel plate as the counter electrode and the reinforcing steel bar embedded in the specimen as the working electrode. The polarization resistance (R_p) was determined using the linear polarization scan within a range of ±10 mV of the corrosion potential. The linear polarization scanning was conducted at a rate of 0.1 mV/s. The Stern and Geary formula was used to determine the corrosion current density (I_{corr}), according to (Stern and

Geary 1957):

$$I_{corr} = B/R_P$$

Where I_{corr} is the corrosion current density measured in $\mu A/cm^2$, R_p is the polarization resistance measured in Ohm-cm^2 and the Stern-Geary constant, B, as 26 mV for active corrosion and 52 mV for passive corrosion (Ahmad and Bhattacharjee 1995).

2.8 Resistance to sulfate attack

In order to evaluate the performance of the concrete mixtures against sulfate attack, cylindrical concrete specimens were immersed in the sulfate solution. The concentration of the sulfate solution used in this study was 2.5% $MgSO_4$+2.5% Na_2SO_4. According to ACI 318-14 (2014), this sulfate concentration is considered as 'very severe'. The specimens were fully submerged in the solution, which was agitated every week while its concentration was monitored and adjusted every 4 months. Other similar sets of cylindrical concrete specimens were cured in water to serve as the control specimens. At the end of the sulfate exposure period (i.e., after 360 days), the specimens were inspected visually to see any signs of deterioration. The compressive strength of the specimens, exposed to the sulfate solution and water, was determined and compared to calculate the *strength deterioration factor* as follows (Al-Amoudi 1995):

$$Strength\ Deterioration\ Factor\ (SDF) = \frac{(\sigma_{Water} - \sigma_{SO_4})}{\sigma_{Water}} \times 100$$

Where, σ_{Water} is the compressive strength after 360 days of water curing and σ_{SO_4} is the compressive strength after exposure to sulfate solution for the same period.

2.9 Depth of carbonation

The cubical mortar specimens of 50-mm size were exposed to an accelerated carbonation environment (Ahmad *et al*. 2017) for a period of 90 and 180 days. CO_2 content was kept constant at 3% by volume of the container. It was distributed uniformly by passing it through 75-mm deep water and keeping the specimens 25 mm above the water level. After the period of exposure to the accelerated carbonation, the specimens were split from the middle to assess the depth profile with the help of a wedge and uniaxial compressive strength machine. Phenolphthalein solution was sprayed on the freshly split surfaces which gave pink color to indicate the non-carbonated zone. The average of the depth of carbonation of three replicate specimens for each mix was reported.

3. Results and discussion

3.1 Compressive strength

The compressive strengths of all the four mixtures, determined after curing for different durations, were used to depict the evolution of compressive strength with the progress of hydration, as shown in Fig. 1. The results therein indicate that the OPC concrete exhibited higher compressive strength at all ages. However, after 360 days of curing, the concrete specimens prepared with partial replacement of OPC with NPs displayed comparable strength to OPC. Further, it can be seen that all the three NPs considered in the present work performed almost similarly. This may be ascribed to the fact that their chemical compositions and physical properties are almost similar (Khan 2013). It can be noted from Fig. 1 that up to 90 days of the water curing, the compressive strength of the OPC mixture was 20% higher than the NP-admixed mixtures. Thereafter, the difference between the compressive strength of OPC and NP-admixed concretes narrowed down to 12% and 4% after the water curing for 180 and 360 days, respectively. The compressive strength results obtained in the present work are in agreement with those reported by other researchers. This reveals the fact that the strength development in concrete prepared with partial replacements of OPC with NP is relatively slow, and at early ages, the strength of OPC concrete is always higher than that of the NP-admixed concrete (Shannag and Asim 1995, Colak 2003, Najimi *et al*. 2012).

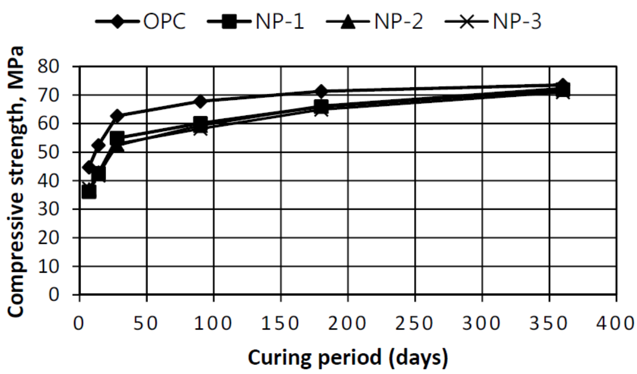

Fig. 1 Evolution of compressive strength with curing period

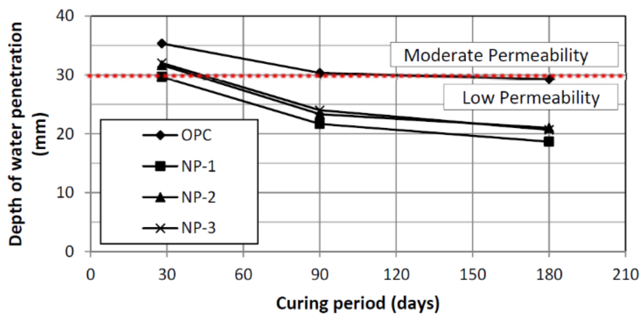

Fig. 2 Depth of water penetration in OPC and NP concretes

3.2 Depth of water penetration

Fig. 2 shows the variation of the depth of water penetration in the concrete specimens prepared using OPC and all the three types of NP. The specimens prepared with partial replacement of OPC with NP exhibited lower depth of water penetration. It can be observed from Fig. 2 that the water permeability of the OPC concrete mixture, having depth of water penetration more than 30 mm after 28 days

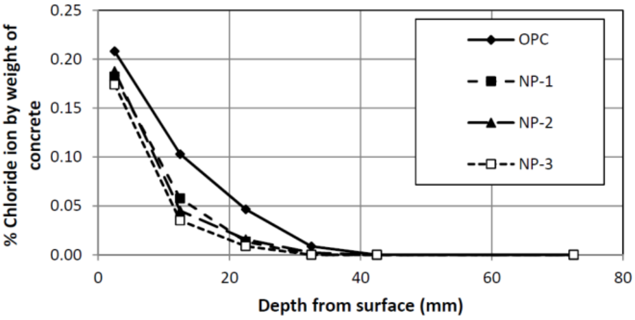

Fig. 3 Chloride profiles of OPC and NP concretes

curing and almost equal to 30 mm after 90 and 180 days of curing, may be rated as 'moderate'. On the other hand, the water permeability of NP-admixed concrete mixtures with a depth of water penetration almost equal to 30 mm after 28 days of water curing and much below 30 mm after 90 and 180 days of water curing, and may be rated as 'low'.

The reduction in the depth of water penetration in NP-admixed concrete mixtures with the progress of hydration, as observed in the present study, is in agreement with that reported by Najimi *et al*. (2012). They reported that the replacement of OPC with 15 and 30% of NP decreased the depth of water penetration after 28 and 90 days of water curing. This is true for all curing ages at which the test was conducted, but the difference is more obvious at later ages (i.e., 90 and 180 days). This behavior may be ascribed to the fact that NP takes some time to react with portlandite through the pozzolanic reaction, which, at later stage, helps in refining the pore structure thereby making the microstructure denser and resulting in lower depths of water penetration (Al-Amoudi *et al*. 1993).

3.3 Chloride diffusion coefficient

Fig. 3 displays the chloride profiles obtained by testing the powdered samples collected at different depths from the specimens of OPC and NP-admixed concretes after six months of exposure of the specimens to the 5% NaCl solution. It can be clearly observed that the chloride concentration in NP-admixed concretes at all the depths is significantly less than that of OPC concrete. It is seen that there is a small difference in the chloride concentrations near the surface but this difference becomes significant at higher depths. This observation confirmed the fact that the addition of supplementary cementing material such as NP helps in reducing the permeability of concrete to chloride ions (Wlison *et al*. 2016). Kaid *et al*. (2009) reported that the addition of Algerian natural pozzolan helped reduce the chloride diffusion in concrete. Table 4 summarizes the chloride diffusion coefficients of OPC and NP-admixed concretes, which were calculated based on the Fick's second law of diffusion using the chloride profiles shown in Fig. 3.

Although the order of the diffusion coefficient is similar for all concretes, it can still be noted from the data in Table 4 that with the incorporation of NPs into the mixtures as a partial replacement of the OPC, the coefficient of diffusion has clearly decreased by about more than two times.

Table 4 Chloride diffusion coefficient of concrete mixtures

Mixture ID	Chloride diffusion coefficient ($\times 10^{-8}$ cm^2/s)	Improvement factor
OPC	6.11	--
NP-1	3.17	1.93
NP-2	2.55	2.40
NP-3	2.28	2.68

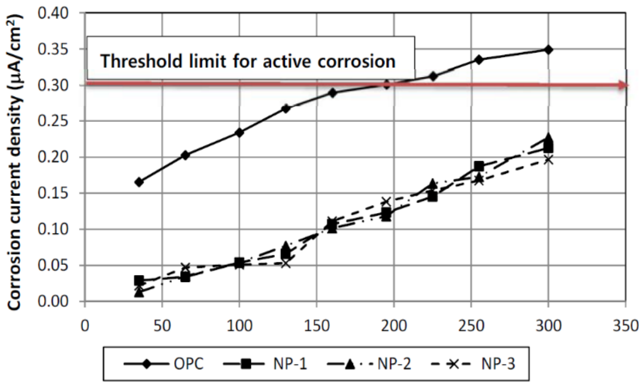

Fig. 4 Corrosion current density of steel reinforcement in OPC and NP concrete specimens

3.4 Resistance to reinforcement corrosion

Fig. 4 shows the corrosion current density (I_{corr}) test results for reinforcing steel embedded in OPC mixture as well as mixtures prepared with natural pozzolan (all three types), all exposed to the 5% NaCl solution simulating the condition for an accelerated reinforcement corrosion. In this study, 0.3 $\mu A/cm^2$ is taken to be the threshold corrosion current density for the initiation of active corrosion of steel bar embedded in concrete (Al-Amoudi 1993). After about 193 days of exposure, the I_{corr} for steel bar embedded in OPC concrete was more than the threshold value of 0.3 $\mu A/cm^2$, whereas, none of the specimens prepared using NPs as a partial replacement of OPC, crossed this threshold even after 300 days of exposure.

The positive effect of the NPs in resisting reinforcement corrosion, as observed in the present work, is in agreement with the findings by Fajardo *et al*. (2009) and Najimi *et al*. (2012) who reported that concretes prepared with NP exhibited superior resistance against reinforcement corrosion. Both of these studies included linear polarization resistance test on reinforced concrete specimens prepared with the addition of natural pozzolan and reported that there is a significant improvement in the resistance to corrosion as compared to OPC control mix. The reduction in reinforcement corrosion rates in NP-admixed concrete mixtures may be attributed to the fact that the chloride diffusion coefficients in concrete specimens containing natural pozzolan were less than that of OPC mixture by a factor above two. As most of the problems associated with corrosion of steel reinforcement embedded in concrete exposed to marine environment are chloride-induced (Al-Amoudi *et al*. 2006, Kaid *et al*. 2009), the usage of NP-admixed concrete would be highly beneficial to the construction industry in the marine regions.

(a) OPC concrete mixture

(b) NP concrete mixture

Fig. 5 Specimens of OPC and NP concretes after 12 months of exposure to sulfate environment

Table 5 Compressive strength loss of specimens prepared with OPC and NP after 12 month of exposure to sulfate environment.

Mixture ID	Strength Deterioration Factor (SDF)	Improvement factor
OPC	4.03	--
NP-1	1.74	2.32
NP-2	2.10	1.92
NP-3	1.68	2.40

3.5 Resistance to sulfate attack

Cylindrical concrete specimens, after twelve months of exposure to the mixed sulfate environment, were taken out of the exposure tanks and their compressive strength was evaluated. These specimens were also visually examined for any signs of surface deterioration. Fig. 5 depicts the specimens of OPC and NP-admixed concretes after the exposure period. It is to be noted that the specimens prepared with NPs exhibited no signs of surface deterioration, while the OPC specimens displayed spot marks on the surface owing to the deterioration due to sulfate salt. Table 5 shows the strength deterioration factor after 12 months of exposure, which is higher in OPC than in NP-admixed concretes by a factor of about two. The data in Table 5 indicate that NP-admixed concretes performed better than OPC concrete exposed to sulfate. The beneficial effect of admixing NP on the resistance of concrete against sulfate attack is also reported by several researchers. Ghrici *et al*. (2007) reported that the addition of 30% natural pozzolan helped in improving the sulfate resistance of concrete and exhibited half as much expansion as in OPC. Rodriguez and Uribe-Afif (2002) reported that the mix prepared with NP performed even better than sulfate resistant Type V cement. Kilinckale (1997) reported that mixes with natural pozzolan exhibited better durability than OPC. Hossain and Lachemi (2006) reported up to 18 months of exposure, the specimens prepared with natural pozzolans performed almost equal to OPC but after that, all natural pozzolan specimens exhibited higher weight loss. Further, Al-Amoudi (1995) reported that blended cements exposed to magnesium sulfate environment displayed higher strength loss than OPC. However, on exposure to sodium sulfate, they exhibited much better performance in terms of weight loss and expansion. The present investigation showed that the NP-blended concretes performed better than OPC in mixed-sulfate exposure within the exposure period of 12 months.

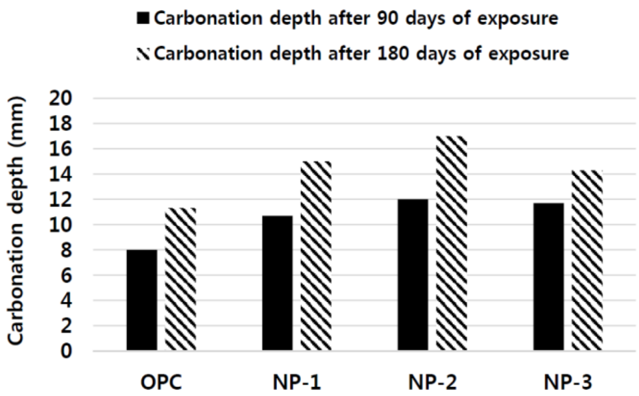

Fig. 6 Carbonation depth of OPC and NP concrete specimens after 90 and 180 days of exposure

3.6 Depth of carbonation

50-mm cubic specimens of mortar were cured for 28 days in water. After curing, the specimens were exposed to accelerated carbonation environment (3% CO_2 by volume) for 90 and 180 days. Fig. 6 shows the plots of the depths of carbonation in the specimens of all the four mixtures after 90 and 180 days of exposures. It can be observed from the data in Fig. 6 that after both exposure periods, the depth of carbonation was relatively higher in the specimens prepared with NP-admixed concrete mixtures as compared with that of OPC. This is in agreement with the fact that concretes containing pozzolanic admixtures possess lower resistance to carbonation as compared to the concrete mixtures containing Portland cement alone due to the less amount of portlandite, $Ca(OH)_2$, present in the pozzolanic concrete after the portlandite is consumed in the secondary hydration (Hewlett 2003). Due to the less amount of the portlandite present in the pozzolanic concrete, the CO_2 penetrating concrete is not much engaged in the reaction with portlandite and, therefore, the carbonation front moves faster inside concrete resulting into a relatively higher carbonation depth (Thomas and Matthews 1992, Sulapha *et al*. 2003). On an average, the carbonation depth in OPC specimens, after 180 days of exposure, was 11.3 mm, which was 3.7, 5.7 and 3.0 mm less than the depth of carbonation in NP-1, NP-2 and NP-3 specimens, respectively.

Carbonation lowers the pH of concrete, which is critical for the sustenance of the passive layer around steel reinforcement. Even though the depth of carbonation in NP specimens under accelerated conditions was higher, the carbonation depth was still much lower than the depth of concrete cover for reinforcement corrosion, which is normally provided for reinforced concrete structural members. Since the carbonation depths in the NP concrete mixtures, even under accelerated carbonation, are well below the normal concrete cover thickness provided to reinforced concrete elements as a protective measure, the risk of depassivation of the protective layer around the steel reinforcement, due to carbonation, is minimal.

4. Conclusions

Based on the results obtained through the experimental investigation conducted under the present investigation that focused on strength and durability testing of the specimens of plain Portland cement concrete and concretes containing blends of Portland cement and the natural pozzolans from three sources, the following conclusions could be drawn:

1. Performance of natural pozzolans obtained from three different sources (NP-1, NP-2, and NP-3) were almost the same, as evident from the small variations in the results of strength and durability tests. This is because of the marginal differences in their chemical compositions and physical properties, as presented in Tables 2 and 3, respectively.
2. At all curing periods, the compressive strength of OPC concrete was higher (around 20% after 90 days of curing, 13% and 4% after 180 and 360 days of curing, respectively) than that of NP concretes. Nevertheless, due to the low water/binder ratio of 0.40 (by weight) and the relatively higher binder content of 370 kg/m^3, the 28-day compressive strength of all three NP-admixed concrete mixtures were above 50 MPa, qualifying these mixtures as 'high-strength concrete'.
3. The depth of water penetration in NP-admixed concretes was less than that of OPC concrete thereby indicating the dense microstructure of the former concretes. Further, the quantum of improvement increased with the extension in the curing period. Based on the values of the depth of water penetration measured in the present work, the water permeability of OPC concrete and NP-admixed concrete may be rated as 'moderate' and 'low', respectively.
4. Chloride diffusivity in NP-admixed concretes was less than that of OPC concrete, making them more resistant to reinforcement corrosion.
5. As indicated by the measured values of corrosion current density, active reinforcement corrosion of steel bar embedded in OPC concrete started after about 193 days of exposure. On the other hand, reinforcement corrosion remained in a passive state in all the three NP-admixed concretes even after 300 days of exposure to 5% NaCl solution simulating the condition for an accelerated reinforcement corrosion.
6. NP-admixed concretes were less affected by sulfate attack after 12 months of exposure to mixed sulfate solution. On an average, the strength deterioration factor for NP-admixed concretes were less as compared to OPC concrete by a factor about 2.
7. The depth of carbonation of mortars, carried out under the accelerated conditions, increased with the admixing NPs in the mortar mixtures. However, the depth of carbonation in both OPC and pozzolanic mortars was less than the concrete cover for steel normally provided in structural members, indicating no risk of reinforcement corrosion due to depassivation of reinforcing bars caused by carbonation.

In summary; the results of this investigation proves the viability of Saudi natural pozzolans to be used to improve the durability characteristics of concrete subjected to chloride and sulfate exposures. Calcination of the natural pozzolans before their pulverization is recommended for enhancing their pozzolanic activity that might enhance the development of early strength to be similar to that of plain Portalnd cement or even more besides further improvements in the durability characteristics.

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References

ACI 318-14 (2014), Building Code Requirements for Structural Concrete, ACI Committee 318, American Concrete Institute, Farmington Hills, Michigan, USA.

Ahmad, S. and Bhattacharjee, B. (1995), "A simple arrangement and procedure for in-situ measurement of corrosion rate of rebar embedded in concrete", *Corros. Sci.*, **37**(5), 781-791.

Ahmad, S., Assaggaf, R.A., Maslehuddin, M., Al-Amoudi, O.S.B., Adekunle, S.K. and Ali, S.I. (2017), "Effects of carbonation pressure and duration on strength evolution of concrete subjected to accelerated carbonation curing", *Constr. Build. Mater.*, **136**, 565-573.

Al-Amoudi, O.S.B., Rasheeduzzafar, Maslehuddin, M. and Al-Mana, A.I. (1993), "Prediction of long-term corrosion resistance of plain and blended cement concretes", *ACI Mater. J.*, **90**(6), 564-570.

Al-Amoudi, O.S.B. (1995), "Performance of 15 reinforced concrete mixtures in magnesium-sodium sulphate environments", *Constr. Build. Mater.*, **9**(3), 149-158.

Al-Amoudi, O.S.B., Maslehuddin, M., Al-Hozaimy, A., Al-Neghaimesh, A. Khushefati, W., Al-Saiyed, S. and Al-Shuraim, A. (2006), "Materials and construction requirements in the Saudi building code", *Proceedings of the 8th International Conference on Concrete in Hot and Aggressive Environments*, Manama, Bahrain, November.

Ashish, D.K., Singh, B. and Verma, S.K. (2016), "The effect of attack of chloride and sulphate on ground granulated blast furnace slag concrete", *Adv. Concr. Constr.*, **4**(2), 101-121.

ASTM C 618 (2017), Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, West Conshohocken, PA.

ASTM C150 (2018), Standard Specification for Portland Cement, ASTM International, West Conshohocken, PA.

ASTM C33 (2018), Standard Specification for Concrete Aggregates, ASTM International, West Conshohocken, PA.

ASTM C39 (2018), Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA.

BS EN 12390 (2009). Hardened Concrete-Part 8: Depth of Penetration of Water under Pressure, BSI, London, UK.

Celik, K., Jackson, M.D., Mancio, M., Meral, C., Emwas, A.H., Mehta, P.K. and Monteiro, P.J.M. (2014), "High-volume natural volcanic pozzolan and limestone powder as partial replacements for Portland cement in self-compacting and sustainable concrete", *Cement Concrete Compos.*, **45**, 136-147.

Colak, A. (2003), "Characteristics of pastes from a Portland cement containing different amounts of natural pozzolan", *Cement Concrete Res.*, **33**(4), 585-593.

Crank, J. (1975), *The Mathematics of Diffusion*, 2nd Edition, Oxford University Press, New York, USA.

Djamila, B., Othmane, B., Said, K. and El-Hadj, K. (2018), "Combined effect of mineral admixture and curing temperature on mechanical behavior and porosity of SCC", *Adv. Concr. Constr.*, **6**(1), 69-85.

Fajardo, G., Valdez, P. and Pacheco, J. (2009), "Corrosion of steel rebar embedded in natural pozzolan based mortars exposed to chlorides", *Constr. Build. Mater.*, **23**(2), 768-774.

Ghrici, M., Kenai, S. and Said-Mansour, M. (2007), "Mechanical properties and durability of mortar and concrete containing natural pozzolan", *Cement Concrete Compos.*, **29**(7), 542-549.

Hewlett, P.C (2003), *Lea's Chemistry of Cement and Concrete*, 4th Edition, Elsevier, UK.

Hossain, K.M.A., and Lachemi, M. (2006), "Performance of volcanic ash and pumice based blended cement concrete in mixed sulfate environment", *Cement Concrete Res.*, **36**(6), 1123-1133.

Jenaa, T. and Panda, K.C. (2018), "Mechanical and durability properties of marine concrete using fly ash and silpozz", *Adv. Concr. Constr.*, **6**(1), 47-68.

Kaid, N., Cyr, M., Julien, S. and Khelafi, H. (2009), "Durability of concrete containing a natural pozzolan as defined by a performance-based approach", *Constr. Build. Mater.*, **23**(12), 3457-3467.

Khan, M.I. and Alhozaimy, A.M. (2011), "Properties of natural pozzolan and its potential utilization in environmental friendly concrete", *Can. J. Civil Eng.*, **38**(1), 71-78.

Khan, S.M.S. (2013), "Production of sustainable concrete using indigenous Saudi natural pozzolans", MS Dissertation, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia.

Kilinckale, F.M. (1997), "The effect of $MgSO_4$ and HCL solutions on the strength and durability of pozzolan cement mortars", *Cement Concrete Res.*, **27**(12), 1911-1918.

Lenkaa, S. and Panda, K.C. (2017), "Effect of metakaolin on the properties of conventional and self compacting concrete", *Adv. Concr. Constr.*, **5**(1), 31-48.

Moon, J., Bae, S., Celik, K., Yoon, S., Kim, K.H., Kim, K.S. and Monteiro, P.J.M. (2014), "Characterization of natural pozzolan-based geopolymeric binders", *Cement Concrete Compos.*, **53**, 97-104.

Moufti, M.R., Sabtan, A.A., El-Mahdy, O.R. and Shehata, W.M. (2000), "Assessment of industrial utilization of scoria materials in central Harrat Rahat, Saudi Arabia", *Eng. Geol.*, **57**(3-4), 155-162.

Mouli, H. and Khelafi, H. (2008), "Performance Characteristics of light weight aggregate concrete containing natural pozzolan" *Build. Environ.*, **43** (1), pp. 31-36.

Najami, M., Sobhani, J., Ahmadi, B. and Shekarchi, M. (2012), "An experimental study on durability of concrete containing zeolite as a highly reactive natural pozzolan", *Constr. Build. Mater.*, **35**, 1023-1033.

Najimi, M., Jamshid, I.M. and Pourkhorshidi, A. (2008), "Durability of concretes containing natural pozzolan", *Pro. Inst. Civil Eng. – Constr. Mater.*, **161**(3), 113-118.

Nas, M. and Kurbetc, S. (2018), "Durability properties of concrete containing metakaolin", *Adv. Concr. Constr*, **6**(2), 159-175.

Pekmezci, B.Y. and Akyuz, S. (2004), "Optimum usage of a natural pozzolan for the maximum compressive strength of concrete", *Cement Concrete Res.*, **34**(12), 2175-2179.

Rahmani, H. and Ramazanianpour, A.A. (2008), "Effect of binary cement replacement materials on sulphuric acid resistance of dense concretes", *Mag. Concete. Res.*, **60**(2), 145-155.

Rodriguez, R.E. and Uribe-Afif, R. (2002), "Importance of using natural pozzolan on concrete durability", *Cement Concrete Res.*, **32**(12), 1851-1858.

Roobol, M.J., Pint, J.J., Al-Shanti, M.A., Al-Juaid A.J., Al-Amoudi, S.A. and Pint, S. (2002), "Preliminary survey for Lava-Tube Caves on Harrat Kishb, Kingdom of Saudi Arabia", Open-File Report, Saudi Geological Survey.

Sabtan, A.A. and Shehata, W.M. (2000), "Evaluation of engineering properties of scoria in central Harrat Rahat, Saudi Arabia", *B. Eng. Geol. Environ.*, **59**(3), 219-225.

Shannag, M.J. and Asim, Y. (1995), "Properties of pastes, mortars and concretes containing natural pozzolan", *Cement Concrete Res.*, **25**(3), 647-657.

Siad, H., Mesbah, H.A., Khelafi, H., Kamali-Bernard, S. and Mouli, M. (2010), "Effects of mineral admixture on resistance to sulphuric and hydrochloric acid attack in self-compacting concrete", *Can. J. Civil Eng.*, **37**(3), 441-449.

Stern, M. and Geary, A.L. (1957), "A theoretical analysis of the slope of the polarization curves", *J. Electrochem. Soc.*, **104**(1), 56-63.

Sulapha, P., Wong, S.F., Wee, T.H. and Swaddiwudhipong, S. (2003), "Carbonation of concrete containing mineral admixtures", *J. Mater. Civil Eng.*, **15**(2), 134-143.

Thomas, M.D.A. and Matthews, J.D. (1992), "Carbonation of fly ash concrete", *Mag. Concr. Res.*, **44**(160), 217-228.

Uzal, B. and Turanli, L. (2003), "Studies on blended cements containing a high volume of natural pozzolan", *Cement Concrete Res.*, **33**(11), 1777-1781.

Wlison, M.L. and Kosmatka, S.H. (2016), *Design and Control of Concrete Mixtures*, 16th Edition, Portland Cement Association, Illinois, USA.

Yahiaoui, W., Kenai, S., Menadi, B. and Kadri, E.H. (2017), "Durability of self compacted concrete containing slag in hot climate", *Adv. Concr. Constr.*, **5**(3), 271-288.

Yu, L., Zhoua, S. and Deng, W. (2015), "Properties and pozzolanic reaction degree of tuff in cement–based composite", *Adv. Concr. Constr.*, **3**(1), 71-90.

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