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Performance of concrete in a coastal environment

Maher A. Bader *

Department of Civil Engineering, King Fahd University of Petroleum and Minerals, Dhaharan 31261, Saudi Arabia

Abstract

This paper reports the results of a study conducted to evaluate the performance of concrete exposed to below ground conditions in a coastal area. The concrete specimens were prepared with varying water/cement ratio, cement content, and polymer/epoxy additions and varying consolidation efforts prior to exposure to below ground conditions in a coastal area for more than four years. The performance of the concrete specimens exposed to the highly concentrated chloride and sulfate environment was evaluated by measuring the chloride diffusion and reduction in compressive strength due to sulfate attack. Results indicated that the mix design parameters, such as water–cement ratio and cement content, significantly affected both the chloride diffusion and the sulfate-resistance of concrete. Similarly, the level of consolidation and the period of curing influenced the performance of concrete in the aggressive environment. Further, the performance of latex and epoxy modified concrete was better than that of polymer concrete.

Keywords: Chloride–sulfate environment; Concrete mix design parameters; Consolidation and curing; Modified concrete

1. Introduction

Accelerated deterioration of reinforced concrete structures, say within 10–15 years of construction in the Arabian Gulf, is a well reported phenomenon [1–4]. The rapid deterioration of concrete is attributable to the interplay of several causal factors, namely aggressive environment, marginal aggregates, inappropriate specifications, and unskilled manpower. While the latter two factors are noted to some extent in the other parts of the world, the first two are specific to the coastal areas of the Arabian Gulf. The environmental conditions of the Arabian Gulf are characterized by high temperature and humidity. The daily mean air temperature in the summer usually varies from 30 to 35 °C with the maximum temperature reaching to as high as 50 °C [5]. The mean seasonal change in the temperature may be as high as 10–15 °C. The relative humidity varies between 40% and 80% reaching up to 98% at times. The aggressivity of the environmental conditions, with regard to concrete durability, is further compounded by the prevalence of high salt concentrations in the soil, groundwater and atmosphere. Due to the closed nature of the Arabian Gulf, the salinity of the seawater is more than that in the other areas of the world [6].

The chloride content of the Arabian Gulf seawater is about 1.6–2 times that of the seawater from Mediterranean or the Atlantic [7]. The chloride and sulfate pollution in the ambient environment in the Arabian Gulf is about 490 times that in the air along California beach in the USA. This high salt concentration in the environment is attributed to the geological formation in the region. The geological sequences, in which layers of salt are extensively interbedded, are fairly widespread in the area [8]. The salts reach the groundwater and soil either by weathering of salt-bedded rocks or as wind-blown particles from the salty surface crusts of salt playas, sabkhas, and salinas. These are commonly occurring features of the desert terrain along the Arabian Gulf coast and they contaminate the soil, groundwater, and atmosphere with chloride and sulfate salts.

The groundwater table in the coastal areas is very shallow and highly concentrated with chloride and sulfate salts [7]. Due to the shallow depth of the water table there is immense rise in the capillary water to the surface. Due to the high rate of evaporation the salt is deposited on the surface of the soil. The salt encrusted layers, known locally by the term sabkha, are widely spread in the coastal areas of the Arabian Gulf. Structures one to two kilometers away from the sea are invariably placed in a shallow groundwater table. In such

* Tel.: +966-3-860-4229; fax: +966-3-860-3996.
E-mail address: mbadr@kfupm.edu.sa (M.A. Bader).

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a situation, the groundwater is transported in the foundations and columns until it is evaporated at the grade level. Concrete deterioration at such locations is primarily due to salt weathering and/or reinforcement corrosion.

The other important factor contributing to the low durability of concrete construction in the Arabian Gulf is the low quality of the available aggregates. Most of the aggregate available in the region is crushed limestone that is marginal, porous, absorptive, relatively soft and excessively dusty on crushing. The aeolian dune sand and the coastal sands form the main source of fine aggregates. These sands are essentially fine grained and have narrow grading [9]. The fine and coarse aggregates are characterized by excessive dust content. Dust and excessive fines cause high water demand resulting in lower strength and greater shrinkage of concrete. Dust also forms a fine interstitial layer between the aggregates and the cement paste thereby weakening the bond at the aggregate–paste interface. This transition zone, being the weakest link of the concrete composite, may further lower the concrete strength and durability. Due to the weak nature of the coarse aggregates it is not possible to obtain concrete of more than 50 MPa even using a low water to cement ratio of 0.40 in conjunction with silica fume [10].

Realizing the unique nature of the environmental conditions and the local construction materials of the Arabian Gulf, research was initiated at King Fahd University of Petroleum and Minerals to assess concrete performance under local environmental conditions. As part of this endeavor, both laboratory and field studies were initiated.

This paper reports result of a study conducted to evaluate the performance of plain and modified cement concretes exposed to below ground conditions in the coastal area of the Arabian Gulf. The influence of concrete type, namely epoxy modified concrete and polymer modified concrete, mix design in terms of water to cement ratio and cement content, construction practices, such as degree of consolidation and curing, on the performance of concrete exposed to below ground conditions was evaluated. The performance was evaluated by assessing the resistance to salt attack and chloride diffusion. The effect of sulfate attack was assessed by evaluating the reduction in compressive strength.

2. Methodology

2.1. Preparation of test specimens

The effect of following parameters on the chloride diffusion and sulfate deterioration of concrete specimens exposed to below ground conditions in a coastal area was evaluated:

1. water/cement ratio;
2. cement content;
3. period of curing;
4. degree of consolidation;
5. admixtures.

Five series of concrete specimens were prepared. In Series I, the effect of water/cement ratio on the sulfate-resistance and chloride diffusion was evaluated. The concrete specimens in this series were prepared with water/cement ratios of 0.4, 0.5 and 0.65. A cement content of 390 kg/m^3 was kept invariant in this series of concrete specimens. The cement content was varied in the Series II concrete specimens. The concrete specimens in this series were prepared with cement contents of 270, 390, and 450 kg/m^3. The concrete mixtures in this series were designed for a constant workability of 50–75 mm. In Series III, the effect of period of curing on sulfate-resistance and chloride diffusion was assessed while in Series IV the effect of degree of consolidation was assessed. The concrete mixtures for Series III were prepared with a cement content of 390 kg/m^3 and a water/cement ratio of 0.45. The concrete specimens in Series IV were prepared with a cement content of 330 kg/m^3 and water/cement ratio of 0.4. In Series V the type of concrete was varied. The type of concrete included, normal, latex modified, epoxy modified and polymer impregnated concrete. The concrete specimens in this series were prepared with a cement content of 390 kg/m^3 and water/cement ratios of 0.261 and 0.285.

Concrete cube specimens measuring $100 \times 100 \times 100$ mm were prepared for the purpose of exposure.

2.2. Exposure

After four months of the concrete specimens were transported to the exposure site that is located in a coastal area along the Arabian Gulf. They were placed in special plastic boxes, with large holes, and buried at about three meters below the ground level. Fig. 1 shows the placement of the concrete specimens. Table 1 shows the chemical analysis of the ground water at the exposure site. The specimens were retrieved from the exposure site after 4.5 years of exposure.

2.3. Evaluation

The effect of experimental variables, stated earlier, on the performance of concrete specimens exposed to below ground conditions in the coastal area was evaluated by measuring the chloride diffusion and the deterioration due to sulfate attack.

2.3.1. Chloride diffusion

The retrieved specimens were cleaned and cores were obtained for chloride analysis. Powder samples were

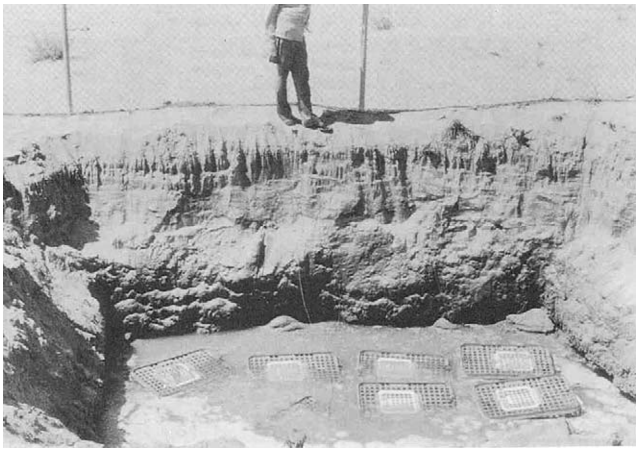

Fig. 1. Concrete specimens placed at the exposure site.

Table 1
Chemical analysis of groundwater at the exposure site

Constituent/parameter	Value
Sodium (g/l)	24.2
Calcium (g/l)	1.29
Magnesium (g/l)	4.35
Potassium (g/l)	1.08
Chloride, Cl^- (g/l)	50.0
Sulfate, SO_4^{--} (g/l)	10.7
Strontium (mg/l)	39.8
Bicarbonate (mg/l)	434
pH	8.1
Conductivity (ms/cm)	156

obtained from the core specimens at depths of 12.5, 19, 32, and 50 mm (0.5, 0.75, 1.25, and 2 in.). The chloride concentrations in the powder samples were determined by the spectrophotometric method [11].

The chloride concentration was then plotted against depth. The coefficient of chloride diffusion was determined from the chloride profile by solving Fick's second law of diffusion as shown below:

$$C_x = C_s\left(1 - \operatorname{erf}\frac{x}{2\sqrt{Dt}}\right)$$

where C_x is the chloride concentration at depth x, after exposure, time t; x, depth in cm; C_s, the chloride concentration at the surface; t, the time at which the chloride concentration was measured in seconds; D, the chloride diffusion coefficient, cm^2/s; erf, the error function.

In order to arrive at a suitable value for C_s, the chloride profile was extrapolated to $x = 0$.

2.3.2. Sulfate-resistance

The sulfate-resistance was evaluated by determining the change in compressive strength. The change in compressive strength was assessed as the difference in the compressive strengths of the concrete specimens before and after the exposure. Three specimens from each mix were tested and the mean value was utilized to calculate the change in the compressive strength due to exposure.

3. Results and discussion

3.1. Effect of concrete mix design and construction practices on chloride diffusion

3.1.1. Effect of curing on chloride diffusion

The chloride profiles for concrete specimens cured for varying durations are shown in Fig. 2. As expected the chloride concentration decreased with the depth and the period of curing. Several other researchers [12–18] have also enunciated the importance of curing period with regard to durability. It is now well known that a minimum of 80% humidity is required for cement hydration [12]. If concrete is not sufficiently cured, the permeability of the surface layer may be increased by 5 to 10 times. High wind and temperatures encourage drying of the concrete surface, leading to insufficient curing. The sensitivity of curing is especially pronounced if cements with high percentages of supplementary cementing materials (e.g. blast furnace slag, fly ash, or silica fume) are used. Tests conducted by Grafe and Grube [13] on the influence of curing on the gas permeability of concrete prepared with different types of cement indicated that concretes containing blast furnace slag and fly ash had greater permeabilities than those with Portland cement, when curing was poor (1-day curing). However, they concluded that with prolonged sealed curing, mixes prepared with the cement replacement materials might become more impervious than analogous concretes (same water/cement ratio and same cementitious materials content) containing only Portland cement.

Data developed by Rasheeduzzafar et al. [14] indicated that the protection provided by concrete against corrosion of steel by migration of chlorides into the concrete is greatly dependent upon the duration of curing. The improvement in the concrete durability due to increased curing has been reported by Broderson [15], Bakker [16], and van Yperen and Sluijter [17]. Page et al. [18] reported that in a hardened cement diffusivity of chloride ions increases from 45×10^{-9} to 1.15×10^{-7} cm^2/s when the curing medium was changed from lime water to saturated air. Table 2 shows the coefficient of chloride diffusion in the concrete cured for varying durations. A significant reduction in the co-efficient of concrete diffusion was noted in concrete specimens cured for 28 days as compared to other curing periods.

3.1.2. Effect of degree of consolidation on chloride diffusion

The chloride concentration profiles for the concrete specimens prepared with varying consolidation effort are

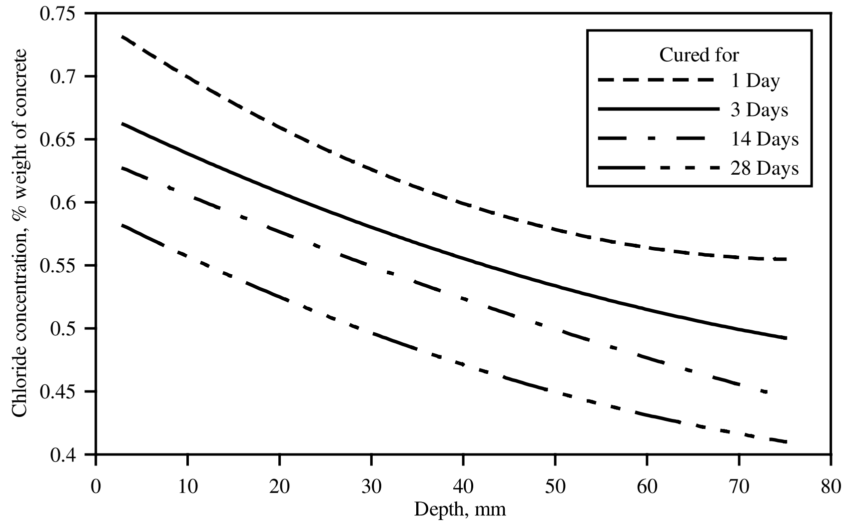

Fig. 2. Effect of curing period on chloride concentration.

Table 2
Effect of curing period on chloride diffusion

Curing period (days)	Chloride diffusion coefficient (cm^2/s)
1	2.39×10^{-10}
3	2.25×10^{-10}
14	2.15×10^{-10}
28	0.07×10^{-10}

shown in Fig. 3. The chloride concentration decreased with the degree of consolidation. The chloride concentrations for the concrete specimens prepared with 60% and 100% consolidation effort were near to each other while a significant variation was noted in the concrete specimens prepared with 40% and 60% consolidation effort. The effect of degree of consolidation from durability perspective is amplified from these results. Similar results on the effect of degree of consolidation on reinforcement corrosion were reported by Rasheeduzzafar et al. [14].

Improper consolidation of concrete may lead to the formation of voids and honey combs. These defects in concrete are helpful in accelerating reinforcement corrosion. In the majority of cases of serious deterioration [19], it was noted that disintegration due to corrosion of reinforcement invariably took place at locations of voids and honeycombs. Laboratory studies to evaluate the effect of concrete consolidation supported the field observations [14]. The time to initiation of reinforcement corrosion in the concrete specimens with 40%, 60% and 80% of the full consolidation effort was 60%, 76% and 95% of that in the specimens where full consolidation was achieved. As shown in Table 3, the coefficient of

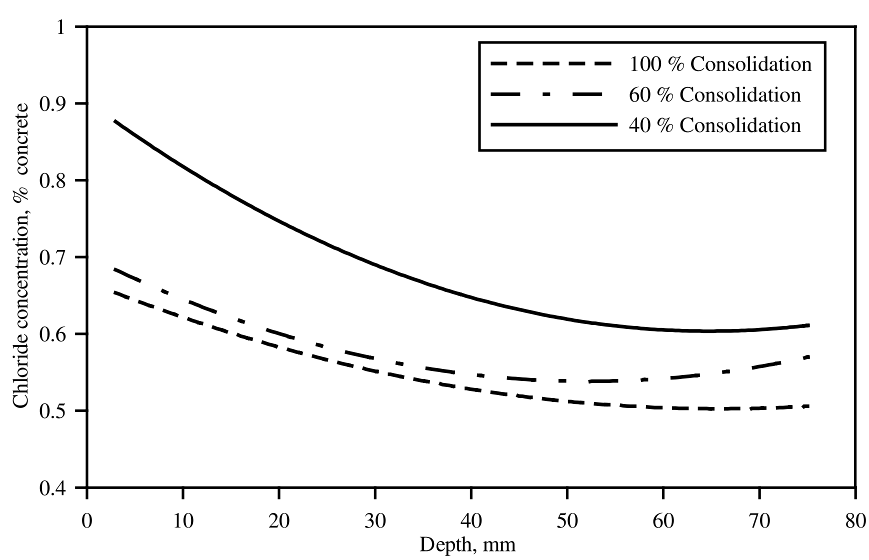

Fig. 3. Effect of consolidation effort on chloride concentration.

Table 3
Effect of consolidation on chloride diffusion

Consolidation (%)	Chloride diffusion coefficient (cm^2/s)
100	2.183×10^{-10}
60	3.436×10^{-10}
40	5.149×10^{-10}

Table 4
Effect of water/cement ratio on chloride diffusion

Water/cement ratio	Chloride diffusion coefficient (cm^2/s)
0.40	1.18×10^{-10}
0.50	5.95×10^{-10}
0.65	6.92×10^{-10}

chloride diffusion also decreased with the degree of consolidation, though the reduction was not that significant.

3.1.3. Effect of w/c ratio on chloride diffusion

The chloride concentration profiles for the concrete specimens prepared with water/cement ratios of 0.4, 0.5 and 0.65 are shown in Fig. 4. The chloride concentration generally decreased with a decrease in the water/cement ratio. The chloride concentration profiles for the concrete specimens prepared with water/cement ratios of 0.4 and 0.5 were not significantly different from each other. However, a significant difference in the chloride concentration profiles was noted for the concrete specimens prepared with water/cement ratios of 0.5 and 0.65. The data on coefficient of chloride diffusion, shown in Table 4, also indicated a similar trend.

The effect of water/cement ratio on concrete durability is well reported in the literature. Several researchers [20–23] have reported the importance of low water/cement ratio to obtain a durable concrete. Work by Manmohan and Mehta [20] on permeability of concrete has shown that capillary pore sizes of more than 1320 Å are significant from a permeability viewpoint. Keeping the w/c ratio to 0.50 or less substantially reduced such pore size formation. Gotto and Roy [21] showed a 100-fold increase in the permeability of hardened cement paste when the w/c ratio was increased from 0.35 to 0.45. In accelerated corrosion tests [22], the time to initiation of reinforcement corrosion in a concrete mix of 0.40 w/c ratio was observed to be approximately two times more than that in a 0.55 w/c ratio concrete.

According to Al-Saadoun et al. [22], the w/c ratio is also important from the cement chemistry viewpoint. They observed that cement composition has undergone a significant change globally during the last 20 years. This change is more noticeably reflected in the composition of cements manufactured in the Arabian Gulf than elsewhere. With no upper limit specified for the C_3S content, the modern cements contain a much higher percentage of C_3S and a significantly lower content of C_2S than the old cements. The new cements, therefore, have a higher rate of hydration and strength gain. Concrete prepared with these cements, therefore, complies with the specified 28-day strength at higher w/c ratios and lower cement content than would have been possible in the case of concretes prepared with cement 20 years ago. Concrete prepared with a high water/cement ratio and C_3S/C_2S ratio will have a more open and continuously linked pore structure with lower density and higher permeability, although such a concrete would still easily meet the 28-day compressive strength requirement. Therefore, concrete specifications for reinforced concrete structures in aggressive exposure conditions should be based on the w/c ratio rather than the strength.

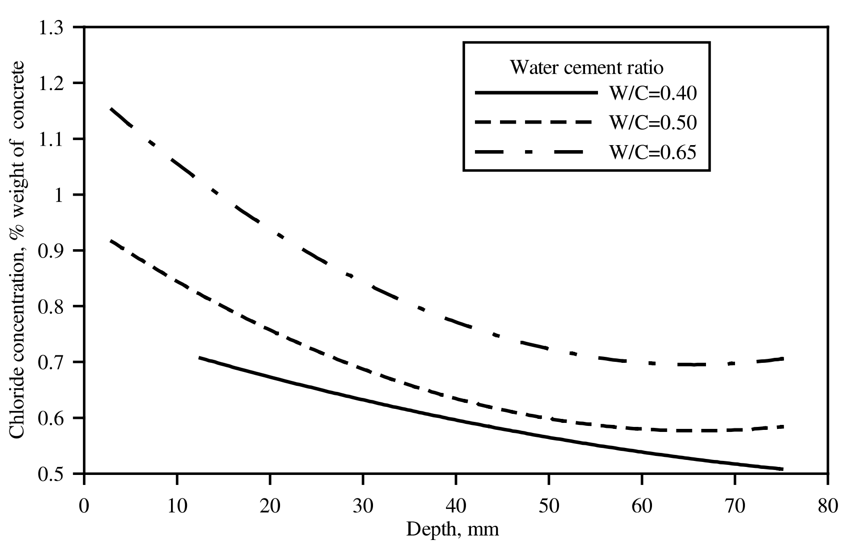

Fig. 4. Effect of water/cement ratio on chloride concentration.

3.1.4. Effect of cement content on chloride diffusion

The chloride concentration profiles for the concrete specimens prepared with cement content of 270, 390 and 450 kg/m^3 are shown in Fig. 5. A significant variation was noted in the chloride profiles for concrete specimens prepared with cement contents of 270 and 390 kg/m^3 while the chloride profiles for concrete specimens prepared with cement contents of 390 and 450 kg/m^3 were close to each other. This indicates the beneficial role of cement content on reducing chloride diffusion. It is possible that the presence of sufficient cement produces a cohesive mix that produces a dense concrete thereby producing fewer pores. The beneficial role of cement content is now recognized by all the international standards, such as ACI and BS. As a result, concrete is now specified in terms of a maximum water/cement ratio and minimum cement content.

Mehta [23] in a review of the performance of concrete structures in harsh marine environments cites several examples of concrete sea structures built with high C_3A (14–15%) cement that have exhibited excellent durability performance as they were prepared with rich mixes in conjunction with low w/c ratios; on the other hand, structures prepared with lean mixes deteriorated prematurely. The data on chloride diffusion coefficients in the concrete specimens prepared with cement content of 270, 390 and 450 kg/m^3 are summarized in Table 5. While there was no significant change in the chloride diffusion co-efficient in the concrete specimens prepared with cement contents of 270 and 390 kg/m^3 the decrease in the chloride diffusion co-efficient was almost one fold in the concrete specimens prepared with a cement content of 450 kg/m^3. These data also emphasize the usage of high cement content to produce a durable concrete.

Table 5
Effect of cement content on chloride diffusion

Cement content (kg/m^3)	Chloride diffusion coefficient (cm^2/s)
270	4.139×10^{-10}
390	8.950×10^{-10}
450	0.300×10^{-10}

3.1.5. Effect of admixtures on chloride diffusion

The chloride concentration profiles for acrylic, latex and epoxy modified concretes prepared with a water/cement ratio of 0.261 are shown in Fig. 6. Lowest chloride concentration was indicated in the concrete specimens modified by the addition of an epoxy while maximum chloride concentration was noted in the concrete specimens modified with an acrylic admixture. Further, the chloride concentration profiles for latex and epoxy modified concretes were closer to each other relative to that for the acrylic modified concrete. The coefficient of chloride diffusion for the concrete specimens of this series are summarized in Table 6.

3.2. Sulfate resistance

3.2.1. Effect of w/c ratio and cement content on the sulfate-resistance of concrete

The effect of w/c ratio and cement content in the concrete mixes on sulfate-resistance, evaluated in terms of the change in compressive strength, is shown in Fig. 7. The concrete specimens were prepared with w/c ratios of 0.4, 0.5 and 0.65. It is seen that all buried specimens have gained in strength, except those prepared with a cement content of 270 kg/m^3 and w/c ratio of 0.65. The increase in strength noted in the high cement content and/or low water/cement ratio concretes is in line with the common observation that strength of concrete test

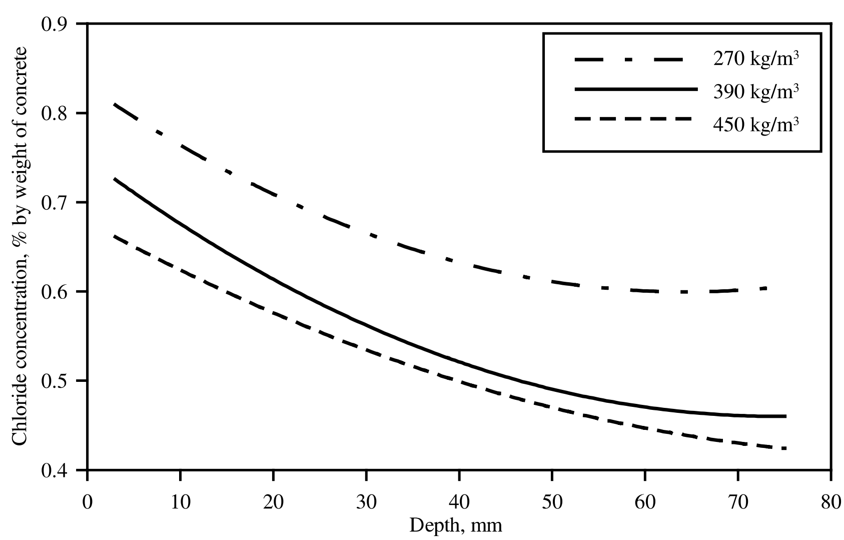

Fig. 5. Effect of cement content on chloride concentration.

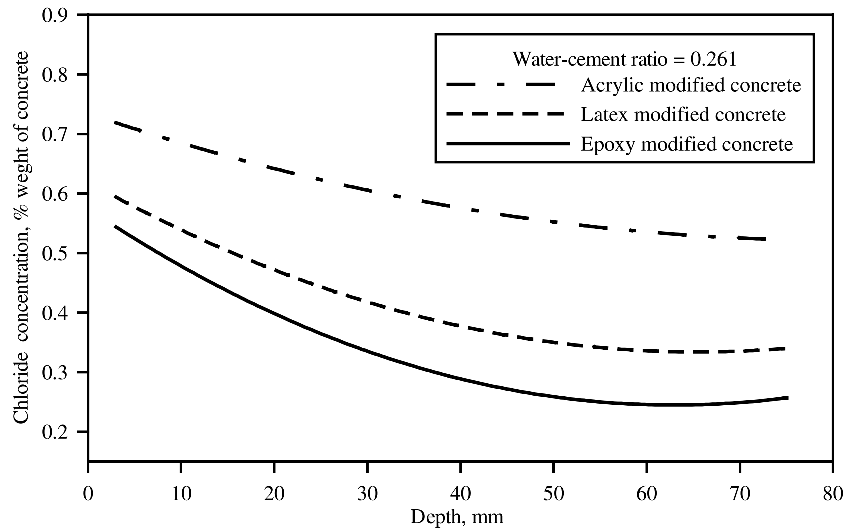

Fig. 6. Chloride concentration in modified concrete.

Table 6
Effect of concrete modification on chloride diffusion

Concrete modification type	Chloride diffusion coefficient (cm^2/s)
Acrylic	2.700×10^{-10}
Latex	1.160×10^{-10}
Epoxy	0.670×10^{-10}

specimens increases over those cured in water in the early stages of exposure to even strong sulfate solutions [24]. This is attributed to higher and more intense hydration on immersion in the ground water and to the filling of pores by the products of reaction between cement hydrates and sulfate ions. The deterioration usually occurs only after sufficient time when the sulfate attack on the concrete overshadows the gain in strength due to hydration [24].

It is apparent from the data in Fig. 7 that cement hydration is reflected in the gain of strength and the sulfate attack never materialized to the extent that the degradation would overshadow the gain in strength. The data show that only significantly lean mixes, such as with cement content of 270 kg/m^3 will undergo enhanced deterioration. However, when the cement content is increased to 390 kg/m^3, the performance differential is insignificant.

3.2.2. Effect of curing time on the sulfate-resistance of concrete

The effect of curing time on sulfate attack is shown in Fig. 8. It is seen that for specimens which were cured for 1 day, the sulfate deterioration after 4.5 years of immersion overshadows the gain in strength due to increased hydration. However, as the curing time, prior to

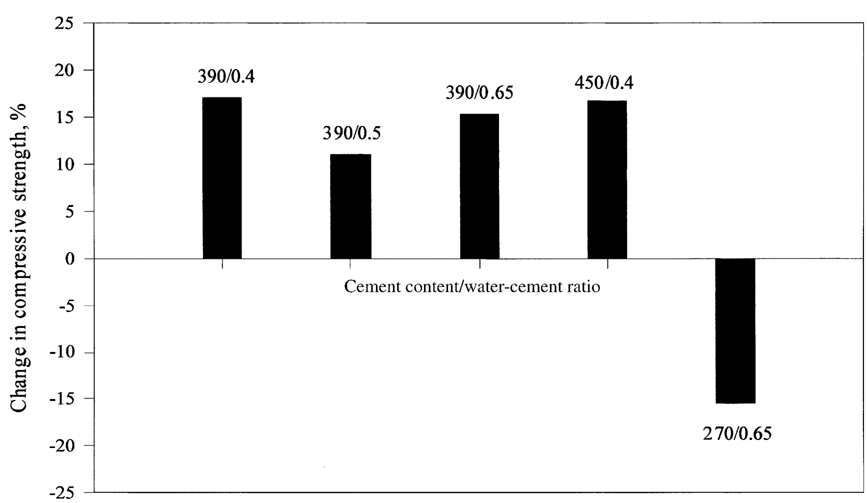

Fig. 7. Effect of water/cement ratio and cement content on change in compressive strength in buried concrete specimens.

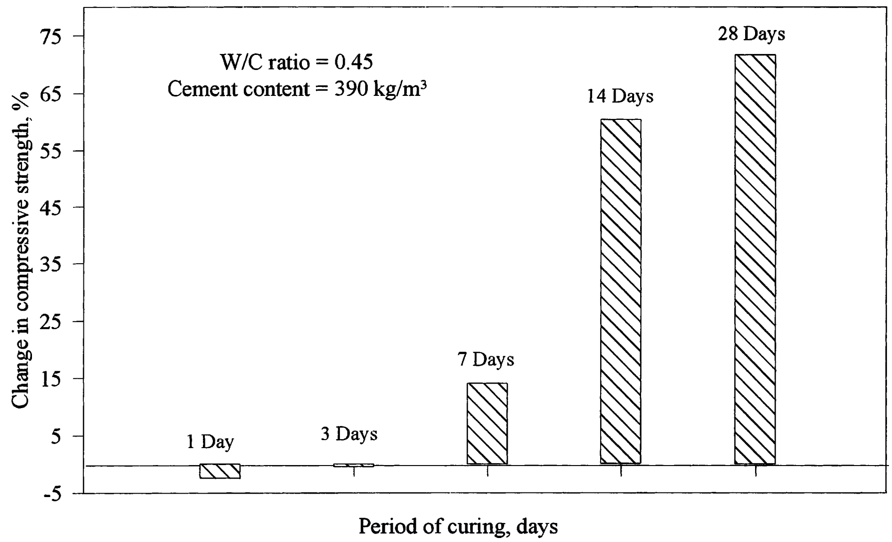

Fig. 8. Effect of curing period on change in compressive strength in buried concrete specimens.

burial increases, the strength gain effect also increases. This position is ascribable to the fact that increased curing of a 0.45 w/c ratio mix results in a dense impermeable concrete which is not permeated by the sulfate bearing groundwater resulting in sulfate attack which is only confined to the concrete skin.

3.2.3. Effect of consolidation on the sulfate-resistance of concrete

The effect of consolidation on sulfate attack on concrete is shown in Fig. 9. The strength reduction in the concrete specimens prepared with 40% consolidation effort was more than that in the concrete specimens prepared with 60% and 100% consolidation effort. Further, the strength reduction noted in the concrete specimens of this series may be attributed to the low cement content (330 kg/m^3) used in their preparation.

3.2.4. Effect of admixtures on the sulfate-resistance of concrete

The effect of admixtures on the sulfate-resistance of concrete is shown in Fig. 10. A reduction in strength was noted in latex and epoxy modified concrete specimens. This indicates that these admixtures polymerize more effectively in air than in water. Although buried specimens did not show signs of deterioration, it is also clear that they did not gain strength either. It seems admixing concrete with latex and epoxy hinders the normal cement hydration. This behavior was not noted in the acrylic modified concrete specimens prepared with a water/cement ratio of 0.261.

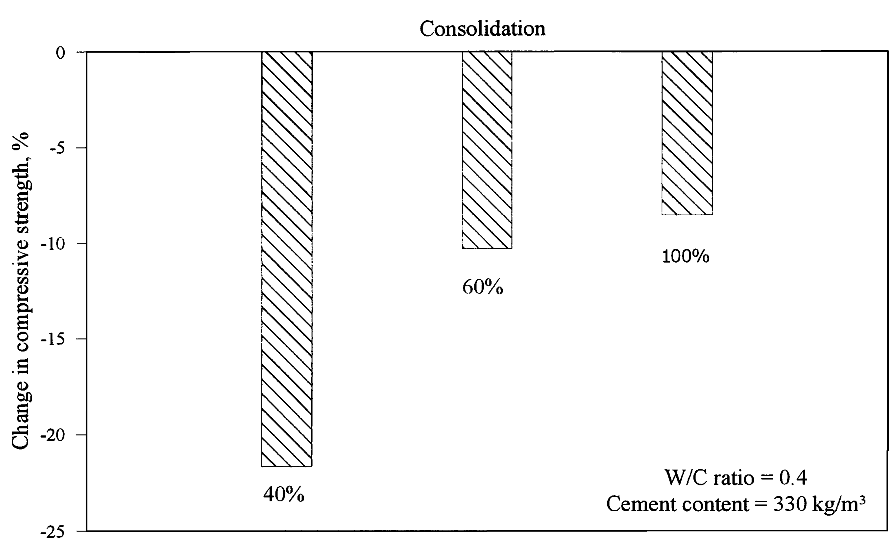

Fig. 9. Effect of consolidation effort on change in compressive strength of buried concrete specimens.

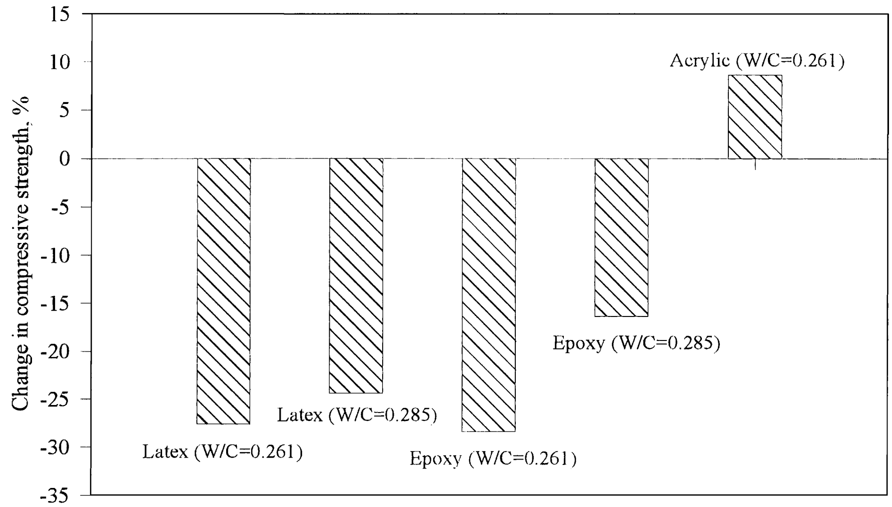

Fig. 10. Change in compressive strength of modified concrete specimens.

4. Conclusions

As expected, curing significantly affected the chloride diffusion in concrete. The chloride diffusion decreases with the period of curing.

Consolidation significantly influenced chloride diffusion in concrete. The chloride concentration decreased with the degree of consolidation. Similarly, the chloride diffusion decreased with decreasing w/c ratio. The chloride diffusion in the rich mixes, prepared with attendant reduction in the w/c ratio was less than that in the lean mixes.

A marked decrease in the chloride diffusion was noted in the concrete specimens modified with both latex and epoxy compared to acrylic modified concrete.

The compressive strength of concrete specimens buried in the soil at a coastal area was more than those cured in laboratory. This is attributed to the accelerated hydration of cement. The data also show that the highest strength gain was in the concrete specimens prepared with a w/c of 0.40.

Sulfate attack was more intense in the concrete specimens prepared with a high w/c ratio. However, as the cement content was increased to 390 kg/m^3, the strength gain was more predominant compared to the sulfate deterioration. There was only a marginal difference in the strength gain when the cement content was increased to 450 kg/m^3.

Sulfate attack was noted in the concrete specimens that were cured for one day. However, no reduction in strength, due to sulfate attack, was noted when the curing period was further increased.

Deterioration of concrete, due to sulfate attack, increased with improper consolidation. The reduction in strength, due to sulfate attack, became more significant in the under consolidated concrete.

The compressive strength of latex and epoxy modified concrete specimens buried underground at the coastal site was less than that of similar specimens stored in the laboratory. This indicates that these admixtures polymerize more effectively in air than in the water. Although buried specimens did not show any signs of deterioration, they did not gain strength either.

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