

Effect of Chloride and Sulfate Contamination in Soils on Corrosion of Steel and Concrete

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The durability performance of plain and blended cements in sabkha soils (soils contaminated with high concentrations of chloride and sulfate salts) was investigated. Specimens placed in the sabkha soil were obtained at periodic intervals and evaluated by conducting strength loss measurements, corrosion potentials monitoring, and corrosion rate measurements at regular intervals. Results indicate that the strength reduction after 540 days of exposure to sabkha soils was greater in silica fume cement mortar specimens compared with plain and other blended cements. Reinforcement corrosion was, however, much lower in silica fume cement concrete than in plain, fly ash, and blast furnace slag cements. This indicates that use of silica fume cement in structural components placed in sabkha soils will be beneficial from the viewpoint of reinforcement corrosion. Additional protective measures, such as application of a water-resistant epoxy-based coating, will have to be adopted to minimize deterioration related to sulfate salts.

Sabkhas are saline flats underlain by sand, silt, or clay and often encrusted with salt. These subaerial evaporative areas border partially landlocked sea (coastal sabkhas) or cover a number of continental depressions (inland or continental sabkhas). Both types form under hot, arid climates and are associated with a shallow groundwater table. Sabkha soils are generally unconsolidated, heterogeneous, layered or unlayered sedimentological framework bathed in highly concentrated subsurface brines. These types of soils normally have a loose, rather porous, and permeable, gritty structure, and their surfaces are highly hygroscopic (1). These soils typically exist in the form of alternating cemented and uncemented layers. The cementation is brought about by the presence of saturated brines coupled with excessive evaporation rates (2).

Several potential geotechnical problems are associated with sabkha soils (2). The problems emerge principally from the high salt content in the soil and groundwater. The sulfate and chloride concentrations in the sabkha soils are approximately five to six times as high as those in typical seawater (3). The high salt concentrations, particularly those of chlorides and sulfates, are highly corrosive to both concrete and steel. Moreover, the conjoint prevalence of chloride and sulfate salts

poses several unresolved questions regarding their concomitant and interactive effect on the durability of reinforced concrete structural components placed in such an environment. The problem is significantly magnified by the coexistence of moisture with this high salt content, which may lead to crystallization of salts in concrete pores, thereby leading to its disintegration. This form of crystallization-induced disintegration usually occurs above the water table, where crystallization is enhanced by the prevailing high rates of evaporation.

Geotechnical engineers usually investigate the load-bearing and compressibility characteristics of sabkhas and are rarely concerned with the durability performance of concrete in such environments. This unintentional ignorance of the aggressive service environment has led to a substantial reduction in the useful service life of concrete structures. The normal practice in the Arabian Gulf region is to use ASTM C150 Type V cement to resist deterioration due to sulfate salts. The structural components placed in sabkhas, however, are subjected to both sulfate and chloride attack. In such situations, use of Type V cement, though providing adequate protection against sulfate attack, fails to remove free chlorides from concrete. To inhibit reinforcement corrosion, cement with a high tricalcium aluminate (C_3A) content should be used (4). Rasheeduzzafar et al. (5) indicated better performance by high- C_3A cements in chloride environments. Although the use of cement with high C_3A phase, more than 12 percent per se, is useful from a reinforcement corrosion standpoint, it poses the danger of deterioration and disintegration of concrete due to the reaction between sulfate salts and the compounds of cements. A useful approach to solve this problem seems to use a medium C_3A cement in conjunction with suitable admixtures to decrease the permeability of concrete, thus retarding the ingress of the aggressive species (6).

Mineral admixtures like natural pozzolan, fly ash, and industrial by-products like silica fume and blast furnace slag are used in concrete to make it dense and impermeable. Whereas there are considerable data on the sulfate resistance performance of these cements (7–9) and some data are available on the performance of these cements in chloride environments (10–13), data are fairly sparse at this time on the durability performance of these cements in environments characterized by the interaction of chloride and sulfate ions. In the absence of data on the performance of blended cements in the chloride-sulfate (sabkha) environment, a more rigorous approach

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to the selection of appropriate composite binder components is required before their use can be recommended in such aggressive environments.

This investigation was carried out to evaluate the performance of three types of ASTM C150 cements (Types I, II, and V) and Type I cement blended with fly ash, silica fume, and blast furnace slag in the sabkha soils. The plain and blended cement concrete and mortar specimens were made with water-cement ratios of 0.35 and 0.50. The cement mortar specimens were buried in sabkha soils and retrieved after 3, 6, 12, and 18 months of exposure. The performance of plain and blended cements in the sabkha environment was evaluated by determining the reduction in the compressive strength and analyzing the crushed mortar specimens to measure chloride and hydroxyl ion concentrations. The reinforcement corrosion was evaluated by conducting accelerated laboratory studies using simulated sabkha groundwater. The corrosion activity was monitored by measuring corrosion potentials and corrosion current density at regular intervals.

MATERIALS AND TECHNIQUES

Materials

ASTM C150 Type I, Type II, and Type V cements were used in preparing plain mortar specimens. ASTM C618 Class F fly ash was used as 20 percent replacement by weight of Type I cement to prepare portland fly ash blended cement. For the silica fume mortar specimens, silica fume was used as 10 percent replacement by weight of Type I cement. In addition, one blast furnace slag cement, containing 60 percent granulated blast furnace slag, was used. A sand-to-cement ratio of 2.75 was used for mortar specimens, whereas a cement content of 350 kg/m³ was used in the reinforced concrete specimens used for evaluation of steel corrosion. The coarse aggregate was 19 mm maximum size crushed limestone of bulk specific gravity 2.42 and average absorption 3.77 percent. A coarse to fine aggregate ratio of 2.0 by weight was kept invariant in all the concrete mixes.

Techniques

Casting of Specimens

Mortar cube specimens 25 mm in size were used to monitor the effect of sabkhas on compressive strength. Concrete cylinders 75 mm in diameter and 150 mm in height, with a centrally embedded 12 mm reinforcing bar were used to investigate reinforcement corrosion. The steel bar was coated with an epoxy paint at the concrete-air interface and at its end, which was embedded in concrete. An effective length of 75 mm of uncoated steel was enclosed in concrete. The concrete ingredients were mixed in a revolving mixer, whereas mortar was mixed in a mortar mixer. After casting, the specimens were covered with wet burlap for 24 hr before demolding.

After demolding, the specimens were cured in potable water for a further period of 13 days. The field specimens were placed in plastic cages, which were placed below the groundwater table. The placement of the specimens was properly documented, and the pit was refilled with the native soil. For

investigating reinforcement corrosion, three reinforced concrete specimens representing similar mix constituents were immersed in the simulated sabkha solution (15.7 percent Cl⁻ + 0.5 percent SO₄²⁻). Sodium chloride was used to provide the chloride ions, and sodium sulfate and magnesium sulfate were used to provide the sulfate ions. The latter two salts were proportioned to provide 50 percent of the sulfate concentration from each of them.

Reduction in Compressive Strength

Deterioration due to exposure to the aggressive environment of the sabkha soils was documented by evaluating the reduction in compressive strength. Mortar specimens (25-mm cubes) were tested in compression after 3, 6, 12, and 18 months using a special 200-kN automatic machine suited for testing small cubes. At the scheduled time, the specimens were retrieved from the exposure site and rinsed in distilled water for about 15 min to remove any salt deposits and loose materials. They were air dried for a period of about 24 hr and tested in compression according to ASTM C39.

Chemical Analysis

After retrieval from the field, the specimens were cleaned of the salt deposits, air dried, and crushed to fine powder (passing #100 sieve). The crushed portion was used to determine the following: (a) water soluble chlorides, by titrating against mercuric nitrate (14), and (b) hydroxyl ion concentration, by dissolving 10 g of the powder sample in 500 mL distilled water and titrating the filtrate against 0.01 M sulfuric acid.

Corrosion Monitoring

Reinforcement corrosion was monitored by measuring corrosion potentials and corrosion current density at regular intervals. The corrosion potentials were measured using a high-impedance voltmeter and recording the potentials with respect to a saturated calomel electrode (SCE). Linear polarization resistance technique was used to measure the corrosion current density. The polarization resistance (R_p) was determined by conducting a linear polarization scan in the range of ± 10 mV of the corrosion potential. A microprocessor-based potentiostat/galvanostat was used for polarizing the steel. A stainless steel frame placed outside the specimen was used as a counterelectrode, whereas an SCE was used as a reference electrode. A scan rate of 0.1 mV/sec was used. Positive feedback technique was used to compensate for the ohmic drop (IR) between the reference electrode and the reinforcing bar. The corrosion current density I_{corr} was determined using the Stern Geary formula (15):

$$I_{\text{corr}} = B/R_p$$

where

$$\begin{aligned} I_{\text{corr}} &= \text{corrosion current density } (\mu\text{A}/\text{cm}^2), \\ R_p &= \text{polarization resistance } (\text{ohms} \cdot \text{cm}^2), \text{ and} \\ B &= (\beta_a \cdot \beta_c) / [2.3(\beta_a + \beta_c)]. \end{aligned}$$

β_a and β_c are the anodic and cathodic Tafel constants. For steel in concrete, values of B equal to 52 in the passive condition and 26 in the active condition are used. Gonzalez and Andrade (16) have demonstrated a good correlation between corrosion rates determined by linear polarization resistance technique and weight loss measurements for active and passive steel in concrete using these values of B .

RESULTS

Strength Development

The effect of the high salinity of the sabkha groundwater and soil on the integrity of the cement mortar specimens was evaluated by measuring the compressive strength after exposure periods of 3, 6, 12, and 18 months. The compressive strength after these exposure periods was compared with the compressive strength before placement in the exposure site. In normal situations, concrete strength generally increases with the period of curing. Any reduction in strength with increasing period of curing indicates deterioration of the internal structure, which could be caused by surface softening or expansion caused by the reaction between sulfate salts and the cement. The compressive strength development in plain cement mortar specimens made with a water-cement ratio of 0.5 is shown in Figure 1. The data indicate that the compressive strength in mortar specimens made with Type I, Type II, and Type V cement continues to be higher than the 14-day value even after an exposure period of about 540 days. The data on strength development in cement mortar specimens made with Type I and Type V cements and a water-cement ratio of 0.35 are shown in Figure 2. These data indicate an initial increase in the strength of these specimens in the range of 120 percent over the 14-day value up to an exposure period of about 3 months. The strength development appears to decrease after this exposure period (i.e., 3 months). After an exposure period of about 540 days, the compressive strength of these specimens was 70 to 90 percent of the 14-day value. The reduction in strength in specimens made with a water cement ratio of 0.35 may be attributed to the reaction between the sulfate ions in the groundwater and the compounds of cement.

The strength development in cement mortar specimens made with a water-cement ratio of 0.5 and blended with fly ash (20 percent replacement of cement), silica fume (10 percent cement replacement level), and blast furnace slag cement (60 percent granulated blast furnace slag and 40 percent Type I cement) specimens is shown in Figure 3. These data indicate an increase in compressive strength with period of immersion for mortar specimens made with fly ash and blast furnace slag cement. The strength development with increasing period of immersion was found to be higher in fly ash cement mortar specimens compared with blast furnace slag cement mortar specimens. In the silica fume mortar specimens, compressive strength reduction was indicated after an exposure period of about 200 days. Figure 4 shows the strength development in cement mortar specimens made with Type I cement and a water-cement ratio of 0.35 and blended with fly ash and silica fume. The data indicate a trend similar to that indicated by the strength data in Figure 3. The strength reduction was again observed to be higher in silica fume mortar specimens compared with that in the fly ash mortar specimens. The strength

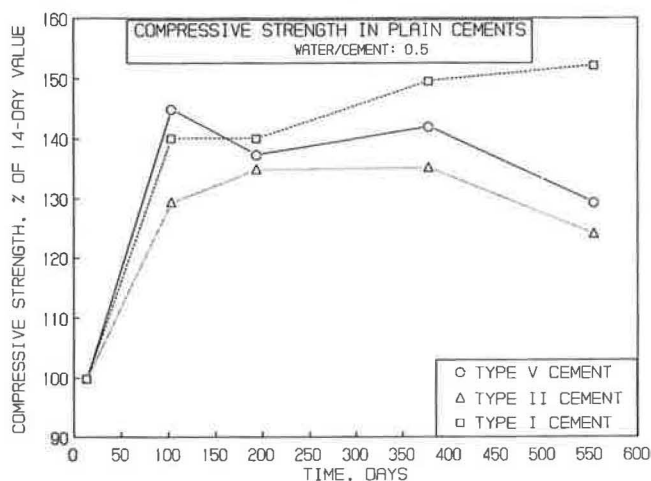


FIGURE 1 Compressive strength development in plain cements (w/c: 0.50).

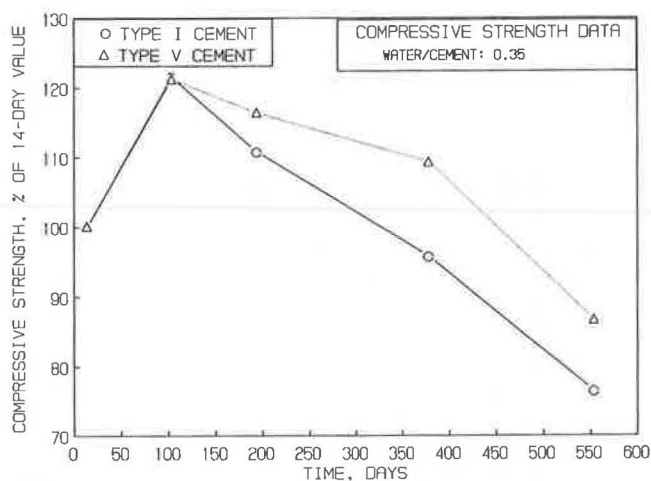


FIGURE 2 Compressive strength development in plain cements (w/c: 0.35).

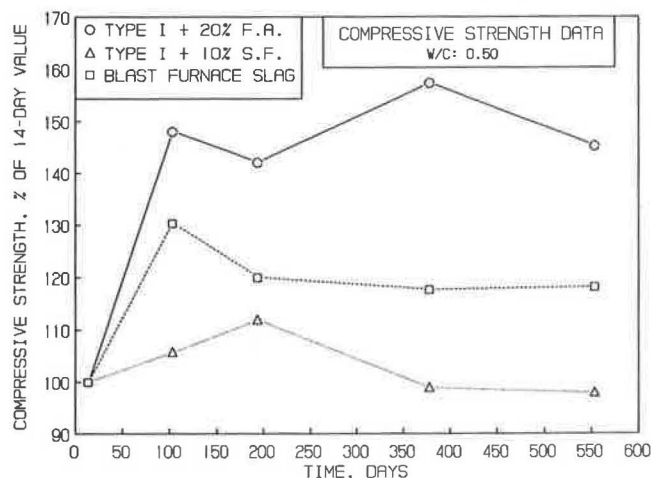


FIGURE 3 Compressive strength development in blended cements (w/c: 0.50; Type I cement).

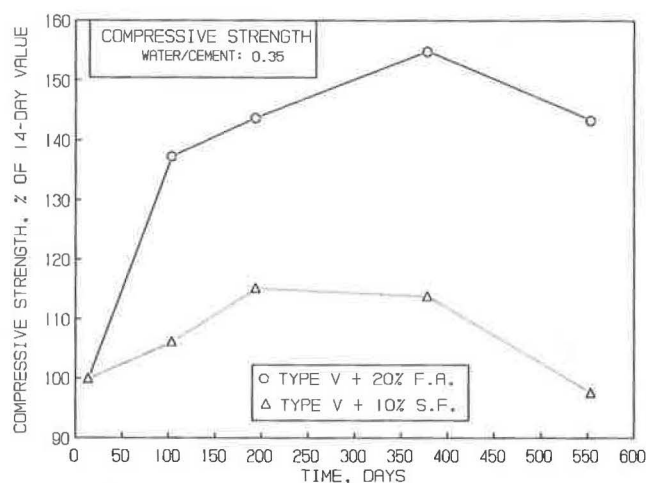


FIGURE 4 Compressive strength development in blended cements (w/c: 0.35; Type I cement).

development data for specimens made with Type V cement and blended with fly ash and silica fume and a water-cement ratio of 0.5 are shown in Figure 5. These data indicated a trend similar to that shown in Figures 3 and 4.

Chloride and Hydroxyl Ion Concentration

The data on hydroxyl and chloride ion concentration are presented in Table 1. The OH^- ion concentration in the plain cements was in the range of 8 to 10.5 percent by weight of cement. The OH^- ion concentration in mortar specimens made by blending Type I cement with silica fume, fly ash, and blast furnace slag cement mortar was 5.54, 6.56, and 6.00 percent by weight of cement, respectively. The OH^- ion concentration of mortar specimens made by blending Type V cement with silica fume and fly ash was 4.9 and 5.3 percent, respectively.

The water-soluble chloride content was approximately 6.28 percent by weight of cement in Types I, II, and V cements. This indicates that the effect of cement type was not very significant on water-soluble chloride concentration. The water-

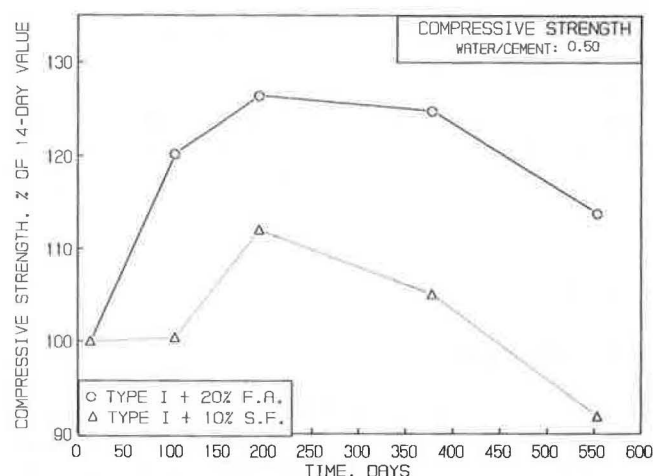


FIGURE 5 Compressive strength development in blended cements (w/c: 0.5; Type V cement).

soluble chloride concentration was 5.36, 4.62, and 5.54 percent in specimens made with Type I cement blended with fly ash, blast furnace slag, and silica fume, respectively. The chloride concentration in Type V cement mortar specimens blended with fly ash and silica fume was 6.28 and 5.73 percent, respectively. The chloride concentration in Type I and Type V cement made with a water-cement ratio of 0.35 was 4.80 and 4.62 percent, respectively. The chloride concentration in specimens made with a water-cement ratio of 0.35 and blended with fly ash and silica fume was 3.70 and 2.59 percent, respectively. The lower chloride concentration in specimens made with silica fume and fly ash and using a water-cement ratio of 0.35 is due to the densification of the paste matrix resulting in the use of the mineral admixtures and the low water-cement ratio. The water soluble chloride concentration in all the specimens is, however, higher than the allowable value of 0.15 percent suggested by ACI Committee 318.

Reinforcement Corrosion

Figure 6 is a corrosion potential-time record for plain and blended cements made with a water-cement ratio of 0.50 and for Type I cement with a water-cement ratio of 0.35. The corrosion potentials were measured for three specimens representing similar composition, and the potentials indicated in Figure 6 are the average of these three values. The corrosion potentials provide a qualitative indication of reinforcement corrosion. Potential values more negative than -270 mV SCE indicate initiation of reinforcement corrosion. The corrosion potential-time record (Figure 6) indicates the initiation of reinforcement corrosion in plain and blended cements in the range of 75 to 150 days. The average corrosion potential of steel embedded in silica fume mortar specimens was approximately -270 mV, indicating no initiation of corrosion, even after an exposure period of 450 days. The corrosion potentials of steel in blast furnace slag cement mortar specimens were more than -270 mV at the time of immersion of these specimens in the test solution. This indicates that the ASTM C876 criterion of -270 mV SCE is not useful for detecting the

TABLE 1 HYDROXYL AND CHLORIDE ION CONCENTRATION IN MORTAR SPECIMENS PLACED IN SABKHA ENVIRONMENT

Cement Type	OH^- ion (% wt. cement)	Soluble Chloride (% wt. cement)	Cl^-/OH^- (Ratio)
Type I	9.0	6.28	0.70
Type V	9.12	6.28	0.69
Type I + F.A.	6.56	5.36	0.82
Blast furnace slag	6.00	4.62	0.77
Type I + S.F.	5.54	5.54	1.00
Type II	10.10	6.28	0.62
Type I (w/c: 0.35)	8.74	4.80	0.55
Type V (w/c: 0.35)	10.54	4.62	0.44
Type V + F.A.	6.46	6.28	0.97
Type V + S.F.	4.96	5.73	1.12
Type I + 20% F.A.	5.38	3.70	0.69
Type I + 10% S.F.	5.32	2.59	0.49

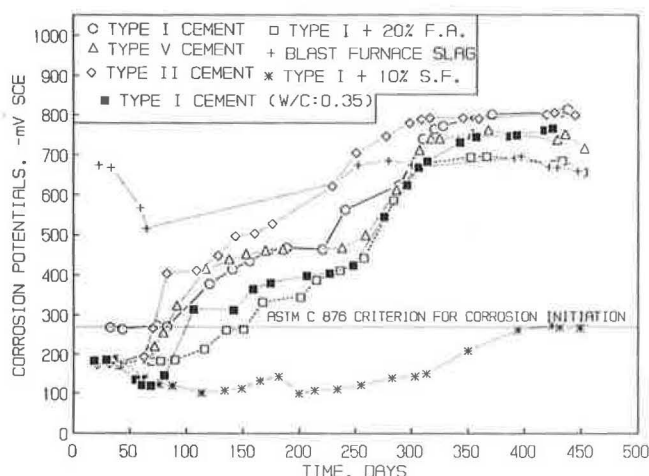


FIGURE 6 Corrosion potential-time record.

onset of corrosion in blast furnace slag cements (17). Another criterion normally used to detect corrosion initiation is a substantial increase in corrosion activity marked by a sudden increase in the corrosion potential-time curve. Such a transition has not been observed in the potential-time curve for bars in blast furnace slag cement concrete. This indicates that reinforcement steel in the blast furnace slag cement concrete is in a passive condition (i.e., corrosion has not yet begun).

The data on corrosion current density for bars embedded in specimens tested in this investigation are shown in Figure 7. The corrosion current density was 3.0 to 3.87 $\mu\text{A}/\text{cm}^2$ in Type I, Type II, and Type V cements (w/c: 0.5). The corrosion current density on bars in fly ash blended cement concrete was about 1.04 $\mu\text{A}/\text{cm}^2$. The corrosion current density on steel in blast furnace slag and silica fume cement concretes was 0.25 and 0.08 $\mu\text{A}/\text{cm}^2$, respectively. The corrosion current density on steel in concrete made with a water-cement ratio of 0.35 was 2.17 $\mu\text{A}/\text{cm}^2$. These data indicate that blending of portland cement with either mineral admixtures or industrial by-products was beneficial from a reinforcement corro-

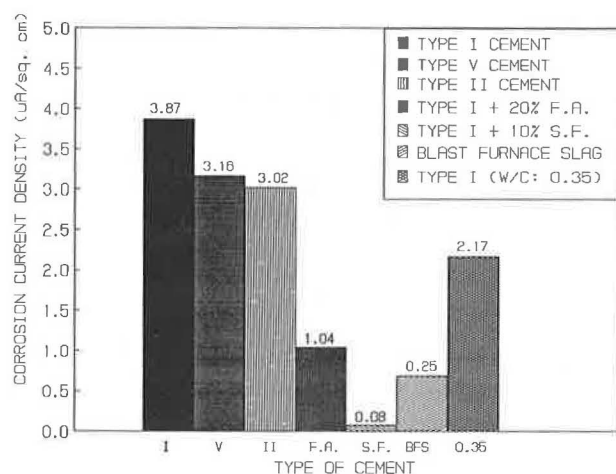


FIGURE 7 Data on corrosion current density on steel in plain and blended cements.

sion viewpoint. Reinforcement corrosion was minimum in silica fume cement concrete, followed by blast furnace slag and fly ash cement concretes in decreasing order. Reinforcement corrosion activity was higher in plain cement concretes than in blended cement concrete specimens. Even an improvement in concrete quality brought about by the reduction of the water-cement ratio from 0.5 to 0.35 did not significantly improve its performance compared with incorporation of the mineral admixtures (fly ash) and industrial by-products (blast furnace slag and silica fume).

DISCUSSION OF RESULTS

The performance of plain and blended cements in sabkha soils was evaluated by determining strength development, measuring the chloride and hydroxyl ion concentrations, and evaluating reinforcement corrosion. The compressive strength data indicate insignificant reduction in compressive strength with period of exposure in plain cement mortar specimens made with a water-cement ratio of 0.5. The effect of the cement type (i.e., C_3A variation) on strength development was not significant. The compressive strength in plain cements made with a water-cement ratio of 0.35 was between 75 and 90 percent of the 14-day value after an exposure period of 540 days. This indicates that specimens made with a water-cement ratio of 0.35 may deteriorate more rapidly than those made with a water-cement ratio of 0.5. Similar results have been reported by Ben-Yair (18). In his experiments, mortar specimens made with a water-cement ratio of 0.3 and exposed to 3.5 percent NaCl + 0.4 percent Na_2SO_4 solution for more than 8 years expanded more than specimens made with a water-cement ratio of 0.5. The authors attribute this behavior to the very fine pore structure formed in the low water-cement ratio mixes compared with those made with a water-cement ratio of 0.50. The salts of crystallization formed as a result of reaction between cement and sulfate salts are not well accommodated in the finer pore structure in the low water-cement ratio specimens. These salts exert considerable pressure, resulting in greater expansion and deterioration in the low water-cement ratio mixes than in concretes made with a high water-cement ratio whose coarser pore structure can accommodate the salts of crystallization.

The compressive strength data for fly ash and blast furnace slag blended cements indicated an increase in strength in fly ash and blast furnace slag cement mortar specimens over the 14-day value, even after an exposure period of about 540 days. The strength development was found to be higher in fly ash concrete than in blast furnace slag cement specimens. Mortar specimens made with silica fume blended cements, however, indicated a reduction in strength over the initial values after about 200 days of exposure. The reduction in strength in silica fume cement mortar specimens is attributed to softening of the cement matrix due to reaction of the secondary calcium silicate hydrate (C-S-H) with magnesium sulfate associated with the groundwaters. This sort of deterioration is manifested by softening and deterioration of the surface skin leaving the aggregates exposed to environment (scaling). Such a failure was more prominent in specimens made with blast furnace slag and silica fume cement specimens. Surface scaling was noticeably higher in blast furnace slag cement concretes than

in plain cements in marine exposure studies carried out by one of the authors (19). Schroder and Smolzyk (20) relate the surface deterioration to the glass content of the slag. A minimum glass content of the slag (> 61 percent) was necessary to improve the sulfate resistance of the blend.

The reduction in strength in silica fume cement mortar specimens is attributed to the presence of Mg^{++} cations associated with sulfate salts. Mg^{++} cation is destructive to the secondary C-S-H gel by partially converting it to a cohesionless, porous, reticulated magnesium silicate hydrate (M-S-H) gel. The enhanced deterioration of silica fume blended cement paste in the magnesium sulfate environment has also been observed by Cohen and Bentur (21). They reported that brucite (MH) was not traceable in silica fume blended hardened cement pastes that had undergone deterioration due to magnesium sulfate attack. MH is relatively insoluble in water and is known to block the pores of the hardened cement paste matrix, thereby providing a protective shield to the ingress of sulfate ions. In view of this position, it may be hypothesized that the absence of MH in the deteriorated silica fume blended cements, in contrast to its presence in plain cements, presents a more open structure, thereby making silica fume blended cement mortar/concrete more vulnerable to magnesium-based sulfate attack.

The concentration of free chloride (water-soluble chloride) was considerably more than a value of 0.15 percent (by weight of cement) recommended by ACI 318 for concrete structures exposed to chloride-bearing waters for avoiding risk of corrosion. According to Hausmann (22), the risk of corrosion is greater when the Cl^-/OH^- ratio is above 0.6. The Cl^-/OH^- ratio in most of the cement/mixture proportions investigated is more than this value (see Table 1 for the values of the Cl^-/OH^- ratio for each of the mixes investigated). This indicates that the changes of corrosion are elevated in reinforced concrete structures placed in the aggressive environment of the sabkha. The other factor for the corrosion to proceed is the availability of oxygen. The rate of oxygen diffusion is significantly affected by the extent to which the concrete is saturated with water. Since the availability of oxygen is limited in structures placed below ground level, reinforcement corrosion is assumed to proceed at a slower pace, even in the presence of high concentrations of chloride ions. However, at the soil-air interface, where abundant oxygen is available, corrosion proceeds at a rapid rate. This phenomenon appears to be of importance in structures submerged deep in the ground and only a small portion of which are exposed above ground. If these structures are placed in highly contaminated soils, reinforcement corrosion is initiated at the soil-air interface, whereas the buried portion remains free of corrosion because of non-availability of oxygen. The small anode (the soil-air interface) compared with a large cathode (submerged portion) leads to localized corrosion at the anodic sites. Reduction in the diameter of reinforcing steel, in deep foundations placed in sabkha soils, to the extent of more than 50 percent has been observed (23).

The reinforcement corrosion data indicate superior performance by blended cements in resisting reinforcement corrosion compared with plain cements. The corrosion rate of steel in fly ash, blast furnace slag, and silica fume concretes was 3, 12, and 38 times lower than in plain cement concrete. The corrosion rate of steel in blended cements made with a water-

cement ratio of 0.50 was lower than in plain Type I cement (C_3A : 8.5 percent) concrete made with a water-cement ratio of 0.35. The corrosion current density on steel in Type I cement (w/c: 0.35) was 2, 9, and 27 times that of corrosion current density on steel in fly ash, blast furnace slag, and silica fume cement concrete specimens made with a water-cement ratio of 0.50. Furthermore, the corrosion potential-time record does not indicate initiation of reinforcement corrosion in silica fume cement concrete specimens, whereas reinforcement corrosion was active in all the plain and fly ash cement concrete specimens. The authors believe that the time to initiation of corrosion is an important parameter controlling the service life modeling for structures suffering from reinforcement corrosion. The other parameter used in the life prediction models is the propagation period. The propagation time remains fairly constant in all the cement types. A longer time period for corrosion initiation observed in silica fume cement is indicative of its usefulness in increasing the useful service life of concrete structures compared with other cements.

The corrosion data indicate a superior performance by silica fume blended cement concretes, implying that surface softening leading to a reduction in the compressive strength in this cement does not accelerate the reinforcement corrosion process. Furthermore, the magnitude of deterioration observed in the mortar specimens is probably due to the specimen size. It is possible that the reduction in strength due to sulfate ions in actual structures may not be as high as that observed in the small laboratory specimens. The surface deterioration can be mitigated by applying a water-resistant epoxy-based coating.

CONCLUSIONS

Mortar specimens prepared using plain cement (Type I, Type II, and Type V), and blended cements (blended with fly ash, blast furnace slag, and silica fume) were placed in sabkha soil for a period of more than 540 days. The performance of these cements was evaluated by conducting compression tests, analyzing the crushed specimens for chloride and hydroxyl ion concentrations, and monitoring reinforcement corrosion. The conclusions from the data developed in this study are as follows:

1. The compressive strength development in plain cements was not affected by placement in the aggressive sabkha soils. The compressive strength measured after about 540 days of exposure to the sabkha environment was not affected in fly ash and blast furnace slag cements, whereas the compressive strength in silica fume blended cements was 70 to 80 percent of the 14-day value.
2. The compressive strength after about 540 days of exposure was 75 to 90 percent of the 14-day value in specimens made with a water-cement ratio of 0.35. The compressive strength in cement mortar specimens made with a water-cement ratio of 0.5 was more than 100 percent of the 14-day value.
3. The water-soluble chloride concentration in all the cement mortar specimens placed in the sabkha was more than the normally accepted threshold value of 0.15 percent by weight of cement. Similarly, the chloride/hydroxyl ion ratio was more

than 0.6 in most of the cement mixtures investigated. This indicates that the chances of corrosion in all the cements placed in sabkha environments are greatly increased.

4. The data on reinforcement corrosion in plain and blended cements developed by measuring corrosion potentials and corrosion current density indicate that the corrosion activity was lower in blended cement concretes than in plain cement concretes. The corrosion current density on steel in fly ash, blast furnace slag, and silica fume concretes was 3, 12, and 38 times lower than in plain cement concrete. The reinforcement corrosion in Type I cement (C_3A : 8.5 percent) made with a water-cement ratio of 0.35 was more than that in blended cement concretes made with a water-cement ratio of 0.5. The best corrosion protection was offered by plain cements blended with 10 percent silica fume.

5. Data developed in this investigation indicate that blending of cement with silica fume protects the reinforcing steel from chloride-induced corrosion. However, protective measures like coating the exterior surface with a water-resistant epoxy-based coating will be necessary to protect concrete from deterioration due to magnesium-based sulfate salts.

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