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Suitability of Sea Water for Mixing Structural Concrete Exposed to a Marine Environment

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Abstract

As part of a durability study, this paper describes the mixing and curing effect of sea water on setting time, compressive strength of cement–sand mortar and corresponding concrete, rebar corrosion, chloride content and variation of alkalinity over a period of 18 months in a laboratory simulated splash/tidal zone of marine environment. The test results indicate that sea water is not suitable for the mixing and curing of both plain and reinforced concrete in such marine conditions.

Keywords: Durability, compressive strength, rebar corrosion, plain water, sea water marine environment, chloride concentrations.

INTRODUCTION

The successful performance of a marine structure depends to a great extent on its durability against the aggressive marine environment. Particularly, the splash/tidal zone of a marine structure suffers greatly as it has to face several superimposed cycles of wetting and drying (of different amplitude and frequency) due to tidal action, frequent salt water spray caused by waves, and freeze–thaw action, etc., in the presence of atmospheric oxygen and carbon dioxide. An understanding of the aggressive elements of the environment and the mechanism of their attack on concrete structures is essential to develop the right course of action in providing structures to best withstand the aggression. However, most of the problems regarding concrete durability can be eliminated if appropriate measures are taken in the selection of materials, mix design, reinforcement detailing, construction techniques and quality control methods.[1] As an ingredient material, the quality of mixing and curing water has an important role in making the concrete durable.

It is a common belief amongst engineers that sea water is not suitable for use in making concrete as it may lead to impairment of strength and corrosion of reinforcement. However, a number of reinforced concrete structures built during and after the second world war, in the islands of the Atlantic Ocean and along the coasts of Los Angeles and Florida,[2] bear testimony to the satisfactory use of sea water for mixing and curing concrete. On the other hand, there are also reports of cracking and spalling of concrete in structures in coastal areas because of the corrosion of steel due to use of sea water in the concrete mix.[3]

The need to use sea water for construction can arise in situations where no other source of water is available or where fresh water is costly to transport. Such conditions have often occurred at construction sites along the sea coast and construction engineers in the field are then beset with doubts about the advisability of using sea water. The results of several investigations, as well as the recommendations of different codes of practice regarding the use of salt water for mixing and curing, are summarized in Table 1.

A careful study of this data reveals that the experimental reports/recommendations given in Table 1 are contradictory. Some of them report an increase in strength while others a decrease in strength of concrete made with sea water. However, most agree that considerable reduction in the setting time of cement occurs and that the risk of rebar corrosion is increased when sea water is used for mixing and curing.

Table 1. Past observations/recommendations of various researchers/codes regarding effect of sea water (SW) on concrete

Salt/sea water	*Observations/recommendations*	*Reference*
SW (Mixing)	Water cured: higher strength at 3 and 7 days but lower strength after 28 days in comparison to fresh water concrete (80–88%) Air cured: lower strength at 3 months and then showed recovery after 1 year	Abrams[4]
Great Salt Lake	Strength reduction at 28 days and over (65–77% of PW concrete)	Abrams[4]
SW (mixing)	Increase in strength by 17% during first month. After 3 months, a constant strength of 6% lower than the identical mix made with PW	Narver[5]
SW (mixing)	Gain in early strength but later strength has been observed to fall by 8% to 15%	Steinour[6]
SW (mixing)	Gain in strength both in early and later stages	Griffin & Henry[7]
SW/brackish water	Corrosion is negligible for good, and dense, concrete. May have corrosive action if continuously exposed to air and moisture	Dempsey[8]
SW (mixing)	Four-year study on reinforced mortar specimens revealed: (a) negligible corrosion for submerged specimen; (b) serious corrosion in case of specimens stored in the air of moist room	Shalon *et al.*[9]
SW (mixing + curing)	No sign of harm to the reinforced concrete for up to 10 years exposure	Chen[10]
SW (mixing + curing)	Reduction of initial and final setting time of cement by 25% over PW. Compressive strength of concrete was unaffected up to 17 months	Ghorab[11]
SW (mixing)	In 4-year study, concrete mixed with SW was observed to be highly dangerous as a crack of relatively small width tended to cause great corrosion	Makita *et al.*[12]
SW (mixing)	Approximately 3-year study on plain concrete revealed that the degree of deterioration under the action of SW was greatest with SW as mixing water in comparison to PW	Nishibayashi[13]
Ocean salts	Strength increases with salinity of mixing water	Dewar[14]
Sodium chloride/ ocean salt	The 28-day compressive strength of concrete increased with increasing salinity even up to 7 wt% of water	Taylor *et al.*[15]
SW (mixing)	May be used in concrete provided crushing strength is not lower than 90% of the strength of concrete mixed with distilled water	IS: 456-1964[16]
SW (mixing + curing)	Mixing or curing of concrete with sea water is not recommended. Under unavoidable circumstances, it may be used for plain concrete or concrete structures which are permanently submerged	IS: 456-1978[17]
SW (mixing)	May be allowed provided the initial setting time does not differ by more than 30 min and compressive strength of corresponding concrete not less than 80% of that concrete made with distilled water	CP-114: 1965[18]
SW (mixing)	Mixing water shall be potable and free from salts. Gives no specific reference to SW. Mortar test cubes made with non-potable mixing water shall have 7-day and 28-day strength equal to at least 90% of strength of similar specimen made with potable water	ACI: 318-1983[19]
SW (mixing)	Permits the use of all kinds of water occurring in nature for RC structures	DIN 1045[20]
SW (mixing)	Prohibits the use of sea water in RC marine structures in hot dry regions in view of danger of corrosion and efflorescence	The Russian code[24]
SW (mixing)	Not recommended for use in reinforced, pre-stressed, or other structural concrete	FIP[21]

As sea water contains an appreciable amount of chlorides, the mixing and curing of concrete with such water may lead to a sufficient amount of free chloride ions coming in contact with the rebars within a short period. Combined with carbonation, even small chloride concentrations can depassivate the steel and accelerate the corrosion process. Many researchers have attempted to evaluate the threshold of chloride concentration for rebar corrosion in concrete; some of the values are given in Table 2.

Although some of the researchers and codes of practice recommend the use of sea water for making plain concrete and even for reinforced concrete in the permanently submerged condition, it still remains an area requiring further study and research, particularly the use of such concrete in marine structures located in the splash/tidal zone. The primary objective of this investigation was to carry out an experimental programme to study the use of sea water for mixing and curing of concrete for the splash/tidal zone in a laboratory-simulated marine environment. The physical, as well as chemical, aspects of concrete and rebar corrosion and their dependence on basic parameters are discussed.

EXPERIMENTAL PROGRAMME

A laboratory study was undertaken to investigate the effect of sea water used for mixing and curing on the hydration characteristics of cement and the properties of the corresponding concrete. The programme included the determination of standard consistency, setting time and compressive strength (up to 28 days) of cement using sea water of different concentrations. Plain and reinforced concrete cubes made with the same cement and mixing water were subjected to alternate wetting and drying (AWD) cycles in sea water of different concentrations over a period of 18 months to observe the overall effects on concrete durability.

Material used

Ordinary portland cement (OPC) conforming to IS: 269-1976 from a single lot was used for the entire investigation. Crushed stone (maximum size 12·5 mm, fineness modulus 6·7) and red sand (fineness modulus 2·5) conforming to IS: 383-1970 were used as coarse aggregate and fine aggregate, respectively.

Twelve millimetre diameter plain mild steel bars conforming to IS: 432-1966 (Part I) were cut into pieces of different lengths, 7 cm and 5 cm, as required to provide different depths of cover. The bar pieces were then cleaned carefully to remove any rust product, after which the weights of all the bar pieces were measured on an electronic balance (to $\pm 0{\cdot}1$ mg).

Variables studies

(a) Artificial sea water of different concentration (1 N, 5 N, 10 N). The 1 N denotes normal sea water made in the laboratory by mixing tap water with exact amounts and proportions of different salts as generally found in actual sea water (Table 3). Thus 5 N and 10 N will have salt ion concentrations enhanced to 5 and 10 times those of normal simulated sea water. The enhanced salt concentration of sea water was used to obtain accelerated effects.

(b) Two different grades of concrete, namely concrete A and B, and a cement mortar, were used. The average 28-day compressive strengths of concrete A, B and the mortar were 49·5, 39·5 and 41·6 MPa, respectively (Table 4).

(c) Both plain water (PW) and sea water (SW) of different concentrations were used as mixing and curing water. Plain water (PW) means fresh water or tap water.

(i) For mortar specimens: mixing water —

Table 2. Threshold total chloride ion concentration for rebar corrosion in concrete[22,23]

Researchers	*Year*	*Chloride content (ppm in concrete)*
Hausman	1967	75–1175
Clear & Hay	1973	250–370
Van Daveer *et al.*	1975	800
Cady	1978	250–500
Bazant	1979	3640
Pleifer *et al.*	1986	230–380

Table 3. Different salt contents of artificial sea water

Salts	*Amount (gm)*	*Remark*
NaCl	27·2	These amounts of salts were dissolved in tap water to prepare 1000 gm of SW of 1 N concentration
$MgCl_2$	3·8	
$MgSO_4$	1·7	
$CaSO_4$	1·2	
K_2SO_4	0·9	
$CaCO_3$	0·1	
$MgBr_2$	0·1	

Table 4. Concrete mix proportion and strength

Concrete/ mortar	*Mix proportion cement: fine: coarse*	*W/C ratio*	*28-day strength (MPa)*
A	1:1·37:1·86	0·40	49·5
B	1:1·48:2·22	0·48	39·5
Mortar	1:3	0·39	41·6

PW, 1 N, 5 N, 10 N; curing water — PW. Relevant tests — normal consistency, initial and final setting time, compressive strength. The number of replicatons at each test point was five.

(ii) For concrete specimens: Mixing water — PW, 1 N; pre-curing for 28 days in PW and then subjected to AWD cycles in SW of different concentrations (PW, 1 N, 5 N, 10 N). Relevant tests — visual examination, compressive strength, carbonation, chloride content, rebar corrosion, etc. The number of replications at each test point was six for plain concrete and three for reinforced concrete.

(d) Depth of cover to reinforcement — 15 mm, 25 mm.

(e) Exposure periods — 3, 7, 14, 28 days; 3, 6, 9, 12, 18 months.

(f) Type and size of test specimens — (i) 70 × 70 × 70 mm cubes for cement mortar; (ii) 100 × 100 × 100 mm cubes for concrete.

A total number of 300 cube specimens of two different sizes were cast as per test requirement and the variables introduced. Suitable arrangements were made to hold the reinforcement in the correct position during casting. The specimens were demoulded after 24 h and pre-cured in plain water for 28 days at 27°C. The pre-cured concrete specimens were then subjected to AWD cycles in artificial sea water of different concentrations in a temperature controlled room (T=50°C) for different exposure periods. Each AWD cycle consisted of 12 himmersion in sea water followed by 12 h drying, which is considered to simulate the splash/tidal zone conditions of a tropical marine environment.

After specific periods, the specimens were taken out from the environment for different tests, such as visual examination, compressive strength, etc. Some of the specimens were split into two halves and subjected to a carbonation test with the help of phenolpthalene indicator solution. Concrete powder was drilled out from various depths with the help of a masonry drill. The drilled powder was then ground further to pass through a 150 μm sieve and kept in sealed plastic bags to avoid carbonation. Out of the total chloride content the water soluble chloride is known to be responsible for rebar corrosion in concrete. The soluble chlorides were determined by silver nitrate titration according to the Volhard method and was expressed as a percentage of the concrete mass. Using the same powder, the pH value of concrete was determined according to IS: 2720 (Part XXVI).

After performing a systematic nondestructive and destructive test programme, the specimens were broken to extract the rebar pieces. The surface condition of the embedded steel pieces was inspected visually for corrosion pits, if any, and they were ultimately cleaned by dipping in inhibited Clark's solution. The difference between the initial and final weight was the loss in weight and was expressed as a percentage of the original weight, to indicate the extent of corrosion.

RESULTS AND DISCUSSION

The test results regarding the properties of cement are shown in Fig. 1 and Table 5. PW as well as SW of different concentrations were used to find out the various properties. It is seen that when SW is used for making concrete, it considerably affects both the initial and final setting time. Up to a salt concentration of *t* N in the mixing water, the setting time decreases and then increases again. It is also noticed that the initial setting time is affected more in comparison to the final setting time. The reduction of setting time is due to the presence of chloride ions of some salts which accelerate the hydration process.[11] Again, Fig. 1 shows the rate of gain in strength of cement mortar made with different sea water solutions. For low concentration of SW, a higher rate of gain in strength is observed up to 7 days followed by a gradual decrease with time when compared with mortar made with PW. As the SW concentration increases, both the early and later gains in strength are seen to decrease with time. Thus, it may be concluded that SW, on mixing, affects the rate of gain in strength. The early increases in strength are basically due to blocking of the pores by products of hydration. But ultimately the strength decreases with time due to leaching out of the soft hydration product.

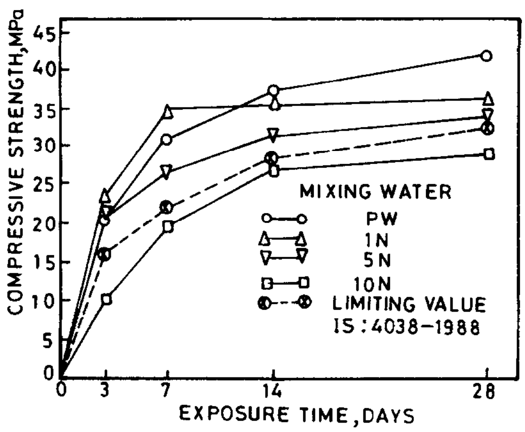

Fig. 1. Compressive strength–exposure time relation for cement mortar (cured in PW).

The compressive strength of concrete cube specimens cast and cured with PW and SW of different concentrations is plotted against exposure time in Figs 2 and 3. The strength value corresponding to '0' month exposure time, represents the 28-day strength of concrete cured in PW. Compressive strength is found to increase up to an age of 6–9 months and then decreases for both grades of concrete and curing solution although the nature of variation is not the same. For any particular curing period and curing solution, the strength of PW concrete was relatively higher than that of SW concrete. For example, for a similar curing condition in PW, the concrete A and B made with normal (1 N) sea water had 5–8% lower strength than PW concrete. Similar observations were also reported by some of the past researchers (refer to Table 1). As expected, the reduction of strength was higher for the lower strength concrete in a curing solution of higher concentration. Even after 18 months exposure in both normal and accelerated environments, the compressive strength of concrete specimens was higher than the 28-day PW cured concrete.

The amount of water soluble chloride ions

Table 5. Normal consistency and setting time of cement in different SW solutions

Mixing water	Normal consistency (%)	Setting time (min) Initial	Setting time (min) Final
PW	25	51	113
1N	28	19	60
5N	26·5	13	74
10N	26	16	78
IS limiting value	—	≮30	≯600

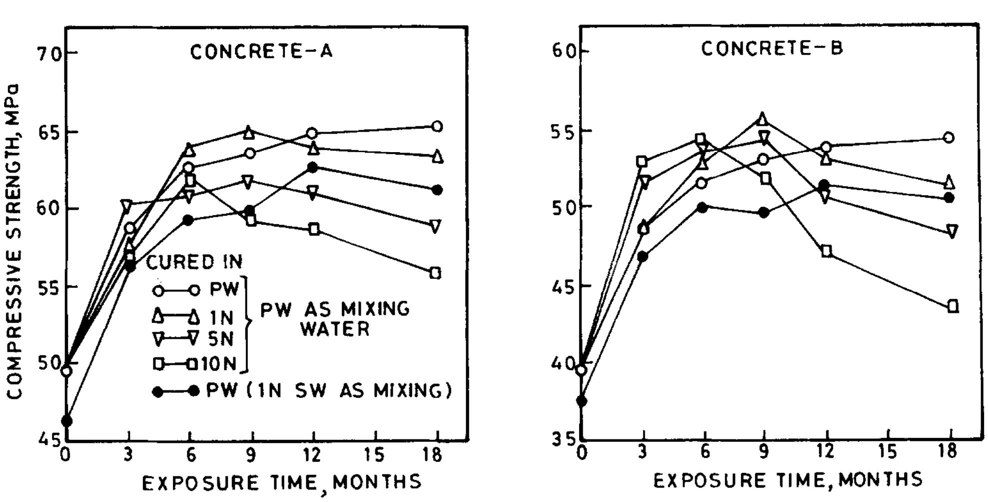

Fig. 2. Compressive strength–exposure time relation for concretes A and B (PW as mixing water).

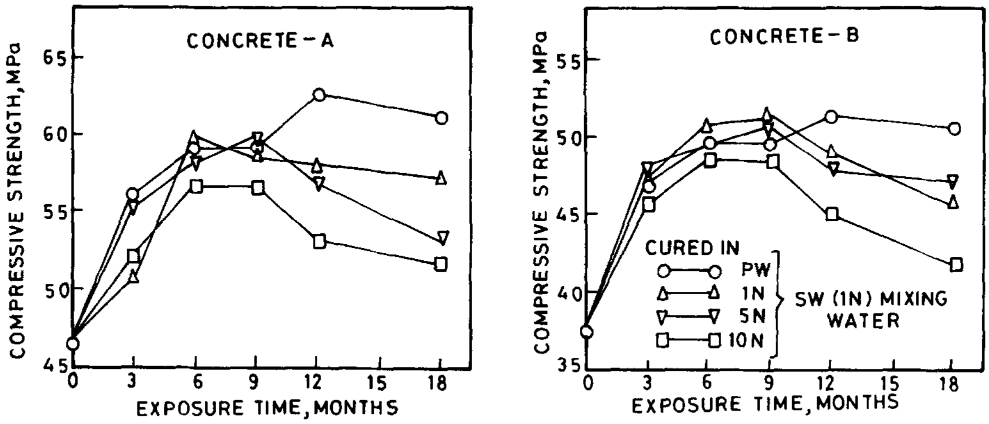

Fig. 3. Compressive strength–exposure time relation for concretes A and B (SW — 1N as mixing water).

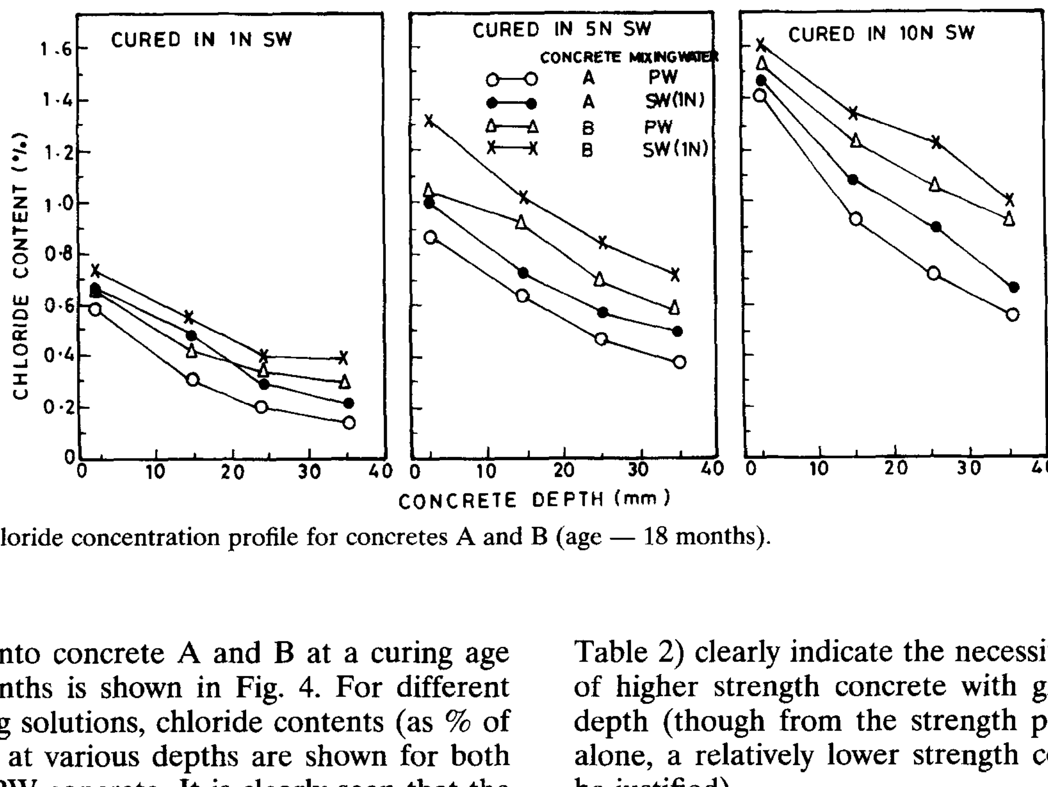

Fig. 4. Chloride concentration profile for concretes A and B (age — 18 months).

diffused into concrete A and B at a curing age of 18 months is shown in Fig. 4. For different SW curing solutions, chloride contents (as % of concrete) at various depths are shown for both SW and PW concrete. It is clearly seen that the diffusion rate mostly depends on the grade of concrete and concentraton of the surrounding curing solution. The higher the salt concentration of the curing solution, the higher is the chloride content at a particular depth, but the variation is not proportional. Also, the higher strength concrete with low permeability showed a fair resistance against chloride penetration over the relatively lower strength concrete. Again for a particular curing age and curing solution, the chloride content at any depth of concrete made with SW was higher than that of PW concrete. This is due to the initial addition of chloride during the making of SW concrete. However, the observed values when compared with the threshold chloride content (as given in Table 2) clearly indicate the necessity of the use of higher strength concrete with greater cover depth (though from the strength point of view alone, a relatively lower strength concrete may be justified).

To assess the change of alkalinity over depth, the pH value of concrete powder obtained from various depths of concrete specimens, was measured. For any grade (A or B) and type (SW or PW) of concrete and curing solution, the variation of pH values with depth was small showing slightly lower values at shallow depths.

Moreover, with an increase of salt concentration in the curing water, the pH value decreases with time but again the variation was found to be negligible. After a curing age of 18 months, the average pH value of all types of specimen at a depth of 15 mm was in the range of (12·3–11·70), which is well above the limiting value (11·5) for the initiation of corrosion by the carbonation process. Also, the test results of carbonation depth indicate a maximum carbonation depth of 0·5–1 mm at a few spots and in all cases it was limited to the concrete surface only. Hence it may be concluded that the observed corrosion of reinforcement was only due to the presence of excess chloride ions around it and not by the carbonation process.

The rebar corrosion (expressed as % weight loss) against exposure time is shown in Figs 5 and 6. Although the overall corrosion is observed to be small, the extent varies with the strength/grade of concrete, cover depth, salt concentration of the curing solution and quality of mixing water. As the salt concentration increases, the rate of rebar corrosion also increases, but the rate is not proportional. Concretes A and B made with SW showed the first appearance of corrosion, in a relatively short period in comparison with PW concrete, and the amount of corrosion was also higher in SW concrete. It is due to the presence of the higher amount of chloride ions (i.e. addition of penetrated chloride with pre-existing chloride during mixing) at the rebar level as shown in Fig. 4. Moreover, the use of sea water tends to cause dampness which can provide good electrolytic action between the anodic and cathodic regions of the embedded reinforcement, thereby accelerating the corrosion process. Thus, it is seen that SW used for mixing mortar or concrete for reinforced concrete structures exposed to air, specially in the tidal/splash zone of a marine environment, tends to make the reinforcement highly vulnerable to corrosion. Similar observations/conclusions were also reported by other researchers.[8,9,12]

CONCLUSIONS/RECOMMENDATIONS

(1) Based on this study, as well as recommendations in the existing literature, it is

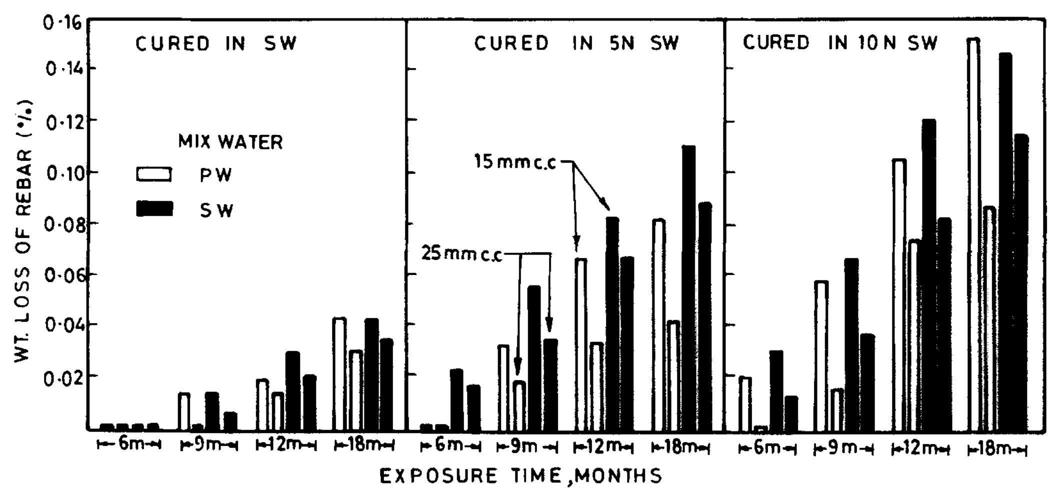

Fig. 5. Weight loss–exposure time relation for concrete A.

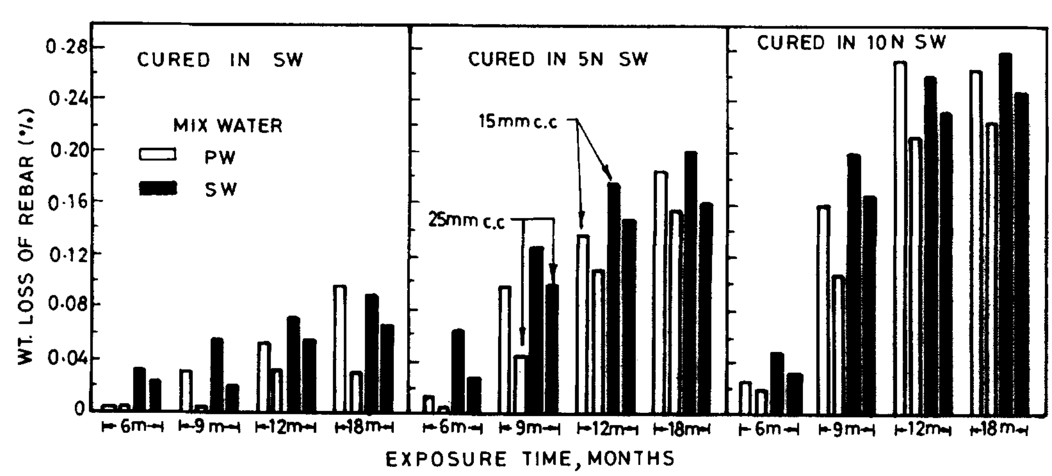

Fig. 6. Weight loss–exposure time relation for concrete B.

recommended that sea water should not be used as mixing water in plain, reinforced and pre-stressed concrete. Pre-curing in fresh water is also necessary before exposure to a sea water environment. Reduction of strength due to the use of SW for making concrete must be taken into consideration along with proper selection of ingredient materials, quality control and appropriate construction techniques while designing such structures.

(2) Based on limited exposure time and a fixed number of tests done on cement and the corresponding concrete with sea water used for mixing as well as curing media, in both normal and accelerated environment, the following conclusions are drawn:

(i) Sea water decreases the setting time of cement by 30–75% as the concentration of the mixing sea water increases from 1 N to 10 N. Therefore, the use of suitable retarding admixtures is recommended in such cases.

(ii) SW affects the gain in strength of cement when used for mixing. It increases the early strength up to 7 days but ultimately the strength decreases by about 13% at 28 days.

(iii) After 18 months exposure, concrete made with sea water shows a decrease in strength by 5–10% in comparison to similar concrete made with plain water.

(iv) Concrete made with both PW and SW, when subjected to curing in SW of different concentrations, lost compressive strength after definite periods (9–12 months) although there was an initial gain in strength. However, up to 18 months exposure, the strength of both grades of concrete was well above the 28 day strength of normally cured concrete.

(v) Both the mixing and curing of concrete with SW had an insignificant effect on the concrete alkalinity.

(vi) Relatively higher strength concrete having low permeability showed a fair resistance to chloride penetration and rebar corrosion. However, for any exposure period and curing solution, a relatively greater concentration of chloride was observed in the case of SW concretes at any particular depth.

(vii) The degree of deterioration of reinforced concrete, particularly the rebar corrosion under the action of sea water, was high when SW was used as mixing water in comparision to plain water.

Practically, no measurable carbonation depths were observed in both types and grades of concrete except in a few spots (a maximum of 0·5–1 mm) and in most cases it was limited to the surface only. Therefore, the observed rebar corrosion was due to ingress of chloride ions and not due to the carbonation process.

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