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Carbonation of Concrete Structures in Hot Dry Coastal Regions

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Abstract

This paper reports the results of a condition survey of 50 concrete buildings undertaken in the State of Kuwait. Concrete cores were extracted from walls and columns of these buildings and their density, compressive strength and depth of carbonation were evaluated. The buildings surveyed in the hot dry salty environment carbonated, on average, a little more than 1 mm per year. The coastal buildings, however, carbonated at a higher rate than the near-coastal and inland buildings. The results of this survey have furnished realistic values of a constant to predict the depth of carbonation of structures built with differing strength grades of concrete in a severe environment like Kuwait. The paper recommends that concrete structures located in hot dry coastal regions should be built with a compressive strength, at least in the range of 30–50 MPa, in order to avoid premature durability problems. © 1997 Elsevier Science Ltd.

Keywords: Hot dry environment, compressive strength, depth of carbonation, concrete structures.

INTRODUCTION

In the Arabian Gulf it is the combination of salty geology and the extreme climate which makes the environment potentially more aggressive to concrete than anywhere else in the world.[1] Extreme conditions are provided by high, fluctuating temperatures and humidity on the coast and similar temperatures, but with lower humidity, inland. This aggressiveness of the environment can cause premature degradation of the concrete structures by expansive cracking, due to sulphate attack and depassivation of the reinforcement by concomitant action of carbonation and the ingress of chloride ions. In the Gulf conditions concrete should be dense and impervious for high durability performance.[2] 'Recent studies show that concrete mixes for use in severe environments can be made essentially impermeable to air, water and chloride ions if they possess a minimum of 50 MPa compressive strength at 28 days'.[3]

Recently, a condition survey of 50 concrete buildings was undertaken in the State of Kuwait with an end objective to formulate recommendations to enhance the durability of concrete structures.[4] This paper reports on the *in situ* compressive strength and the depth of carbonation determined on the cores extracted from the walls and columns of the buildings surveyed. The role of carbonation is crucial to the performance of concrete structures in the Gulf region, first, because the evaporative drying of concrete almost completely supersedes the hydration drying, which eventually leads to a higher rate and depth of carbonation.[2] Second, carbonation appreciably aids in the release of chlorides by causing a breakdown of hydrated cement phases that had initially rendered the chloride insoluble through chemical reactions such as formation of chloroaluminate hydrate.[5]

SURVEY OF EXISTING STRUCTURES

The best protection of reinforced concrete (RC) structures against premature degradation in hot dry salty coastal regions is to use concrete mixes which are impermeable to air, water and chloride ions. Normally, the higher the strength of a properly designed concrete mix, the more impervious it is to the ingress of the damaging species. The carbonation of RC structures is an important mechanism which can lead to the depassivation of the concrete cover and the eventual corrosion of the reinforcement. Of course, in the severe coastal regions other concomitant mechanisms which lead to durability problems are also in action. Accordingly, it was decided to undertake a survey of existing RC structures with an objective to formulate guidelines for designing durable RC structures.

Fifty existing concrete buildings were included in this survey. These buildings were located 0.5–18 km from the coast. These concrete buildings are uniformly distributed all over the residential area in the State of Kuwait as shown in Fig. 1. Many of the buildings surveyed are located at a somewhat similar distance. It was necessary to have a fairly large sample size and to include the effect of differing construction practices etc. The majority of the buildings included in this survey were constructed in the period from 1984 to 1986 using Portland cement.

Concrete cores were extracted from all the buildings included in this survey. The cores extracted were tested for density, compressive strength, depth of carbonation, sulphate and chloride contents. This paper includes a discussion on the density, compressive strength and depth of carbonation of the extracted concrete.

TESTING TECHNIQUES

From each building, four cores of 100 mm diameter were taken from an exposed unpainted member. The majority of the sites considered are precast concrete buildings. Cores were extracted according to BS 1881: Part 120.[6] All cores were extracted horizontally from columns and walls. The density was measured according to BS 1881: Part 114.[7] Initial, saturated and oven-dried densities were determined. The compressive strength of concrete cores was determined according to BS 1881: Part 120. The depth of carbonation was assessed by splitting the concrete cores and spraying the split specimens uniformly with phenolphthalien indicator. The depth of carbonation was measured with a steel ruler to the nearest 1 mm. Several measurements were

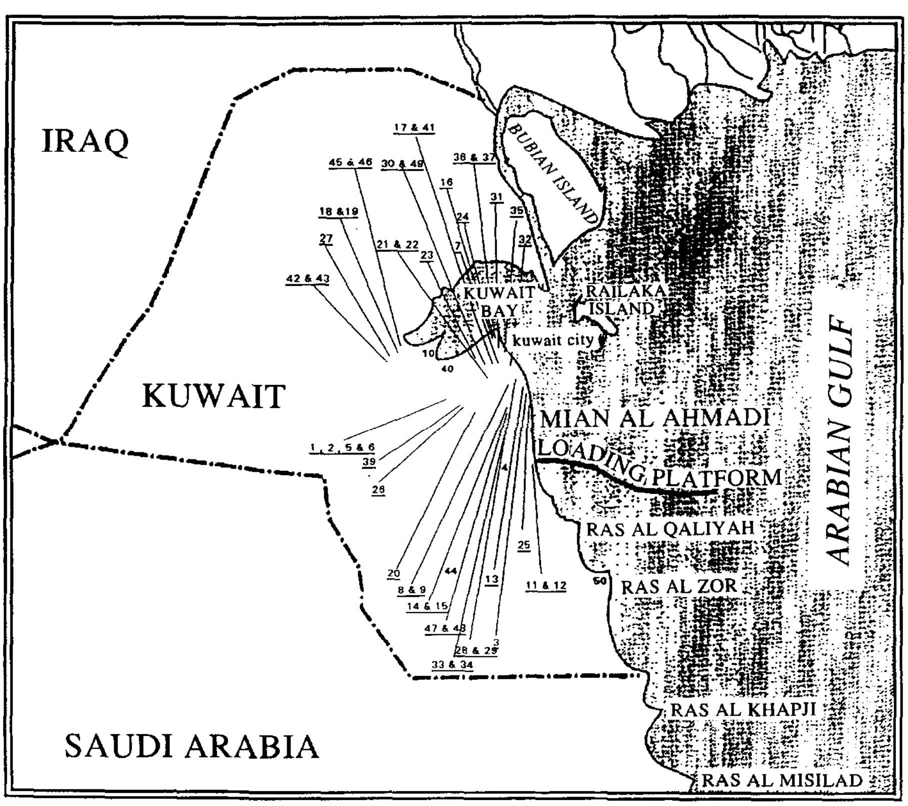

Fig. 1. Locations of sites.

taken on a given specimen. The results are included in Tables 1–4 according to the nearness of the buildings from the coast.

For ease of discussion, the following terminology has been adopted in this paper.

(1) Coastal buildings: upto 2 km from the coast
(2) Near-coastal: 3–10 km from the coast
(3) Inland: > 10 km from the coast
(4) Low strength (LS): core strength less than 20 MPa
(5) Adequate strength (AS): core strength from 20 to 30 MPa
(6) Medium strength (MS): core strength from 30 to 40 MPa
(7) High strength (HS): core strength from 40 to 50 MPa

RESULTS AND DISCUSSION

Density of concrete

The as-received density of all the concrete cored from the buildings is included in Tables 1–4. Those concretes do not seem to be well compacted where the density values are less than 2200 kg/m^3. The as-received density of the cored specimens is more than 2000 kg/m^3 except a low value of 1868 kg/m^3 (see Table 4, St. no. 46) which is suggestive of a lightweight

Table 1. Depth of carbonation and strength of cores taken from buildings (0.5–2 km from coast)

Structure no.	*Distance from coast (km)*	*Age (years)*	*Strength (MPa)*	*Carbonation depth (mm)*	*Density (kg/m^3)*	*Expected depth of carbonation in 20 years (mm)*	*Expected time to carbonate 25 mm cover (years)*
1	0.5	10	24.9	9.2	2049	13.0	74
2	0.5	8	26.2	6.4	2190	10.3	118
3	1	8	28.5	19.7	2148	31.3	13
4	2	10	24.8	12.5	2036	17.9	39
5	2	10	24.1	13.7	2047	19.2	34
6	2	8	18.1	25.0	2178	39.4	8
7	2	10	36.4	11.8	2270	16.6	46
8	2	7	42.4	7.4	2338	12.5	80
9	2	8	28.2	5.9	2242	9.4	142

Table 2. Depth of carbonation and strength of cores taken from buildings (3–5 km from coast)

Structure no.	*Distance from coast (km)*	*Age (years)*	*Strength (MPa)*	*Carbonation depth (mm)*	*Density (kg/m^3)*	*Expected depth of carbonation in 20 years (mm)*	*Expected time to carbonate 25 mm cover (years)*
10	3	5	26.1	3.6	2160	7.2	244
11	3	8	47.4	7.4	2308	11.6	92
12	3	9	28.0	11.5	2109	17.0	43
13	3	5	21.2	9.3	2180	18.9	35
14	4	8	32.9	12.9	2284	20.6	30
15	4	9	33.6	7.2	2192	10.7	106
16	4	9	24.8	9.5	2149	14.3	61
17	4	10	27.3	10.2	2143	14.3	61
18	4	9	27.2	13.7	2170	20.6	30
19	4	5	30.3	3.5	2148	7.2	244
20	4	10	28.7	12.3	2169	17.4	41
21	4	8	27.4	8.8	2254	12.5	80
22	4	6	27.7	6.4	2160	11.6	92
23	4	5	28.9	7.9	2170	15.7	51
24	5	9	45.5	7.4	2278	11.2	100
25	5	13	24.9	15.6	2173	19.2	34
26	5	8	25.8	7.4	2215	11.6	92
27	5	9	30.4	11.1	2116	16.6	46

Table 3. Depth of carbonation and strength of cores taken from buildings (6–10 km from coast)

Structure no.	*Distance from coast (km)*	*Age (years)*	*Strength (MPa)*	*Carbonation depth (mm)*	*Density (kg/m^3)*	*Expected depth of carbonation in 20 years (mm)*	*Expected time to carbonate 25 mm cover (years)*
28	6	9	28.0	8.3	2240	12.5	43
29	6	8	29.0	5.9	2031	9.4	142
30	6	8	29.6	7.5	2070	12.1	86
31	6	8	29.6	7.6	2070	12.1	86
32	6	8	29.8	8.9	2227	14.3	61
33	7	8	30.5	6.2	2100	9.8	129
34	7	7	29.8	8.9	2227	15.2	54
35	7.5	8	31.1	4.8	2155	7.6	216
36	8	10	28.2	5.4	2220	7.6	216
37	9	8	26.6	6.4	2191	10.3	118
38	9	10	17.2	5.4	2181	7.6	216
39	10	8	27.7	9.4	2253	14.8	57
40	10	5	26.4	6.9	2167	13.9	65
41	10	11	26.7	12.5	2239	17.0	43
42	10	9	26.3	11.4	2293	17.0	43

concrete. The compressive strength of this concrete is only 12.7 MPa. The average density of all the cores is 2180 kg/m^3 which is indicative of a poor quality normal weight concrete.

Compressive strength

The compressive strength of all the concrete cored is included in Tables 1–4. As given in Tables 1 and 3 <TBLR> 4 </TBLR> (see St. no. 6, 38 and 46), only 3 out 50 buildings surveyed have been built with concrete compressive strength less than 20 MPa. All these three buildings are located within 12 km from the coast and can be classified as coastal and near-coastal locations. From a climatic and exposure point of view, all these three buildings are located in a very severe regime. Now, when structures are being designed for durability, even in benign exposure conditions, no structure is allowed to be built with a concrete compressive strength of less than 20 MPa.[8] So when designing for durability, these three buildings fail to meet the specified strength. Three out of 50 represents a 6% non-compliance.

Thirty six out of 50 buildings have been built with a concrete compressive strength of between 20 and 30 MPa i.e. 72% of the buildings surveyed. Out of these 36 buildings, 30 buildings are located, according to the terminology adopted here, on the coast and near-coast. According to the situation of these buildings, 20–30 MPa compressive strength is simply 'inadequate'.[8] The coastal and near-coastal exposure conditions are very severe and no structure should be built with a concrete compressive strength of less than 30 MPa. So if designing for durability, another 60% of the buildings surveyed represents non-compliance as regards concrete compressive strength. The

Table 4. Depth of carbonation and strength of cores taken from buildings (11–20 km from coast)

Structure no.	*Distance from coast (km)*	*Age (years)*	*Strength (MPa)*	*Carbonation depth (mm)*	*Density (kg/m^3)*	*Expected depth of carbonation in 20 years (mm)*	*Expected time to carbonate 25 mm cover (years)*
43	12	5	28.5	12.4	2302	24.6	21
44	12	10	27.7	4.4	2173	6.3	319
45	12	10	23.4	4.9	2236	6.7	278
46	12	7	12.7	6.0	1868	10.3	118
47	13	8	25.9	12.3	2237	19.2	34
48	13	14	24.6	15.4	2170	18.3	37
49	18	10	32.6	8.3	2092	11.6	92
50	45	8	27.0	21.7	2177	34.4	11

remaining six buildings, built of adequate strength (20–30 MPa), can be considered to be adequate because of their distance from the coast (see Table 4 — located between 12 and 45 km from the coast). Of course, eight buildings are constructed with 30–40 MPa compressive strength (MS) and the remaining three with HS concrete. Ideally, most coastal and near-coastal structures should be built with a concrete compressive strength in the range of 30–50 MPa.[8]

Depth of carbonation

The depth of carbonation as determined on the cores extracted from the 50 buildings surveyed is included in Tables 1–4. More than two-thirds of the buildings surveyed were only 8–10 years old at the time of investigation. The depth of carbonation varies from a low of 3.5 mm in a 5-year-old building to a maximum of 25 mm in an 8-year-old building (see St. no. 19 and 6, respectively). In general, the depth of carbonation in the buildings investigated is higher than normally expected in 8–10 year old structures. Roberts[9] has reported that an average Portland cement concrete may show a depth of carbonation of 5–8 mm after 10 years and 10–15 mm after 50 years. Fookes[10] reports that in hot dry environments carbonation penetrates at about 1 mm per year depending on the concrete: it may be a little more in dry situations and significantly less in wetter situations. Of course, the carbonation is a diffusion phenomenon and the rate of penetration of CO_2 depends mainly on the concrete quality and the exposure conditions. The average depth of carbonation of all the 50 buildings included in this survey is 9.6 mm, whereas the average age of the buildings is 8.5 years. Accordingly, the buildings surveyed have, on average, carbonated a little more than a 1 mm per year. This rate is similar to that reported by Fookes[10] for hot climatic conditions and more than that reported by Roberts,[9] probably for temperate climes.

Table 5 includes the variation of average depth of carbonation of the buildings with their distance from the coast. The average compressive strength of these structures as determined from Tables 1–4 is very similar, i.e. 28, 30, 28 and 25 MPa, respectively. It can be assumed that the average quality of the concrete used in these coastal, near-coastal and inland structures is the same. With this assumption, it seems that coastal structures (0.5–2 km) carbonated the most, 12.4 mm, and then those located within 3–5 km from the coast with a carbonation depth of 9.2 mm. The structures located within 6–10 km seem to have carbonated the least, 7.7 mm. In the inland buildings 11–20 km from the coast, the depth of carbonation seems to have increased again to 9.1 mm. While the highest depth of carbonation of coastal buildings can be attributed to both high temperature and sufficiently high ambient humidity, the decrease in this value for buildings located within 3–5 and 6–10 km from the coast can be due to decreasing humidity with an increasing distance from the coast, whilst an increase in the depth of carbonation for buildings 11–20 km may be due to an increased condensation during the night, where the drop in temperature may be more due to the desert-like conditions. It is very difficult to generalize these findings, but it seems most likely that the coastal structures are subjected to higher carbonation rates, as is shown in the results included in Table 5.

Table 5. Variation of depth of carbonation with distance from the coast

Distance from coast (km)	*Average strength (MPa)*	*Average depth of carbonation (mm)*
0.5–2	28.2	12.4
3–5	29.9	9.2
6–10	27.8	7.7
12–20	25.1	9.1

As mentioned earlier, the 50 structures surveyed have been constructed using LS, AS, MS and HS concretes. The average values of the compressive strength of these four grades of concrete of 16, 27, 32 and 45 MPa, respectively, have been plotted against the corresponding average depth of carbonation of 12.1, 9.6, 8.2 and 7.4 mm in Fig. 2. The figure suggests, amongst other factors, that the depth of carbonation of concrete structures is a linear function of compressive strength of the concrete. Accordingly, the best safeguard against the depassivation of reinforcement, where rate and total depth of carbonation is expected to be high, is to use higher strength and better quality concrete. These results corroborate with the findings of Sims and Haque.[11–13]

The maximum depth of carbonation of 25 mm observed in this investigation occurred in a ground floor wall of a school building

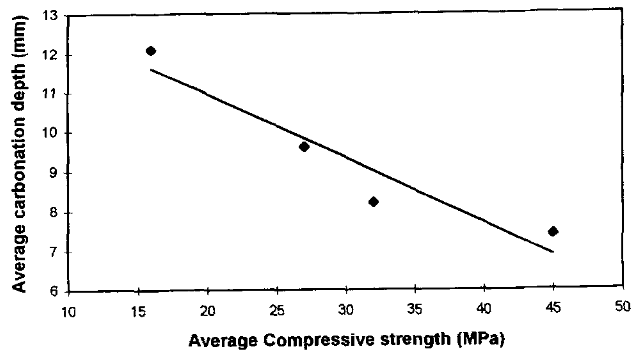

Fig. 2. Variation of carbonation depth for LS, AS, MS and HS concretes.

which was only 8-years-old (see St. no. 6, Table 1). The compressive strength of the concrete used was only 18 MPa in this coastal building. A compressive strength of 18 MPa is simply inadequate for a coastal structure which is exposed to the ingress of other aggressive salts as well.[8] In addition, there are two other buildings (see St. no. 38 and 46), where even lower compressive strength concrete of about 17 and 13 MPa have been utilized. The depth of carbonation, however, in both of these buildings is only 5.4 and 6 mm after 10 and 7 years of exposure, respectively. Although the compressive strength of 17 and 13 MPa is undesirably low, the possible reason for the much lower depth of carbonation of these buildings is their distance from the coast, of 9 and 12 km, respectively.

Predicted depth of carbonation

The depth of carbonation can be predicted by using[11] = 10BÂt, where d is the depth of carbonation in mm; t is the age of the concrete in years and B is a constant, whose value depends on both concrete strength and storage condition. These predictions are only indicative, as B would vary for different combinations of concrete quality and exposure conditions.

The buildings surveyed in this investigation were between 5 and 14 years old. It was desirable to predict the depth of carbonation of these buildings, say, at the age of 20 years. In addition, it would be interesting to know how long it would take for the buildings surveyed to carbonate 25 mm. This information can be used to predict the design life of a structure, assuming that carbonation was the only mechanism of deterioration. Accordingly, the above equation was used to determine the B values for all the 50 buildings, knowing both their age and the measured depth of carbonation at a given age. It is envisaged that the B values, thus calculated, are much more reliable as the measured carbonation depth have adequately incorporated the effect of both concrete quality and the exposure regime. Accordingly, the predictions based on these B values are likely to be more reliable.

The expected depth of carbonation after 20 years and the expected time to carbonate 25 mm cover concrete are included in Tables 1–4. According to these predictions, structures number 3, 6, 14, 18, 43 and 50 are likely to carbonate to the depth that steel depassivation may be a possibility in 20 years. It is worth noting that an adequate strength (20–30 MPa) may not be adequate in some cases, as regards depth of carbonation, because of demanding exposure conditions (see St. nos. 3, 14, 18, 43 and 50). These predictions suggest that it is safer to use a 40 MPa good quality concrete in hot dry coastal regions, so that damaging species like salts, moisture and carbon dioxide cannot penetrate the concrete easily.

As mentioned earlier, the structures surveyed were grouped in the HS, MS, AS and LS ranges. The average values of the compressive strength of the structures falling in these categories and the corresponding average of the B values calculated are included in Table 6. These B values have then been used to predict the 25

Table 6. Average values of B for structures surveyed

Concrete designation	*Strength range (MPa)*	*Average strength (MPa)*	*B*	*Carbonation depth after 25 years (mm)*	*B from Ref. 11*
HS	40–50	45.1	0.27	13.5	0.1
MS	30–40	32.2	0.28	14.0	0.2
AS	20–30	26.9	0.34	17.0	–
LS	upto 20	16.0	0.43	21.51	0.6

year carbonation depth of the structures built using high strength (HS), medium strength (MS), adequate strength (AS) and low strength (LS) concrete (see Table 6). These predicted values suggest, correctly, that the lower the concrete strength the higher the depth of carbonation. Finally, the B values which are more realistic for the hot dry coastal exposure conditions of Kuwait (or the Gulf region) are compared with those reported by Sims[11], which may be of more relevance in a temperate environment.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are based on the core compressive strength and the depth of carbonation determined on samples taken from 50 buildings from the State of Kuwait.

(1) The results suggest that to limit the depth of carbonation of concrete to an acceptable level in the severe environmental conditions prevailing in Kuwait (and maybe in the Middle East), structures should be built with a concrete compressive strength in the range of at least 30–50 MPa.

(2) The buildings surveyed had carbonated, on average, at a rate of little more than 1 mm per year. The coastal buildings (within 0.5–2 km), however, carbonated at a higher rate than the near-coastal and inland buildings. On average, the depth of carbonation of the structures was found to be proportional to the compressive strength of the concrete.

(3) The results of the survey has yielded realistic values of a constant which can be used to predict the depth of carbonation of structures built with low, medium and high strength concrete in a hot dry coastal environment.

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