ELSEVIER

Cement & Concrete Composites 26 (2004) 307–314

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

Strength and durability of lightweight concrete

M.N. Haque *, H. Al-Khaiat, O. Kayali

Department of Civil Engineering, College of Engineering and Petroleum, Kuwait University, P.O. Box 5969, Safat 13060, Kuwait

Received 16 April 2002; accepted 2 December 2002

Abstract

Two lightweight aggregate concretes, SLWC35 and SLWC50, of 35 and 50 MPa 28 day cube compressive strength were cast. The concrete specimens made with lightweight coarse aggregates and a dune sand were continuously cured in water for one or 7 days and then exposed to predominantly hot and humid seaside ambient conditions containing air-borne salts. After 7 days of initial curing and on subsequent exposure to hot and humid air both SLWCs attained an almost similar strength to those continuously water cured cubes at an age of 12 months. In contrast, the water penetrability of SLWC35 and SLWC50 after 7 days of initial curing and subsequent exposure to the sea side was about 2 and 1.8 times the water penetration of those slabs which were water cured for the entire duration of 12 months. However, the depth of carbonation of the two sand lightweight concretes up to an age of 12 months were negligibly small. The results suggest that compressive strength is comparatively less sensitive to the curing regimes investigated. Both the chloride and sulphate penetration after 12 months exposure were found to be within tolerable limits. Also replacement of lightweight fine aggregate with normal weight sand produces a concrete that is somewhat more durable as indicated by their water penetrability and depth of carbonation when concretes are of equal strength.

Keywords: Carbonation; Curing; Durability; Hot; Humid; Sand lightweight concrete; Strength development; Water penetration

1. Introduction

A unique attribute of concrete, which makes it truly versatile is that it consists of a family of materials with a large range in colour, density, strength and durability characteristics. It can be manufactured from a great number of materials, in many ways for differing applications. Structural concrete is now available with a density range between 1800–3000 kg/m^3 as lightweight, normal weight and heavy weight concrete.

Lightweight concrete (LWC) is a very versatile material for construction, which offers a range of technical, economic and environment-enhancing and—preserving advantages and is destined to become a dominant material for construction in the new millennium [1–7]. The only perceived limitation of the LWC is that it requires manufactured lightweight aggregates (LWA). Now with a range of proprietary LWA available, manufactured mainly using industrial byproducts such as flyash and blast furnace slag, LWC in the strength range of 30–80 MPa can be easily made. Previously, the authors have evaluated and reported the long term strength development and durability characteristics of LWC made with lightweight coarse and lightweight fine aggregates [1–3]. The results of the study suggested that for comparable strength normal weight concrete (NWC) and LWC, the water penetration, depth of carbonation and chloride ion built-up in the LWC was higher than that in the corresponding NWC [1–3]. Accordingly, it was decided to design comparable strength LWC using normal sand and lightweight coarse aggregates (SLWC). This paper reports the strength development and durability performance of 35 and 50 MPa SLWCs up to a period of 12 months after differing periods of initial water curing. For comparison the values of various parameters after a period of 9 months for both LWC and NWC are plotted against those of SLWC. The results indicate that the water penetrability and carbonation depth of SLWC are almost identical to those of the corresponding strength NWC and much less than those made with both fine and coarse LWA.

* Corresponding author. Tel.: +965-481-1188x5762; fax: +965-481-7524.

E-mail address: naseer@civil.kuniv.edu.kw (M.N. Haque).

0958-9465/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0958-9465(02)00141-5

2. Experimental program

Two sand-lightweight concretes (SLWC) using Lytag, imported from UK, as a coarse LWA and a dune sand, were made to evaluate their strength and durability characteristics. The cement used was normal Portland cement manufactured in Kuwait. The SLWCs were designed for a 28 day cube compressive strength of 50 and 35 MPa, hereafter referred to as SLWC50 and SLWC35, respectively. A few initial trial mixes were made for both SLWC50 and SLWC35 to obtain a slump of about 100 mm, fresh concrete density about 1800 kg/m^3 and desired compressive strength.

The 24-h water absorption capacity and bulk specific gravity on oven dried basis and bulk density of the Lytag coarse aggregate were found to be 13.6%, 1.42 and 820 kg/m^3, respectively. The dune sand used was washed, oven-dried and stored in sealed containers. The Lytag coarse aggregate, 12 mm, oven-dried and stored in sealed containers, was soaked and mixed with about 30% of the mixing water for approximately 10 min in a pan mixer. Thereafter sand, cementitious materials and the rest of the mixing water were added and mixed. The superplasticiser admixed with about 1 kg of the water was added in the final stage of mixing.

The slump, density, air content and temperature of each batch of concrete were determined. Another slump measurement was done 10 min after the first one to determine loss in slump. The average value of the various characteristics of the fresh concrete are given in Table 1. In addition, Table 1 also includes the characteristics of the comparable total LWCs, LWC50 and LWC35, and NWC NWC50 whose results have been reported previously [1–3].

All the concrete batches made were very cohesive and workable. The slump of the two sand-lightweight concretes varied between a value of 80 and 100 mm. In summary, the slump and workability of the two concretes made were very similar. The average value of the fresh concrete density of SLWC35 and SLWC50, were 1775 and 1800 kg/m^3, respectively, and are included in Table 1. The two LWCs are about 23% less in density than the NWC. The temperature of the fresh concretes was similar. There was no requirement for air-entrainment in Kuwait and the values recorded for these concretes were nominal and similar.

2.1. Specimens cast

The following specimens, for each concrete, were cast in this investigation:

(i) 100 mm cubes for compressive strength evaluation;
(ii) 100 × 100 × 500 mm beams to determine modulus of rupture;
(iii) 150 × 300 mm cylinders for indirect (splitting) tensile strength and modulus of elasticity;
(iv) 200 × 200 × 120 mm slabs to determine depth of water penetration;
(v) 150 × 150 × 750 mm beams to determine depth of carbonation, chloride and sulphate concentration.

After casting all the specimens were covered with their lids and stored in the laboratory environment maintained at 23 ± 2 °C and 45 ± 5% relative humidity (RH). The specimens were demoulded after 24 h of casting.

2.2. Initial curing and exposure regimes

The specimens were initially cured as given below:

Full curing: curing in water tank maintained at 23 ± 2 °C till the age of testing;
1 day curing: no water curing after demoulding;
3 day curing: curing in water tank for 2 days after demoulding;
7 day curing: curing in water for 6 days after demoulding.

Table 1
Mix proportions (kg/m^3) and characteristics of fresh concretes

Ingredient	Concrete				
	LWC35	SLWC35	LWC50	SLWC50	NWC50
Cement	353	280	536	480	450
CSF	35.3	28	53.6	48	45
Total water content	280	195	294	200	219
Lytag coarse	625	700	567	726	1084[a]
Lytag fine	499	–	357	–	–
Sand (washed and dried)	–	570	–	345	571
Superplasticizer	3.5	3	6.5	5.5	5
Slump (mm)	90	100	95	80	85
Bulk density (kg/m^3)	1795	1775	1815	1800	2355

[a] Normal weight crushed gravel.

In addition to the continuous water curing, specimens were placed at an exposure site near the sea at a yacht club after 1 and 7 days of initial curing (as described above) and are referred to as 1SS and 7SS exposure regimes, respectively. The specimens were exposed to the elements but not subjected to seawater splash. During May-Sept. the mean maximum temperature reached 40% or beyond. Likewise, the RH varied between 5% and 95% during the storage period.

The relevant British Standards [8,9] were used to evaluate strength and durability characteristics of the concrete. Slices were obtained from the prismatic specimens to determine sulphate and chloride contents of concretes after varying periods of exposure. These slices were broken into lumps taking care to prevent aggregate fracture. These portions were dried in an oven at 105 °C, allowed to cool and divided into sub-samples. After crushing a powder passing 150 μm fine mesh sieve was collected to determine sulphate and total chloride contents. Permeability of concrete to water was determined by DIN 1048 Part 2 [10]. This test was performed on thick plate shaped specimens of 200 × 200 × 120 mm. The existing moisture state of the plate specimens was not determined before the start of test. The test takes 4 days for completion. At first a pressure of 1 bar was applied for 24 h, then pressures of 3 and 7 bars, each for 24 h. Immediately after the test, the plate was split in the middle and the water penetration depth and its distribution were measured. The depth of carbonation on the site exposed beams was determined using phenolphthalein indicator. The strength and durability results, an average value of 3 or a minimum of two tests, are included in Tables 2–8.

Table 2
Compressive strength of SLWC (MPa) after 1 year

Curing	SLWC35		SLWC50	
	Age (days)		Age (days)	
	28	365	28	365
Full	38.0	48.0	49.5	64.5
1 SS	40.0	41.0	49.5	52.5
7 SS	42.5	47.0	57.0	62.5

Table 3
Indirect tensile strength (σ_t) and modulus of rupture (σ_r) of fully cured SLWC (MPa) after 1 year

Strength	SLWC35		SLWC50	
	Age (days)		Age (days)	
	28	365	28	365
σ_t	3.00	3.35	3.70	4.25
σ_r	4.00	4.55	4.65	5.50

Table 4
Modulus of elasticity of SLWC (MPa) after 1 year

Curing	SLWC35		SLWC50	
	Age (days)		Age (days)	
	28	365	28	365
Full	23,782	26,120	26,648	29,040
1 SS	21,991	23,030	27,058	27,190
7 SS	24,003	25,240	28,198	29,000

Table 5
Water penetrability of SLWC (mm) after 1 year

Curing	SLWC35		SLWC50	
	Age (days)		Age (days)	
	28	365	28	365
Full	40	34	26	24
1 SS	73	115	35	65
7 SS	49	72	26	43

Table 6
Carbonation of SLWC (mm) after 1 year

Curing	SLWC35		SLWC50	
	Age (days)		Age (days)	
	28	365	28	365
1 SS	1.0	1.5	0.4	1.0
7 SS	0.6	1.0	0.0	0.5

Table 7
Average sulphate content (% by weight of cement) in SLWC specimens after 1 year

Curing	SLWC35		SLWC50	
	Age (days)		Age (days)	
	28	365	28	365
1 SS	1.8	2.0	1.5	1.7
7 SS	1.5	1.6	1.4	1.5

Table 8
Average chloride content (% by weight of cement) in SLWC specimens after 1 year

Curing	SLWC35		SLWC50	
	Age (days)		Age (days)	
	28	365	28	365
1 SS	0.17	0.28	0.14	0.24
7 SS	0.11	0.16	0.11	0.15

3. Results and discussion

3.1. Strength and durability characteristics of hardened concrete

3.1.1. Strength development

Table 2 presents compressive strength for the two concretes with various curing periods. To eliminate the

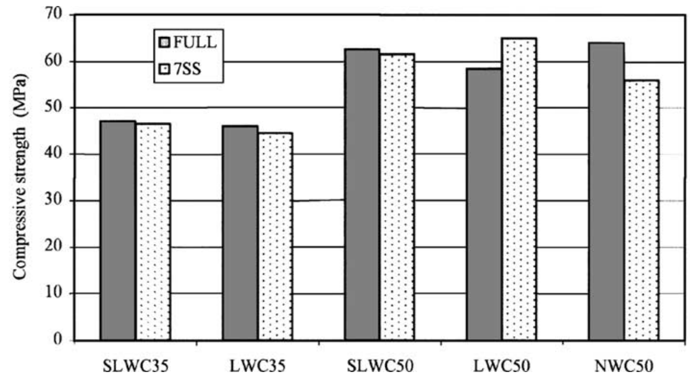

Fig. 1. Compressive strength of sand LWC, total LWC and NWC after 270 days water curing and exposure on seaside.

possible variation in strength due to surface moisture, all strength specimens were tested in saturated surface dry condition. The compressive strength of SLWC50 control specimens at 28 days was 49.5 MPa and kept on increasing and reached 64.5 MPa at 365 days with a 26% increase. SLWC35 control specimens had compressive strength of 48 MPa at 1 year. As shown in Table 2, as the period of initial curing of concrete in water increased compressive strength also increased for all testing ages. Seven days of initial water curing and subsequent exposure to uncontrolled predominantly hot-humid exposure conditions resulted in almost similar strength to those of the continuously water cured cubes at the age of 12 months.

To avoid duplication, compressive strength and the depth of water penetration results, after a period of 270 days, plotted in Figs. 1 and 2 have not been included in Tables 2 and 5, respectively. In Fig. 1, the strength development of the total LWCs, LWC35 and LWC50, as reported by Al-Khaiat and Haque [2], is compared with SLWC35 and SLWC50. As can be seen, under similar curing and exposure conditions, the total and sand LWCs strength development is nearly similar to a period of 270 days.

Indirect (splitting) tensile strength and the modulus of rupture development of the two concretes are included in Table 3. As can be seen in the table, the indirect tensile and the modulus of rupture values of the two concretes are about 1/15th and 1/11th of the corresponding value of their compressive strength, respectively. According to Bradhan-Roy [11] compared to NWC, the elastic modulus, the modulus of rupture and tensile strength are generally lower for LWA concrete of equivalent grade. Zhang and Gjorv [12] have also reported that the tensile/compressive strength ratio appears to be lower for high strength LWC than that of normal weight high strength concrete.

3.1.2. Modulus of elasticity (E)

As shown in Table 4, 1 and 7 days of initial water curing and subsequent exposure of specimens to hot-humid conditions gave very similar E values to those of the continuously water cured specimens. Also, the E value of SLWC50 is about 12% higher than that of the SLWC35. Bamforth [13] has reported an E value of 24.5 GPa at 180 days in comparison to a value of 28.7 GPa at 270 days as reported here. For LWC different researchers have proposed different relationships to estimate E value from compressive strength and unit weight [12,14,15]. However, these relationships very much depend on the type and source of LWA and whether the concrete is all lightweight or sand lightweight.

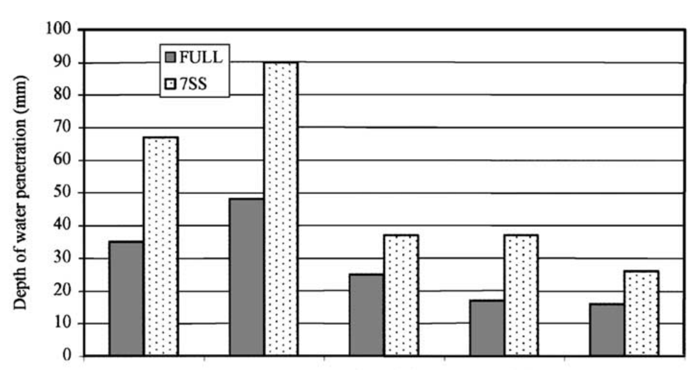

Fig. 2. Depth of water penetration of sand LWC, total LWC and NWC after 270 days water curing and exposure and seaside.

3.1.3. Water penetration

The water penetration in the two concretes tested is included in Table 5. As water penetrability of concrete is indicative of its durability [13,16], an in-depth analysis of these results is warranted.

First, in both the concretes, the greater the extent of initial water curing before exposure to the ambience the lesser is the depth of water penetration and hence the better is the quality (durability) of concrete. Proper and adequate curing seems to be more critical for water penetrability than strength. The water penetrability of SLWC35 and SLWC50 after 7 days of curing and subsequent exposure to the ambience is about 2 and 1.8 times that of the fully water cured specimens after 12 months. These results also suggest that compressive strength is less sensitive to lack of curing (see Table 2).

Second, from the viewpoint of water penetrability (and hence durability), SLWC50 is much better in comparison to SLWC35. Under practical curing conditions, the water penetrability of SLWC35 is approximately 1.7 times that of the SLWC50.

Third, the water penetrability of LWC35, LWC50 and NWC50 as reported previously [2] has been plotted in Fig. 2 for comparison with SLWC. As can be seen in Fig. 2, the 35 MPa sand lightweight concrete has lower water penetrability than the corresponding total LWC. Of course, the 50 MPa (higher strength) concretes water penetrability is comparable.

3.1.4. Depth of carbonation

The depth of carbonation of the two sand-lightweight concretes up to an age of 12 months appears to be marginal and negligible (Table 6). Like water penetration, carbonation depth for SLWC35 is higher than that of SLWC50. Osborne [17] has also reported that after 5 years of exposure most lightweight and NWCs showed very low depth of carbonation, generally below 1 mm. Mays and Barne [18] measured carbonation depth on samples taken from 16 LWA concrete structures. Results varied from 6–25 mm carbonation after 20 years. In the same exposure conditions, the carbonation depth in the LWC was equal to, or slightly greater than, adjacent NWC of similar age.

In Fig. 3, depth of carbonation of the corresponding sand LWC, total LWCs and NWC are plotted. At the age of 9 months and under identical curing and exposure conditions, the extent of carbonation of sand LWCs is almost insignificant in comparison with the corresponding total LWCs. Further, the depth of carbonation of SLWCs is lesser than and of the same order of that of the NWCs as reported earlier [2] and shown in Fig. 3.

3.1.5. Sulphate contents

Sulphate concentration in the two concretes, after 1 year's exposure, is included in Table 7. Sulphate concentration in SLWC50 is somewhat less than that in SLWC35. Likewise 7 day initial curing has improved the resistance of the two concretes to the ingress of sulphate ions. The sulphate concentration in the concretes is much lower than the 5% limit as prescribed by the concrete structures codes [19,20]. Obviously, the wind-blown and mist carried salts are the source of sulphate buildup in the specimens exposed on the seaside. The sulphate concentration in SLWCs is, comparatively, lesser than that in the total LWCs as shown in Fig. 4. Again, the extent of sulphate penetration in SLWC50 and NWC50 are comparable.

3.1.6. Chloride penetration

After 12 months of exposure the acid soluble chloride concentration in the two concretes is less than 0.4% by weight of cement (see Table 8). The chloride concentration in the two concretes, especially after 7 days of initial curing is similar. Again extent of curing has improved the resistance of the two concretes to the ingress of chloride (see Table 8). The chloride concentration in

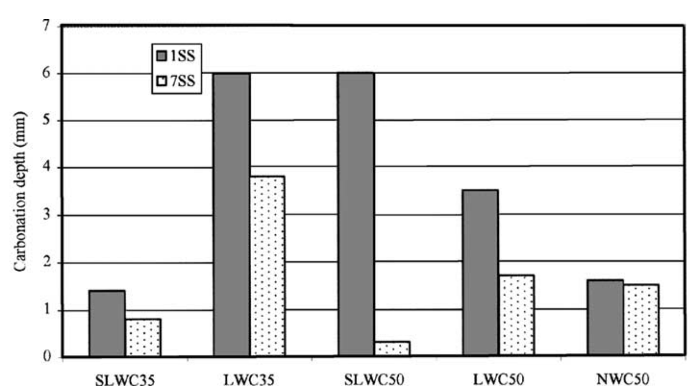

Fig. 3. Carbonation depth of sand LWC, total LWC and NWC after 270 days exposure on seaside.

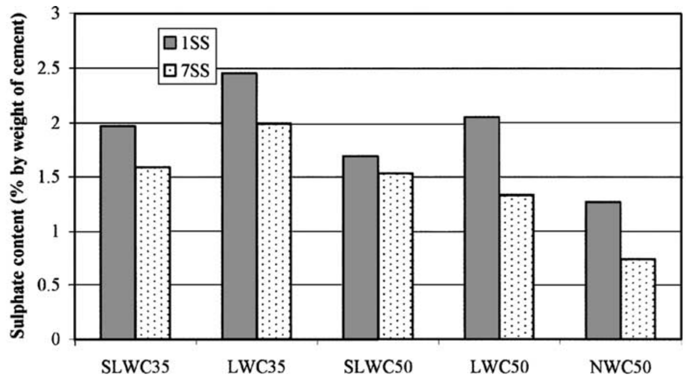

Fig. 4. Sulfate concentration in sand LWC, total LCW and NWC after 270 days exposure on seaside.

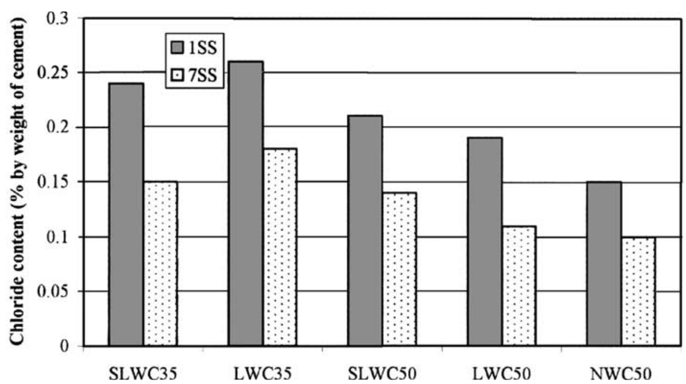

Fig. 5. Chloride concentration in sand LWC, total LWC and NWC after 270 days exposure on seaside.

sand LWCs are comparable to those reported in the corresponding total LWCs by the authors [2] and as shown in Fig. 5. Osborne [17] has observed that chloride levels in LWCs exposed to seawater were somewhat higher than those in the NWC. The salt content at the surface of the LWC has also been reported to be higher than in the NWC, although the depth of penetration was small [18].

3.1.7. Water penetrability—an indicator of durability

The depth of water penetration of total LWC, sand LWC and NWC of 50 MPa compressive strength, at different ages up to 1 year, have been plotted against the corresponding values of depth of carbonation, chloride and sulphate concentrations in Figs. 6–8, respectively. In all cases, a linear best fit was aimed for. It can be concluded from these plots that depth of water penetration

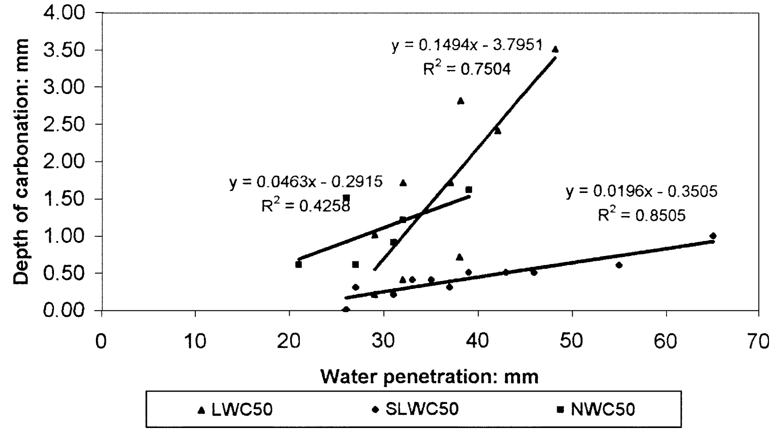

Fig. 6. Depth of carbonation versus water penetration of concretes to 1 year exposure on seaside.

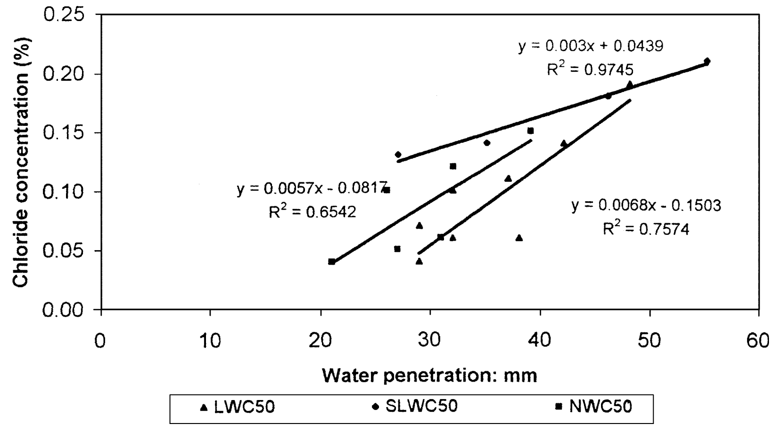

Fig. 7. Chloride concentration versus water penetration of concretes to 1 year exposure on seaside.

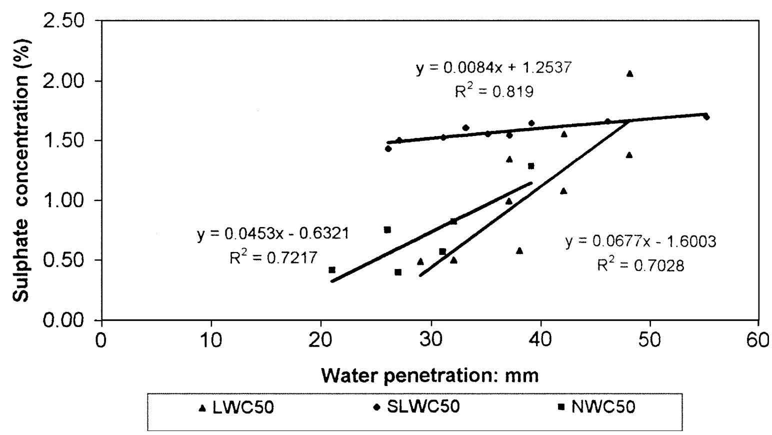

Fig. 8. Sulphate concentration versus water penetration of concretes to 1 year exposure on seaside.

of concrete, as monitored in this investigation, can be used as an approximate indicator of durability parameters like extent of carbonation and penetration of chloride and sulphate ions in concrete. Of course, the nature of these relationships very much depend on type and grade of concrete. The linear correlation seems to be better for the SLWC50 and LWC50 than for the NWC50.

4. Conclusions

1. As expected, the best strength development of the two concretes, total LWC and sand LWC, took place under water curing. However, 7 days of initial curing and subsequent exposure to the sea side ambience seems to achieve about the full potential strength.
2. At the age of 1 year, the indirect tensile strength and modulus of rupture of the SLWCs were found to be about 1/15th and 1/11th of their compressive strength; lower than those reported for NWCs.
3. The water penetrability and the extent of carbonation of sand light weight concretes have been found to be more sensitive to the extent of initial curing than their compressive strength.
4. The water penetrability and depth of carbonation of adequately cured sand LWC have been found to be less than those of the corresponding total LWCs.
5. The results suggest that the higher the water penetrability of a given concrete, the higher is the penetration of the damaging species like carbon dioxide, sulphate and chloride ions into a concrete. Further, the depth of water penetrability of a concrete can be used as an indicator of its durability.

References

[1] Al-Khaiat H, Haque MN. Effect of curing on concrete in hot exposure conditions. Mag Concr Res 1999;51(4):269–74.

[2] Al-Khaiat H, Haque MN. Strength and durability of lightweight and normal weight concrete. ASCE Mater J 1999;11(3): 231–5.

[3] Haque MN, Al-Khaiat H. Strength and durability of lightweight concrete in hot marine exposure conditions. Mater Struct 1999;32(August–September):533–8.
[4] Kayali OA, Haque MN. Status of SLWC in Australia as the new millennium dawns. Concr Aus 1999–2000;25(4):22–5.
[5] Owens PL. Structural lightweight aggregate concrete—the future? Concrete 1999;33(10):45–7.
[6] Alduaij J, Alshalah K, Haque MN, Ellaithy K. Lightweight concrete in hot coastal areas. Cement Concr Compos 1999;21: 453–8.
[7] Hughes DW, Hodgkinson L, Cullen D, Seaton H. Adjusted density concrete. Concr Eng Int 1999;3(7):54–8.
[8] British Standard Institution, Part 120—determination of core cube strength, BS 8110, BSI, London, 1996.
[9] British Standard Institution, Part 124—testing concrete. Methods for analysis of hardened concrete, BS 8110, BSI, London, 1996.
[10] German Standard, DIN 1048—test methods of concrete impermeability to water: Part 2, Deutscher Institute Fur Normung, Germany.
[11] Bradhan-Roy BK. A review of prestressed lightweight concrete in the UK. Concrete 1987;21(4):15–6.
[12] Zhang M, Gjorv OE. Permeability of high-strength lightweight concrete. ACI Mater J 1991;88(5):463–9.
[13] Bamforth PB. The properties of high strength lightweight concrete. Concrete 1987;21(4):8–9.
[14] Kayali OA, Haque MN. A new generation of structural lightweight concrete, ACI, SP-171, 1997, pp. 568–88.
[15] Al-Khaiat H, Haque MN. Effect of initial curing on early strength and physical properties of lightweight concrete. Cement Concr Res 1998;28(6):859–66.
[16] Lampacher EJ, Blight GE. Permeability and sorption properties of mature near-surface concrete. J Mater Civil Eng 1998;10(1): 21–5.
[17] Osborne GJ. The durability of lightweight aggregate concretes after 10 years in marine and acid water environments. In: Int. Symp. on Structural Lightweight Aggregate Concrete, Norway, 1995, pp. 591–603.
[18] Mays GC, Barne RA. The performance of lightweight aggregate concrete structures in service. Struct Eng 1991;69(2):351–60.
[19] American Concrete Institute, Building Code/Commentary, 318/318R, 1996.
[20] Standard Australia, AS3600—concrete structures, 2001, p. 154.