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Water permeability and chloride penetrability of high-strength lightweight aggregate concrete

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Abstract

This paper presents an experimental study on the water permeability and chloride penetrability of high-strength lightweight concrete (LWC) in comparison to that of high-strength normal-weight concrete (NWC) with or without silica fume. The results were also compared with those of the concrete at a normal-strength level of about 30–40 MPa. In order to compare the water permeability and chloride-ion penetrability, LWC and NWC had the same proportion by volume. The only difference between them was the coarse aggregate used. The results indicated that at the strength level of about 30–40 MPa, the water permeability of the LWC was lower than that of the corresponding NWC. However, the water permeability of the high-strength LWC and NWC was of the same order. The resistance of the LWC to the chloride penetration was similar to that of the corresponding NWC both in the normal-strength and high-strength levels. As the compressive strength of the LWC was lower than that of the corresponding NWC, the results indicated that for a given 28-day strength, the LWC would probably have high resistance to water and chloride-ion penetration than the NWC. The results indicated that the resistance to the chloride penetration does not seem to be correlated to the water permeability of the concrete. There appears to be, however, a direct relationship between the rapid chloride penetrability determined by ASTM C1202 and the observed chloride penetration depth determined by the immersion and salt ponding tests. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Chloride; Concrete; High strength; Lightweight aggregate; Silica fume; Water permeability

1. Introduction

Lightweight concrete (LWC) has been used for structural purposes for many years. The density of LWC typically ranges from 1400 to 2000 kg/m^3 compared with that of 2400 kg/m^3 for normal-weight concrete (NWC). The use of high-strength LWC can reduce the self-weight of structures and cross-sectional areas of structural elements. Both can increase the effective usable space for high-rise buildings and increase the span length for bridges.

Besides the strength/weight ratio, the other factor that is of significant importance for structures is the long-term durability. This is affected to a large extent by the permeability of concrete. Concrete with high permeability will provide ready access for both water and harmful substances resulting in deterioration of either concrete or steel reinforcement embedded in the concrete or a combination of both. Chloride-induced corrosion of reinforcing steel is one of the most pressing problems worldwide that the construction industry is facing today.

In any composite material, the properties of the constituents and the interactions between them determine the behaviour of the material. Concrete is a composite material with coarse and fine aggregates embedded in a cement paste matrix. As such, the aggregate and the cement paste as well as the interfacial zone between them affect the mechanical behaviour and permeability, thus durability of concrete. In concrete, it is generally not the porosity but the pore structure that is essential in establishing the permeability. In addition to that, microcracks in the matrix may contribute significantly to the permeability. Fig. 1 shows the difference between porosity and permeability schematically, and it indicates that the connectivity of the pore system is a prerequisite for permeability (i.e. an open pore system). A material can be porous and still perform tight as long as the pores are not interconnected (i.e. closed pore system).

Although lightweight aggregate (LWA) is more porous compared with normal-weight aggregate, Khokhrin [1]

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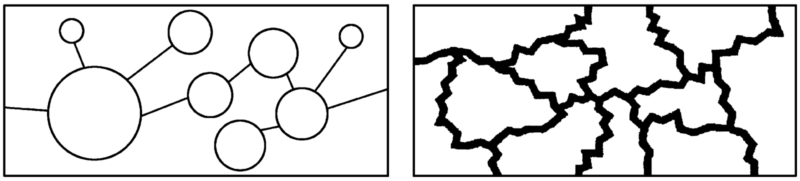
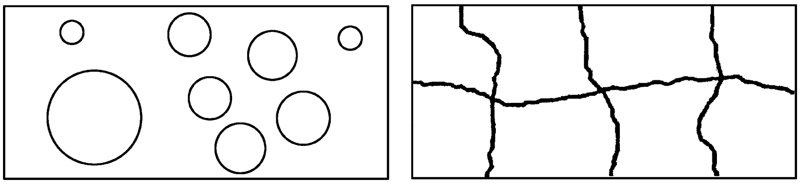


a. high porosity / low permeability b. porous / high permeability



c. porous / non-permeability d. low porosity / high permeability

Fig. 1. Schematic diagram showing differences between porosity and permeability (EuroLightCon, 1998).

found that the permeability of LWC made with porous LWA is actually lower than that of NWC. This was attributed to a combination of improved interfacial zone between the aggregate and mortar matrix and a more unified microstructure compared with NWC. However, it is not clear if LWC has similar advantage over the NWC at high-strength levels as the interfacial zone of the high-strength NWC can be improved substantially by the reduction of water/cement ratio (w/c) and by the incorporation of silica fume.

The main objective of the present work is to study the water permeability and chloride penetrability of high-strength LWC in comparison to that of high-strength NWC with or without silica fume. The results were also compared with those of the LWC and NWC at a normal-strength level of about 30–40 MPa.

2. Experimental

2.1. Materials used

2.1.1. Cement

ASTM Type I ordinary Portland cement was used for all the concrete mixtures. The chemical composition and physical properties of the cement used are given in Table 1.

2.1.2. Silica fume

The silica fume used was a dry uncompacted powder from the production of silicon metal with SiO_2 content of 93.6%. The amount retained on a 45-μm sieve was 1.8%. Detailed physical properties and chemical composition of the material are given also in Table 1.

2.1.3. Aggregates

2.1.3.1. Lightweight coarse aggregate. The LWA used in this study was expanded clay type commercially manufactured. The particle density of the dry aggregate was 1.2, and the bulk density was 650 ± 25 kg/m^3. The particle size ranged from 4 to 8 mm. The aggregate had water absorption of 5%, 7% and 9% at 1 h, 24 h and 7 days, respectively, above the as-received moisture content of 7.3%. The water absorption rate of the LWA was determined on as-received aggregates with initial moisture content of 7.3%.

The aggregate used in this project had lower particle density than those used in high-performance LWCs for some large projects such as Heidrun offshore oil platform in North Sea in the 1990s. The aggregate commonly used for the high-performance LWC then had density of approximately 1.45–1.55 g/cm^3. According to the manufacturer, it is currently not available unless there is a special request. The aggregate used for this project was recommended by the manufacturer for producing concrete with density of less than 2000 kg/m^3 when used in combination with natural sand.

2.1.3.2. Normal-weight coarse aggregate. Crushed granite with a nominal size of 10 mm was used for NWC. The grading curve of the aggregate is given in Table 2, and the specific gravity of the aggregate was 2.65.

Table 1
Physical properties and chemical composition of the cement and silica fume

		Cement	Silica fume
Physical properties	Specific surface (m^2/g)	0.35[a]	23[b]
	Specific gravity	3.15	2.0
	Amount retained on 45-μm sieve (%)	–	1.8
Chemical composition (%)	CaO	64.0	0.9
	SiO_2	21.1	93.6
	Al_2O_3	4.9	0.5
	Fe_2O_3	3.0	1.5
	SO_3	2.1	0.3
	MgO	1.6	0.6
	K_2O	0.78	0.54
	Na_2O	0.18	0.04
	LOI	2.1	2.0
	Free CaO	0.95	–

[a] Blain fineness.

[b] Determined by nitrogen absorption method.

Table 2
Grading of fine and normal weight coarse aggregates

Size (mm)	Fine aggregate (%)		Normal weight coarse aggregate (%)	
	Cum retained	Cum passing	Cum retained	Cum passing
19			0.0	100
12.5			1.2	98.8
10			2.2	97.8
6.3			82.7	17.3
4.75	2.1	97.9	92.8	7.2
2.36	12.9	87.1	97.6	2.4
1.18	27.4	72.6	100	0.0
0.60	56.6	43.4		
0.30	86.0	14.0		
0.15	94.9	5.1		
Pan	100	0.0		

2.1.3.3. Sand.

2.1.3.3. Sand. The fine aggregate used was natural sand, and its specific gravity was 2.65. The grading of the aggregate is given also in Table 2.

2.1.4. Superplasticizer

A superplasticizer based on naphthalene sulfonates and modified lignosulfonates was used in the concrete mixtures with a water/cementitious materials ratio (w/cm) of 0.35. The superplasticizer is a dark brown solution with specific gravity of 1.20.

2.2. Concrete mixtures

The mixture proportions of the concrete studied are given in Table 3. The volume proportions of each ingredient in the NWC and the corresponding LWC were the same, and the only difference between the LWC and the NWC was the coarse aggregate used. For concrete mixtures with a low w/cm of 0.35, superplasticiser was added with a dosage of 1.5 l/100 kg cement to improve workability for placement.

Series 1 shown in Table 3 consisted of normal-strength concrete with a w/c of 0.55 and 28-day compressive strength of about 30–40 MPa. Series 2 and 3 consisted of high-strength concrete with a w/cm of 0.35 and 28-day compressive strength of about 50–90 MPa. The difference between the concrete of Series 2 and 3 was the incorporation of 10% silica fume as cement replacement in Series 3.

The slump of the fresh concrete and the 28-day compressive strength of the hardened concrete are given also in Table 3. The LWC had higher slump and lower strength than the NWC of equivalent mix proportion. The higher slump was due to excess mixing water (equivalent to 1-h water absorption of the LWA) added in the concrete mixtures to account for the water absorption of the aggregate. The lower strength of the LWC was expected due to the higher porosity and lower strength of the aggregate included in the concrete.

2.3. Preparation and curing of concrete specimens

In the preparation of the LWC mixtures, one of the main concerns was how to determine the amount of water being absorbed by the LWA during mixing and placement. In our experiment, the LWA was not presoaked, but the water required for the absorption of the aggregates in 1 h was added to the concrete mixes.

Specimens were made for various tests and demolded after 24 h for concrete of Series 1 and 36 h for concrete of Series 2 and 3. The longer time needed for the latter was due to the retarding effect of the superplasticiser. Despite the higher slump observed compared with the NWC, there was no segregation for the LWC.

All the specimens were cured in an outdoor water tank (approximately 25–27 °C) for 28 days. The high-strength concrete specimens were transferred to a fog room (~ 30 °C) and cured for another 42 days prior to testing. The shorter curing time for the normal-strength concrete was due to the time limitation for the project.

2.4. Testing

Except for the specimen subjected to the rapid chloride penetrability test (ASTM C1202), all the other specimens were taken out from the water bath or from the fog room and tested without any preconditioning. These specimens were assumed to be water saturated.

2.4.1. Water permeability test

Two tapered cylinders with a height of 180 mm and a diameter of 100 mm at one end and 110 mm at other end were used for determining the water permeability of each

Table 3
Mix proportions of concrete

Series	Mix no.	Type of coarse aggregate	Cement (kg/m^3)	Silica fume (kg/m^3)	W/(C + SF) (effective)	Mix proportion W/(C + SF)/FA/CA	Density of concrete (1 day; kg/m^3)	Slump (mm)	Compressive strength (28 day; MPa)
1	1	NWA	400	0	0.55	0.55:1:1.68:2.51	2248	60	42.8
	2	LWA	400	0	0.55	0.55:1:1.68:1.14	1768	160	34.2
2	3	NWA	470	0	0.35	0.35:1:1.52:2.27	2312	20	78.2
	4	LWA	470	0	0.35	0.35:1:1.52:1.03	1834	180	50.2
3	5	NWA	421	47	0.35	0.35:1:1.52:2.27	2294	30	92.3
	6	LWA	421	47	0.35	0.35:1:1.52:1.03	1836	180	55.8

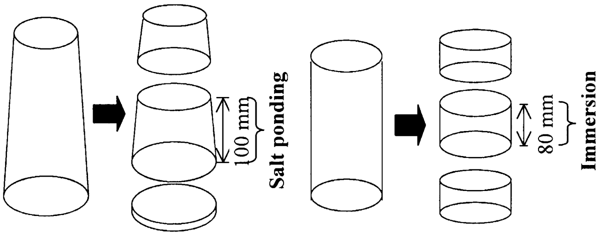


Fig. 2. Specimens for the salt ponding and immersion tests.

concrete mixture. The specimens had 3 mm removed from the top casting surfaces of the cylinders by grinding to minimise the difference associated with cast or trowelled surface. The specimen was fixed into the permeability test rig, and the side of each specimen was sealed with a moisture-insensitive epoxy to prevent water leakage. All the specimens were subjected to a water pressure of 4 MPa. At the end of the test, each specimen was removed from the rig and split into two halves lengthwise for determining the water penetration depth. Average depth was taken from five equidistant spots along each face of the split specimen.

2.4.2. Immersion test

Four specimens of 100 mm in diameter and 80 mm in thickness taken from the middle of concrete cylinders (Fig. 2) were used to determine the ingress of chloride for each concrete mixture. The specimens were immersed in a solution containing 31.0 g/l (0.53 M) of sodium chloride, with an average chloride concentration of 18,940 ppm. The solution was changed on a regular basis to maintain a constant chloride concentration. After 15, 30, 60 and 90 days, the specimen was split parallel to the top and bottom surfaces and sprayed with a 0.1-N silver nitrate solution to determine the chloride penetration depth of the side-casting surface of the cylinder. The formation of silver chloride manifested as white precipitate would occur at places where the concentration of the free chloride ions was above 0.15% by weight of cement [2]. The average depth of penetration was determined by measuring at five equidistant spots along the circumference of each face of the split specimen.

2.4.3. Salt ponding test

Three specimens of 100 mm thick, with a diameter of about 100 and 105 mm at each end obtained from the bottom half of a 200-mm tapered cylinder (Fig. 2), were used for the salt ponding test for each concrete. The side of each specimen was coated with moisture-insensitive epoxy and left to dry before being encased into a PVC pipe, leaving a 25-mm gap between the test surface and the top of the pipe. Silicon gel was used to seal off along the edge of the test surface to prevent leakage of salt solution. The top of the PVC pipe was covered with a piece of clear Plexiglass with a center hole for the change of the salt solution. A salt solution of the same concentration as that used for the immersion test was filled up to a height of about 20 mm on the concrete test surface. Fig. 3 shows the setup of the salt ponding test.

At prescribed ages, each specimen was split and examined for the chloride penetration depth. The normal-strength concrete specimens were examined at 15, 30 and 60 days, and the high-strength concrete specimens were examined at 30, 60 and 90 days. Method of examination was the same as that used for the immersion test.

2.4.4. Rapid chloride penetrability test

The test was conducted in accordance with ASTM C1202. This test measures the ease with which concrete allows the charge to pass through and gives an indication of

Fig. 3. Salt ponding test setup showing concrete specimens encased in PVC pipes.

Table 4
Water penetration depths

Series	Mix no.	Coarse aggregate type	W/(C + SF) (effective)	Silica fume (%)	Water penetration depth (mm)	Duration under pressure (days)	Age of concrete at each test
1	1	NWA	0.55	0	54, 63	12	28
	2	LWA	0.55	0	20, 19	12	28
2	3	NWA	0.35	0	23, 21	49	70
	4	LWA	0.35	0	16, 21	49	70
3	5	NWA	0.35	10	7, 8	56	70
	6	LWA	0.35	10	11, 8	56	70

the concrete resistance to chloride-ion penetration. Three specimens of 100 mm in diameter and 50 mm in thickness conditioned according to the standard were subjected to 60-V potential for 6 h. The total charge that passed through the concrete specimens was determined and used to evaluate the chloride penetrability of each concrete mixture.

3. Results and discussion

3.1. Water permeability

The water permeability of concrete are given in Table 4, and the results indicated that at the strength level of about 30–40 MPa the permeability of the LWC (Mix 2) was lower than that of the NWC (Mix 1). This is consistent with that reported by other researchers [1,3–5]. The penetration depth recorded for the concrete Mix 2 was about one-third of that for the concrete Mix 1 after 12 days under the water pressure of 4 MPa. The lower permeability of the LWC was probably due to a denser interfacial zone between the aggregate and the mortar matrix compared with that of the NWC. The frequency of microcracking in the former was probably also lower due to less difference in the modulus of elasticity between the aggregate and the mortar matrix compared with that in the latter [6].

The penetration depth for both the high-strength NWC (Mix 3) and high-strength LWC (Mix 4) was similar. Although the curing time and the test duration for concrete with w/cm of 0.35 (Mixes 3 and 4) was longer compared with that for concrete with w/c of 0.55 (Mixes 1 and 2), the water penetration depth of the two LWCs was similar, but that of the NWC Mix 3 was much lower than that of Mix 1. This indicated a significant improvement in the permeability of the NWC from the strength level of about 40–80 MPa due to reduced w/cm from 0.55 to 0.35, which contributed to an improvement in the mortar matrix and the interfacial zone between the aggregate and the matrix. Furthermore, microcracking might have been reduced in high-strength NWC by the reduction of elastic mismatch between the aggregate and the mortar matrix.

The incorporation of 10% silica fume as cement replacement reduced the water permeability of the concrete further compared with that of the control concrete with equivalent w/cm. Mixes 5 and 6 had the water penetration depths that were less than half of those for Mixes 3 and 4 even though the testing period of the former was longer than the latter. This indicated that using silica fume further refined the pore structure. The water permeability, however, was similar for the LWC and NWC of equivalent mix proportion.

From the above results, it appears that the quality of the mortar matrix is the most important parameter that controls the permeability of the high-strength concrete regardless of the coarse aggregate used.

As the compressive strength of the NWC Mixes 3 and 5 was higher than that of the corresponding LWC Mixes 4 and 6, respectively, the above results indicated that for a given 28-day strength, the water permeability of the high-strength LWC would probably be lower than that of the high-strength NWC.

3.2. Resistance to chloride-ion penetration

3.2.1. Immersion test

The main transport mechanism in this test was diffusion of chloride ions into the concrete due to a concentration

Table 5
Chloride penetration depth determined by the immersion test

Series	Mix no.	Coarse aggregate type	W/(C + SF) (effective)	Silica fume (%)	Chloride penetration depth (mm)			
					15 days	30 days	60 days	90 days
1	1	NWA	0.55	0	8.0	16.0	–	29.0
	2	LWA	0.55	0	6.0	14.0	–	27.0
2	3	NWA	0.35	0	5.0	6.0	8.0	9.5
	4	LWA	0.35	0	6.0	7.5	11.0	11.5
3	5	NWA	0.35	10	2.5	4.0	4.5	4.5
	6	LWA	0.35	10	3.0	3.5	5.0	5.0

Table 6
Chloride penetration depth determined by the salt ponding test

Series	Mix no.	Coarse aggregate type	W/(C + SF) (effective)	Silica fume (%)	Chloride penetration depth (mm)			
					15 days	30 days	60 days	90 days
1	1	NWA	0.55	0	9.0	13.0	20.0	–
	2	LWA	0.55	0	8.5	13.0	20.0	–
2	3	NWA	0.35	0	–	6.0	10.5	11.0
	4	LWA	0.35	0	–	7.5	10.0	12.0
3	5	NWA	0.35	10	–	4.0	4.0	5.0
	6	LWA	0.35	10	–	8.5	7.5	5.0

gradient. The type of penetrated surface was circumferential cast surface. Average mortar cover at the cast surface edge was about 2–3 mm thick. The mortar cover is defined as the zone where there is no coarse aggregate particle. Thus, the effect of the interfacial zone is zero.

From the results shown in Table 5, there was a progressive reduction in the chloride penetration from normal-strength concrete (Series 1) to high-strength concrete without silica fume (Series 2) and to high-strength concrete with silica fume (Series 3). However, the chloride penetration depth of the LWC was similar to that of the corresponding NWC in each of these series.

During the examination of the split LWC specimens, it was observed that the white silver chloride deposit did not form on the interior of the split LWA particles. This indicated that there was less than 0.15% of free chloride in the interior of the LWA particles. Thus, it is suspected that most chloride ions did not penetrate into the LWAs. This could be attributed to a denser outer layer of the LWA used [7] and a high-quality interfacial zone between the LWA and the mortar matrix [8].

3.2.2. Salt ponding test

Similar to the results from the immersion test, the NWC and LWC in each series appeared to have similar resistance to the chloride penetration (Table 6). While the data in Series 1 and 2 showed similar resistance for the LWC and NWC at each of the test period, the LWC Mix 6 in Series 3 showed poorer performance at 30- and 60-day tests compared with that of the corresponding NWC. However, the result at 90 days for the LWC was similar to that of the NWC. This might be due to higher localized porosity for the LWC specimens used for the 30- and 60-day tests.

3.2.3. Rapid chloride penetrability test

Table 7 summarizes the rapid chloride penetrability data of the concrete. The results appear to be consistent with those obtained by the immersion and salt ponding tests. The electric charge passed through the LWC was in the same order as those through the corresponding NWC. The resistance of concrete to chloride penetration was increased with the reduction of w/cm and with the incorporation of silica fume.

The above results indicated that for the concrete at the strength level of about 30–40 MPa and with a w/c of 0.55, the lower water permeability of the LWC compared with that of the NWC did not correlate to the chloride penetrability of the concrete. This suggests that the water permeability data may not be used to predict the concrete resistance to the chloride-ion penetration and vice versa. The discrepancy may be related to the different transport mechanisms involved in the water permeability test and the chloride penetration tests.

There appears to be, however, a direct relationship between the rapid chloride penetrability determined by ASTM C1202 and the observed chloride penetration depth determined by the immersion and salt ponding tests.

4. Summary and conclusions

In order to compare the water permeability and chloride-ion penetrability, LWC and NWC in each series had the

Table 7
Rapid chloride penetrability

Series	Mix no.	Coarse aggregate type	W/(C + SF) (effective)	Silica fume (%)	Charge passed (coulombs)			Chloride [a] penetrability
					Data	Average	Standard deviation	
1	1	NWA	0.55	0	4264, 5991, 6110	5445	1033	High
	2	LWA	0.55	0	5052, 5559, 4679	5095	444	High
2	3	NWA	0.35	0	2343, 2156, 2370	2290	117	Moderate
	4	LWA	0.35	0	3079, 3336, 2115	2843	644	Moderate
3	5	NWA	0.35	10	382, 465, 415	421	42	Very low
	6	LWA	0.35	10	340, 315, 294	316	23	Very low

[a] According to ASTM C1202.

same proportion by volume. The only difference between them was the coarse aggregate used. Based on the results, the following conclusions may be drawn:

1. At the strength level of about 30–40 MPa, the water permeability of the LWC with a w/c of 0.55 was lower than that of the corresponding NWC when the concrete was subject to a pressure of 4 MPa.

2. The water permeability of the high-strength LWC and NWC with a w/cm of 0.35 was of the same order regardless whether silica fume was incorporated. The 28-day compressive strength of the high-strength LWC was about 50–55 MPa, whereas that of the high-strength NWC was about 80–90 MPa. From the results, it appears that the quality of the mortar matrix is the most important parameter that controls the permeability of the high-strength concrete regardless of the coarse aggregate used.

3. There was a progressive increase in the resistance to chloride-ion penetration from the normal-strength concrete (Series 1) to the high-strength concrete without silica fume (Series 2) and to the high-strength concrete with silica fume (Series 3). However, the resistance of the LWC to the chloride penetration was similar to that of the corresponding NWC in each of these series.

4. As the compressive strength of the LWC was lower than that of the corresponding NWC, the results indicated that for a given 28-day strength, the LWC would probably have high resistance to water and chloride-ion penetration than the NWC.

5. The results indicated that the resistance to the chloride penetration does not seem to be correlated to the water permeability of the concrete. There appears to be, however, a direct relationship between the rapid chloride penetrability determined by ASTM C1202 and the observed chloride penetration depth determined by the immersion and salt ponding tests.

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