Cement & Concrete Composites 32 (2010) 757–766

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Development of lightweight concrete with high resistance to water and chloride-ion penetration

Xuemei Liu *, Kok Seng Chia, Min-Hong Zhang

Department of Civil Engineering, National University of Singapore, Singapore 117576, Singapore

ARTICLE INFO

Article history:
Received 4 September 2009
Received in revised form 2 August 2010
Accepted 10 August 2010
Available online 16 August 2010

Keywords:
Chloride-ion
Concrete
Internal curing
Lightweight aggregate
Permeability
Porosity
Sorptivity

ABSTRACT

This paper presents an experimental study to evaluate the influence of coarse lightweight aggregate (LWA), fine LWA and the quality of the paste matrix on water absorption and permeability, and resistance to chloride-ion penetration in concrete. The results indicate that incorporation of pre-soaked coarse LWA in concrete increases water sorptivity and permeability slightly compared to normal weight concrete (NWC) of similar water-to-cementitious materials ratio (*w*/*cm*). Furthermore, resistance of the sand-lightweight concrete (LWC) to water permeability and chloride-ion penetration decreases with an increase in porosity of the coarse LWA. The use of fine LWA including a crushed fraction <1.18 mm reduced resistance of the all-LWC to water and chloride-ion penetration compared with the sand-LWC which has the same coarse LWA. Overall, the quality of the paste matrix was dominant in controlling the transport properties of the concrete, regardless of porosity of the aggregates used. With low *w*/*cm* and silica fume, low unit weight LWC (~1300 kg/m^3) was produced with a higher resistance to water and chloride-ion penetration compared with NWC and LWC of higher unit weights.

1. Introduction

Lightweight concrete (LWC) has been successfully used in a wide range of constructions for many years from conventional structures such as long-span bridges, high-rise buildings, and buildings where soil conditions are poor, to highly specialized structures such as floating structures and offshore platforms. In some LWC, only coarse lightweight aggregate (LWA) are used (known as 'sand-LWC'), whereas in others, both coarse and fine LWA are used (known as 'all-LWC').

Most LWC used for long-span bridges and floating structures built in the last 30 years incorporated only coarse LWA. For example, the LWC used for the Heidrun tension leg platform in the North Sea and the Nordhordland floating bridge in Norway [1] used natural sand and coarse LWA with a concrete density of more than 1800 kg/m^3. For structures with design requirements of much lower unit weight, both coarse and fine LWA may be used to further reduce the self weight of structures. When such a structure is exposed to aggressive environments such as floating structures in marine environments, long-term durability of the structure is to a large extent controlled by water permeability and resistance to chloride-ion penetration of the concrete.

Lightweight aggregates are generally more porous than hydrated cement paste matrices. Porosity is the ratio of the volume of voids to the total volume of material. Permeability is a measure of the ease with which fluids will flow through a porous media. Although a concrete may be highly porous, if the pores are not interconnected, then fluids cannot move into the closed, isolated pores. For sand-LWC with only coarse LWA, harmful substances may not be able to penetrate into the concrete easily if the porous aggregate particles are evenly distributed and embedded in a dense mortar matrix (assuming natural sand particles have negligible porosity). However, when porous fine LWA are added in concrete in addition to the coarse LWA, the total porosity of the all-LWC will be increased and the probability for increased pore connectivity in the concrete will be higher compared with the sand-LWC. Hence, harmful substances may penetrate into the all-LWC more easily than the sand-LWC, assuming everything else is equal.

Therefore, this paper presents an experimental study to evaluate the effects of coarse and fine LWA in LWC (water/cementitious materials ratio (*w*/*cm*) = 0.38) on water absorption, water permeability, and resistance to chloride-ion penetration. Furthermore, to determine a dominant factor from between porosity of embedded LWA versus porosity of surrounding paste matrix, LWCs with different *w*/*cm* and aggregates but similar unit weight and compressive strength were evaluated for their transport properties.

---

* Corresponding author. Tel.: +65 6516 6347; fax: +65 6779 1635.
E-mail address: xmdripdrop@gmail.com (X. Liu).

0958-9465/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2010.08.005

Table 1
Characteristics of aggregates used.

Aggregate type	Particle size, mm	Dry particle density, kg/m^3	1 hr water absorption, % mass	24 hr water absorption, % mass	1 hr water absorption, % vol.	24 hr water absorption, % vol.	Porosity, %, vol.			Shape and surface texture
							Open	Closed	Total	
Granite	4.75–9.50	2610	–	–	–	–	–	–	–	Irregular
Natural sand	<4.75	2560	0.6	–	–	–	–	–	–	Irregular
Expanded clay F6.5	4.75–9.50	1200	8.4	13.0	10.1	15.6	25.8	31.4	57.2	Spherical
Expanded clay F6.5	2.36–4.75	1300	8.7	11.6	11.3	15.1	28.1	23.8	51.9	Spherical
Expanded clay F4.5	1.18–2.36	1050	10.8	12.8	11.3	13.4	36.6	19.2	55.8	Spherical
Expanded clay F4.5	4.75–9.50	780	12.4	26.0	9.7	20.3	29.8	41.1	70.9	Spherical
Expanded clay crushed	<1.18	1600	25–30	25–30	40–48	40–48	~40	~3	~43	Irregular
Expanded Glass	2.36–4.75	350	12.0	46.0	4.2	16.1	30.2	55.5	85.7	Spherical and smooth
Expanded Glass	1.18–2.36	420	6.0	52.0	2.5	21.8	36.4	46.4	82.8	Spherical and smooth
Expanded Glass	<1.18	560	~3	~28	~2	~16	~42	~35	~77	Spherical and smooth

2. Experimental details

2.1. Materials

ASTM Type I Portland cement was used in all the concretes. A naphthalene-based superplasticizer[1] was used in all the concretes with a design water-to-cementitious materials ratio by mass (*w*/*cm*) of 0.38, and a polycarboxylate-based superplasticizer[2] was used in LWC with a *w*/*cm* of 0.20 for workability purpose. Uncompacted silica fume was used in LWC with *w*/*cm* = 0.20 to obtain a denser paste matrix. The naphthalene-based superplasticizer was a dark brown solution with a specific gravity of 1.2 and a solids content of about 40%. The polycarboxylate-based superplasticizer had a specific gravity of 1.1 and a solids content of about 36%. Both superplasticizers conform to the requirements of ASTM C494 [2] – Type F high range water-reducing admixtures.

All the aggregates were separated into four size fractions of <1.18 mm, 1.18–2.36 mm, 2.36–4.75 mm, and 4.75–9.5 mm, and then recombined to satisfy ASTM C 33-03 [3] and ASTM C 330-05 [4] grading requirements respectively. Characteristics of aggregates used in this study are summarized in Table 1. Granite aggregate (size 4.75–9.5 mm) and natural sand (size < 4.75 mm) had densities of 2610 and 2560 kg/m^3, respectively. Water absorption capacity of the natural sand was 0.6%. Lightweight aggregates consisted of spherical expanded clay[3] (F6.5, F4.5, sizes 1.18–9.5 mm), crushed expanded clay[4] (size < 1.18 mm) and spherical expanded glass[5] (size < 4.75 mm).

From Table 1, the F6.5 and F4.5 aggregates had 1-h and 24-h water absorptions from about 8–12% and 12–26% by oven-dry mass. The crushed LWA had similar 1-h and 24-h absorptions estimated to be 25–30%. Due to high fineness and high volume of exposed open pores, the crushed LWA was likely to be water saturated at 1 h, as the absorption at 1-h was similar to the 24-h absorption. With its high fineness, it was difficult to accurately determine the water absorption of the crushed LWA.

The expanded glass is produced from recycled glass and was used in some of the concretes to achieve further reductions in unit weight. The low density was due to a highly porous internal structure. The 1-h and 24-h water absorptions ranged from about 3–12% and 28–56%, respectively. In addition, the expanded glass had a greater increase in the water absorption from 1 to 24 h compared with the spherical expanded clay (F6.5, F4.5). The absorption value for the expanded glass <1.18 mm given in Table 1 is an approximation due to difficulty in obtaining accurate water absorption for very fine particles.

Total porosity of the LWA particles presented in Table 1 was calculated based on their density and the density of the solid material as follows:

$$f_a = 1 - \frac{\rho_b}{\rho_s} \qquad (1)$$

where f_a = total porosity of aggregate (by volume), ρ_s = density of solid material (kg/m^3), and ρ_b = density of aggregate particles (kg/m^3). The density (ρ_s) of the solid material was determined by helium pycnometry using a crushed LWA sample passing through a 150 μm sieve. The density of the aggregate (ρ_b) was determined according to ASTM C 128-04a [5]. The pores filled by water under vacuum conditions were considered as open pores. The difference between the total and open pores was considered as closed pores.

2.2. Concrete mixtures

Seven concretes were included in the study and their mixture proportions are given in Table 2. The volumes of coarse and fine aggregates were kept the same in all the concretes. All the concretes were designed to have a *w*/*cm* of 0.38 except for LW5 which had a *w*/*cm* of 0.20.

In series I, effects of coarse aggregates on water absorption, water permeability, and resistance to chloride-ion penetration of concrete were evaluated. The concretes contained the same type of natural sand, but different types of coarse aggregates. Mixture NC1 is a control normal weight concrete (NWC) with granite as coarse aggregate. Lightweight concretes LC1 and LW1 contained coarse LWA with particle densities of 1200 and 780 kg/m^3, respectively.

In series II, effect of fine aggregate was evaluated. The LWC had the same type and amount of coarse LWA (F6.5), but different fine aggregate types. Mixture LC1 contained natural sand while LC4 contained fine LWA, of which a portion <1.18 mm was crushed LWA. Due to uncertainty in the water absorption for such fine aggregate, two mixtures LC4-25 and LC4-30 were prepared which covered the estimated range of water absorption from 25–30%. Besides these mixtures, a series of other mixtures were also prepared with the same design *w*/*cm* in another study [6]. The LC4-25 contained 2.1 L/m^3 superplasticizer and had a slump of 80 mm, while the LC4-30 with no superplasticizer had a similar slump of 85 mm. The other mixtures with the same design *w*/*cm* and using 2.3–2.7 L/m^3 superplasticizer had slumps of 70–125 mm. In addition, by comparing the sorptivity, water permeability, and resistance to chloride-ion penetration of LC4-25 and LC4-30 with other concretes in that study [6], it appears that the water absorption

---

[1] Super 20, W.R. Grace Pte. Ltd. Singapore – This may not be the only product which can be used for such purpose.

[2] Adva 181, W.R. Grace Pte. Ltd. Singapore – This may not be the only product which can be used for such purpose.

[3] Liapor (F6.5, F4.5), Liapor GmbH & Co. KG. Germany – This may not be the only product which can be used for such purpose.

[4] Liapor (K-sand), Liapor GmbH & Co. KG. Germany – This may not be the only product which can be used for such purpose.

[5] Liaver, Liaver GmbH & Co. KG. Germany – This may not be the only product which can be used for such purpose.

Table 2
Mixture proportions of concretes.

Series	Concrete ID	Design *w/cm*	Cementitious materials, kg/m^3		Mixing water[A], kg/m^3	Abs. water[B], kg/m^3	NWA (SSD), kg/m^3				Dry LWA, kg/m^3				SP[C], l/m^3
			Cement	Silica fume			0–1.18 mm	1.18–2.36 mm	2.36–4.75 mm	4.75–9.5 mm	0–1.18 mm	1.18–2.36 mm	2.36–4.75 mm	4.75–9.5 mm	
I	NC1	0.38	500	–	188	–	517	172	76	850	–	–	–	–	2.5
	LC1	0.38	500	–	190	51	517	172	76	–	–	–	–	395[b]	2.7
	LW1	0.38	500		188	66	517	172	76	–	–	–	–	255[a]	1.8
II	LC1	0.38	500	–	190	51	517	172	76	–	–	–	–	395[b]	2.7
	LC4-25[E]	0.38	500	–	190	147	–	–	–	–	321[d]	83[a]	40[b]	395[b]	2.1
	LC4-30[F]	0.38	500	–	190	163	–	–	–	–	321[d]	83[a]	40[b]	395[b]	–
III	LW4	0.38	500	–	190	70	–	–	–	–	112[c]	83[a]	40[b]	395[b]	3.6
	LW5	0.20	594	66	134	73	–	–	–	–	112[c]	28[c]	10[c]	255[a]	7.2[D]
Vol. proportion of paste & aggregate			37.5%[G]			–	20.2%	6.7%	3.0%	32.6%	20.2%	6.7%	3.0%	32.6%	–

[a] F4.5.
[b] F6.5.
[c] Expanded glass.
[d] Crushed LWA.
[A] Includes water content in SP but excludes water absorbed by LWA.
[B] Water absorbed by LWA.
[C] Superplasticizer – naphthalene-based.
[D] Superplasticizer – polycarboxylate-based.
[E] Assume water absorption of the crushed LW sand is 25%.
[F] Assume water absorption of the crushed LW sand is 30%.
[G] Paste volume includes volume of cement, silica fume, and mixing water.

of 25% might be underestimated while 30% might be overestimated. Therefore, it was likely that the actual water absorption of the crushed LWA probably lies between 25% and 30%. Mixture LW4 had the same design *w/cm* and coarse aggregate as mixture LC4 but different fine aggregate (expanded glass was used in LW4). This mixture was not included in series II for comparison because the *w/cm* of LW4 was uncertain due to the high water absorption of the expanded glass particles between 1 h and 24 h.

In series III, the influence of the quality of the paste matrix on the various transport properties was evaluated. Two all-LWC mixtures were designed with similar density and compressive strength. They were prepared such that the relative porosity of LWA in one mixture (LW4) was lower than the other (LW5), while the relative porosity of the paste matrix in the former was higher than in the latter. This was achieved by using lower densities LWA (F4.5 as coarse and expanded glass as fine) and a low *w/cm* of 0.20 inclusive of 10% silica fume in LW5. On the other hand, LW4 had denser LWA (F6.5 as coarse and mostly expanded clay as fine) and a more porous matrix with higher *w/cm* of 0.38 without silica fume. The aim of series III was to determine the dominant factor on the various transport properties, from between porosity of the embedded LWA verse porosity of the paste matrix. This will be useful for the design of very lightweight concrete (<1450 kg/m^3) with a high resistance to water and chloride-ion penetration. Although expanded glass has high water absorption, the result of LW4 is valid to consider in series III as the effective *w/cm* of LW4 would not be below 0.32 assuming expanded glass particles absorbed 24-h water absorption before the initial setting. This *w/cm* is significantly higher than the effective *w/cm* of LW5 (0.20).

2.3. Specimen preparation and curing

The concretes were mixed in a pan mixer with a mixing speed of 50 rpm at an ambient temperature of about 28 °C. The spherical expanded clay LWA (both F6.5 and F4.5, including fine aggregates) was pre-soaked in water for 24 h before concrete mixing. For the fine crushed LWA and expanded glass particles, the oven dry aggregates and the water that would be absorbed in 1 h was added in addition to mixing water at the time of mixing. Both 1-h and 24-h water absorptions for the crushed LWA were estimated to be about 25–30%, while the 1-h water absorption for expanded glass was between 3% and 12% (Table 1). Prior to the soaking/mixing, all LWA was oven dried and cooled down to room temperature. Table 2 shows the oven-dry mass of the LWA and the amount of absorbed water for the LWA.

For each mixture, specimens listed in Table 3 were cast for various tests. The molded specimens were covered with wet linen and a plastic sheet to prevent water evaporation and left in the laboratory for about 24 h. The specimens were then transferred to a fog room after demolding and cured for another 6 days at a temperature of about 28 °C. After that, the specimens were exposed to laboratory air with a relative humidity of about 80–85% at a similar temperature until the time of testing, except for those used for the water permeability test.

2.4. Basic properties of the concretes

Slump, unit weight, and compressive strength of the concretes are presented in Table 4. The slump was determined according to ASTM C 143/C 143 M [7], and the unit weight and compressive strength were determined according to British Standard BS EN 12390: Part 7 and Part 3 [8–9], respectively. The results of unit weight and strength were from the average of three specimens.

The slump of the concretes was controlled to be 100 ± 30 mm. The control concrete NC1 had a 1-day unit weight of 2360 kg/m^3 and 28-day compressive strength of 71 MPa. At *w/cm* of 0.38, the 28-day compressive strength of the LWC decreased from 50 to 24 MPa with the decrease of concrete unit weight from 1900 to 1390 kg/m^3. With *w/cm* of 0.20, LW5 had a 28-day compressive strength of 21 MPa and a 1-day unit weight of 1310 kg/m^3. The strength of LW5 was not increased with the reduction in *w/cm*. This is likely due to the strength limit imposed by the LWA used.

Total porosity of the concretes is presented in Table 4 and is calculated from their mixture proportions and the porosity of the aggregates (Table 1) and cement paste (determined from mercury intrusion porosimeter (MIP)). Porosity of granite aggregate and natural sand was considered negligible. No interfacial transition zone (ITZ) was considered.

Table 3
Specimens used for various tests and their curing conditions.

Properties to be determined	Test age, days	Conditioning	Size of specimen
Density & compressive strength	7, 28, 91	All specimens subjected to 7-day moist curing; exposed to lab air (RH ≈ 85%) afterwards	100 × 100 × 100 mm cubes
Water absorption	28		3 × ø100 × 50 mm discs cut from ø100 × 200 mm cylinder
Water accessible porosity test	28		3 × ø100 × 50 mm discs cut from ø100 × 200 mm cylinder
Rapid chloride penetrability (ASTM C 1202)	28		3 × ø100 × 50 mm discs cut from ø100×200 mm cylinder
Migration coefficient (NT Build 492)	28		3 × ø100 × 50 mm discs cut from ø100 × 200 mm cylinder
Water permeability	7		ø75 × 150 mm cylinders

Table 4
Variables and basic properties of the concretes.

Concrete ID	Design *w/cm*	Silica fume	Variables	Slump, mm	Average unit weight, kg/m^3	Average compressive strength[A], MPa			Water accessible porosity[B], % vol.	Estimated total porosity[C], % vol.
					1 day	7 days	28 days	91 days		
NC1	0.38	–	Coarse aggregate: Granite	105	2360	54 (2)	71 (1)	75 (3)	10.6	8.8
LC1	0.38	–	Coarse aggregate: F6.5 LWA	125	1900	47 (1)	50 (1)	58 (3)	11.0	28.2
LW1	0.38	–	Coarse aggregate: F4.5 LWA	80	1790	26 (2)	30 (1)	31 (1)	13.0	32.7
LC1	0.38	–	Fine aggregate: Natural sand	125	1900	47 (1)	50 (1)	58 (3)	11.0	28.2
LC4-25	0.38	–	Fine aggregate: LWA with crushed 0 –1.18 mm particles	80	1610	31 (7)	38 (2)	45 (1)	21.5	~42
LC4-30	0.38		Fine aggregate: LWA with crushed 0 –1.18 mm particles	85	1620	31 (2)	34 (8)	42 (4)	20.7	~42
LW4	0.38	–	Low unit weight concrete with high resistance to water and chloride-ion penetration	100	1390	24 (3)	24 (3)	24 (1)	17.1	49.0
LW5	0.20	10%	Low unit weight concrete with high resistance to water and chloride-ion penetration	70	1310	19 (0)	21 (1)	23 (1)	13.6	49.9

[A] Standard deviation is presented in the parenthesis after the average value from three specimens.
[B] (Mass of "saturated surface dry" concrete – mass of oven dry concrete) / (volume of the concrete).
[C] Calculated based on mix proportion of concrete, total porosity of LWA in Table 1, and porosity of cement paste from MIP test.

Water accessible porosity of concrete is also presented in Table 4 and is calculated by the mass increase of concrete from oven dry to "SSD" conditions divided by volume of the concrete. Three ∅100 × 50 mm specimens cut from a ∅100 × 200 mm cylinder were used for the test with approximately 10 mm from the top and bottom being removed. It is recognized that utilizing cut surfaces exposes porous LWA directly to the surrounding environment, which may influence the results. The "SSD" condition of the concrete specimens was achieved by a vacuum process similar to the one used in the ASTM C 1202 test. For very dense concrete, saturation may not be guaranteed.

2.5. Test methods

2.5.1. Water absorption

Initial water absorption and sorptivity of the concretes were tested according to ASTM C 1585 [10] by measuring the increase in mass of the specimens resulting from absorption of water as a function of time when one surface of the specimen was exposed to water.

For each mixture, three ∅100 × 50 mm specimens were obtained from a ∅100 × 200 mm cylinder (Table 3) with approximately 10 mm from the top and bottom being removed. The specimens were moist cured (RH = 100%) for 7 days at a temperature of about 28 °C followed by exposure in laboratory air (RH = 80–85%) with the similar temperature for 21 days. The end-surfaces of the specimens were ground before the test. The specimens were then placed in an environmental chamber at a temperature of 50 °C and relative humidity of 80% for 3 days before being stored in a sealable plastic bag at 23 ± 2 °C for 15 days. Finally, the specimens were coated with epoxy on the side surfaces before the absorption test to ensure one-dimensional absorption. The top surface was covered to prevent evaporation during the test. Increase in mass of the specimens with time was monitored. After the test, two parameters were calculated according to Buyle-Bodin and Hadjieva-Zaharieva [11] as follows:

- The initial water absorption (kg/m^2) which is the quantity of water absorbed by a unit surface area during the 1st hour of the test.
- The sorptivity (kg/m^2 h$^{0.5}$) which is the slope of the regression curve of the quantity of water absorbed by a unit surface area versus square root of the elapsed time from 1 to 24 h.

2.5.2. Water permeability

Depth of water penetration in the concrete was determined on specimens with 7 days of moist curing according to BS EN 12390-8 [12] with some modifications. The specimens were subjected to a pressure about 0.75 MPa for 14 days for relative comparison of different concretes. The reason for testing at an early age of 7 days was due to relatively the low maximum pressure that can be achieved by the equipment, thus it would be difficult to get water penetration if the concrete was cured longer.

Specimens with a diameter of 75 mm and a height of 150 mm were roughened on the circumferential surface immediately after demolding, and cured in a fog room for 7 days. The circumferential surface of the specimens was then coated with epoxy mortar after surface drying to ensure one dimensional flow of water. Both end-surfaces of the cylinder specimens were then ground level to prevent water leakage under pressure. The mass of the specimens coated with hardened epoxy mortar was determined before the permeability test.

After testing, the face of the specimen exposed to the water pressure was wiped dry and mass of the specimen was recorded. The specimen was then split into two halves to determine the average depth of water penetration. The water permeability coefficient can be calculated according to Valenta's equation [13]:

$$K_P = \frac{d^2 \cdot v}{2 \cdot h \cdot t} \tag{2}$$

where K_P = coefficient of water permeability (m/s); d = depth of water penetration in concrete (m); v = the porosity of the concrete; h = hydraulic head of water (m); and t = time under pressure (s).

The value v can be calculated from Eq. (3).

$$v = \frac{m}{Ad\rho} \tag{3}$$

where m = gain in mass (g); A = cross-sectional area of the specimen (mm^2), ρ = density of water (~1000 kg/m^3).

2.5.3. Resistance to chloride-ion penetration

Resistance of the concrete to the chloride-ion penetration was evaluated by the following two methods.

2.5.3.1. Rapid chloride penetrability test. The rapid chloride penetrability test (RCPT) was carried out at 28 days according to ASTM C 1202-05 [14]. The total charge passed after 6 h was obtained from integration of the current over the time duration. Three ∅100 × 50 mm specimens obtained from the cylinder as described above were used for the test. The specimens were vacuum saturated prior to testing as described in ASTM C1202.

2.5.3.2. Rapid migration test. Migration coefficient (also referred to as apparent diffusion coefficient) was determined according to NT Build 492 method [15] using three specimens with a diameter of 100 mm and a depth of 50 mm obtained from the cylinder as described above.

Each specimen was exposed to a 10% NaCl solution on one side and a 0.3 M NaOH solution on the other. An external potential of 30 V was applied across the specimen for 24 h. After that the specimen was split into two halves across its circular cross section. The split open interior surfaces were sprayed with 0.1 N $AgNO_3$ solution to determine a chloride penetration depth, which was then used to calculate a migration coefficient according to

$$D_m = \frac{RT}{zFE} \cdot \frac{x_d - \alpha\sqrt{x_d}}{t} \tag{4}$$

where

$$E = \frac{U-2}{L} \tag{5}$$

$$\alpha = 2\sqrt{\frac{RT}{zFE}} \cdot \mathrm{erf}^{-1}\left(1 - \frac{2c_d}{c_0}\right) \tag{6}$$

where D_m = migration coefficient (m^2/s); z = absolute value of ion valence, for chloride $z = 1$; F = Faraday constant (9.648×10^4 J/(V mol)); U = absolute value of the applied voltage (V); R = gas constant (8.314 J/(V·mol)); T = average value of the initial and final temperatures in the anolyte solution (K); L = thickness of the specimen (m); x_d = average value of the penetration depths (m); t = test duration (s); erf^{-1} = inverse of the error function; c_d = chloride concentration at which the color changes, $c_d \approx 0.07$ N for OPC concrete; c_0 = chloride concentration in the catholyte solution, and $c_0 \approx 2$ N [15].

3. Results and discussion

3.1. Differences of LWC and NWC that may affect transport of water and ions in concrete

3.1.1. Porosity

Comparing LWC and NWC of the same *w/cm*, the differences are mainly aggregate and ITZ between the aggregate and cement paste. Lightweight aggregates are porous and have the ability to absorb water. As shown in Table 1, pores occupy more than half of the total volume of the spherical LWA particles used in this study. However, some pores are closed depending on the type and size of LWA. Assuming that the cement paste matrix in NWC and LWC with equivalent *w/cm* was the same, porosity of LWC would be increased significantly due to the incorporation of porous aggregate compared to that of NWC. The total porosity of LC1 and LW1 was approximately more than triple that of NC1 by considering the pores in the aggregate and cement paste (Table 4, series I). Similarly, the total porosity of all-LWC LC4 was increased by about 14% due to the pores in the fine LWA compared with sand-LWC LC1 in series II. In the design of very lightweight concrete (<1400 kg/m^3) such as the all-LWC LW4 and LW5 in series III, the total porosity was close to 50% of total volume. With the increased porosity, the probability for increased pore connectivity in the concrete is likely to increase. As water and ions can penetrate through porous media, the porous LWA may reduce concrete resistance to water and chloride-ion penetration.

3.1.2. Interfacial transition zone

Penetration of water and ions in concrete depends not only on concrete porosity but also on pore size distribution, pore connectivity, and pore tortuosity. Fig. 1 shows schematic differences between porosity and permeability [16]. It is clear that connectivity of the pore system is essential for water and chloride-ion penetration. A material can be porous but still have a low permeability as long as the pores are not interconnected and/or are small in diameter. On the other hand, a material can have lower porosity but higher permeability if the pores are interconnected and large.

For NWC, there is an ITZ between aggregate and cement paste which is generally more porous than bulk cement paste due to a "wall effect". In principle, high porosity of the ITZ would facilitate ingress of water and ions. Bentz [17] reviewed some research work on ion diffusion in ITZ compared with that in bulk paste. Bretton et al. [18] conducted model experiments using a cylindrical aggregate surrounded by cement paste and concluded that the ITZ exhibits a chloride ion diffusion coefficient that is 12–15 times that of bulk paste with *w/cm* of 0.5 cured for 10 days and an assumed ITZ thickness of 100 μm. Bourdette [19] suggested a lower diffusivity ratio of 3 between the ITZ and bulk paste for a mortar with *w/cm* = 0.4 cured for 3 months, assuming an ITZ thickness of 120 μm. Otsuki et al. [20] suggested that the diffusion coefficient for the ITZ could be over 100 times that of the bulk paste for concretes with *w/cm* between 0.4 and 0.7, assuming that an ITZ thickness is a function of aggregate size and varies between 0 and about 80 μm. Based on a multi-scale microstructure model, Bentz [21] found that the average diffusivity ratio of ITZ to bulk cement paste ranged from 0.7 to 21. Larger values near 20 observed for concrete with *w/cm* of 0.5 [21] are in reasonable agreement with that of Bretton et al. [18]. The lower ratio of less than one was obtained for silica fume concrete with *w/cm* of 0.3.

However, Delagrave et al. [22] found a significant decrease in diffusion coefficient of mortars compared with cement paste of the same *w/cm*, therefore concluded that increased pore tortuosity due to the presence of normal weight aggregates is more important to resist chloride-ion penetration than ITZ. The aggregate particles

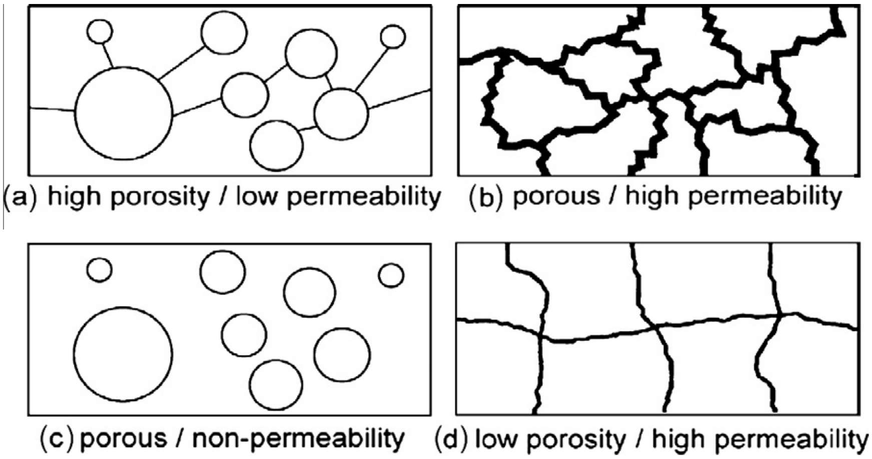

Fig. 1. Schematic diagram showing differences between porosity and permeability [16].

act as obstacles which increase travel length for water and chloride-ions to penetrate into concrete around aggregates.

For LWC, water absorption of LWA reduces the "wall effect" and improves the quality of ITZ compared with that in NWC. The improved ITZ for LWC would have a positive effect in resisting water and chloride-ion penetration [23].

3.1.3. Internal curing effect

The porous structure of LWA allows absorption of water into the aggregate particles, and the water can later be used for "internal curing" during the hardening process of the concrete. Thus there would be increased cement hydration which reduces capillary pores and their connectivity and increases their tortuosity in concrete. Henkensiefken et al. [24] found that the inclusion of saturated fine LWA can reduce water absorption of mortar specimens due to the internal curing effects. In addition, this observation was reinforced with electrical conductivity measurements that exhibited similar reductions. Bentz [17] found that chloride ion diffusivity estimated from the chloride penetration depths of mortars with 31% fine LWA was at least 25% lower compared with another mortar with normal weight sand. He attributed the reduced chloride ion diffusivity to reduced ITZ percolation and enhanced cement hydration due to internal curing effects from the pre-wetted fine LWA. Therefore, internal curing is another positive effect to resist water and chloride-ion penetration in LWC.

3.1.4. Microcracks

In LWC, differences in modulus of elasticity between aggregate and cement paste is typically less compared with those in NWC. Thus, the frequency of microcracking in the ITZ caused by drying shrinkage or under loading is generally lower in LWC compared with that in NWC. Reduced microcracking is also positive to resist water and chloride-ion penetration in LWC.

3.1.5. Water accessible porosity

The overall resistance of LWC to water and chloride-ion penetration depends on all the factors discussed above, and depends on which ones are more dominant. In comparison to total porosity, water accessible porosity of concrete is more representative of "global" porosity accessible by water and ions with consideration of the factors discussed above. Results given in Table 4 show that when only coarse LWA was used the water accessible porosity of the sand-LWC LC1 and LW1 was comparable to/slightly higher than that of the NWC NC1. However, when both coarse and fine LWA were used, the water accessible porosity of all-LWC LC4-25 and LC4-30 was approximately 90% higher than that of LC1. All-LWC LW5 had water accessible porosity comparable to that of LW1 even though the former had a lower unit weight and contained more porous fine LWA.

3.2. Water absorption

Average weight increase of different concretes due to water absorption from 1 to 24 h is shown in Fig. 2. Sorptivity of the concretes is obtained by linear regression from the slope of the absorption graph versus the square root of time. The regression coefficient for the sorptivity was >0.98 for all the mixtures. Initial water absorption is the y-intercept at $\sqrt{}$time = 1.0 of the absorption graph. The initial water absorption of concretes which is the intercept in Fig. 2 and the sorptivity of the concretes which is the slope of the regression curve in Fig. 2 are shown in Fig. 3, and error bars represent standard deviations of the results. Since the initial water absorption of the LWC was affected by the open pore structure of the cut surface, the discussion will be focused on the sorptivity of the concretes.

3.2.1. Effect of coarse aggregate type

Comparing sand-LWC LC1 and LW1 with NWC NC1, they had the same cement paste/mortar, and the difference was mainly the coarse aggregate type and quality of the ITZ between the coarse aggregate and the paste matrix. The incorporation of coarse LWA in LC1 and LW1 increased the sorptivity by about 19% and 21%, respectively, which are significantly different from NC1 (Fig. 3). The comparable sorptivity of LC1 and LW1 indicates that different porosities of the coarse LWA did not affect sorptivity of the concrete significantly as long as the aggregate were embedded in the same dense matrix.

In addition to the factors discussed in Section 3.1, another factor that influences sorptivity of the concrete is the size of its pores. In principle, water absorption is caused by capillary effects in the pores. The greater the pore size, the smaller the capillary effect. Large pores in LWA may contribute little to water absorption even if they are continuous.

3.2.2. Effect of fine aggregate type

Mixtures LC1 and LC4 had the same design w/cm and coarse aggregate (F6.5) but different types of fine aggregate. Mixture LC1 contained natural sand while LC4 contained fine LWA with fraction <1.18 mm being crushed particles. From Fig. 3, the sorptivity of both LC4-25 and LC4-30 was higher than that of LC1. It should be noted that the results for LC4 with w/cm of 0.38 were between those of LC4-25 and LC4-30. In LC1, porous coarse LWA particles were embedded in a dense mortar matrix. In LC4, however, porosity of the mortar matrix was increased due to the

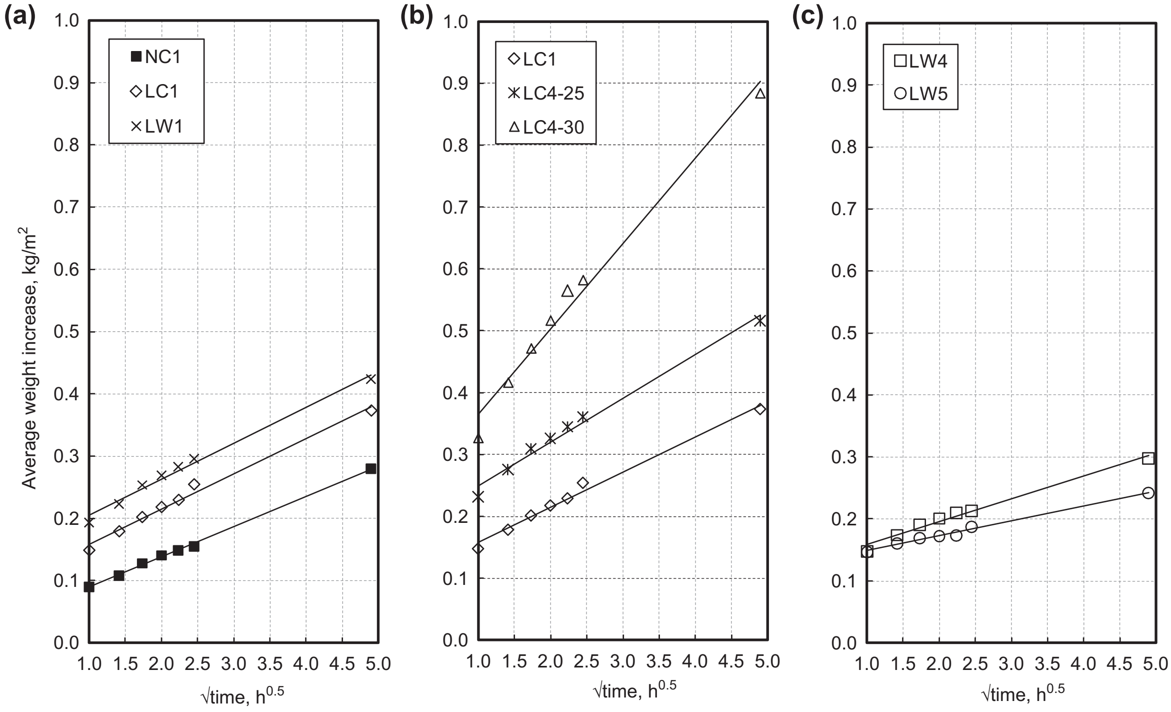

Fig. 2. Average weight increase of different concretes due to the water absorption against √time.

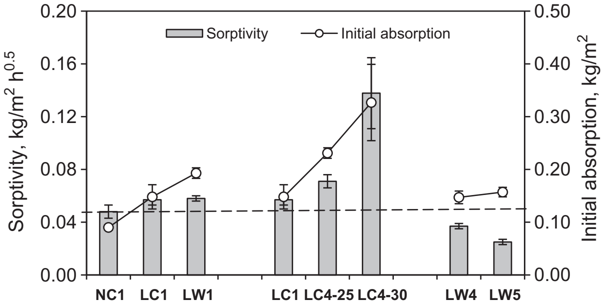

Fig. 3. Initial water absorption and sorptivity of different concretes.

presence of the fine LWA, in particular the crushed fraction <1.18 mm which constituted approximately 20% of the total mixture volume and one-third of the total aggregate volume (Table 2). The porous fine LWA reduced the thickness of the dense matrix among coarse LWA in LC4 and possibly increased interconnectivity of pores, as compared with LC1.

3.2.3. Water absorption of low unit weight concrete

LW4 and LW5 had similar densities (~1350 kg/m^3) and compressive strengths (~20 MPa). The relative porosity of LWA in LW4 was lower than LW5, while the relative porosity of the paste matrix in the former was higher than in the latter. From the results in Fig. 3, LW5 had lower sorptivity than LW4 due to a denser paste matrix from a lower *w/cm* and incorporation of silica fume. The above results indicate that LWC with very low unit weight can be produced with low water absorption as long as the LWA particles are embedded in a dense cement paste matrix.

3.3. Water permeability

Measured penetration depths of water under a pressure about 0.75 MPa and calculated water permeability coefficients of the concretes are summarized in Table 5. The results show that the concretes with *w/cm* of 0.38 had relatively low water permeability (10^{-14}–10^{-13} m/s) regardless of the type and amount of the porous LWA used in the concretes. Specific effects of coarse and fine aggregates will be discussed next.

Table 5
Water permeability of the concretes.

Concrete ID	Design *w/cm*	Silica fume	Variables	1-day unit weight, kg/m^3	28-day strength, MPa	Water penetration depth[a], mm	Permeability coefficient[a], $\times 10^{-13}$ m/s
NC1	0.38	–	Coarse aggregate: Granite	2360	71	20.6 (2.6)	0.9 (0.2)
LC1	0.38	–	Coarse aggregate: F6.5 LWA	1900	50	12.4 (0.2)	1.1 (0.2)
LW1	0.38	–	Coarse aggregate: F4.5 LWA	1790	30	15.7 (1.0)	1.2 (0.3)
LC1	0.38	–	Fine aggregate: Natural sand	1900	50	12.4 (0.2)	1.1 (0.2)
LC4-25	0.38	–	Fine aggregate: LWA with crushed 0 -1.18 mm particles	1610	38	12.8 (0.1)	1.2 (0.2)
LC4-30	0.38	–	Fine aggregate: LWA with crushed 0 -1.18 mm particles	1620	34	24.2 (2.6)	4.0 (0.8)
LW4	0.38	–	Low unit weight concrete with high resistance to water and chloride-ion penetration	1390	24	9.9 (0.9)	0.4 (0.1)
LW5	0.20	10%	Low unit weight concrete with high resistance to water and chloride-ion penetration	1310	21	3.1 (0.1)	0.1 (0.1)

[a] Standard deviation is presented in the parenthesis after the average value from three specimens.

3.3.1. Effect of coarse aggregate type

As shown in Table 5, LC1 and LW1 have slightly higher permeability coefficients than that of the NWC NC1. However, the water penetration depths of the LWC (LC1 and LW1) were lower than that of NC1 as pores in the porous LWA became reservoirs to contain water during penetration. This is important from a durability point of view. For example, initiation of corrosion of steel reinforcement embedded in concrete is affected by the concentration of chloride-ions in the vicinity of the steel reinforcement bars where the chloride-ions can be brought into the concrete by hydraulic pressures. Advancement of the critical chloride front toward the steel is of significant importance for consideration of service life of reinforced concrete structures exposed to, e.g. marine environment.

The water penetration depth and permeability coefficient of LW1 with more porous coarse LWA was higher than LC1 with less porous coarse LWA.

3.3.2. Effect of fine aggregate type

The permeability coefficient of LC4-25 is similar to that of LC1 (Table 5). However, that of LC4-30 is much higher than those of LC1. Therefore, the results for the mixture with *w*/*cm* of 0.38 lying in between LC4-25 and LC4-30 would have a higher permeability coefficient than that of LC1. This indicates that the fine LWA could increase permeability of the LWC with the same coarse LWA. Therefore, with the same *w*/*cm*, the fine LWA would probably increase the permeability of the LWC compared with that containing only coarse LWA.

3.3.3. Water permeability of the low unit weight concrete

The low unit weight concrete LW5 had a lower water penetration depth and permeability coefficient compared with LW4 (Table 5). In LW5, the low *w*/*cm* and silica fume played dominant roles for its low water permeability. The results indicate that low water permeability can be achieved even for LWC with very low unit weight and high total porosity.

3.4. Resistance to chloride-ion penetration

Resistance of the concretes to chloride-ion penetration was evaluated by two different methods described in Section 2.5.3 and results are summarized in Table 6.

3.4.1. Effect of coarse aggregate type

From Table 6, charge passed through LC1 with coarse LWA F6.5 was slightly lower than that of the NC1. The charge passed through LW1 with coarse LWA F4.5 of higher porosity was higher than those passed through LC1 and NC1, although they were all within the range from 2000 to 4000 coulombs, which was classified as "moderate" chloride penetrability according to ASTM C 1202. The trend for migration coefficient of the concretes determined by NT Build 492 method appeared to be consistent with that obtained from the ASTM C 1202 test.

Lightweight aggregate is generally more porous than cement paste in LWC. It was found that the diffusion coefficient of LWA, similar to F6.5 used in the present study, was on the order of 10^{-11} m^2/s [25] which was similar to that of a pure cement paste with a *w*/*cm* of 0.9 cured in a sealed condition for at least half a year [26]. It was also found that the diffusion coefficient of expanded clay LWA increased with the increase in porosity [25]. Thus the resistance to chloride-ion penetration of the more porous coarse LWA F4.5 in LW1 was probably lower than that of the coarse LWA F6.5 in LC1. In consideration of the results obtained, porosity of the coarse LWA could influence the concrete resistance to chloride-ion penetration. Nevertheless, it should be noted that the samples used for the diffusion test in Ref. [25] were sliced from the middle of LWA particles. Therefore the outer shell of the aggregate was removed and its influence on diffusion was not considered.

3.4.2. Effect of fine aggregate type

As shown in Table 6, all-LWC LC4-25 had charge passed and migration coefficient similar to those of sand-LWC LC1. However, LC4-30 had all these properties higher than those of LC1. Therefore, given the same *w*/*cm*, all-LWC LC4 would likely have had charge passed and migration coefficients higher than those of sand-LWC LC1. This indicates that the total replacement of sand with fine LWA may reduce concrete resistance to chloride-ion penetration.

3.4.3. Resistance of low unit weight concrete to chloride-ion penetration

Lightweight concrete LW5 had very low charge passed, chloride penetration depth, and migration coefficient compared with LW4 as shown in Table 6. Similar to water absorption and water permeability, the high resistance of LW5 to chloride-ion penetration was mainly attributed to a high quality paste matrix due to the low *w*/*cm* and use of silica fume. The results indicate that the quality of the paste matrix exerted a dominant influence on resistance to chloride-ion penetration.

3.5. Discussion

The results presented and discussed above indicate that the quality of the cement paste matrix has a dominant effect in controlling the penetration of water and chloride-ions in concrete and would therefore be an important parameter in design for durable concrete, regardless of whether porous fine and coarse LWA are used. For various LWC and the control NWC, although there were some discrepancies due to different mechanisms of water and chloride-ion penetration, the results on water absorption,

Table 6
Resistance of concrete to chloride-ion penetration.

Concrete ID	Design *w*/*cm*	Silica fume	Variables	1-day unit weight, kg/m^3	28-day strength, MPa	Total charges passed[a] (ASTM C 1202), Coulombs	Migration coefficient[a], $\times 10^{-12}$ m^2/s
NC1	0.38	–	Coarse aggregate: Granite	2360	71	2528 (210)	8.8 (0.6)
LC1	0.38	–	Coarse aggregate: F6.5 LWA	1900	50	2385 (141)	6.5 (1.8)
LW1	0.38	–	Coarse aggregate: F4.5 LWA	1790	30	3676 (900)	10.4 (0.8)
LC1	0.38	–	Fine aggregate: Natural sand	1900	50	2385 (141)	6.5 (1.8)
LC4-25	0.38	–	Fine aggregate: LWA with crushed 0 -1.18 mm particles	1610	38	2245 (562)	6.4 (1.3)
LC4-30	0.38	–	Fine aggregate: LWA with crushed 0 -1.18 mm particles	1620	34	3620 (529)	8.9 (0.6)
LW4	0.38	–	Low unit weight concrete with high resistance to water and chloride-ion penetration	1390	24	1581 (60)	5.2 (0.5)
LW5	0.20	10%	Low unit weight concrete with high resistance to water and chloride-ion penetration	1310	21	110 (35)	2.4 (0.6)

[a] Standard deviation is presented in the parenthesis after the average value from three specimens.

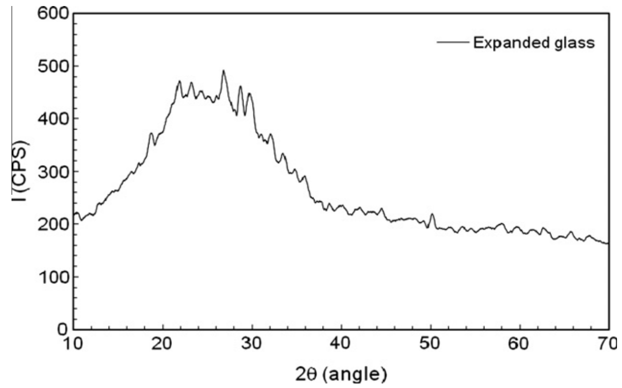

Fig. 4. X-ray diffraction spectrum of ground expanded glass particles.

permeability, and chloride-ion penetrability were generally consistent. Capillary pores and pore structure influence both water absorption and water permeability. However, in the water permeability test, some isolated pores within the concrete may be penetrated through under pressure. The rapid chloride-ion penetrability test and migration test were accelerated methods with application of external voltages. The results, therefore, are affected by pore solution chemistry in addition to the porosity and pore structure of the concretes.

From the results, it seems that the transport properties of the concretes were more closely related to the water accessible porosity than the total porosity of the concretes presented in Table 4. Water sorptivity, permeability coefficient, and migration coefficient of the concretes may increase with the increase in the water accessible porosity of the concretes. However, unit weight of the concrete, which is related to the total porosity of the concrete, does appear to influence the transport properties of the concrete as well to a certain extent. The correlations between transport properties and water accessible porosity and unit weight of the LWC and NWC will be discussed in a separate paper.

In the all-LWC LW4 and LW5, expanded glass particles were used as fine aggregate to achieve lower unit weights. According to its manufacturer, the expanded glass consists of about 72% SiO_2, 13% Na_2O, and 8% CaO. X-ray diffraction analysis indicated that the structure is mostly amorphous (Fig. 4). Due to this, the fine expanded glass aggregates may react with alkalis from cement [27] and cause potential damage. Therefore, further research is needed.

4. Summary and conclusions

Lightweight aggregate concrete differs from NWC in a number of aspects such as increased porosity, improved interfacial transition zone, improved cement hydration due to internal curing, and reduced microcracking that may affect the transport of water and chloride-ions in the concrete. The actual transport properties of the LWC in comparison to those of the NWC depend on which of these factors are dominant. Based on the experimental results and discussion, the following conclusions can be drawn:

1. The incorporation of coarse LWA in concrete increased the water sorptivity and permeability slightly compared to NWC of similar *w/cm*. This is related to increased porosity of the concrete due to pores in coarse LWA. Resistance of the sand-LWC to chloride-ion penetration depends on the porosity of the coarse LWA. Performance of the LWC with less porous coarse LWA (F6.5) was similar to that of NWC, whereas the more porous coarse LWA (F4.5) tends to reduce resistance of the LWC to chloride-ion penetration.
2. Total replacement of sand by fine LWA including crushed fraction <1.18 mm tends to reduce the resistance of the all-LWC to sorptivity, water permeability and chloride-ion penetration compared with the sand-LWC which has the same coarse LWA at a given *w/cm*.
3. Quality of the paste matrix was more important in controlling the transport properties of the concrete regardless of the porosity of aggregates used. With low *w/cm* and silica fume, low unit weight LWC ($\sim$1310 kg/m^3) was produced with a higher resistance to water and chloride-ion penetration compared with NWC and LWC of higher unit weights.
4. The transport properties of concretes such as water sorptivity, permeability coefficient, and resistance to chloride-ion penetration were more closely related to the water accessible porosity than the total porosity of the concrete.

Acknowledgement

Grateful acknowledgement is made to National University of Singapore for providing scholarship to the first author. Appreciation is made to Mr. Yap Miin Kai for some experimental work.

References

[1] FIB, lightweight aggregate concrete, in recommended extension to model code 90. Föderation International du Beton, Bulletin 8; 2000.

[2] ASTM, C 494/C 494M-05a. Standard specification for chemical admixtures for concrete. West Conshohocken (PA): ASTM International; 2006.

[3] ASTM, C 33-03. Standard specification for concrete aggregates. West Conshohocken (PA): ASTM International; 2003.

[4] ASTM, C 330-05. Standard specification for lightweight aggregates for structural concrete. West Conshohocken (PA): ASTM International; 2006.

[5] ASTM, C 128-04a. Standard test method for density, relative density (specific gravity), and absorption of fine aggregate. West Conshohocken (PA): ASTM International; 2006.

[6] Liu XM, Chia KS, Zhang MH. Water absorption, permeability, and resistance to chloride-ion penetration of lightweight aggregate concrete. Construct Build Mater 2010. doi:10.1016/j.conbuildmat.2010.06.02.

[7] ASTM, C 143/C 143M-05a. Standard Test method for slump of hydraulic-cement concrete. West Conshohocken (PA): ASTM International; 2006.

[8] BS, EN 12390. Testing hardened concrete, in part 7: density of hardened concrete. London: British Standards Institution; 2000.

[9] BS, EN 12390. Testing hardened concrete, in part 3: compressive strength of test specimens. London: British Standards Institution; 2000.

[10] ASTM, C1585-04. Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes. West Conshohocken (PA): ASTM International; 2006.

[11] Buyle-Bodin F, Hadjieva-Zaharieva R. Influence of industrially produced recycled aggregates on flow properties of concrete. Mater Struct/Mater Construct 2002;35(252 SPEC.):504–9.

[12] BS, EN 12390. Testing hardened concrete, in part 8: depth of penetration of water under pressure. London: British Standards Institution; 2000.

[13] Valenta O. The permeability and durability of concrete in aggressive conditions. In: Proceedings of 10th international congress on large dams. Montreal; 1970. p. 103–17.

[14] ASTM, C 1202-05. Standard test method for electrical indication of chloride's ability to resist chloride. West Conshohocken (PA): ASTM International; 2006.

[15] NTBUILD492. Concrete, mortar and cement-based repair materials chloride migration coefficient from non-steady-state migration experiments. Espoo, Finland: NordTest; 1999.

[16] EuroLightCon. LWAC material properties state-of-the-art. In: Economic design and construction with light weight aggregate concrete. Brite-EuRam III; 1998. p. 47–8.

[17] Bentz DP. Influence of internal curing using lightweight aggregates on interfacial transition zone percolation and chloride ingress in mortars. Cem Concr Compos 2009;31(5):285–9.

[18] Bretton D, Ollivier JP, Ballivy G. Diffusivite des ions chlore dans la zone de transition entre pate de ciment et roche granitique, in interfaces in cementitious composites. In: Maso JC, et al. editors. Proceedings of the international conference held by RILEM (the international union of testing and research laboratories for materials and construction) at the Université Paul Sabatier, Toulouse, and organised by RILEM technical committee 108 and the laboratory for materials and durability of constructions (LMDC), INSA-UPS, Toulouse, France, Toulouse, October 21–23, 1992. E & FN Spon, London, New York; 1993. p. 269–78.

[19] Bourdette B, Ollivier JP. Durabilité du mortier: prise en compte des auréoles de transition dans la caractérisation et la modélisation des processus physiques et chimiques d'altération (the durability of mortar: consideration of interfacial

transition zones to characterize and to model the physicals and chemicals mechanisms involved in mortar corrosion), in institut national des sciences appliquées de Toulouse, Université de soutenance: Toulouse, France; 1994. p. 188.

[20] Otsuki N et al. Experimental study on influence of ITZ around aggregate on Cl-diffusivity of concrete. J Soc Mater Sci 2006;55(10):899–904 [in Japanese].

[21] Bentz DP. Influence of silica fume on diffusivity in cement-based materials II. Multi-scale modeling of concrete diffusivity. Cem Concr Res 2000;30(7): 1121–9.

[22] Delagrave A et al. Influence of the interfacial zone on the chloride diffusivity of mortars. Adv Cem Based Mater 1997;5(3–4):86–92.

[23] Zhang MH, Gjørv OE. Microstructure of the interfacial zone between lightweight aggregate and cement paste. Cem Concr Res 1990;20(4):610–8.

[24] Henkensiefken R et al. Water absorption in internally cured mortar made with water-filled lightweight aggregate. Cem Concr Res 2009;39(10): 883–92.

[25] Zhang MH. Microstructure and properties of high strength lightweight concrete. Trondheim, Norway: The Norwegain Institute of Technology; 1989.

[26] Gautefall O, Havdahl J, Vennesland Ø. Modified Portland cement, part 8, chloride diffusion, Sintef report no. STF65 A86014; 1986.

[27] Mladenovič A et al. Alkali–silica reactivity of some frequently used lightweight aggregates. Cem Concr Res 2004;34(10):1809–16.