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The effects of air content on permeability of lightweight concrete

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Abstract

Air entraining agent is used to control the floatation of lightweight aggregate (LWA) in lightweight aggregate concrete (LWAC), therefore reducing the segregation of LWAC. At the same time, using an air entraining agent will affect the water sorption of the concrete. In this paper, two lightweight concrete mixes of density 1000 kg/m^3 and air content of 13.5% and 31.9% were compared and the effects of entrained air on the strength, surface sorptivity, and chloride permeability of LWAC are presented. Results show that the use of porous LWA would not lower the permeability resistance of concrete. Entrained air had little effect on sorptivity but a major effect on chloride permeability. The weaker pores' network in the cement paste is the basic cause for the high chloride permeability of concrete than the use of porous LWA. Although chloride permeability of low density LWAC concrete decreased with age of concrete, it was found that the concrete was not dense enough to stop the chloride ion to penetrate through the concrete before the concrete mature at 90 days.

Keywords: Lightweight concrete; Lightweight expanded clay aggregate; Sorptivity; Chloride permeability; Air content; Compressive strength

1. Introduction

Low strength lightweight concrete is used for prefabrication of dry partition walls, washing room and kitchen modules [1–3]. For lightweight aggregate concrete (LWAC), air entraining agent is used to control the floatation of lightweight aggregate (LWA) therefore reducing the segregation of LWAC and lowering the density of the resulting concrete. However, the water sorption of the concrete will be increased at the same time. Past findings [4–7] indicated that sorptivity can be correlated to permeability, and is a function of porosity, pore diameter, distribution and continuity of pores within the concrete matrix. In many cases, the chloride permeability of ordinary concrete using AASHTO method [8] is used to compare the permeability of concrete but few researchers have studied the chloride permeability of LWAC. In this study, the effects of the entrained air on the strength, sorptivity and permeability of concrete of two LWAC mixes of density 1000 kg/m^3 will be studied. Results of the surface sorptivity and chloride permeability of concrete were analyzed.

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2. Materials and experimental details

2.1. Materials and specimens preparation

The binders used were Portland cement (OPC) to BS12:1989 [9], with Blaine surface area of 330 m^2/kg and a density of 3150 kg/m^3. The LWA was a lightweight expanded clay aggregate. Fine and 10 mm coarse aggregates were of bulk densities of 955 kg/m^3 and 403.8 kg/m^3, respectively. The LWA was pre-wetted with half of the total gauging water for 30 min so that the aggregate was 'surface saturated' prior to mixing. Water absorption of 30 min of the fine and coarse aggregate is 14.5% and 5.4%, respectively. The mix proportions are summarized in Table 1. Two concrete mixes of the same w/c ratio but different air contents were prepared.

Liquid air entraining agent in accordance with BS4887 [10] was added to the concrete mix to control the floatation of LWA in the cement paste. The resulting fresh concrete had good workability and the floatation of lightweight aggregate and segregation of concrete were well controlled.

For each concrete mix, four $100 \times 100 \times 100$ mm^3 cubes were prepared for test at each age. Three of them were for compressive test and the last one was for sorption test. In addition, one disc

Table 1
Mix proportions of lightweight concrete

Cement	400 kg/m^3
Coarse LWA (pre-wetted)	232 kg/m^3
Fine LWA (pre-wetted)	378 kg/m^3
Water	160 kg/m^3
Reducing agent	2.6 L/m^3
w/c ratio	0.40
AEA	Mix A: 0.3 L/m^3
	Mix B: 0.6 L/m^3

[ϕ100 × 50 mm^2] was prepared for rapid chloride permeability test [RCPT]. All tests were carried out at the ages of 7, 28 and 90 days. After demolding for 24 h, the specimens were water cured at 27 °C ± 3 °C until the time of testing [11]. The air content of the freshly mixed concrete was measured by the pressure method [12] and the test of compressive strength f_c follows BS1881 [13].

2.2. Experimental details

2.2.1. Sorption test

Sorptivity is a measure of the capillary forces exerted by the pore structure causing fluids to be drawn in to the body of the material. The sorptivity of concrete is a quantity that measures the unsaturated flow of fluids into the concrete [14].

The concrete cubes used in the sorption test were taken out from the curing tank 2 days before test and cut into two equal halves by concrete cutting machine. The specimens were dried in an oven at 105 °C until a constant mass was reached, then cooled to room temperature inside desiccators. The weight and the immersion surface area of the oven-dried specimens were measured to the nearest 0.01 g and 1 mm^2, respectively. The specimen was immersed in a tray (see Fig. 1) containing water to a depth of 1–2 mm and was rested on steel wires to permit the free access of water to the inflow surface. Immediately after the immersion of the cube surface into water, the start time of the test was recorded; at intervals of 5, 10, 30, 60, 120 and 240 min after the start of the test, the specimen was removed from the tray; after the surplus water was wiped off with tissue papers, it was weighed to the nearest 0.01 g and then returned to the tray.

The relationship between water sorption and time was determined by Hall [14] as:

$$i = A + St^{1/2} \quad (1)$$

where S [in mm/min$^{0.5}$] is the water sorptivity of the concrete and i [in mm] is the cumulative absorbed volume per unit area of inflow surface for duration of time t. A represents the effect of initial water filling at concrete surface.

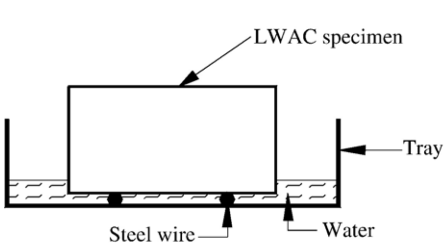

Fig. 1. Schematic diagram of sorption test.

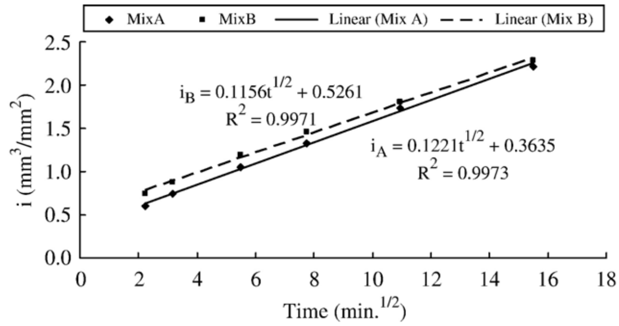

Fig. 2. Sorptivity of LWAC at 7 days.

2.2.2. Rapid chloride permeability test

The concrete disc specimen for rapid chloride permeability test was taken out from the curing tank 5 days before testing. It was washed and dried at room conditions for 24 h. The circumference of the disc specimen was sealed up by applying 2 layers of epoxy coatings. The disc was submerged in de-aired water and placed under vacuum suction so that all internal voids of the concrete were air evacuated and filled with water. The disc was then mounted onto the two-part testing cell with one side (negative pole) subjected to a 3% NaCl solution and the other side (positive pole) to a 0.3 M NaOH solution. A constant electric field of 60 V ± 0.1 V was applied for 6 h. The electric charges passing through the disc, which represented the specimen's chloride permeability, were recorded.

3. Results and discussion

3.1. Sorptivity of LWAC

Results of water sorption for both concrete mixes were presented in Figs. 2–4. It is seen that the water sorptions of the 2 mixes are close to each other throughout the test period. A linear relationship between water sorptivity and time which follows Eq. (1) was found. The sorptivity S denoted by the slope of the regression lines was found ranging between 0.11 and 0.13 mm/min$^{0.5}$ (see Table 2).

According to Neville [15], typical sorptivity is 0.09 mm/min$^{0.5}$ for normal concrete with a w/c ratio of 0.4, and 0.17 mm/

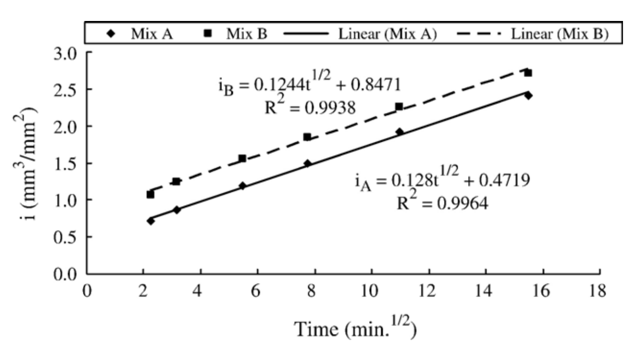

Fig. 3. Sorptivity of LWAC at 28 days.

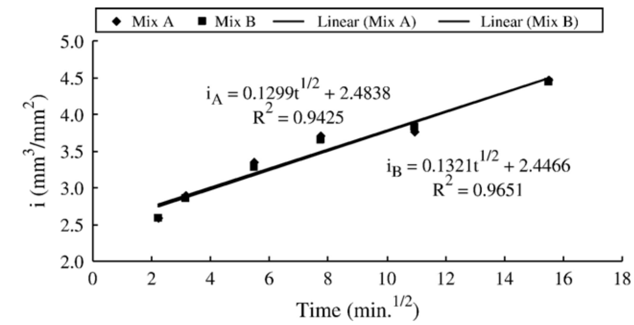

Fig. 4. Sorptivity of LWAC at 90 days.

min$^{0.5}$ at a w/c ratio of 0.6. Some other research studies suggested that OPC concrete with w/c ratio of 0.4–0.5 would have sorptivity of about 0.23 mm/min$^{0.5}$ [19–22]. Therefore, the sorptivity value for these LWAC with low strength and air content at w/c ratio of 0.40 was not particularly high when compared to normal weight concrete of the same w/c ratio. As sorption is mainly through capillary pores, the similarity of water sorptivity of the mixes with different air content suggested that the pores within the two concrete mixes were larger than capillary pores. However, the change of water sorptivity with age is different from that of normal weight concrete. For normal concrete, water sorptivity generally decrease with the increase in age. In this research, sorptivity of LWAC increase with age. For Mix A, the sorptivity at 7 days was 0.122 mm/min$^{0.5}$ and it increases to 0.130 mm/min$^{0.5}$ for 90 days. The similar phenomenon also occurs in Mix B. The main reason for this phenomenon was the application of the air entraining agent and the use of lightweight aggregate.

The initial sorption (A) as per Table 2 increases with age of concrete indicated the mean of the initial sorption for Mixes A and B of the LWAC changes from 0.444 mm, 0.66 mm to 2.465 mm at 7 days, 28 days and 90 days, respectively. It is clear that concrete sorption is closely related to the surface pores of the concrete paste. The surface pore reduces as C–S–H and LWAC strength also develop with time. Accordingly, it reduces the permeability and water sorptivity of concrete.

The above phenomenon can be attributed to the fact that the quantity of pores of Mix B is greater than that of Mix A due to the higher air content; the surface sorption of Mix B is higher at the early ages but becomes similar at 90 days. Since the cement contents of both Mixes A and B are the same, the cement hydration and the structure of capillary pore will be similar. This explains why in Fig. 4 the surface sorptions of the two mixes at the age of 90 days are similar. Moreover, it also induced that the effect of addition of air entraining agent to lightweight aggregate concrete on water sorptivity of the concrete became insignificant after 90 days.

Table 2
Water sorptivity of LWAC mixes

LWAC mixes	Water sorptivity (mm/min$^{0.5}$)			Initial sorption (mm^3/min^2)		
	7-day	28-day	90-day	7-day	28-day	90-day
Mix A (13.5%)	0.122	0.128	0.130	0.363	0.472	2.484
Mix B (31.9%)	0.116	0.124	0.132	0.526	0.847	2.447

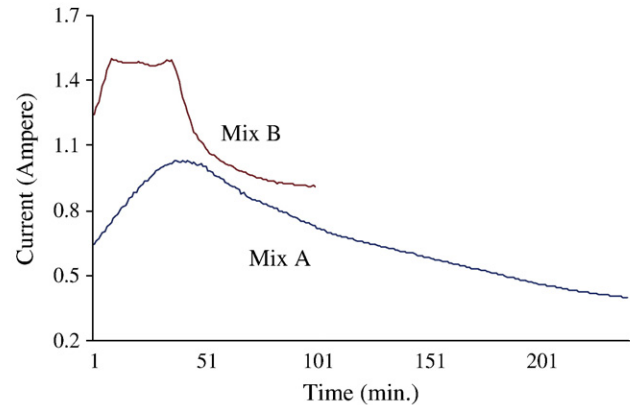

Fig. 5. Current of LWC RCPT at 7 days.

3.2. Chloride permeability of LWAC

Chloride permeability of the LWAC at different ages was measured in terms of the current passing the concrete specimens (in A) versus time (in min). The total charges in terms of Coulombs are presented in Figs. 5–7. As seen in the Figures, the currents passing through concrete mixes showed a rapid initial increase, reaching a peak value at around 30 min, and then dropped steadily with time. The current passing through Mix B is always higher than Mix A because air content in Mix B is higher. The relationship between porosity and permeability of mortar and concrete has been explained by past researchers [23–25]. For concrete adding entraining air admixture, it can be known that if the porosity is high and the pores are interconnected the permeability is also high; on the other hand, if the pores are discontinuous the permeability of the concrete is low although the porosity is high. Therefore, the chloride permeability of LWAC at the age of 90 days becomes more or less constant as seen in Fig. 7 when the average pore size reduced when the age of concrete increased.

During the experiment, most of the cells reached the temperature of 88 °C before the standard duration of 6 h. Only the

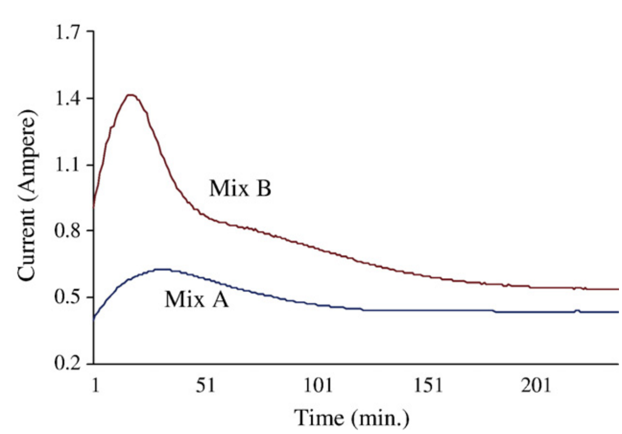

Fig. 6. Current of LWC RCPT at 28 days.

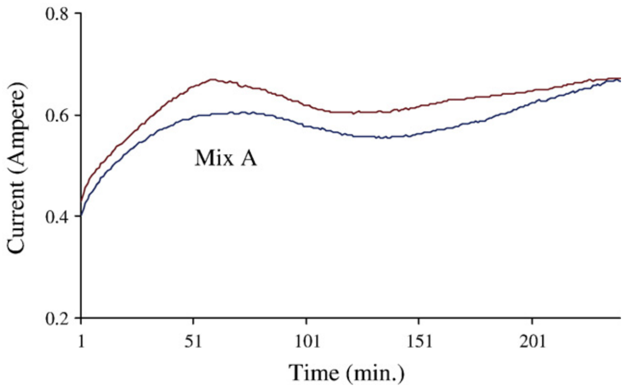

Fig. 7. Current of LWC RCPT at 90 days.

90-day specimens can be tested for 6 h. Therefore, the RCPT may not be the appropriate method for highly porous LWAC. It is because a porous hardened cement matrix has a greater tendency to heat up than a densely hardened cement matrix due to the large current flow through porous media [16]. In order to prevent damaging the cells by the high temperature, the test was stopped. Anyway, both values are much higher than the critical value of high permeability of normal concrete because the permeability of concrete would depend on the porosity of the cement paste rather than the type of aggregate. The RCPT result reflects the interconnected pores' network of concrete in which ions migrate. The use of porous LWA would not lower the permeability of concrete indicated the aggregate/cement paste interface of the LWA is as good as the ordinary normal weight concrete.

The total charges passing the specimens during the first 100 min and 240 min were calculated and listed in Table 3. It can be found that the charge that passed through the LWAC decreases with age for both Mix A and Mix B. Moreover, concrete with higher air content has higher chloride permeability. The phenomenon can be explained as the degree of hydration of cementitious materials improves with age. The reduction in size of capillary pores of the LWAC restricted the penetration of chloride ion through the concrete. The finding indicating the total charges passing Mix B is higher than Mix A confirms that the pores' network in the cement paste was the major effect on the chloride permeability of LWAC. Higher air content resulting in weaker pores' network in the cement paste is the basic cause of higher chloride permeability than the use of porous LWA. The finding suggests that entrained air had little effect on sorptivity but a major effect on chloride permeability.

Table 3
Parameters of RCPT of LWAC

Item	Time	Mix A (13.5%)			Mix B (31.9%)		
		7-day	28-day	90-day	7-day	28-day	90-day
Charge passed (C)	100 min	5256	3292	3376	7095	5870	3644
	240 min	9787	7008	8376	–	10 853	8954

Table 4
Effect of air content on compressive strength of LWAC

Mix No.	Air content	Density (kg/m^3) at 28 days	Compressive strength (MPa)		
			7-day	28-day	90-day
A	13.5%	1020	3.94	4.59	7.12
B	31.9%	990	1.44	2.90	5.08
% decrease in strength			63.5%	36.8%	26.7%
% decrease in strength per % increase of air content			3.45%	2%	1.45%

It is mainly because sorptivity test evaluate the quality of concrete based on surface pore of the concrete while RCPT provides a direct measurement on the chloride ion penetration on the bulk properties of the concrete.

3.3. Chloride permeability versus compressive strength

The effects of air content on compressive strength of LWAC can be seen in Table 4. It was seen that when the air content of LWAC increased from 13.5% and 31.9%, the 28-day and 90-day compressive strength decreased 36.8% and 26.7%, respectively. The phenomenon that compressive strength decreases with the increase in air content is similar to but less in magnitude than the normal weight concrete added with entraining agent [15].

In most cases, capillary and gel pores within the matrix are the key parts in the cement matrix controlling permeability of concrete [17,18] which included cement hydration, strength development of concrete, decrease in the average pore size of the cement paste and an improvement in the aggregate/cement interface [20–22]. In order to identify the relationship between LWAC compressive strength and chloride permeability, the Coulomb charge is plotted against the compressive strength of the concrete. The results as shown in Fig. 8 clearly indicated that the chloride permeability of concrete measured by the total charges passing through the specimen reduces with the increase in compressive strength. The improvement in permeability resistance and decreases the Coulomb charge of the LWACs are attributed to the reduced average pore size as well as the improvement of the interfacial zone which increase the resistance to the ingress of ions.

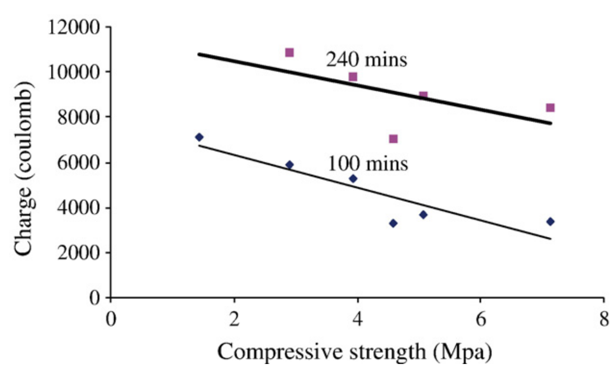

Fig. 8. Relationship between compressive strength and chloride permeability.

4. Conclusion

Based on the above test investigation and data analysis, the following conclusions can be drawn:

1. For lower-graded strength lightweight concrete with a density of 1000 kg/m^3, sorptivity of surface concrete is not particularly high when compared to that of normal concrete with high w/c ratio. The effect of addition of air entraining agent to lightweight aggregate concrete on water sorptivity of the concrete became insignificant after 90 days.
2. The weaker pores' network in the cement paste is the basic cause for the high chloride permeability of concrete than the use of porous LWA. The concrete with designated 0.4 w/c ratio is not dense enough to stop the chloride ion penetrate through the concrete before concrete mature at 90 days.
3. The improvement in permeability resistance and decreases the Coulomb charge of the LWACs are attributed to the reduced average pore size as well as the improvement of the interfacial zone which increase the resistance to the ingress of ions.

Acknowledgements

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