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WATER AND CHLORIDE ION PENETRATION RESISTANCE OF HIGH-STRENGTH ULTRA LIGHTWEIGHT CEMENT COMPOSITE

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ABSTRACT

Durability is a significant issue to focus on for a newly developed structural lightweight cement composite (ULCC). This paper presents an experimental study to evaluate the resistance of ULCC to water and chloride ion penetration. Chloride penetrability and sorptivity were evaluated for ULCC (unit weight about 1450 kg/m^3) and compared with those of a normal weight concrete (NWC), a lightweight aggregate concrete (LWC), and an ultra lightweight composite with propriatary cementitious binder (DB) (unit weight about 1450 kg/m^3) at similar compressive strength of about 60 MPa. Rapid chloride penetrability test, rapid migration test, water absorption (sorptivity) test, and water peremability test were conducted on these mixtures. Results indicate that ULCC and DB had comparable performance. Compared with control LWC and NWC at similar strength level, the ULCC and DB mixtures had higher resistance to chloride ion penetration and lower water absorption. They were virtually impermeable to water penetration.

Key-words: chloride penetration, ultra lightweight cement composite, durability, permeability, sorptivity.

INTRODUCTION

A type of ultra lightweight cement composite (ULCC) was developed, using microspheres as filler (cenosphere), to achieve low unit weight with high compressive strength. The distinct advantage of the ULCC lies in its ultra low unit weight which is 60% that of conventional concrete, and still possesses high compressive strength of 60 MPa. In addition, the ULCC is highly versatile for customised tailoring in various applications, especially for offshore floating structures. As the ULCC is new novel structural cement composite, there is very limited information available on its behaviour and properties. Basic mechanical properties of the ULCC had been reported in a separate paper[1]. Objective of current paper is to provide information relating to durability of the ULCC in terms of transport properties including resistance to chloride-ion penetration, sorptivity and water permeability. The ULCC was evaluated in comparison with a normal weight concrete (NWC) and a lightweight aggregate concrete (LWC) with similar strength. In addition, the ULCC was also compared against a ready-mix proprietary mixture of similar compressive strength and density. Water absorption, water permeability, and chloride penetration tests were conducted, and results were evaluated to understand the transport properties of the ULCC.

EXPERIMENTAL STUDIES

Materials and mixture proportions

The ULCC was designed using ordinary Portland cement (OPC – ASTM Type I and EN CEM I 52.5N), silica fume, and lightweight filler called cenosphere. Another mixture, with similar mechanical properties as the ULCC, was designed with similar mixture proportions as the ULCC but used a proprietary cementitious binder. This mixture was denoted as DB. In both mixtures, 0.9% of 6 mm polyvinyl alcohol (PVA) fibre by volume of the composite was used. Both mixtures had similar water−to−cementitious material ratio (w/cm) of 0.35 (Table 2).

A normal weight aggregate concrete (NWC) and a lightweight aggregate concrete (LWC) with 28 - day cubic compressive strength similar to that of the ULCC were included for comparison. Bulk ingredients of the NWC (water - cement ratio, w/c = 0.45) were water, OPC, quartz sand as fine aggregate and granite of 20 mm as coarse aggregate. The LWC (w/cm = 0.35) consisted of similar ingredients as the NWC, except that the coarse aggregate was 4 - 8 mm expanded clay type lightweight aggregate with a particle density of 1.28 to 1.35 g/cm^3, and silica fume was used to achieve required strength. Grading of the sand meets the requirement of ASTM C 33[2]. Table 1 shows chemical composition of the cement and silica fume, and Table 2 shows the mixture proportions of all the mixtures.

Table 1 – Chemical properties of silica fume and Portland cement

Elements (wt. %)	Al_2O_3	SiO_2	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	LOI
Portland cement	4.2	20.5	3.2	65.3	4.1	0.17	0.50	2.1	2.2
Silica fume	-	95.5	-	-	-	-	-	-	2.4

Table 2 – Comparison of properties of different mixtures

	w/cm	Mixture proportion* W : (c+s) : FA : CA	Flow table, mm	Slump, mm	1-day Unit weight, kg/m^3	28-day compressive strength, MPa
ULCC	0.35	0.35 : (0.92 + 0.08) : 0.42 : -	165	-	1465	59
DB	0.35	0.35 : (1.00**) : 0.42 : -	173	-	1480	62
LWC	0.35	0.35 : (0.92 + 0.08) : 1.59 : 0.82	-	87	1870	58
NWC	0.45	0.45 : 1.00 : 1.57 : 2.57	-	90	2350	68

*w – water, c+s – cement and silica fume, FA – fine aggregate (quartz sand for LWC and NWC, lightweight filler for ULCC & DB), CA – coarse aggregate (granite for NWAC, expanded clay lightweight aggregate for LWAC).
** Proprietary cementitious binder

Specimen preparation and testing

In preparing ULCC & DB, the cementitious binder and lightweight filler were first dry - blended in an 80 - litre pan mixer before water was added. When the mixture was homogeneously mixed with suitable fluidity, usually within 5 minutes after adding the water and superplasticizer, the fibres were then added and mixing continued for another 5 minutes. The resulting mixture was then sampled to determine unit weight and workability in terms of flow table consistency.

The flow table consistency test was chosen as a workability indicator for the ULCC and DB as it is suitable for grouts and mortars. For the control LWC and NWC, slump test was used instead as a workability indicator. After mixing, the mixture was poured into different sets of moulds for various mechanical and durability tests, and compacted using a table vibrator. The moulded specimens were covered with moist cloths and protected from drying with a plastic sheet. The ULCC specimens were demoulded within 48 hours after casting, and cured in a moist room at relative humidity of 100% and temperature of 28 ± 2 ^{o}C until 28 days. The NWC and LWC specimens were demoulded within 24 hours and moist‑cured for 7 days in the same moist room followed by 21 days of air‑drying at a temperature of 30 ± 2 ^{o}C. The purpose of curing 28 days for ULCC is due to the high content of cementitious material contents. Three specimens were prepared for each type of test at each test age. Table 3 shows the list of the material properties evaluated, the relevant test standards used and type of test specimens involved.

Table 3 – List of material properties evaluated and relevant test methods

Properties	Test standard	Specimen type and size
Flowability (using flow table)	BS EN 1015-3:1999	--
Density of hardened specimens	BS EN 12390-7: 2009	100 mm cube
Compressive strength	BS EN 12390-3: 2009	100 mm cube
Resistance to chloride-ion penetration	ASTM C 1202 – 05 NT Build 492	Ø100×50 mm cylinder
Water sorptivity	ASTM C 1585 – 04	Ø100×50 mm cylinder
Water permeability	BS EN 12390 - 8	Ø100×200 mm cylinder

Rapid chloride penetrability test (RCPT)

Rapid chloride penetrability test was carried out at 28 days in accordance with ASTM C 1202[3] using cylindrical specimens (Table 3). Total charges passed during the test were obtained from integration of current over the test duration (6 hours).

Rapid migration test (RMT)

Migration coefficient (or apparent diffusion coefficient) was determined according to NT Build 492[4] method using specimens (Table 3) after 28 days of curing. 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 about 24 hours. After that the specimen was split into two halves (lengthwise). The split surfaces were sprayed with 0.1 N $AgNO_3$ solutions to determine chloride-ion penetration depth, which was then used to calculate migration coefficient according to the standard.

Sorptivity (absorption) test

After 28 days, water absorption was determined according to ASTM C 1585[5] by measuring the increase in mass of the specimens as a function of time with one surface exposed to water. The test consisted of registering the increase in mass of a cylinder specimen (Ø100X50 mm) at given intervals of time when permitted to absorb water by capillary suction. Only one surface of the specimen was allowed to be in contact with water, with the depth of water around 3mm (Figure 1). After the test, sorptivity (kg/m^2 h$^{0.5}$) were calculated as the slope of regression curve of the quantity of water absorbed by a unit surface area versus square root of elapsed time from 1 to 24 hours according to Buyle‑Bodin and Hadjieva‑Zaharieva[6].

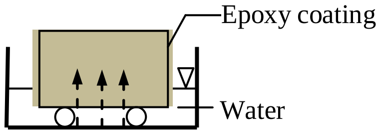

Figure 1 – Schematic diagram of sorptivity test (specimen dimension: Ø100×50mm).

Water permeability test

Depth of water penetration into mixtures ULCC and DB specimens was measured according to BS EN 12390-8[7] with modified conditions including the curing age, test duration, water pressure used, and boundary condition. The standard specifies a curing age of 28 days, a test duration of 3 days, and a water pressure of 0.5 MPa. In this study, however, the specimens were tested at earlier age, i.e. 7 days for DB and 3 days for ULCC. Reason for testing at an earlier age was due to the high density of the mixtures, so it would be difficult to get water penetration if the specimens were cured longer. In the test, a water pressure of 0.75 MPa was applied to the specimens for 14 days. For each mixture, three cylinder specimens (Table 3) were used for this test. The circumference surface of the specimen was coated with epoxy after surface drying before the test to ensure one dimensional flow of water. The two flat faces of the cylinders were ground to prevent water leakage under pressure. After the test, each specimen was split into two halves to determine the depth of water penetration. The water permeability coefficient can be calculated according to the Valenta's equation[8].

RESULTS AND DISCUSSION

Unit weight and compressive strength

Properties of the mixtures ULCC and DB are presented and discussed in comparison to those of the controls NWC and LWC at similar strength level. Workability, unit weight, and strength of the mixtures are presented in Table 2. The fresh ULCC and DB mixtures had similar average flow table values of 165 and 173 mm, respectively, while the fresh LWC and NWC had similar average slumps of 87 and 90 mm, respectively. All mixtures were properly compacted at such flowability. Unit weight of the ULCC and DB at 1 day was 1465 and 1480 kg/m^3, respectively. The LWC and NWC had higher unit weight at 1870 and 2350 kg/m^3, respectively. The 28−day compressive strength for the four mixtures ranged from 58 to 68 MPa.

Resistance to chloride-ion penetration

Table 4 summarizes resistance of different mixtures after a 28-day curing period to chloride-ion penetration determined by two methods as described above. Total charge passed through ULCC and DB according to ASTM C1202 test were only 153 and 103 coulombs which was comparable to that of the control LWC (242 C), but much lower than that of the control NWC (2890 C). Accordingly, the mixtures of ULCC, DB, and LWC were classified as "very low" chloride penetrability while the NWC was classified as ''moderate" chloride penetrability according to ASTM standard (Table 5). The lower charges passed through the mixtures ULCC, DB, and

LWC in comparison to that through the NWC might be attributed to lower w/cm, silica fume used, and curing in the former. As mentioned earlier, the LWC and NWC were cured in moisture condition for 7 days, whereas the ULCC and DB were cured in moist room for 28 days. The longer moist curing for the ULCC and DB increased cement hydration and pozzolanic reaction of silica fume and refined pore structures, therefore improved their resistance to chloride-ion penetration. Comparing LWC and NWC, the LWC had internal curing effect because of water absorbed in the LWA which contributed to continuous cement hydration and high resistance to chloride-ion penetration. However, it should be mentioned that the electrical conductivity of cementitious materials are affected by pore structure and pore solution chemistry of the test materials [9,10]. Therefore, ASTM C1202 method may exaggerate the effectiveness of the silica fume on the reduction of penetrability and the results should be interpreted with caution.

The migration coefficients of ULCC and DB are similar as shown in Table 4 and the coefficients are in the same order of 10^{-13}. Both the ULCC and DB had migration coefficient one order lower than that of LWC (in the order of 10^{-12}), two orders lower than that of NWC (in the order of 10^{-11}).

Both test methods showed that the ULCC and DB had high resistance to chloride ion penetration. With the similar compressive strength, NWC had the lowest resistance to chloride ion penetration which is likely due to its higher w/c without silica fume, shorter moist curing leading to a more porous paste matrix which induces easier penetration of chloride ions.

Table 4 – Resistance to chloride penetration and sorptivity of mixtures

	w/cm	Total charge passed, Coulombs		Rapid migration coefficient, m^2/s		Sorptivity, $\times 10^{-2}$ $kg/m^2h^{0.5}$	
		Data	Average	Data	Average	Data	Average
		147		3.7		1.8	
ULCC	0.35	150	153 (8)	3.9 $\times 10^{-13}$	4.1 (0.5) $\times 10^{-13}$	1.8	1.8 (0.1)
		162		4.6		1.7	
		93		3.1		2.0	
DB	0.35	105	103 (9)	3.4 $\times 10^{-13}$	3.8 (0.9)$\times 10^{-13}$	2.8	2.4 0.4)
		110		4.8		2.4	
		244		2.7		5.2	
LWC	0.35	251	242 (10)	2.3 $\times 10^{-12}$	2.6 (0.2) $\times 10^{-12}$	5.5	5.7 (0.6)
		232		2.7		6.4	
		2907		1.7		8.8	
NWC	0.45	2970	2890 (90)	1.5 $\times 10^{-11}$	1.5 (0.3) $\times 10^{-11}$	8.7	8.3 (0.8)
		2792		1.2		7.4	

Note: The data in brackets are standard deviations.

Table 5 – Classification of charge passed in coulombs according to ASTM C 1202

Charge passed, Coulombs	Chloride ion penetrability	Typical of
> 4,000	High	High w/c ratio
2,000-4,000	Moderate	0.4-0.5 w/c ratio
1,000-2,000	Low	w/c ratio < 0.4
100-1,000	Very Low	Latex Modified concrete
< 100	Negligible	Polymer concrete

Sorptivity (Water absorption)

Table 4 presents the sorptivity values of the different mixtures determined after a 28-day curing period according to ASTM C 1585. Sorptivity test was conducted to determine the different capillary suctions (absorption) at similar strength level. Cumulative water absorption per unit area of the specimen up to 24 hours was fitted using linear regression and the slope provided the sorptivity. Figures 2 – 5 shows weight increase of each mixture due to water absorption against √time based on 3 specimens each. Figure 6 shows comparison of those mixtures ULCC, DB, LWC and NWC at similar strength level in terms of water absorption capacity against √time.

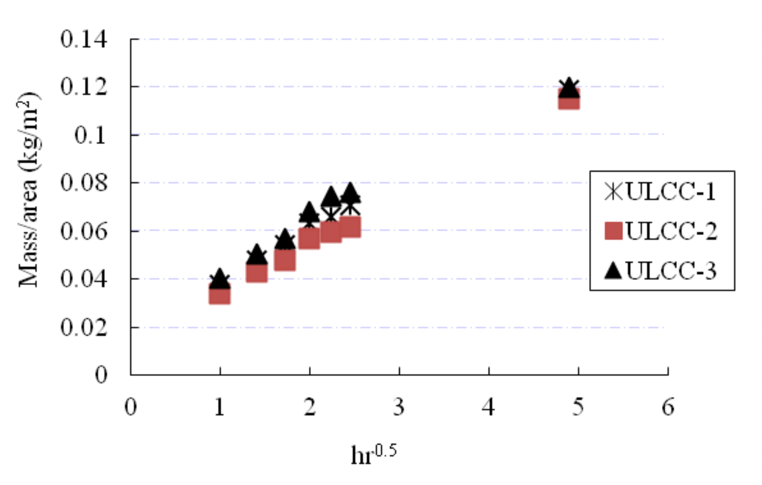

Figure 2 – Weight increase of ULCC due to water absorption against √time.

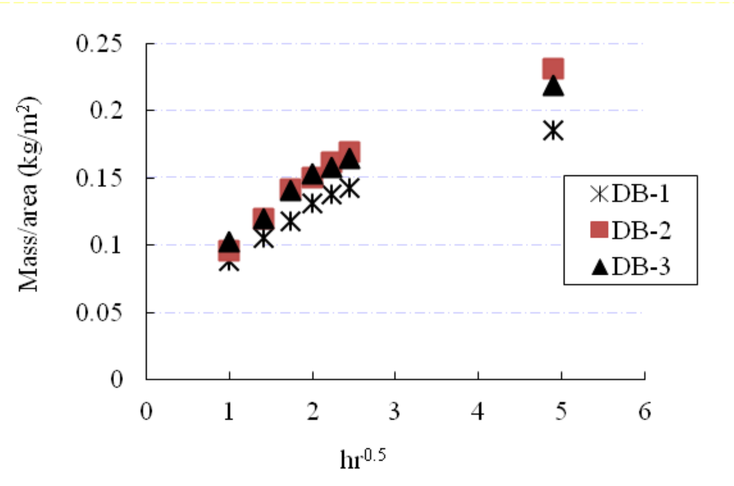

Figure 3 – Weight increase of DB due to water absorption against √time.

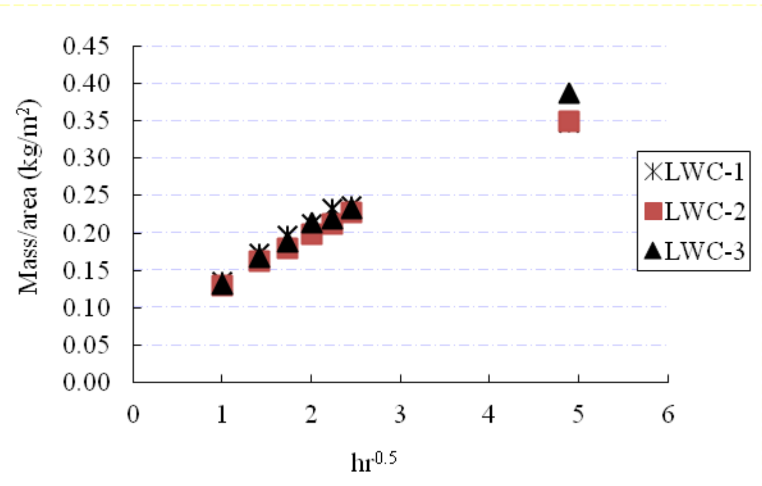

Figure 4 – Weight increase of LWC due to water absorption against √time.

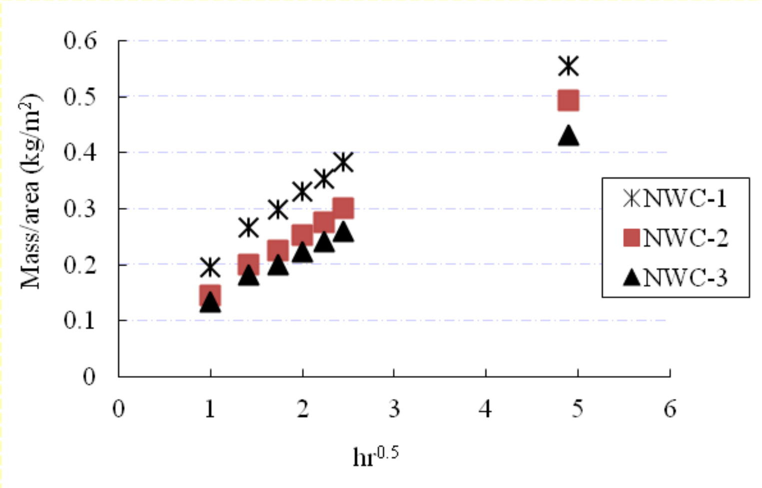

Figure 5 – Weight increase of NWC due to water absorption against √time.

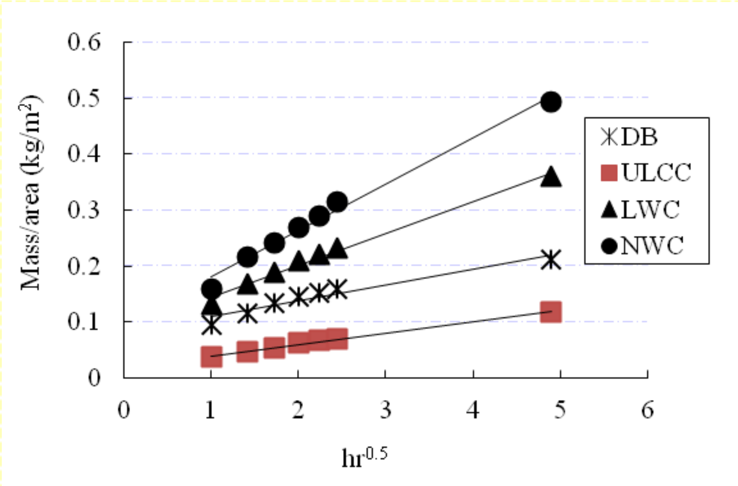

Figure 6 – Average weight increase of all mixtures due to water absorption against √time.

Sorptivity of the LWC is more than double of that of ULCC and DB. The sorptivity of NWC is significantly higher than those of ULCC and DB as shown in Table 4. The results indicated that mixtures ULCC and DB had higher resistance against water absorption compared with LWC and NWC which means that the sorptivity of ULCC and DB as newly developed construction materials were lower than those of conventional concrete mixtures at a similar strength level. Reasons for the lower sorptivity of the ULCC and DB may be attributed to the lower w/cm, incorporation of silica fume, and longer moist curing as mentioned earlier. The fibers used in ULCC and DB also reduced the frequecy of micro-crackings and improved the resistance to water absorption. The higher sorptivity in the NWC could be attributed mainly to its higher w/c compared to other mixtures. In addition, the existence of micro-cracks in the interfacial transition zone around stiff coarse aggregate in the NWC maybe another reason for its higher sorptivity.

Water permeability

Water penetration depth of the ULCC and DB were measured and presented in Table 6. It was found that no water penetration was found after 14 days of exposure to water pressure of 0.75

MPa. It indicates that the ULCC is virtually impermeable. The impermeability of ULCC and DB could be attributed to the low w/cm, incorporation of silica fume, absence of coarse aggregates, reduced frequencies of microcracking, and disconnectivity of the pores.

Table 6 – Water permeability of cement-based mixtures

	w/cm	28-day compressive strength, MPa	Water penetration depth, mm	Water permeability coefficient, $\times 10^{-13}$ m/s	Test duration, days	Specimen age, days
ULCC	0.35	59	0	0	14	3
DB	0.35	62	0	0	14	7
LWC1*[11]	0.38	50	12	1.1	14	7
NWC1*[11]	0.38	49	21	0.9	14	7

*LWC1 and NWC1 did not contain silica fume

Potential applications

In practice, high performance LWC is generally used where the applications require a high structural efficiency with a reduction in dead weight such as in high-rise buildings, floating structures, and long-span bridges. A material with high structural efficiency is one that has high specific strength (strength-to-density ratio). An example is the Heidrun tension leg platform which was constructed using high-strength LWC. Many offshore and marine structures are floating structures at some point of their life as they are often constructed in shipyards or graving docks and must be towed to sites. Thus, there is a need to reduce the mass and improve the structural efficiency of these structures, especially where part of the voyage includes shallow water conditions that will mandate lower draft requirement for the structures. Structural efficiency is increased for material with similar strength but lower density since it is directly related to specific strength. The improvement in structural efficiency is even more pronounced for lightweight structures in submerged conditions due to water buoyancy. With a high structural efficiency, the ULCC is suitable for shipbuilding and marine structures based on sandwich design concept. Typical lightweight sandwich design consists of a lightweight core structure sandwiched between two surface steel plates. Such design has been identified as feasible in shipbuilding [12].

Conclusions

The ultra lightweight cement composites and control LWC and NWC were designed with similar 28 - day compressive strength. The results from the various tests in this study showed that the performance of the ULCC and DB (made with a proprietary cementitious binder) was comparable. The mixtures ULCC and DB had very low chloride - ion penetrability based on ASTM C1202 test which was similar to that of LWC. However, the NWC had moderate chloride penetrability. The migration coefficient of ULCC and DB were in the same order, but significantly lower than that of NWC and LWC. The sorptivity of ULCC and DB were also lower than those of NWC and LWC. The ULCC and DB were found virtually impermeable when exposed to water penetration under a pressure of 0.75 MPa.

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