Permeability of high-performance concrete incorporating presoaked lightweight aggregates for internal curing

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This paper presents an experimental study on the effect of presoaked lightweight aggregates (LWAs) for internal curing on water permeability, water absorption and resistance of concrete to chloride-ion penetration in comparison with those of a control concrete and a concrete with shrinkage reducing admixture (SRA) of similar water/cement ratios (w/c). In general, the concretes with LWA particles had initial water absorption, sorptivity and water permeability similar to or lower than those of the control concrete and the concrete with SRA. The charges passed, chloride migration coefficient and chloride diffusion coefficient of such concretes were in the same order as those of the control concrete and the concrete with SRA. However, the incorporation of the LWAs for internal curing reduced unit weight, compressive strength and elastic modulus of the concrete. Comparing the LWAs of different sizes for internal curing, finer particles were more efficient in reducing the shrinkage and generally resulted in less reduction in the unit weight, compressive strength, and elastic modulus. However, the increase in the more porous crushed LW particles in concrete seems to increase the penetration of chloride ions in the concrete. The concrete with SRA had initial water absorption, sorptivity, water permeability and resistance to chloride ion penetration comparable with those of the control concrete. The use of SRA in concrete does not affect the elastic modulus of the concrete, except for a minor influence on the compressive strength of the concrete.

Introduction

There is an increased use of high-performance concrete (HPC) in structures exposed to severe environments for durability considerations. Such concrete typically has lower water-to-cement (w/c) ratios and higher autogenous shrinkage at early age compared with ordinary concrete. The high autogenous shrinkage of such low w/c concrete is generated mainly as a result of rapid reduction of internal relative humidity and self-desiccation caused by cement hydration where the volume of hydration products is less than the combined volume of cement and water. Since concrete is relatively weak at early age, the high autogenous shrinkage may lead to cracking if concrete members are restrained (Lee et al., 2003; Neville and Aitcin, 1998; Persson, 1997). Various approaches have been proposed to reduce the autogenous shrinkage and cracking of such concrete, for example incorporating presoaked or saturated lightweight aggregate (LWA) or incorporating shrinkage reducing admixture (SRA) in concrete.

Philleo (1991) suggested incorporating presoaked LWA in concrete to provide an internal source of water necessary to accommodate that consumed by cement hydration and to reduce autogenous shrinkage and cracking. Since then, a lot of research has been carried out in this area and a comprehensive review was published by Hoff (2003). It has been found that with sufficient amounts of saturated LWAs incorporated in concrete the autogenous shrinkage and its associated stresses can be eliminated from the concrete. The efficiency of the internal curing and reduction in the autogenous shrinkage were affected by the size of LWA incorporated. Smaller-size LWAs are more efficient in reducing autogenous shrinkage as the distances between the smaller particles are shorter so...
that the water inside the LWA does not have to travel far to contribute to the internal curing. It has also been found (Bentz et al., 2002) that the incorporation of presoaked fine LWAs in the concrete does not appear to have adverse effects on the mechanical properties of the concrete and, in many instances, small improvements have been noted.

Most of the published research focuses on the use of LWAs to improve cement hydration and to reduce the autogenous shrinkage and cracking. Only limited information is available on how the use of such porous LWAs affects the chloride penetrability in concrete. Results by Lam and Hooton (2005) show that the use of fine LWAs for internal curing with a w/c of 0.35 reduced the total charge passed in comparison with the control concrete according to ASTM C 1202-05 (ASTM, 2006a) test. The fine LWA used had a 24 h water absorption of about 17% and a bulk specific gravity of 1590 kg/m³ and the concrete was moist cured. However, no information is available on how the use of such porous LWA affects water permeability, water absorption and chloride diffusion in concrete. Nor is information available on how the fine LWAs influence the concrete permeability compared with coarse ones, although fine LWAs are known to be more efficient to reduce autogenous shrinkage. Such information is essential to ensure the resistance of concrete to the penetration of harmful substances and thus durability of structures.

This research was carried out to evaluate the effect of presoaked LWAs of different sizes in concrete on water permeability, water absorption and resistance of the concrete to chloride-ion penetration as permeation, absorption and diffusion are the main mechanisms for the penetration of harmful substances in concrete. The amount of the LWA incorporated was determined according to the equation proposed by Bentz et al. (2005) for internal curing. Mechanical properties and autogenous shrinkage of the concrete were also determined and presented. The results were compared with those of the control concrete and concrete with a SRA at similar w/c ratio of about 0.39.

### Experimental details

**Concrete mixtures**

Five concretes with w/c ratios of 0.39 ± 0.01 were included in this study, and their mixture proportions are summarised in Table 1. Mixture NC was a control concrete. Mixtures RS1 to RS3 incorporated LWA of different sizes for internal curing. Mixture RS4 incorporated SRA for comparison. For mixtures RS1 to RS3, the amount of LWA required to provide sufficient water for internal curing was determined based on the following equation proposed by Bentz et al. (2005)

\[
M_{\text{LWA}} = \frac{C_f \times CS \times \alpha_{\text{max}}}{S \times \phi_{\text{LWA}}}
\]

where \(M_{\text{LWA}}\) is mass of (dry) LWA needed per unit volume of concrete (kg/m³); \(C_f\) is cement factor (content) for concrete mixture (kg/m³); \(CS\) represents chemical shrinkage of cement (g of water/g of solid cement); \(\alpha_{\text{max}}\) is maximum expected degree of hydration of cement; \(S\) is degree of saturation of aggregate (0 to 1); \(\phi_{\text{LWA}}\) denotes absorption of LWA (kg water/kg).

The cement factor \((C_f)\) was obtained from the mixture proportions. The chemical shrinkage \((CS)\) of cement was calculated based on the cement composition to be 0.066 g water/g of solid cement. The expected degree of hydration of cement was conservatively taken as 1 for a w/c ratio of 0.38 according to Bentz et al. (2005). The 24 h water absorption was used for \(\phi_{\text{LWA}}\). About 94% to 98% of the water absorbed in 24 h (Table 2) could be desorbed from the LWAs when exposed to a relative humidity (RH) of about 85% (over saturated potassium chloride solution). The desorbed water would be useful for internal curing, hence the degree of saturation of aggregate \((S)\) was roughly taken as the percentage of water which can be desorbed as listed in Table 2.

In these three concrete mixtures, the LWAs replaced the corresponding fractions of normal weight aggregates (NWAs) so that the volumes of aggregates in various size fractions were kept the same for all the

### Table 1. Mixture proportion of the concretes

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>w/c</th>
<th>Cement</th>
<th>Mixing water</th>
<th>Dry NWA</th>
<th>Dry LWA</th>
<th>SP: l/m³</th>
<th>SRA: l/m³</th>
<th>LWA% of aggregate volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>0.38</td>
<td>500</td>
<td>191</td>
<td>514</td>
<td>171</td>
<td>76</td>
<td>850</td>
<td>2.5</td>
</tr>
<tr>
<td>RS1</td>
<td>0.38</td>
<td>500</td>
<td>194</td>
<td>514</td>
<td>171</td>
<td>76</td>
<td>850</td>
<td>2.6</td>
</tr>
<tr>
<td>RS2</td>
<td>0.39</td>
<td>500</td>
<td>195</td>
<td>514</td>
<td>171</td>
<td>76</td>
<td>850</td>
<td>2.6</td>
</tr>
<tr>
<td>RS3</td>
<td>0.40</td>
<td>500</td>
<td>200</td>
<td>514</td>
<td>171</td>
<td>76</td>
<td>850</td>
<td>1.9</td>
</tr>
<tr>
<td>RS4</td>
<td>0.39</td>
<td>500</td>
<td>188</td>
<td>514</td>
<td>171</td>
<td>76</td>
<td>850</td>
<td>1.7</td>
</tr>
</tbody>
</table>

* The absorption capacity of the dry sand (<4.75 mm) was 0.6%.
concrete mixtures. In the concrete with SRA (RS4), water was reduced owing to the incorporation of SRA.

**Materials used**

ASTM type I normal Portland cement with a specific gravity of 3150 kg/m³ and fineness of 347 m²/kg was used for the concretes. A naphthalene-based superplasticiser with 40% solids was used for workability purpose. A commercially available SRA (glycol derivative) with a specific gravity of approximately 930 kg/m³ was used for mixture RS4.

Granite aggregate with a maximum size of 9.5 mm and natural sand were used for all the concretes. Specific gravities of the coarse and fine aggregates were 2610 and 2560 kg/m³ respectively. Water absorption capacity of the dry normal weight fine aggregate was approximately 0.6%. The aggregates were separated into four fractions of 

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Particle Size: mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>F6.5</td>
<td>4.75–9.50</td>
</tr>
<tr>
<td>F6.5</td>
<td>2.36–4.75</td>
</tr>
<tr>
<td>F4.5</td>
<td>1.18–2.36</td>
</tr>
<tr>
<td>LW sand</td>
<td>&lt;1.18</td>
</tr>
</tbody>
</table>

... and then recombined to satisfy ASTM C 33-03 (ASTM, 2006c) grading requirements.

Lightweight aggregates used in mixtures RS1 to RS3 were expanded clay with four size fractions corresponding to those of the aforementioned NWAs. The properties of the LWAs are summarised in Table 2. The LWAs with sizes > 1.18 mm had a round shape, a smooth surface texture and similar 24 h water absorption of about 11.6% to 13.0%. Whereas the lightweight sand with sizes < 1.18 mm consisted of crushed particles, and thus had more open pores and much higher water absorption than the others. Because of the nature of the crushed particles and more open pores, it is difficult accurately to determine the absorption of the aggregate and to obtain saturated surface dry aggregate. The absorption value for the LWA fraction < 1.18 mm given in Table 2 was, therefore, an approximation. The desorption of the LWAs presoaked for 24 h ranged from 94% to 98% by mass of water absorbed under relative humidity of about 85% (over saturated potassium chloride salt solution at 25°C).

**Concrete preparation and curing**

The concretes were mixed in a pan mixer at an ambient temperature of about 30°C. Before concrete mixing, the LWA was pre-soaked in water for 24 h. Water in excess of the amount required for the aggregate absorption and concrete mixing was used in order to ensure that all the aggregate particles were fully submerged during soaking. After 24 h the excess water was removed and the mass added into the mixer included that of oven-dried aggregate, water absorbed by the aggregate in 24 h (Table 2) and mixing water based on concrete mixture design (Table 1). Prior to soaking, the LWA was oven dried and cooled down to room temperature.

For each concrete mixture, specimens listed in Table 3 were cast for determining the unit weight, compressive strength, modulus of elasticity, water permeability, water absorption, resistance to chloride-ion penetration and autogenous shrinkage of the concrete.

The moulded specimens were covered with wet linen and plastic sheet and left in the laboratory during the curing period. The moulded specimens were cut into smaller sizes as required for testing.

**Table 2. Properties of lightweight aggregates**

<table>
<thead>
<tr>
<th>Aggregate type</th>
<th>Particle size: mm</th>
<th>Dry particle density: kg/m³</th>
<th>24 h water absorption: % by mass of the LWA</th>
<th>Desorption (85% RH): % of water absorbed in 24 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>F6.5</td>
<td>4.75–9.50</td>
<td>1100</td>
<td>13.0</td>
<td>94</td>
</tr>
<tr>
<td>F6.5</td>
<td>2.36–4.75</td>
<td>1300</td>
<td>11.6</td>
<td>94</td>
</tr>
<tr>
<td>F4.5</td>
<td>1.18–2.36</td>
<td>1000</td>
<td>12.8</td>
<td>98</td>
</tr>
<tr>
<td>LW sand</td>
<td>&lt;1.18</td>
<td>1600</td>
<td>~ 25.0</td>
<td>95</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Properties to be determined</th>
<th>Curing age: days</th>
<th>Curing conditions</th>
<th>Size of specimen</th>
<th>Number of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density and compressive strength</td>
<td>7, 28, 91</td>
<td>7-day moist curing, lab air afterwards</td>
<td>100 × 100 × 100 mm cubes</td>
<td>9</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>28</td>
<td>7-day moist curing</td>
<td>ø100 × 200 mm cylinders</td>
<td>3</td>
</tr>
<tr>
<td>Water permeability</td>
<td>7</td>
<td>7-day moist curing + 21-day exposure in lab air</td>
<td>ø75 × 150 mm cylinders</td>
<td>3</td>
</tr>
<tr>
<td>Water absorption</td>
<td>28</td>
<td>7-day moist curing + 21-day exposure in lab air</td>
<td>ø100 × 50 mm discs cut from ø100 × 200 mm cylinders with the top and bottom parts removed</td>
<td>3</td>
</tr>
<tr>
<td>Chloride penetrability (ASTM C 1202)</td>
<td>28</td>
<td>7-day moist curing + 21-day exposure in lab air</td>
<td>ø100 × 200 mm cylinders with the top and bottom parts removed</td>
<td>3</td>
</tr>
<tr>
<td>Migration coefficient (NT Build 492)</td>
<td>28</td>
<td>7-day moist curing</td>
<td>ø100 × 200 mm cylinders with the top and bottom parts removed</td>
<td>3</td>
</tr>
<tr>
<td>Diffusion coefficient (AASHTO T259)</td>
<td>28</td>
<td>7-day moist curing</td>
<td>300 × 300 × 90 mm slabs</td>
<td>3</td>
</tr>
<tr>
<td>Autogenous shrinkage</td>
<td>Refer to the section on test method</td>
<td>75 × 75 × 300 mm prism</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

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first 24 h, except for the specimens for autogenous shrinkage measurement. After demoulding at 24 h, the specimens were transferred to a fog room and cured at about 28°C until 7 days. The specimens were then exposed to laboratory air (relative humidity about 80–85 %) at a similar temperature until the time of testing except for those used for the water permeability test (Table 3).

**Test methods**

**Unit weight, compressive strength, and modulus of elasticity**

The unit weight, compressive strength and elastic modulus of the concretes were determined according to British Standard BS EN 12390: Part 7 and Part 3 and BS 1881-121 (BSI, 2000b, 2000a, 1983).

**Water absorption**

The initial water absorption and the sorptivity of the concrete were tested according to ASTM C 1585-04 (ASTM, 2006b) by measuring the increase in the mass of the specimens resulting from the absorption of water as a function of time when one surface of the specimen was exposed to water.

Three concrete specimens with a thickness of 50 mm and a diameter of 100 mm were used for the test. The specimens were cured in the fog room for 7 days followed by exposure in laboratory air for 21 days. After that, the specimens were placed in an environmental chamber at a temperature of 50°C and relative humidity of 80% for 3 days. The specimens were then stored in a sealable plastic bag and placed at 23 ± 2°C for 15 days. The specimens were coated with epoxy on the side surface before the absorption test to ensure one-dimensional absorption. The top surface was covered to prevent evaporation during the test. The increase in the mass of the specimens with time was monitored.

After the test, the following two parameters were calculated according to Buyle-Bodin and Hadjieva-Zaharieva (2002)

(a) the initial water absorption (kg/m²) – is the quantity of water absorbed by a unit surface area during the first hour of the test

(b) the sorptivity (kg/m² h^0.5) – is the slope of the regression curve of the quantity of water absorbed by a unit surface area against square root of the elapsed time from 1 to 24 h.

According to Balayssac (1992), the initial water absorption is affected by the volume of large capillary pores with a medium size of 1-25 μm and the sorptivity is affected by the water absorption of fine capillary pores with a medium size of 0-04 μm.

**Water permeability**

Depth of water penetration in the concrete under a pressure of 0.75 MPa was determined at 7 days according to BS EN 12390-8 (BSI, 2000c) with some modifications. The reason for a 7-day test was attributable to the relatively low pressure of the equipment, thus making it difficult to achieve water penetration if the concrete was cured for longer.

For each concrete mixture, three cylinder specimens with a diameter of 75 mm and a height of 150 mm were used for this test. The specimens were roughened on the circumference surface immediately after demoulding, and cured in a fog room until 7 days. The circumference surface of the specimens was coated with epoxy mortar after surface drying to ensure one-dimensional flow of water. The two flat faces of the cylinders were then ground to prevent water leakage under pressure. The weight of the concrete cylinders coated with hardened epoxy mortar was determined before and after the permeability test.

During the test, a water pressure of about 0.75 MPa was applied to the concrete specimen for about 14 days. After that, the face of the specimen exposed to the water pressure was wiped dry and the weight of the specimen was recorded. The specimen was then split into two halves for determining the depth of water penetration. The water permeability coefficient can be calculated according to the Valenta’s equation (Valenta, 1970)

\[ K_p = \frac{d^2 v}{2 t h} \quad (2) \]

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

The value of \(v\) can be calculated from Equation 3

\[ v = \frac{m}{A d \rho} \quad (3) \]

where \(m\) represents the gain in mass (g); \(A\) is cross-sectional area of the specimen (mm²), and \(\rho\) is density of the water (~1000 kg/m³).

**Resistance to chloride-ion penetration**

Three methods were used to evaluate the concrete resistance to chloride-ion penetration.

*Chloride penetrability test.* The chloride penetrability test was carried out at 28 days according to ASTM C 1202-05 (ASTM, 2006a). The total charge passed through the concrete after 6 hours was obtained from integration of current over the time duration.

*Rapid migration test.* Migration coefficient (also referred to as apparent diffusion coefficient) was de-
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determined according to NT BUILD 492 (NT BUILD, 1999) test method using three specimens with a diameter of 100 mm and a depth of 50 mm.

The concrete specimen was exposed to a 10% sodium chloride (NaCl) solution on one side and a 0.3M sodium hydroxide (NaOH) solution on the other as shown in Figure 1. The external potential of 30V 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 surfaces were sprayed with 0.1 M silver nitrate (AgNO₃) solution to determine the chloride penetration depth, which was then used to calculate the migration coefficient according to Equation 4

\[ D_{\text{ssm}} = \frac{RT}{zFE} \frac{x_d - \alpha \sqrt{x_d}}{t} \]  

where

\[ E = \frac{U - 2}{L} \]

\[ \alpha = 2 \sqrt{\frac{RT}{zFE}} \text{erf}^{-1} \left( 1 - \frac{2c_d}{c_0} \right) \]

where \( D_{\text{ssm}} \) is non-steady-state migration coefficient (m²/s); \( z \) denotes absolute value of ion valence, for chloride \( z = 1 \); \( F \) is Faraday constant \((9.648 \times 10^4 \text{ J/(V mol)})\); \( U \) represents average value of the applied voltage (V); \( R \) is gas constant \((8.314 \text{ J/(V mol)})\); \( T \) is average value of the initial and final temperatures in the anolyte solution (K); \( L \) is thickness of the specimen (m); \( x_d \) represents average value of the penetration depth (m); \( t \) is test duration (s); \( \alpha \) represents inverse of error function; \( c_d \) is chloride concentration at which the colour changes, \( c_0 \approx 0.07 \text{ N} \) for ordinary Portland OPC (OPC); \( c_0 \) is chloride concentration in the catholyte solution, and \( c_0 \approx 2 \text{ N} \) (NT BUILD, 1999).

Salt ponding test. The resistance of concrete to chloride-ion penetration was also determined according to AASHTO T259 (AASHTO, 2002) method with some modifications. One of the modifications was 3 day lime water ponding of the specimens prior to the salt ponding. The purpose was to create a condition to simulate a diffusion process for chloride ions rather than a combination of diffusion and capillary suction as the original American Association of State Highway and Transportation Officials (AASHTO) test. The other modification was the curing age. AASHTO T259 specifies 14 days moist curing followed by 28 days drying before the test. In this research, the slabs were moist cured for 7 days followed by exposure in laboratory air for 21 days. In addition, concrete was sampled about every 5 mm in depth after the ponding test. At 28 days, the sides and bottom of the slabs were sealed by epoxy, and a dam was built around the top edges of each specimen using foam plates. The epoxy was allowed to dry overnight. After that, the specimens were ponded with lime water for 3 days before the ponding with a 3% sodium chloride solution for 90 days. The top of the ponding dams was covered with a plastic sheet to minimise evaporation, and additional solution was added periodically to keep the 13 mm depth of solution specified by the AASHTO method.

After 90 days of the exposure, the ponding solution was removed and the specimens were allowed to dry. The surfaces were brushed to remove salt crystal build-up. Concrete samples were taken at various depths of the slabs with about 5 mm intervals by drilling at four locations of each slab and then combined. The samples were dried at 105°C and ground to pass a 150 μm sieve. Acid soluble chloride content of the concrete was determined according to BS 1881-124 (BSI, 2000c). The chloride content expressed as percentage of the mass of dry concrete samples was plotted against the depth which was the mid-point of each interval. Based on the chloride profile after the ponding test and application of Fick’s second law, the surface chloride content and chloride diffusion coefficient of the concretes were obtained by curve fitting. The first point in the chloride profile near the surface was not included in the regression analysis according to Frederiksen (1996).

Autogenous shrinkage

The autogenous shrinkage of the concrete was measured by a pair of laser sensors during the first 24 h and by a digital Demec gauge after that.

Figure 2 illustrates the set-up of the measurement with laser sensors. Voltage changes as the specimens shrank were detected by the sensors and the data captured were used to calculate the length change and the shrinkage of the specimens. The laser sensors were fixed on a steel plate, and the distance between the two sensors was about 400 mm. The size of the concrete prisms used was 75×75×300 mm. The position of the sensors was approximately 50 mm from one end of the concrete prism. The measuring range of a laser sensor was ±10 mm, and its resolution was about 5 μm. The
resolution of the shrinkage measurement for the concrete prism was therefore about 10 μm (two sensors), which was approximately 0.003% of the length of the prisms. Screws with a length of approximately 55 mm and a diameter of 3 mm were embedded in the specimen at each end (Figure 2), and the clear distance between the tips of the two screws was about 180 mm. This distance was used in the calculation of the shrinkage. A 3 mm thick Perspex plate was cast at each end of the specimen as a target surface to reduce measurement error due to the possibly uneven surface at the micro-scale level. The Perspex plates were covered with aluminium foil on the surface for reflection of the laser. An 8 mm diameter hole was drilled at the centre of each end plate of the mould so that the laser beam could directly hit the target surface. To reduce friction between the concrete specimen and the walls of the mould, internal surfaces of the mould were lined with 1 mm thick Teflon sheet except for the two end surfaces. Two layers of plastic sheets were fitted well inside the mould leaving two small holes for the screws. After casting the concrete was wrapped with the plastic sheets to prevent moisture loss. The concrete was demoulded after one day and the specimen was wrapped with two layers of aluminium sheets to prevent moisture loss. Two Demec pins, 200 mm apart were glued using epoxy along the centre line of each side-surface of the specimen. A digital Demec gauge was used to measure the length change between the two pins once a day for a week. The initial length was measured at about 8 h after the pins were glued and dried as a reference.

The initial setting time of the control concrete was determined according to ASTM C 403/C 403 M - 05 (ASTM, 2006d). It was used as the starting point of the autogenous shrinkage measurement. The addition of SRA did not affect the unit weight of the concrete mixtures RS1 to RS3 had lower unit weight, compressive strength and elastic modulus compared with those of the control concrete (NC) as expected owing to the incorporation of the LWAs in the former mixtures. The reductions of these properties are more significant for the concrete with larger size LWA (RS1).

During the first day, thermal expansion due to the heat of cement hydration may be generated simultaneously with the autogenous shrinkage. In this study, temperature change of the concrete specimen with time was monitored by a thermocouple embedded in the centre of the concrete specimen. The temperature of the concrete measured with a thermometer right after the concrete mixing was used as a reference. Signals from the laser sensors and thermocouple were recorded by a data logger, thus the autogenous shrinkage and the temperature change of each concrete specimen can be determined at the same time. The autogenous shrinkage was calculated by subtracting the thermal expansion strain from the measured shrinkage strain. The thermal expansion strain was calculated by multiplying the temperature rise of concrete by a thermal expansion coefficient of 10×10⁻⁶/°C (Neville, 1995).

It should be noted that the thermal expansion coefficient used was an average value, and it may vary during the hydration process. Kada et al. (2002) reported that the thermal expansion coefficient of concrete was higher at early age. This indicates that the thermal expansion strain might be higher than the values used in this research. On the other hand, the temperature monitored was at the centre of the specimen, which was the hottest part. As a result, the actual expansion caused by the temperature rise in the concrete might be less than the computed values.

Results and discussion

Unit weight, compressive strength and elastic modulus of the concrete

The slump of the fresh concrete, unit weight after demoulded at 1 day, compressive strength at 7, 28 and 91 days, and elastic modulus of the concretes at 28 days are summarised in Table 4.

The concretes had slumps of 85 ± 20 mm. The concrete mixtures RS1 to RS3 had lower unit weight, compressive strength and elastic modulus compared with those of the control concrete (NC) as expected owing to the incorporation of the LWAs in the former mixtures. The reductions of these properties are more significant for the concrete with larger size LWA (RS1).

The addition of SRA did not affect the unit weight and elastic modulus, but reduced the compressive strength of the concrete somewhat. The observation of the slightly reduced strength was consistent with the findings by other researchers (Pease, 2005; Shah et al., 1992).
Water absorption

The average initial water absorption within 1 h and the average weight gain from 1 to 24 hours are presented in Figure 3 and Figure 4, respectively. The error bars in Figure 3 represent the standard deviation of the initial water absorption for each concrete. The sorptivity of the concrete was obtained from the slope of the curves in Figure 4 by regression. The regression coefficient for the sorptivity was \(0.99\) for all the concrete specimens. The initial water absorption, sorptivity and average weight gain from the three specimens after 8-day test for each concrete are presented in Table 5.

The concrete with LWAs for internal curing had initial water absorption and sorptivity comparable to those of the control concrete except for mixture RS2, which had lower initial water absorption and sorptivity. The difference may be related to the pore structure of the LWA and the degree of cement hydration in concrete.

Comparing the concretes with LWA particles and the control concrete, they had similar w/c for the cement paste, and the differences were mainly the aggregate and degree of cement hydration. Although LWA particles are porous compared with the granite aggregate, many pores in LWAs are discrete and therefore are not accessible by water. Another factor that affects the sorptivity of the concrete is the size of the pores. In principle, water absorption is caused by capillary effect in the pores. The greater the pore sizes, the smaller the capillary stresses. Large pores may contribute little to water absorption even if they are continuous. In the concrete with LWA particles (RS1 to RS3), water inside the LWAs contributed to internal curing, thus the degree of cement hydration in these concretes would be higher compared with that in the control concrete (NC). The increased cement hydration would reduce capillary porosity in the cement paste, which may explain the reduced initial water absorption, sorptivity and mass increase in 8 days in some cases. In addition, the improved interfacial transition zone between the LWA and cement paste may also contribute to the reduced water absorption of the concrete.

No clear correlation was observed between the particle size of the LWA incorporated and the sorptivity of the concrete. This might be due to the different porosities and surface textures of the LWAs used. In mixture RS1, the LWA particles of 4.75 to 9.5 mm were spherical with smooth surface texture, whereas in mixture RS3, the LWA particles < 1.18 mm were crushed with higher porosity and open pores. Mixture RS2 contained

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**Table 4. Unit weight, compressive strength and elastic modulus of the concretes**

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Slump: mm</th>
<th>Unit weight: kg/m³ 1 day</th>
<th>Compressive strength: MPa 7 days</th>
<th>Compressive strength: MPa 28 days</th>
<th>Compressive strength: MPa 91 days</th>
<th>Elastic modulus: GPa 28 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>105</td>
<td>2360</td>
<td>54 ± 2</td>
<td>71 ± 1</td>
<td>75 ± 3</td>
<td>33 ± 0.5</td>
</tr>
<tr>
<td>RS1</td>
<td>75</td>
<td>2030</td>
<td>46 ± 1</td>
<td>53 ± 2</td>
<td>57 ± 3</td>
<td>25 ± 0.5</td>
</tr>
<tr>
<td>RS2</td>
<td>70</td>
<td>2160</td>
<td>50 ± 2</td>
<td>57 ± 4</td>
<td>63 ± 4</td>
<td>27 ± 0.5</td>
</tr>
<tr>
<td>RS3</td>
<td>65</td>
<td>2275</td>
<td>51 ± 3</td>
<td>56 ± 3</td>
<td>69 ± 4</td>
<td>30 ± 0.4</td>
</tr>
<tr>
<td>RS4</td>
<td>75</td>
<td>2350</td>
<td>51 ± 2</td>
<td>63 ± 3</td>
<td>70 ± 2</td>
<td>31 ± 0.6</td>
</tr>
</tbody>
</table>

**Table 5. Water absorption results of the concretes**

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Initial water absorption: kg/m²</th>
<th>Sorptivity: kg/m²·h⁻⁰·⁵</th>
<th>Mass increase in 8 days: g</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>0.09 ± 0.005</td>
<td>0.048 ± 0.005</td>
<td>4.62 ± 0.14</td>
</tr>
<tr>
<td>RS1</td>
<td>0.10 ± 0.021</td>
<td>0.043 ± 0.007</td>
<td>4.05 ± 0.65</td>
</tr>
<tr>
<td>RS2</td>
<td>0.06 ± 0.001</td>
<td>0.026 ± 0.006</td>
<td>2.22 ± 0.34</td>
</tr>
<tr>
<td>RS3</td>
<td>0.08 ± 0.009</td>
<td>0.047 ± 0.003</td>
<td>3.86 ± 0.22</td>
</tr>
<tr>
<td>RS4</td>
<td>0.08 ± 0.013</td>
<td>0.044 ± 0.004</td>
<td>4.59 ± 0.82</td>
</tr>
</tbody>
</table>
LWA with particle sizes $< 4.75$ mm, and some of them were spherical with lower porosities than that of particles $> 4.75$ mm whereas a small amount of the particles $< 1.18$ mm were crushed. The sorptivities of these concretes were in the order of RS2 < RS1 < RS3.

The concrete with the SRA had initial water absorption, sorptivity, and mass increase in 8 days comparable to those of the control concrete. In principle, the sorptivity of a porous material is proportional to the square root of surface tension and inversely proportional to the square root of viscosity of pore solution in the porous material (Hall, 1989). The SRA decreased surface tension and increased viscosity (Bentz, 2006), both of which would reduce the sorptivity. However, the data indicate that the effect of these due to the use of SRA was not significant on the water absorption of the concrete.

**Water permeability**

The water permeability coefficients of the concretes are summarised in Table 6. The test results show that all the concretes had relatively low water permeability ($10^{-13}$ m/s). The water permeability of the concrete with LWAs for internal curing and that with SRA had similar water permeability compared to the control concrete.

Although there is generally improved cement hydration and reduced capillary pores in concrete when LWAs are used for internal curing, the LWAs are porous and water can penetrate into the LWAs under high pressures. This means that under the high pressure the increase in mass $m$ of the concretes with the LWAs (RS1 to RS3) can be higher than that of the control concrete (NC). Some discrete pores in the LWAs could also become continuous under the pressure. The higher $m$ reflected greater porosity $v$ of the concretes with LWAs. However, the water penetration depth of the concrete (RS1 and RS2) was lower than that of the control concrete under the pressure for the same duration. The water penetration depth of the mixture RS3 would also be lower compared with that of the control concrete if it is assumed that the penetration depth was proportional to the duration under pressure. This is important from the durability point of view. For example, the initiation of corrosion of steel reinforcement embedded in concrete is affected by the concentration of chloride ions in the vicinity of the steel bars where the chloride ions can be brought into the concrete by hydraulic pressure.

**Resistance to chloride-ion penetration**

Table 7 summarises the resistance of the concretes to chloride-ion penetration determined by the methods described. Each result was the average from three specimens. The concrete with LWAs (RS1 to RS3) showed higher charges passed compared with the control concrete (NC), whereas the concrete with SRA (RS4) had lower charges passed compared with the control concrete. The charges passed through the concretes, how-

### Table 6. Water permeability of the concretes

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Duration: days</th>
<th>Penetration depth: mm</th>
<th>Porosity: $v$</th>
<th>Permeability coefficient: $\times 10^{-12}$m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>14</td>
<td>0.6 ± 2.6</td>
<td>0.04</td>
<td>0.9 ± 0.2</td>
</tr>
<tr>
<td>RS1</td>
<td>14</td>
<td>0.6 ± 0.7</td>
<td>0.13</td>
<td>1.0 ± 0.2</td>
</tr>
<tr>
<td>RS2</td>
<td>14</td>
<td>0.4 ± 1.8</td>
<td>0.08</td>
<td>1.4 ± 0.1</td>
</tr>
<tr>
<td>RS3</td>
<td>17</td>
<td>0.5 ± 1.6</td>
<td>0.07</td>
<td>1.4 ± 0.5</td>
</tr>
<tr>
<td>RS4</td>
<td>14</td>
<td>0.5 ± 1.0</td>
<td>0.06</td>
<td>1.2 ± 0.1</td>
</tr>
</tbody>
</table>

### Table 7. Resistance of the concretes to chloride-ion penetration

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Total charges passed (ASTM C1202): Coulombs</th>
<th>Rapid migration test</th>
<th>Salt ponding test (AASHTO-T259)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Penetration depth: mm</td>
<td>Migration coefficient: $\times 10^{-12}$m$^2$/s</td>
<td>Surface chloride content, % of concrete mass</td>
</tr>
<tr>
<td>NC</td>
<td>2528 ± 210</td>
<td>18.4 ± 1.1</td>
<td>8.8 ± 0.6</td>
</tr>
<tr>
<td>RS1</td>
<td>2977 ± 257</td>
<td>17.6 ± 0.6</td>
<td>8.2 ± 0.2</td>
</tr>
<tr>
<td>RS2</td>
<td>3112 ± 335</td>
<td>17.8 ± 2.0</td>
<td>9.2 ± 1.5</td>
</tr>
<tr>
<td>RS3</td>
<td>2987 ± 616</td>
<td>20.3 ± 1.2</td>
<td>10.1 ± 0.6</td>
</tr>
<tr>
<td>RS4</td>
<td>2012 ± 119</td>
<td>19.1 ± 2.0</td>
<td>9.7 ± 1.3</td>
</tr>
</tbody>
</table>

* The results were from a concrete with the same w/c and mix proportion but a slightly higher SP dosage of 2.9 L/m$^3$. The initial 3-day ponding for the concrete NC was by water instead of lime water. Because of this, some hydroxide (OH$^-$) ion in the concrete might have leached out. However, owing to the low w/c of the concrete and small volume of water on top of the concrete slabs for the ponding, the effect of leaching of hydroxide ions on results was probably not significant.
ever, were all within the range from 2000 to 4000 coulombs, which was classified as ‘moderate’ chloride penetrability according to ASTM C 1202 (ASTM, 2006a). This method is affected by the pore structure and the chemistry of pore solution of the concrete specimens. The LWAs in the concrete RS1 to RS3 affected the pore structure of the concrete and SRA affected the pore solution which in turn affected the charges passed in the concrete. It should be mentioned that ASTM C 1202 may give a false estimate of the concrete diffusion when some supplementary cementing materials, chemical admixtures, or steel fibres are used (Riding et al., 2008).

The chloride penetration depths and migration coefficients of the concretes with the LWA particles and with SRA determined by the NT Build 492 method were in the same order as those of the control concrete. In this test, the chloride penetration depth was determined by the whitish colour owing to the precipitation of silver chloride. According to the method, chloride concentration at which the colour changes was approximately 0-07N for ordinary Portland cement concrete. According to Otsuki et al. (1992), this whitish colour will only be visible when the chloride content is > 0-15% by weight of cement with the spray of the silver nitrate solution. This means that the actual chloride penetration depth in the specimens for the migration test might be greater than the values given in Table 7.

Figure 5 shows the profiles of chlorides in the concretes after the 90-day ponding test. The surface chloride content and chloride diffusion coefficient of the concretes obtained from curve fitting of the chloride profiles according to Fick’s second law are summarised in Table 7.

The diffusion of chloride ions in the normal weight concrete is primarily dependent on the cement paste and the interfacial zone between the aggregate and cement paste matrix as the diffusion in the normal weight aggregate is negligibly small (Lu et al., 2002). For the concrete with LWA particles, however, the chloride ions may diffuse in the porous LWA.

From the results, although the surface chloride content ($C_s$) for the concrete with LWA particles (RS1 to RS3) was higher than that of the control concrete, the incorporation of presoaked LWAs for internal curing generally did not affect the chloride diffusion coefficient of the concrete significantly as their diffusion coefficients were in the same order as that of the control concrete and the concrete with SRA. The increase in the more porous crushed LWA particles in concrete seems to increase the chloride ion diffusion, and mixture RS3 with crushed LWA particles of sizes < 1.18 mm appears to have somewhat higher chloride diffusion coefficient. However, it is noted that the w/c of the concrete RS3 was 0.40, which was slightly higher than that of the others.

Diffusion of chloride ions in the concrete is affected by the concentration difference of the ions in the concrete pore solution and external sources. The smaller the difference, the lower the driving force for the chloride ion diffusion in the concrete. It is also reported that the diffusion coefficient of chloride ions in concrete decreases with time (Hooton and McGrath, 1995). Further research is needed to determine the long-term diffusion of chloride ions in concrete with porous crushed LWA particles for internal curing.

The incorporation of the SRA in concrete did not affect the surface chloride content and the diffusion coefficient significantly compared with the control concrete.

It should be mentioned that in the salt ponding test the chloride contents were based on the weight of the dried concrete samples from the testing slabs. Owing to the small samples (5 g) used for the determination of the chloride content in the concrete, relative proportion of cement paste and aggregate might vary from sample to sample. This may lead to some errors in the results.

In summary, the charges passed, chloride migration coefficient and chloride diffusion coefficient of the concretes with LWA particles for internal curing were in the same order as those of the control concrete and the concrete with SRA.

**Autogenous shrinkage of the concrete**

The autogenous deformation of the concrete mixtures is presented in Figure 6. The ‘zero’ point of the time

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**Figure 5. Chloride profiles of the concretes after 90 days salt ponding test**

**Figure 6. Autogenous deformation of concrete with different sizes of LWAs or SRA**

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was from the initial setting time of the control concrete (4 h 15 min) determined by penetration resistance method according to ASTM C 403/C 403M-05. The benefit of internal curing by using presoaked LWAs in the concrete RS1 to RS3 for shrinkage reduction is clearly demonstrated in the figure. Furthermore, the smaller size of presoaked LWAs appears to be more effective in reducing the autogenous shrinkage. The results are consistent with other research (HoF, 2003; Lura, 2003).

As shown in Figure 6, the use of SRA or presoaked LWA was efficient in reducing the autogenous shrinkage. The principal of the former was attributable to the reduction in the surface tension of pore solution, and thus reduction of the capillary stress and shrinkage (Berke et al., 2003), whereas the latter was due to the provision of water from internal sources which reduces the shrinkage of the cement paste.

Summary and conclusions

To produce high-quality durable concrete, the early-age cracking caused by the autogenous shrinkage can be reduced by the incorporation of presoaked LWAs or SRA. When the presoaked LWAs or SRA are used in concrete for such a purpose, their effects on the water absorption, water permeability, and resistance to the chloride ion penetration of the concrete and the ease of use have significant impact on the applications. Based on the results presented and discussed, the following conclusions can be made.

(a) In general, the concretes with LWA particles had initial water absorption, sorptivity and water permeability similar to or lower than those of the control concrete and the concrete with SRA. The charges passed, chloride migration coefficient, and chloride diffusion coefficient of such concretes were in the same order as those of the control concrete and the concrete with SRA. However, the incorporation of the LWAs for internal curing reduced unit weight, compressive strength and elastic modulus of the concrete.

(b) Comparing the LWAs of different sizes for internal curing, finer particles were more efficient in reducing the shrinkage and generally resulted in less reduction in the unit weight, compressive strength and elastic modulus. However, the increase in the more porous crushed LW particles in concrete seems to increase the penetration of chloride ions in the concrete. Further research is needed to determine the long-term diffusion of chloride ions in concrete with porous crushed LWA particles for internal curing.

(c) The concrete with SRA had initial water absorption, sorptivity, water permeability and resistance to chloride ion penetration comparable to those of the control concrete. The use of SRA in concrete does not affect the elastic modulus of the concrete, except for a minor influence on the compressive strength of the concrete.

It should be mentioned that the results were obtained from laboratory tests where the specimens were not subjected to restraints. In practice where the concrete is restrained, the reduced shrinkage would reduce potential cracking, thus reducing the penetration of chloride ions through the cracks.

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