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Performance of lightweight aggregate concrete containing slag after 25 years in a harsh marine environment

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ABSTRACT

This paper reports the results of a study on concretes containing lightweight aggregate (LWA) retrieved from the tidal zone of a marine exposure site. In terms of chloride resistance, the LWA concrete performed equivalently to similar concretes of the same age produced with normal density aggregate that were retrieved from the same site 2 years earlier. The partial replacement of Portland cement with slag led to substantial reductions in chloride penetration and the chloride diffusion coefficient. However, at w/cm ≥ 0.50, the incorporation of slag resulted in increased surface deterioration (scaling) attributed to freezing and thawing. Concrete with LWA, silica fume and w/cm = 0.33, showed better-than-expected performance with regard to resistance to chloride-ion penetration and it is speculated that this may be partly attributed to "internal curing" provided by the LWA which reduces the impact of self desiccation. Further studies are needed to confirm this phenomenon.

1. Introduction

Expanded shale, clay and slate lightweight aggregate (LWA) concrete has frequently been used in harsh winter environments where it is subjected to the combined action of salts and freeze–thaw cycles, and appears to provide similar or improved performance to normal-weight concrete [1]. Holm et al. [1] attributed improvements to the superior contact zone (interfacial transition zone or ITZ) between the cement paste and aggregate in LWC, which is less porous than the ITZ in concrete with dense aggregates. Zhang and Gjorv [2] demonstrated that refinement of the ITZ only occurred with LWA that has a porous outer layer and this is due to penetration of cement hydration products into the outer pores thereby leading to mechanical interlock. Steel-reinforced concrete exposed to a marine environment needs to have a low permeability and a high resistance to the penetration of chloride ions and, because of the porous nature of LWA, it is reasonable to expect its incorporation to increase the rate of ingress of aggressive ions. Indeed, based on mathematical predictions, Hobbs recommended that limits on the water absorption of aggregates should be considered for reinforced concrete exposed to chlorides [3]. These recommendations are not substantiated by experimental observations. In fact, in a study involving a number of types of LWA, Zhang and Gjorv [4] showed that the permeability of high-strength LWA concrete was largely dependent on the properties of the paste (w/cm and binder type) rather than the porosity of the aggregate. Bentz [5] suggests that this is because the pores in some commercially-available LWA are discrete and are not percolated across the particle. Thomas [6] showed that the resistance of high-performance concrete (low w/cm and silica fume) to chloride ion penetration may actually be improved by the use of lightweight expanded slate aggregate. The improved performance was attributed to the internal curing provided by the LWA which compensated for self-desiccation in the low w/cm concrete especially at the ITZ. Bentz [5] stated that the use of LWA sand not only provided internal curing but also reduced the fraction of percolated ITZ. More studies are required to determine the impact of LWA on permeability and chloride diffusion, especially in low-w/cm concrete that is prone to self-desiccation.

This paper reports the results of tests conducted on a series of 25-year-old LWA concrete blocks stored at the US Corps of Engineers' marine exposure site facility on Treat Island just off the coast of Eastport, Maine. Tests were also performed on 12-year-old high-performance concrete blocks that were cast during the production of concrete for the construction of a gravity base structure (GBS) in the North Atlantic and then placed on Treat Island; in these concretes 50% (by volume) of the coarse aggregate was LWA.

2. Background: materials and exposure conditions

2.1. Specimens from CANMET study

In 1978 the Canadian Centre for Mineral and Energy Technology (CANMET) initiated a study on the marine performance of concrete

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containing supplementary cementing materials (SCM), which involved placing large concrete blocks (305×305×915 mm, 1×1×3 ft) in the tidal zone of the marine exposure site at Treat Island, Maine [7]. Between 1978 and 1994 sixteen different series of concrete mixtures were placed at Treat Island; these mixes had water-to-cementing materials ratios in the range w/cm = 0.40 to 0.60 and various levels (up to 80% by mass of cementing material in some cases) of fly ash, slag and silica fume. Parameters investigated also included the use of lightweight aggregate, fibers, epoxy-coated steel and alkali–silica reactive aggregates [7].

This paper is concerned with Phase III of this study which was implemented in 1980. A series of 12 concrete mixes was cast with w/cm = 0.40, 0.50 and 0.60 and slag replacement levels of 0, 25, 45 and 65% by mass of cementing materials. The cement met the requirements of ASTM C 150 Type I and the slag was a ground pelletized blast furnace slag from Hamilton, Ontario. Expanded shale LWA was used as the coarse aggregate; the LWA was from Minto in New Brunswick, it had a nominal maximum size of 25 mm (1 in.) and saturated-surface-dry (SSD) specific gravity of approximately 1.6. Details of the cementing materials and concrete mixtures are given in Tables 1 and 2. Table 2 also provides information on the fresh properties of the concrete mixtures and the compressive strength of standard-cured cylinders at 28 days.

From each of these mixtures two blocks (305×305×915 mm, 1×1×3 ft) were cast. The blocks were moist cured for 90 days prior to being shipped to the exposure site at Treat Island, Maine, where they were placed on a timber wharf at mid-tide level. Full details of the manufacture of the concrete prisms are given elsewhere [7]. In 2005, after 25 years' exposure, one block from each mix was retrieved from the site and transported to the University of New Brunswick. Concrete cores (nominally 114 mm, 4.5 in. diameter) were cut from the blocks for testing in the laboratory.

The results from the tests on the concretes from this phase (Phase III) are compared with data from a similar series of tests conducted on concrete specimens from Phase 1 which were reported in an earlier paper [8]. The concretes in Phase 1 were produced at the same w/cm and slag levels, and using cement and slag from the same sources as those used in Phase III. The principal difference in the concrete composition is that normal density coarse aggregate was used in Phase I and LWA in Phase III.

2.2. Specimens from GBS blocks

In 1996 four concrete blocks measuring approximately 0.9×0.9×0.6 m (2.95×2.95×1.97 ft) were placed in the tidal zone of the exposure site at Treat Island, Maine. The specimens are located on the beach at approximately the mid-tide level. The blocks were cast at the site of the construction of a gravity base structure (GBS) using the production concrete for the splash zone of the outer perimeter of the structure (the "ice wall"). The concrete was designated as "Modified Normal Density Concrete, (MNDC)" and contained 470 kg/m^3 (792 lb/yd^3) of blended cement containing 8.5% silica fume, a water-to-cementing-materials ratio of w/cm = 0.33, and an air content of between 4.1 and 5.5% (based on test data available). The coarse aggregate component of the concrete was a blend (approximately 50/50 by volume) of normal density aggregate (470 kg/m^3, 792 lb/yd^3) and lightweight aggregate (230 kg/m^3, 388 lb/yd^3). The lightweight aggregate was an expanded slate with a reported absorption of 6% and SSD specific gravity of approximately 1.52 (ASTM C 127). The concrete was specified to have a compressive strength of 69 MPa (10,000 psi) at 1 year. Test data available indicates that the average 28-day strength of cylinders ranged between 75.8 and 83.2 MPa (10,994 to 12,067 psi) with a median value of 81.8 MPa (11,864 psi). The 28-day modulus of elasticity ranged from 30.2 to 31.9 GPa (4380 to 4627 ksi) with a median value of 31.6 GPa (4583 ksi). Tests conducted on cores taken from the ice wall indicate an average compressive strength of 67.9 MPa (9848 psi) at 28 days and 71.1 to 75.6 MPa (10,312 to 10,965 psi) at approximately 9 months.

In 2008, after an exposure period of 12 years, 100 mm (4 in.) and 150 mm (6 in.) cores were cut from the blocks.

Table 1
Chemical properties of Type I cement and ground pelletized blast furnace slag.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	Na_2O	K_2O	LOI	C_3A
Type I	20.52	5.75	2.10	62.87	3.87	1.62	0.08	1.34	1.29	12.6
Slag	38.78	8.11	1.02	37.88	0.12	9.49	0.49	0.52	–	–

Table 2
Concrete mixture proportions.

Nominal w/cm	Mixture proportions (kg/m^3)					Slump (mm)	Air (%)	Density (kg/m^3)	Strength[b] (MPa)
	Cement	Slag	Water[a]	Sand	LWA				
0.40	473	0	222	661	571	85	5.8	1920	36.5
	360	129	224	653	574	85	6.3	1940	39.4
	261	214	247	616	565	75	5.5	1910	39.9
	166	307	214	628	565	95	6.0	1870	39.7
0.50	356	0	215	777	589	75	5.6	1940	29.4
	268	90	222	764	590	75	6.0	1940	33.3
	198	162	220	750	587	90	6.7	1920	35.6
	129	239	209	747	592	75	6.8	1920	32.5
0.60	240	0	212	866	583	70	6.5	1910	17.9
	183	61	215	869	589	75	6.5	1920	19.0
	135	111	210	877	596	55	5.4	1940	20.5
	84	157	207	856	583	90	7.0	1890	12.8

[a] Total batch water content.
[b] Strength of standard-cured cylinders at 28 days.

2.3. Exposure conditions at Treat Island

Treat Island lies in Passamaquoddy Bay at the mouth of the Bay of Fundy, near the town of Eastport in Maine. The exposure site was established in 1936 to study concrete durability as there was interest at the time in constructing a tidal electrical generating system in Passamaquoddy Bay. The exposure conditions in the Bay of Fundy are extremely aggressive for concrete with tides in excess of 6 m (20 ft) and the alternating condition of immersion in seawater and exposure to air produces an average of 100 freeze–thaw cycles per year for concrete at the mid-tide level.

3. Testing

The following tests were conducted on test specimens prepared from the cores:

- Chloride profiling to determine the extent to which the chlorides have penetrated into the concrete during marine exposure (see below)
- Compressive strength, ASTM C 39
- Static modulus of elasticity, ASTM C 469
- Indirect tensile strength (cylinder splitting), ASTM C 496
- "Rapid chloride permeability" test (RCPT), ASTM C 1202
- Bulk diffusion test, ASTM C 1556.

Specimens for the bulk diffusion and RCP tests were cut from as close to the center of the blocks as possible to minimize the impact of existing chlorides (resulting from seawater exposure) on the test results. The bulk diffusion tests for the CANMET blocks were conducted by immersing specimens in salt solution (165 g/L NaCl) for 90 days whereas a 41-day immersion period was used for test specimens from the GBS blocks.

For the CANMET blocks, the chloride profile of the specimens after exposure to marine conditions for 25 years was determined by slicing

Table 3
Results of mechanical tests and rapid chloride permeability test.

w/cm	Slag (%)	Silica fume (%)	σ_c (MPa)	E (GPa)	σ_t (MPa)	RCPT (Coulombs)
CANMET blocks						
0.40	0	0	46.9	18.9	2.43	2077
	25	0	59.7	18.0	3.59	1364
	45	0	53.9	16.2	4.19	645
	65	0	49.2	17.1	2.45	357
0.50	0	0	36.7	14.8	2.13	4094
	25	0	39.5	16.0	2.85	1291
	45	0	46.4	17.3	3.69	463
	65	0	39.9	18.8	2.62	369
0.60	0	0	23.6	11.8	2.10	4109
GBS blocks						
0.33	0	8.5	73.6	36.2	4.02	537

a core (drilled on the centerline of the block) at 10-mm intervals, grinding the slices to a powder and determining the total chloride content of the powder by chemical analysis. For the GBS blocks the powder was collected at 2-mm increments using a milling machine.

4. Results

After 25 years exposure to approximately 2500 freeze–thaw cycles, all concrete specimens showed some evidence of surface scaling. For blocks with w/cm = 0.40 the scaling was limited to the near surface, and there was little difference in the appearance of blocks with varying amounts of slag. At w/cm = 0.50, the surface scaling increased with increasing slag contents. At w/cm = 0.60, only the control block was intact and the blocks with 25, 45 and 65% slag had deteriorated significantly and cores could not be extracted from these blocks.

There is no indication of deterioration for the 12-year-old concrete from the GBS blocks based on a visual examination of the blocks and microscopic examination of polished surfaces of cores taken from the blocks.

The results of the compressive strength, modulus of elasticity, indirect tensile strength, and "rapid chloride permeability" tests are presented in Table 3. For the CANMET blocks the mechanical properties generally increase as the w/cm decreases. The cores from the concretes containing slag consistently gave higher compressive strengths than the cores from the control blocks at the same w/cm, however, there is no consistent trend with slag content for the other mechanical properties. Comparing the compressive strength of 25-year-old cores with 28-day-old cylinders (Table 2) the average increase in strength is 30% (range = 19 to 52%), but surprisingly the level of increase does not seem to increase with slag content. The compressive strength of the cores from the GBS blocks was in the same range as that established on cores taken from the ice wall at 9 months, indicating that there has been no loss in mechanical properties during exposure.

For the CANMET blocks, the RCP decreases with decreasing w/cm, but the effect of slag is far more pronounced, increases in slag content producing very marked decreases in the electrical charge (Coulombs) passed during the test. Reductions in the RCP value were anywhere in the range from 3 to more than 10 times for concrete containing 45% to 65% slag compared to control concrete (0% slag) at the same w/cm. The RCPT value for the GBS blocks is in the same range as the CANMET concretes with 45% and 65% slag, and all these concretes are categorized as concrete with very low chloride ion penetrability (<1000 C) by the criteria in ASTM C 1202. Concretes with 25% slag (w/cm = 0.40 and 0.50) are classed as having low chloride ion penetrability and concrete with no slag are classed as having moderate to high chloride ion penetrability.

Fig. 1 shows the chloride concentration profiles after 90 days ponding in salt solution (165 g/L NaCl) for test specimens cut from the CANMET blocks with varying amounts of slag (duplicate test results are shown for each concrete). Fig. 2 shows the effect of w/cm for the three control mixtures. As expected the resistance to chloride ion penetration increases with increasing levels of slag and decreasing w/cm. Fig. 3 shows the chloride profiles for specimens taken from each of the four GBS concrete blocks; these specimens were ponded for just 41 days.

Bulk diffusion coefficients (D_a) and chloride surface concentrations (C_s) are calculated by fitting Eq. (1) to the measured profiles (using least squares) and the calculated values for D_a are provided in Table 4. For concretes without slag and with w/cm = 0.50 and 0.60, it was not possible to obtain samples for bulk diffusion tests that were not already heavily contaminated with chloride (as a result of the 25-year exposure to seawater). Consequently, the diffusion coefficients were not determined for these concretes.

$$\frac{C_x}{C_s} = 1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_a t}}\right) \quad (1)$$

The impact of w/cm ratio and the inclusion of slag are again evident with the slag bearing concrete showing significantly reduced chloride diffusion coefficients compared to concrete with only

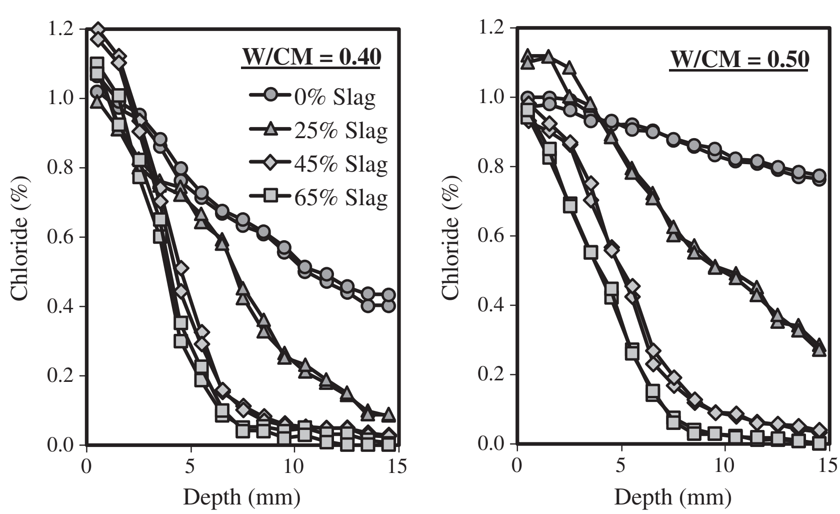

Fig. 1. Chloride profiles for CANMET LWA concrete blocks (w/cm = 0.40 and 0.50) after 90 days ponding in the bulk diffusion test (ASTM 1556) — effect of slag.

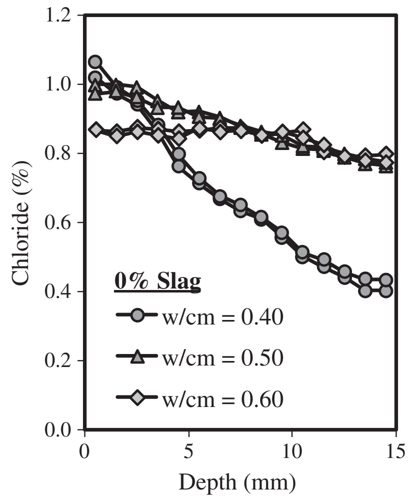

Fig. 2. Effect of w/cm on chloride profiles in CANMET LWA blocks after 90 days ponding (ASTM C 1556).

Table 4
Diffusion coefficients calculated from chloride profiles after ponding in NaCl solution in the laboratory (Bulk Diffusion Test ASTM C 1556) or from existing chloride profiles determined immediately after marine exposure.

w/cm	Slag (%)	Silica fume (%)	D_a ($\times 10^{-12}$ m^2/s)	
			Bulk diffusion test	Existing profiles
CANMET blocks				
0.40	0	0	16.0	2.06
	25	0	4.81	0.89
	45	0	1.22	0.21
	65	0	0.91	0.19
0.50	0	0	*	7.51
	25	0	9.04	2.11
	45	0	2.02	0.71
	65	0	1.32	0.56
0.60	0	0	*	28.7
GBS blocks				
0.33	0	8.5	1.02	**

*Test results affected by chloride contamination of sample prior to test.
**Poor fit between Eq. (1) and measured profile.

Portland cement. For concrete with w/cm = 0.40, compared to the control (0% slag), the diffusion coefficient was reduced by 3, 13 and 18 times for concrete with 25%, 45% and 65% slag, respectively. The GBS concrete with 8.5% silica fume and w/cm = 0.33 recorded a diffusion coefficient that fell between the values for concrete with 45% and 65% slag, with w/cm = 0.40.

The existing chloride profiles, resulting from 25 years exposure to seawater, are shown in Figs. 4 and 5 for the CANMET blocks. The data in Fig. 4 show that incorporating slag is highly effective in terms of reducing the ingress of chloride ions, the depth of chloride penetration decreasing significantly with increasing slag content. The impact of w/cm can be seen in Fig. 5. The surface concentration decreases with increasing w/cm. The reason for this is that cement content reduces with increasing w/cm (volume of coarse aggregate and water was kept constant in these mixes) and this reduces the capacity of the concrete to bind chlorides. However, at depth the chloride content increases with increasing w/cm as expected. Fig. 6 shows the chloride profiles for cores cut from each of the four GBS blocks. Three of these profiles are very close, but there is significantly more chloride penetration in the fourth profile from block C. It was subsequently discovered that this core contained a crack and the increased chloride penetration is attributed to the presence of the crack. Also shown in this figure is the output from the service-life model, Life-365 [9] and this will be discussed later.

The error-function equation (Eq. (1)) can also be used to determine bulk-diffusion coefficients from the existing chloride profiles. Although this is a commonly-used approach, such calculations are based on the assumption that the diffusion coefficient remains unchanged with time and this is not usually the case. Furthermore, this approach fails to account for the influence of temperature on diffusion and assumes that chlorides diffuse at a constant rate throughout the year. This is clearly not the case for blocks exposed at Treat Island. Despite the shortcomings of this approach, the analysis was conducted on the 25-year and 12-year chloride profiles and the results are presented in Table 4. This was done to permit comparisons with similar data for concrete with normal density aggregates as will be discussed below. It is interesting to note that the diffusion coefficients calculated from the existing profiles are significantly lower (2 to 8 times) than coefficients calculated from bulk diffusion tests performed on 25-year-old test specimens cut from the blocks. It should be noted that Eq. (1) did not fit the chloride profiles measured on the 12-year-old GBS concrete blocks. These chloride profiles are not well represented by a typical diffusion relationship as the profiles appear to have two points of inflection (see Fig. 6).

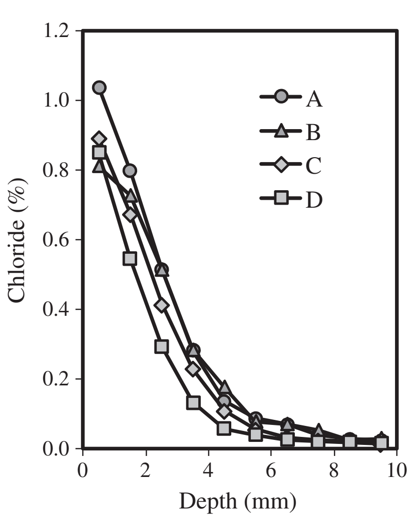

Fig. 3. Chloride profiles in GBS blocks after 41 days ponding (ASTM C 1556).

5. Discussion

The results for the CANMET blocks clearly show the benefits of incorporating slag in concrete exposed to a marine environment as the slag produced substantial reductions in chloride ion penetration. However, the use of slag led to increased surface deterioration at higher w/cm (≥0.50) even at relatively low levels of replacement (25%). Based on the results of this study the optimum concrete mix proportions for resisting both chloride ingress and the surface scaling due to freeze–thaw action in this very aggressive environment would be w/cm ≤ 0.40 with 45% to 65% slag.

The performance of the various LWA concrete mixtures used to produce the CANMET blocks is very similar to that determined for 25-year-old concretes produced with normal density (ND) aggregates that were retrieved and tested 2 years earlier [8]. Fig. 7 compares the profiles for the LWA concrete blocks (w/cm = 0.40) with the profiles from the ND concrete [8]. With the exception of the control mixes, the profiles are very similar for the different aggregates. In the control mix, the chloride content is greater in the LWA concrete close to the surface, but similar at a depth of 75 mm (3 in.).

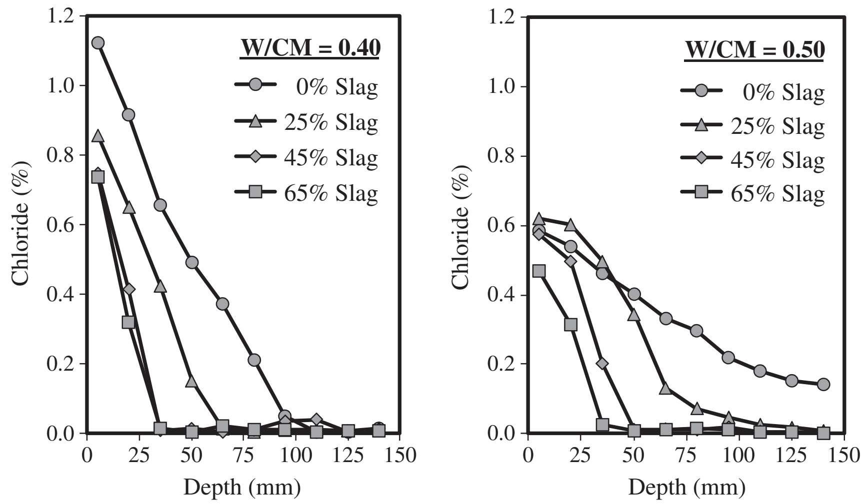

Fig. 4. Existing chloride profiles in 25-year-old CANMET LWA concrete blocks.

Fig. 8 compares the diffusion coefficients calculated from the chloride profiles for the LWA concrete with those for the ND concrete; coefficients calculated from both the bulk diffusion tests and the existing chloride profiles are shown. The diffusion coefficients determined for the bulk diffusion tests (ASTM C 1556) for the LWA concrete are similar or slightly higher than those for the ND concrete, but there is no consistent difference between the diffusion coefficients calculated from the existing profiles for the two different concretes (LWA and ND). Fig. 9 compares the results of the RCPT and the LWA concrete generally gave slightly lower values than the ND concrete.

It is important to demonstrate with long-term field studies that the incorporation of LWA does not lead to increased chloride-ion penetration thereby confirming the findings from some laboratory studies that it is the matrix (binder type and w/cm) that determines the chloride resistance rather than the porosity of the aggregate [4]. These data also support Bentz's [5] claim that it is possible to have porous particles that do not contribute to the transport of chlorides because the pores are discrete and not percolated across the particle. However, the data presented here do not support the findings of an earlier laboratory study by one of the authors [6] where the incorporation of LWA improved the chloride resistance of concrete, this being attributed to internal curing compensating for self desiccation. In the study by Thomas [6] the w/cm ranged from 0.30 to 0.40 and a blended silica fume cement with 8% silica fume was used (with and without fly ash added at the concrete mixer). It is probable that this combination of materials produced a much higher potential for self-desiccation than was the case for the CANMET blocks with w/cm ranging from 0.40 to 0.60 and a relatively slow-reacting slag rather than silica fume. Furthermore, the LWA used in the CANMET was batched in a dry condition rather than being pre-saturated as is now common practice. This means that the water available for internal curing would be limited to that absorbed by the lightweight aggregate during mixing and prior to setting.

Also shown in Fig. 7 is the output from Life-365, a model for predicting chloride ingress and service life for reinforced concrete exposed to chlorides [9]. The default values built in to Life-365 were used; these were: a constant surface concentration of $C_s = 0.8\%$, a 28-day diffusion coefficient of $D_{28} = 7.94 \times 10^{-12}$ m^2/s, an m-value to account for the time-dependent reduction in diffusion of $m =$ 0.20, 0.34, 0.46 and 0.57, respectively, for concrete with 0, 25, 45 and 65% slag, and the temperature history for Eastport, Maine. Generally there is a reasonable fit between the model predictions and the measured chloride content, although the experimental profiles appear to be somewhat steeper. The impact of slag on the service life of reinforced concrete in this environment was discussed in a previous paper on the basis of the data for the normal density concrete [8] and, because the results for the LWA concrete are very similar, no further discussion is presented here.

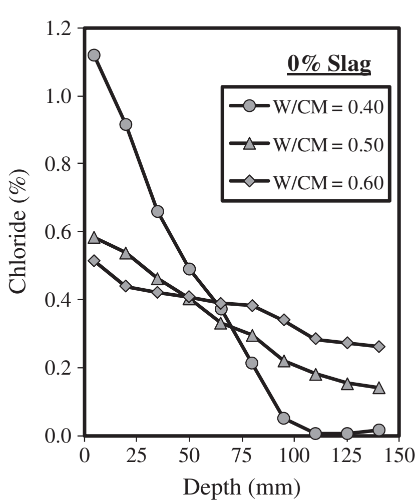

Fig. 5. Effect of w/cm on chloride profiles in CANMET LWA blocks.

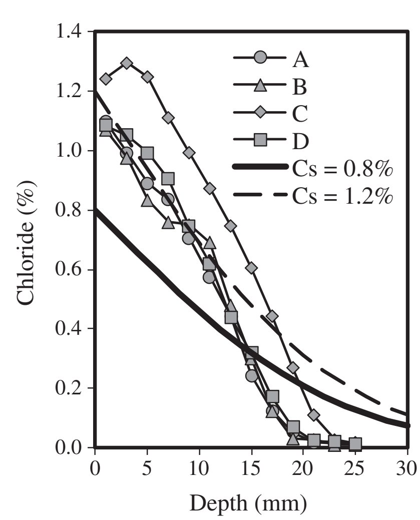

Fig. 6. Chloride profiles in GBS blocks showing Life-365 prediction for $C_s = 0.8$ to 1.2%.

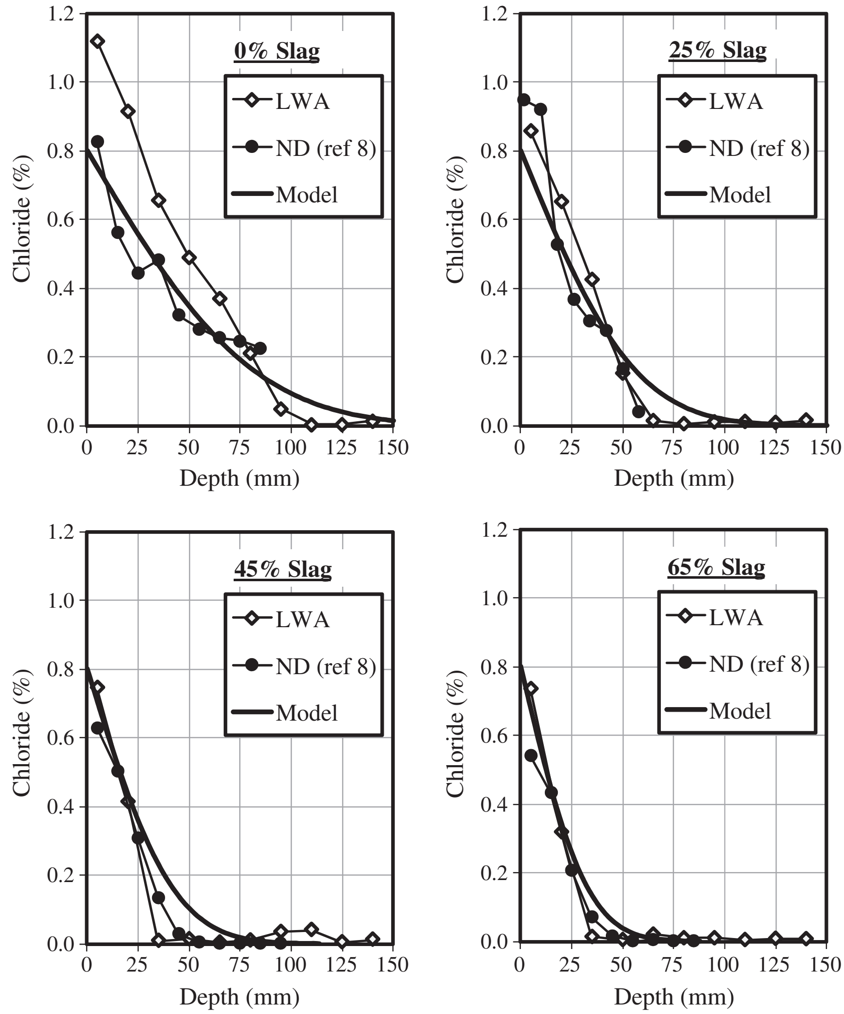

Fig. 7. Chloride profiles for CANMET LWA blocks (w/cm = 0.40) and blocks with normal density aggregates. Also shown are predicted profiles from the model Life-365. From Ref. [8].

The output from Life-365 is also compared with the 12-year profile for the GBS blocks in Fig. 6. The default values built in to Life-365 were used; these were: $D_{28} = 1.23 \times 10^{-12}$ m^2/s and $m = 0.20$. Two prediction curves are shown, one for a surface chloride content of $C_s = 0.8\%$, which is the default value used by Life-365 for a tidal exposure, the other for $C_s = 1.2\%$ to better match the measured values close to the surface of the GBS blocks. It can be seen in this figure that the measured profiles are very much steeper than the output from Life-365 and the data do not fit a typical diffusion profile.

The GBS blocks performed much better than predictions based on Life-365. Unfortunately there are no companion blocks with normal density aggregates with which to draw direct comparisons. However, Life-365 has been validated using data from another study where silica fume concrete was exposed to a marine environment [10]. In this

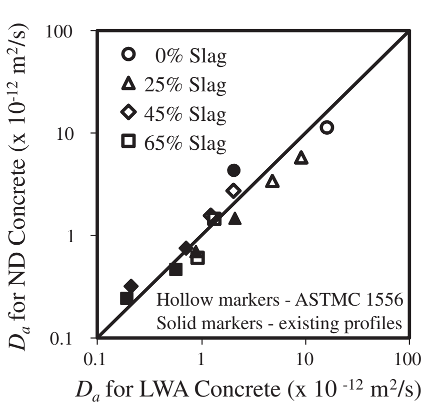

Fig. 8. Comparison of D_a values for LWA concrete and normal density (ND) concrete reported by Thomas et al. [8].

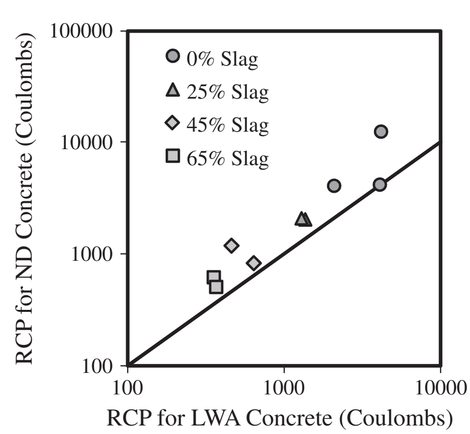

Fig. 9. Comparison of RCP values for LWA concrete and normal density (ND) concrete reported by Thomas et al. [8].

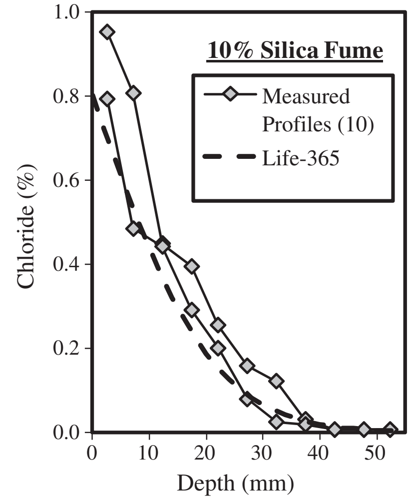

Fig. 10. Chloride profiles for ND concrete exposed to tidal zone for 14 years [10] — also shown prediction by Life-365.

study, large blocks (1.5 × 1.5 × 0.5 m, 4.9 × 4.9 × 1.6 ft) were exposed in the tidal zone in the Trondheim fjord in Norway. Chloride profiles have been measured at various intervals up to 21 years. The reported data at 14 years (closest interval to the 12 years for the GBS blocks) is shown in Fig. 10 for a block with w/cm = 0.41 and 10% silica fume. The profile predicted by Life-365 provides a very close fit to the measured profile. It is quite feasible that the better-than-expected performance of the GBS blocks is, at least in part, attributed to the internal curing provided by the LWA used in the production of this concrete. Concrete with w/cm = 0.33 and 8.5% silica fume would be highly prone to self-desiccation.

Further studies to examine the role of internal curing using LWA on chloride transport properties should examine low-w/cm prone to self-desiccation with and without pre-saturated LWA. It would also be interesting to examine the impact of moisture availability on the time-dependent nature of transport properties of concrete with and without LWA. For the concretes tested in the current study, moisture is constantly available as the blocks are submerged twice a day. In bridges and buildings (e.g. parking structures) some elements will be exposed to moisture sporadically during rainfall and it is likely that such elements will benefit more from internal curing than elements that are continuously wet.

It is somewhat surprising that the diffusion coefficients determined from existing chloride profiles is lower than those determined for the same concrete using the bulk diffusion test. The diffusion coefficient is expected to decrease with time, especially with increasing levels of slag [11]. The diffusion coefficient determined from the existing profiles represents the average diffusion coefficient between the time of placing the blocks at Treat Island when the concrete was approximately 3 months old and the time they were retrieved when the age of the concrete was 25 years. The bulk diffusion test determines the diffusion coefficient of the concrete at an age of 25 years and should thus be lower than the average coefficient between the ages of 3 months and 25 years. However, the opposite trend is observed in the data. This anomaly may be partly explained by a number of factors such as:

- Differences in temperature — diffusion follows an Arrhenius-type relationship and the rate of diffusion on Treat Island would be about half of that measured in the laboratory. Chloride binding (by the hydrates) is also increased at lower temperature [12].
- Differences in chloride concentration — the non-linear nature of the chloride binding isotherm for Portland cement [12] means that a greater proportion of the chlorides will be bound at the lower concentration in the seawater (approximately 0.5 M) compared to the laboratory test solution (approximately 2.8 M). In addition the presence of other ionic species in seawater could have an effect on the chloride-binding capacity of the hydrates and thus on the rate of transport.
- Other reactions — a number of reactions can occur between seawater and concrete, producing aragonite, brucite and magnesium silicates, and these may form a protective layer at the surface of the exposed concrete reducing the rate of chloride penetration [13].

However, it is not clear whether these factors fully explain the significant differences between the diffusion coefficients calculated from either the bulk diffusion test or existing chloride profiles, and this warrants further study.

6. Conclusions

Concrete blocks containing expanded shale or slate LWA as the coarse aggregate were collected from the tidal zone of a marine exposure site off the coast of Maine for testing in the laboratory. The following conclusions are drawn from the test results:

1. With regard to chloride-ion penetration, the performance of the blocks containing LWA was equivalent to that of blocks produced with normal density aggregates that were retrieved 2 years previously.
2. Slag greatly increased the resistance to chloride-ion penetration.
3. Increased levels of slag increased the surface scaling of concrete with w/cm ≥ 0.50, but not at w/cm = 0.40.
4. The concrete blocks containing LWA and silica fume and with w/cm = 0.33 performed better, with regard to resisting chloride penetration, than predictions based on the service-life model, Life-365. It is conjectured that the incorporation of LWA may have improved performance by internal curing, but further testing is required to confirm this.
5. Diffusion coefficients calculated from existing profiles at 25 years were considerably lower than coefficients determined from a laboratory bulk diffusion test performed on 25-year-old specimens from the same concrete.

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