EFFECT OF AIR ENTRAINMENT ON FREEZE-THAW DURABILITY OF TYPE S PORTLAND CEMENT-LIME MASONRY MORTARS

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ABSTRACT

Portland cement-Type S hydrated lime mortars are used extensively throughout the United States and Canada. Air entrained Type S hydrated lime may be used interchangeably with non-air entrained Type S hydrated lime in ASTM C 270 (Standard Specification for Mortar for Unit Masonry), but there is no preference toward either product where freeze-thaw conditions are prevalent. There appears, therefore, to be no perceived difference in freeze-thaw durability of air entrained or non-air entrained Portland cement-lime mortars in the field.

This study will report on the frost durability of three Type S proportion Portland cement-lime mortars (1 Portland cement:½ lime:4½ sand, by volume). Two of these mortars contain an air entrainment additive (8% and 11% measured air volume). The third mortar does not have an air entrainment additive. Plastic and hardened mortar properties are determined for each of the mix designs. Frost durability is determined using the unidirectional freeze-thaw test (BCRL Panel Freezing Test) and visual assessment.

Results indicate that non-air entrained Portland cement-lime mortars, as tested, are no more vulnerable to freeze-thaw damage than air entrained mortars. It is suggested that the well established resistance to moisture penetration resistance of Portland cement-lime mortars could account for this excellent performance.

Key words: Portland cement-lime mortar, freeze-thaw durability, unidirectional freeze-thaw testing, Type S hydrated lime, air content, masonry, Type S mortar

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INTRODUCTION

Freeze-thaw durability of mortar is dependent on the ability of the mortar to:

1) resist water penetration;
2) quickly lose enough water to prevent saturation;
3) have an appropriate pore structure which will accommodate the hydraulic pore pressures associated with pore fluid freezing (Powers, 1945, Feldman, 1970, Litvan & Sereda, 1980)

It is likely that in most parts of North America, mortar will be exposed to water. This is especially true in the spring and fall, when most freeze-thaw cycles occur. In addition, the pore size distributions of most mortars include capillary sized pores (<2 μm) and because of capillary rise these pores will not drain due to simple gravity. Air entraining additives have traditionally been thought to benefit the freeze-thaw durability of mortar by developing the proper pore structure to accommodate the hydraulic pore pressures associated with freezing.

Freeze-thaw durability of masonry, however, is more complex than the durability of the individual parts. It is dependent on the interaction of the masonry unit with the mortar as well as the construction design. The most severe condition will occur when the masonry assemblage is highly saturated with water. Dramatically, this could occur because of a severe driving rainstorm mid-winter that is followed by a dramatic drop in temperature. Under these conditions, the masonry is saturated at the front, with perhaps the back still frozen. Less dramatically, and perhaps more commonly, saturation could also be due to a down-spout not functioning on the south side of a building. The roof snow is melted during the day, saturating the masonry, which freezes at night. Masonry compatibility can also contribute to frost durability. While mortar should be sacrificial to the masonry unit, it is possible to have a mortar that is much less permeable than the brick, not allowing for the movement of water away from the brick. The brick could become water saturated, and damaged if not frost resistant.

Freeze-thaw durability of masonry is an issue that influences much of United States and Canada. The clay brick and concrete brick and block industries have attempted to provide some guidance for frost durability of their products (ASTM C 62 and C 1262 respectively). Standardized test methodologies for freeze-thaw durability testing of mortars are not available in Canadian (Canadian Standards Association) or American (American Society for Testing and Materials (ASTM)) standards. The most commonly applied test method is ASTM C 666A, which was developed for concrete. It is an omni-directional test, meaning freezing occurs on all sides, and is generally accepted as inappropriate (Edgell et al., 1999). van der Klught (1989) was one of the first to demonstrate the value of unidirectional freeze-thaw testing for masonry. It is this type of work which lead to the development of the European Norm prEN 772-22 that is the most commonly used unidirectional freeze-thaw test methodology for mortar.

Portland cement-Type S hydrated lime mortars have been used successfully in different climatic regions in Canada and the United States for over seventy years. The addition of air entrainment to Type S hydrated lime to aid in freeze-thaw damage resistance is not mandatory nor universally used where freeze-thaw durability is an issue, although air entrained hydrated lime products are available from most Type S hydrated lime producers. Masons do not view the addition of air entrainment to mortars to enhance freeze-thaw durability as an issue. In fact it is a more common practice to use air entrained mortars in hot weather regions to provide increased board life (Thomson & Godbey, 2001).

This study will examine the performance of Type S proportioned (1:½:4½) Portland cement-Type S hydrated lime mortars containing no air entrainment, 8% air entrainment, and 11% air entrainment when tested as mortar only in omnidirectional conditions and in a masonry panel in unidirectional freeze-thaw conditions. The British Ceramic Research Ltd. (BCRL) panel freezing test (West *et al*, 1984) will be used to examine the freeze-thaw durability of the three mortars types.

MATERIALS

Portland cement (ASTM C 150) and Type S hydrated lime (ASTM C207) were purchased at a retailer in the Chicago, IL market and shipped to the CERAM laboratory in Stoke-on-Trent, England.

The aggregate was obtained locally by the CERAM laboratory. The size gradation and comparison to ASTM C 144 is given in Table 1. The sand is finer than ASTM C 144 requirements on the 30, 50 and 100 mesh sieves.

Table 1. Aggregate Gradation Analysis

ASTM Sieve Size (metric value)	Mortar Aggregate % Passing	ASTM C 144 Gradation (% Through)
No. 4 Mesh (4.75 mm)	99.8	100
No. 8 Mesh (2.36 mm)	99.6	95-100
No. 16 Mesh (1.16 mm)	98.6	70-100
No. 30 Mesh (0.6 mm)	96.6	40-75
No. 50 Mesh (0.3 mm)	67.3	10-35
No. 100 Mesh (0. 15 mm)	15.2	2-15
No. 200 Mesh (0.075 mm)	1.9	0-5

The air entertainment additive used was Sealmix® which is commonly used in British masonry applications. It is a neutralized salt of vinsol resin.

The brick used for building the masonry prisms was a locally obtained product called Staffordshire Blue. It is smooth, blue in color and known to be frost resistant. The brick properties, as determined by BS 3921, are given in Table 2.

Table 2. Properties of Brick.

Characteristic	Value
Dry density	2208 kg/m^3
Water Absorption (5 hour boil)	4.6 %
Suction Rate	0.20 kg/m^2/min
Compressive Strength	109.6 N/mm^2
Freeze Thaw Durability	FL (very durable)

TEST PROCEDURES

Mortar Mix Designs

Mortar mixes were produced complying with the Type S proportion requirements of ASTM 270. The density of each of the mortar materials was determined in order to provide the weight of the materials for mixing. The weight of the materials for each mortar mix is reported in Table 3. The addition of air entrainment and total water varied.

Table 3. Weight of Materials for Mortars Tested

Component	**Mortar (1 cement:½ lime:4½ sand)**		
	Mortar A	**Mortar B**	**Mortar C**
Portland Cement, Type I (kg)	18.19	18.19	18.19
Hydrated Lime, Type S (kg)	3.64	3.64	3.64
Air Content		8%	11%
Aggregate (kg)	93.3	93.3	93.3
Water added (kg)	27.5	24.1	22.0
Water/cementitious ratio	1.26	1.10	1.01

Mortar Mixing Procedure

The mortar was mixed in a barrel type, inclined mixer. One batch was mixed for each mortar type, with two samples taken from the batch to measure consistency. Enough water was added to the mortar to achieve a flow of 130 $\pm$ 5% as measured on a flow table in accordance with ASTM C 230.

Mortar Properties

Plastic and hardened mortar properties were determined for each of the mortar mixes. Plastic mortar properties measured included flow (ASTM C 230), vicat cone penetration (ASTM C 187), air content (ASTM C 231) and water retention (ASTM C 110). The flow was measured after one hour of mixing to confirm continued workability of the mortar. A loss of 20% was considered an unworkable mortar.

Compressive strength was the hardened mortar property measured. Three sets of 3 compressive strength cubes were made for each mix. It is important to realize that the flow of the mortar was in the 130% range, not the 110% range described in ASTM C 270. The dimension of the cubes measured 70.7 mm on the side following BS 4451 (British Standards Institute), not the 50 mm (2") on the side cubes described in ASTM 270. The curing regime differed for each set of cubes. One set of cubes for each mortar type was cured in lime saturated water for 28 days and tested. The second set of cubes for each mortar type was cured in lime saturated water for 28 days and placed in the freeze-thaw cabinet with an assemblage of the same mortar type. This set of cubes was exposed to 100 freeze-thaw cycles and then tested for compressive strength. The final set of cubes for each mortar type was cured in lime saturated water for 28 days and placed in laboratory air until the freeze-thaw exposures were completed on the second set of cubes. The second and third set of cubes were tested at the same time.

FREEZE THAW DURABILITY TESTING

Panel Preparation

Two masonry test panels were constructed for each mortar mix (6 panels in total for the three mix types). Each panel was made from the same mortar batch and with the same mason constructing all the panels. The panels were built to the standard format of 10 courses of three bricks in half bond (Fig. 1).

Figure 1. Example of running bond test panel.

The panels were cured in doubled plastic bags for 28 days prior to freeze-thaw testing. At 28 days the panels were immersed in water at room temperature for seven days before being installed on the face of the freeze-thaw cabinet.

Freeze-Thaw Cycle Testing

The freeze-thaw test was carried out according to the BCRL (British Ceramic Research Laboratory) Panel Freezing Test that forms the basis of the proposed European Frost Test for Clay Masonry Units prEN 772-22. This unidirectional freeze-thaw test subjects the face of the masonry unit to the following conditions:

- 120 minutes of freezing at an air temperature of $-15 \pm 3^{o}C$
- 20 minutes of thawing with convected air at 25 ± 3°C
- 2 minutes of spraying the face with water.
- 2 minutes to allow the water to drain away before freezing recommences.

This is a severe test of freeze-thaw durability. All six panels were subjected to 100 freeze-thaw cycles. If brick tested by this method show no signs of failure after 100 cycles they would be expected to be durable under all conditions of exposure normally found in practice (West *et al.*, 1984). A panel made with Mortar A (no air entrainment) and a panel with Mortar B (7% air entrainment) were exposed for an additional 200 cycles to determine if failure would occur beyond the normal range of frost resistance. Visual observations of damage to the mortar joints were made every 20 cycles.

RESULTS

Mortar Properties

The property analyses of the mortars are presented in Table 4.

Table 4. Mortar Property Data

Mortar	Flow[a] (%) Initial (final after 1 hour)		Vicat Cone[b] (mm)	Air Content[c] (%)	Water Retention[d] (%)	Compressive Strength[e] N/mm^2 (psi)		
	Sample 1	Sample 2				28 Days	Freeze Thaw Exposed	Air Cured
A	133.00 (132.00)	132.40 (131.80)	49	5.2	90.0	8.40 (1218)	1.57 (228)	9.39 (1362)
B	129.25 (125.90)	127.90 (125.50)	36	8.0	92.3	6.50 (943)	1.42 (206)	7.23 (1049)
C	126.60 (121.80)	126.90 (121.00)	33	11.5	94.2	12.40 (1799)	11.10 (1610)	12.90 (1871)
E	126.00	n/a	n/a	3.5	81.6	ASTM C 270 mix – 14.4 (2088)		

a - ASTM C 230 c - ASTM C 231 (Type B pail) e - BS 4451 n/a - not available
b - ASTM C 187 d – ASTM C 110 E - Edgell *et al.*, 1999

The flow values at time of mixing indicate that the Portland cement-lime mortar without air entrainment was wetter then the other two mortar types. This is supported by cone penetrometer data. Flow values progressively decreased from 133 % to 127 % as air entrainment levels increased. The mason noticed a drier feeling mix with air entrainment despite maintaining flow levels between 125 % and 135%.

The 28 day compressive strength values for all the mortar types are lower than what would be expected for a C 270 volume proportion Type S mortar. Schuller & Thomson (1998) give an average value of 23 MPa of four Portland cement-Type S hydrated lime mortars. Edgell *et al.*, (1999) give a value of 14.4 MPa for the same mortar type, using the same sand source. The higher flow values for the mortars to build the masonry panels, the larger mortar cubes, the different type of mixer and the size distribution of the sand may all have contributed to the differences between the measured test results and those normally obtained for ASTM C 270 Type S mortars. Important is that all the mortars appear to have been treated and cured consistently, making the data internally consistent. Cubes air cured until the end of freeze-thaw cycling showed some compressive strength gain in comparison to cubes tested after 28 days of water curing.

FREEZE THAW DATA

The masonry test panels were visually inspected every 20 cycles for 100 cycles. Since no damage was detected on any of the panels for 100 cycles, the test was extended to 300 cycles for one panel of the non-air entrained mortar and one panel of the 8% air entrained mortar. No visual damage was noted for any of the mortar panels. Table 5 summarizes the visual assessment data.

Table 5. Visual Assessment of Damage to Masonry Panels

Mortar Mix	Panel ID	Cycle Number						
		20	40	60	80	100	120	Through 300
A (non-air entrained)	P1	ND	ND	ND	ND	ND	ND	
	P2	ND	ND	ND	ND	ND	ND	ND
B (8 % air)	P1	ND	ND	ND	ND	ND	ND	
	P2	ND	ND	ND	ND	ND	ND	ND
C (11 % air)	P1	ND	ND	ND	ND	ND	ND	
	P2	ND	ND	ND	ND	ND	ND	

ND - -no damage detected

The compressive strength of the mortar cubes after omnidirectional freeze-thaw testing was tested presuming that damage would show up as loss in strength (Table 4). Mix C which had a higher air content than the other two mixes showed little reduction in compressive strength, while the other lower air entrained and non-air entrained mortar showed up to 80% loss of strength.

DISCUSSION

Test Procedures

The relative performance of the non-air entrained and 8% air entrained Portland cement-type S hydrated lime mortar in omnidirectional and unidirectional freeze-thaw testing dramatically demonstrates the influence of the test technique on the outcome of the results. The omnidirectional testing showed evidence of damage through strength loss and visual deterioration for the non-air entrained and the 8% air entrained mortars. The same mortars when tested in a masonry system, by a unidirectional testing technique, show no damage at all.

Freeze-thaw Durability of Portland Cement-Lime Mortars

Despite testing beyond the 100 cycles normally used to determine frost resistance, all of the Portland cement-lime assemblages tested showed no signs of deterioration.

The development of the proper pore structure (created by the addition of air entrainment additives) appears to enhance the freeze-thaw durability of mortars tested by omni-directional test methods. Other factors, however, appear to be more significant when looking at the freeze-thaw durability of masonry assemblages.

Portland cement-Type S hydrated lime mortars (Type S proportion), have excellent freeze-thaw durability in the field and in unidirectional freeze-thaw testing, regardless of degree of air entrainment. The explanation for this may be the well-established ability of Portland cement-lime mortars to resist water penetration (Schuller & Thomson, 1998; Matthys 1988). The ability of the Portland cement-lime mortar to release absorbed moisture could also be important. This characteristic, however, is not currently well defined. Portland cement-lime mortars will not become as saturated as other mortar types, and therefore, are not put under the same amount of environmental stress as the other mortar types. For a Portland cement-Type S hydrated lime mortar, the addition of air entraining agents appear not to be necessary to provide freeze-thaw resistance. They are not detrimental to freeze-thaw durability either. This is in full support of the seventy years of empirical data.

These conclusions are, for the most part, supported by the work of Edgell *et al.*, (1999). That study indicates that for essentially the same mortar, using the same brick, sand from the same sand source, and similar flow values:

- one of the panels showed no damage at 300 cycles
- one showed damage at 200 cycles, but none additionally, and the test was continued to 300 cycles,
- and the third showed damage at 50 cycles, and the test was terminated after 250 cycles.

It is interesting to note that petrographic analysis of mortar from the least durable panel indicted, "…a significantly higher water-cementitious ratio" than the other mortars analyzed. This anomaly could account for the difference in performance.

CONCLUSIONS

- Portland cement-Type S hydrated lime mortars (Type S by proportion) are freeze-thaw durable by empirical experience and by unidirectional freeze-thaw testing
- Omnidirectional freeze-thaw testing does not represent the freeze-thaw process of masonry, and should not be used to predict the performance of either materials or masonry assemblages.

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