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FREEZE-THAW DURABILITY OF MORTARS IN HISTORIC MASONRY: TEST METHODOLOGIES.

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ABSTRACT

Freeze-thaw durability of mortars was evaluated using a unidirectional freeze-thaw cycling cabinet. Mortars were first evaluated in prism specimens then as mortar bedded in stone masonry walls. Failure was determined by visual assessment and by measurement of expansion. Three freeeze-thaw temperature cycles have been used, to promote different degrees of failure.

INTRODUCTION

Durability of mortar in freeze-thaw conditions is an important consideration for the long term service-life of masonry structures. This is particularly the case in Canada, where as many as 100 freeze-thaw cycles can occur in a 12 month period. Currently there are no standards available in Canada (Canadian Standards Association or American Society for Testing and Materials standards) to evaluate the freeze-thaw cycling performance of mortar used in masonry structures. The purpose of this paper is to discuss:

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- current standards used to evaluate freeze-thaw durability of porous building materials,
- the current research at the Institute for Research in Construction (IRC) in developing a unidirectional freeze-thaw cycling test method to evaluate the freeze-thaw durability of mortars.

FROST DAMAGE MODELS FOR POROUS MATERIALS

A considerable amount of research has been reported on the mechanisms of frost damage in porous materials (*e.g.*. Powers, 1945, Everett, 1961, Feldman, 1970, and Litvan & Sereda, 1980). Two models are often cited to describe the process. The model of ice-lensing was first developed for soils (Everett, 1945). This occurs where the temperature slowly drops from above zero to approximately -5°C and is held for a relatively long period of time. A stable, static freezing front forms and water in large pores (bulk water) freezes. Water from the interior of the material migrates to the freezing front, thereby progressively filling the larger pores with ice. The pressure produced with the growth of the ice lense exceeds the strength of the material and it fails. The resulting failure occurs as a crack which parallels the freezing front.

The second model, often termed the disequilibrium model, considers the physical properties of freezing water in small pores (Powers, 1945, Feldman, 1970, Litvan & Sereda, 1980). Water will first freeze as bulk water in the largest pores, but remain unfrozen in the smaller pores. The unfrozen water has a tendency to migrate from small pores to the larger pores where it freezes. If the freezing rate is rapid large hydraulic pressures and mechanical stresses can build up resulting in cracking of the material.

Critical to these models is a high degree of water saturation. Significant damage will not occur if there is insufficient water to freeze. Inherent in the degree of saturation is the pore size and permeability of the porous material. Litvan & Sereda (1980) point out that materials which have very small or large pores and high permeability tend not to suffer from freeze-thaw damage. Either there is insufficient water to cause a problem, or the water migrates and drains quickly enough to accommodate the freezing. Most mortar, however, fits in the middle ground, making freeze-thaw cycling a potential problem.

CURRENT STANDARDS FOR FREEZE-THAW TESTING OF POROUS CERMANICS

The traditional approach to freeze-thaw testing is freezing on all sides of the sample or omni-directional. Freezing on one side or unidirectional freezing is a common standard in Europe and is gaining attention in Canada. Table 1 presents a summary of the two fundamental approaches currently taken for freeze-thaw resistance standards (after Maciulaitis, 1994).

Table 1. Summary of freeze-thaw resistance standards for ceramic materials.

Country	Omni-directional	Unidirectional
Russian Standards	P. 7, GOST 7025-91	P8, GOST 7025-91
German Standards	DIN 52252, PART 1	DIN 52252, PART 3, 1983
Lithuanian Standards	LST 127-91	LST 1272-92
Spanish Standards	UNE 67-028	
United States Standards	ASTM C 67	
French Standards		NFP 13-034, 1983
British Standard		BS 3931
British Ceramic Research Association		BCRA, 1985
Irish Standards		IS 91, 1983
Austrian Standards		OE NORM B 3219, 1985
The Netherlands		NEN 2872
European Standard		EN202

The Netherlands standard, NEN 2872, is a good representative of a unidirectional freeze-thaw durability test. It was developed primarily for masonry units and tiles and uses an upright stainless steel cabinet fitted with a stainless box (approximately 0.3 m deep, 1.0 m long and 1.3 m wide). The samples are placed on a 25 mm thick gravel bed in the stainless steel box with the face side of the sample horizontal. Spaces between the samples are filled with coarse filler material, usually clean sand. Water saturation of the sample is achieved by soaking the sample in water for at least a 24 hour period, and maintained by using water to thaw the sample. Varying the air temperature controls the freezing and to a certain extent the thawing rate.

Fifty cycles are usually completed for bricks. Damage is assessed by weight loss and the visual estimation of cracks and spalling.

A fast and slow rate of freezing and thawing is combined in this test method (Fig.1). These two cycles are meant to replicate the two models of freeze-thaw damage described above. The cycle combination recommended consists of alternating a single cycle at the slow rate of freezing with a single cycle at the fast rate of freezing or grouping 12 cycles at the slow rate of freezing with 12 cycles at the rapid rate of freezing. This test method has been routinely applied to bricks at IRC, using the unidirectional freeze-thaw cabinet developed by TNO, in The Netherlands.

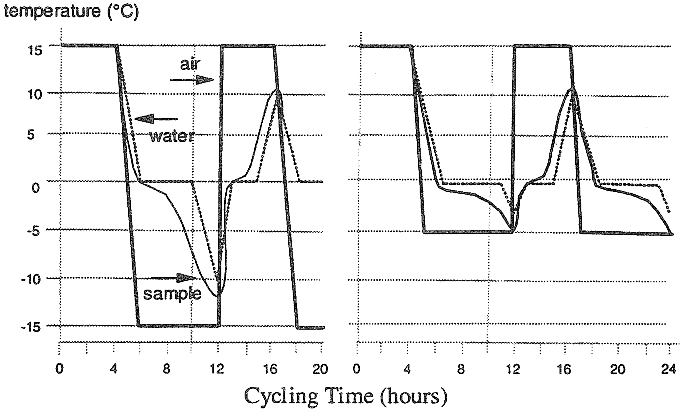


Fig. 1. NEN 2872 recommended freeze-thaw cycle.

The ASTM C-666A, a standard test method for resistance of concrete to rapid freezing and thawing, is representative of a omnidirectional freeze thaw test. Prisms (76 mm to 127 mm in width or depth and 279 mm long) with end measuring pins are usually placed horizontally in the freezing chamber. There is no direct procedure for initial saturation, but experience indicates that in the presence of the thawing water the samples become saturated after a couple of cycles.

The nominal freezing and thawing cycle consists of alternately lowering the temperature of the specimen from 4.4°C to -17.8°C and raising it to 4.4°C in not less than 2 hours and no more than 5 hours.

The samples are cycled up to 300 times. Experience at IRC indicates that damage is best evaluated by changes in weight and length.

The omnidirectional freeze-thaw method is a very stringent test due to the fast rate of freezing and high degree of saturation. Damage is characterised as random cracking perpendicular to the surface. The cracks progressively amalgamate with increasing damage and the sample essentially falls apart. Damage related to the unidirectional freeze-thaw method is generally characterised as a crack, parallel to surface spalling. The style of damage produced by the omnidirectional freeze-thaw test is not consistent with the type of damage noted in the field. The unidirection freeze-thaw test method does in fact replicate this style of damage (van der Klugt, 1989). Uni-directional freeze-thaw testing has been adopted in many countries for this reason. It is being reviewed by the ASTM C-12 committee.

THE IRC FREEZE-THAW DURABILITY TEST DEVELOPMENT PROGRAM.

IRC has been working for about two and half years toward developing a suitable freeze-thaw durability test for mortar in a masonry system. The program has exclusively used The Netherlands developed, unidirectional freeze-thaw testing cabinet. (Fig. 2). The focus of the work has been on assessing the durability of mortar used in the restoration of historic stone masonry. This work has been jointly supported by IRC and Public Works Canada. The following is a summary of the progress made and the problems encountered.

Mortar Prisms.
An initial mortar program (Suter *et al.*, 1993), investigated twelve mortar mixes. The mortar prisms were weighed dry, immersed in water for 56 hours and reweighed, saturated surface dry. Two measuring pins were placed on the ends of each prism. They were packed in a tray, touching each other, and surrounded by gravel (Fig. 2). Two thermocouples were embedded within 50 mm of the front and back of a prism to monitor the temperature regime. The samples were cycled from 13° to -6° to 13° C over 6 hours followed by a cycle of 13° to -17° to 13° C in 20 hours. The prisms were measured at 12, 39 and 64 cycles. The test method was the combination of the ASTM C-666 method in measuring length and weight changes, and the NEN 2872 method in the sample configuration and cycling.

The resulting damage is illustrated in Fig. 3. It became readily apparent that measuring expansion was not relevant to the type of damage which occurred. The prisms cracked parallel to their length, or spalled at the surface. It was not represented by expansion along the length. The weight change data indicated a progressive increase in weight, then a decrease in weight, related to mass loss (Fig. 4). Loss of weight generally correlated with a visual inspection of the damage. The degree of visual damage was given a rating from 1 to 5, with 5 the most damage. This system of damage assessment was not considered satifactory.

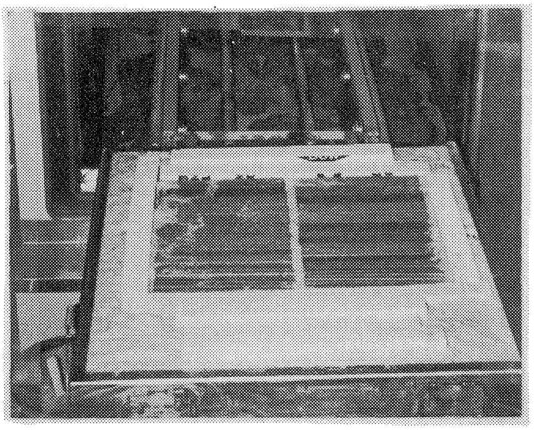


Fig. 2. Interior of freeze-thaw cabinet, showing arrangement of mortar prisms. Blue styrofoam is used to reduce the mass within the tray.

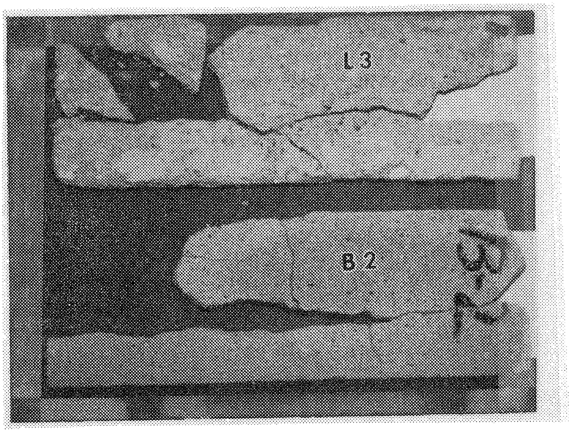


Fig. 3. Examples of damage evident on mortar prisms. Surface spalling and interior cracking. Note pins on the end of prism, have fallen out in two samples.

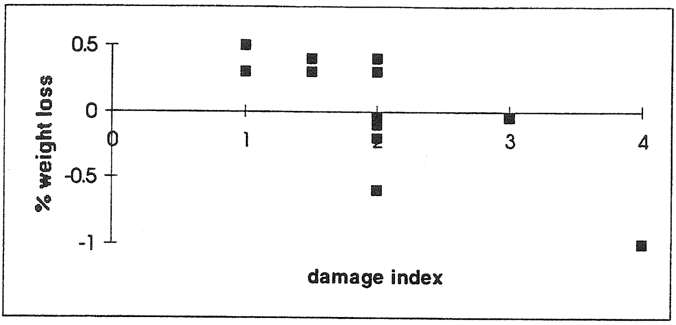


Figure 4. Weight change versus damage index after 64 cycles.

Stone Walls: Fast and Slow Rates of Freezing.
The use of masonry prisms to test mortar durability, was considered unsatisfactory because it did not realistically represent the condition of the mortar and the composite nature of mortar in masonry. Figure 5 illustrates the configuration of one of 16 stone walls investigated the next series of mixes. The following is a list of the significant modifications made to the test procedure:

- mortar was bedded between sandstone blocks,
- thermocouples were placed in mortar joints and monitored continually,
- walls were placed vertically, side by side in the cabinet, jacketed on top, back and sides by 20 mm thick extruded Styrofoam,
- walls were immersed in water for 48 hours prior to cycling,
- walls were thawed by warming the air, and sprayed with water after the air temperature reached 0°C; at no time were the walls immersed in water
- expansion of joints was measured using demec pins and gauge.

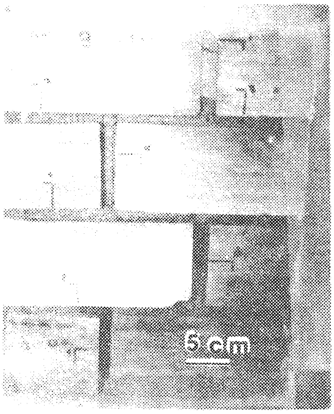
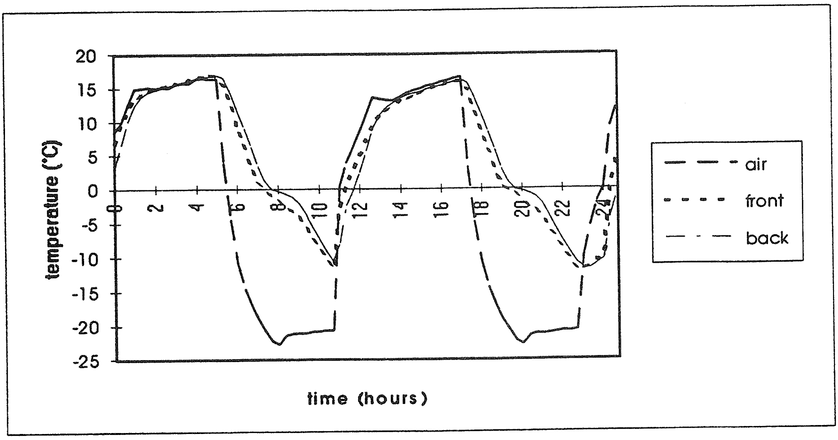


Fig. 5. Example of stone wall built for freeze-thaw cycling, after 134 cycles.

The freeze-thaw cycle used for this test programme is illustrated in Figs. 6a and 6b. It is consistent with the NEN 2872 method. Twelve cycles of fast rate of freezing were followed by 12 cycles of slow rate of freezing. Measurements were taken every 12 cycles. The walls were cycled 134 times.

a) fast rate of freezing



b) slow rate of freezing

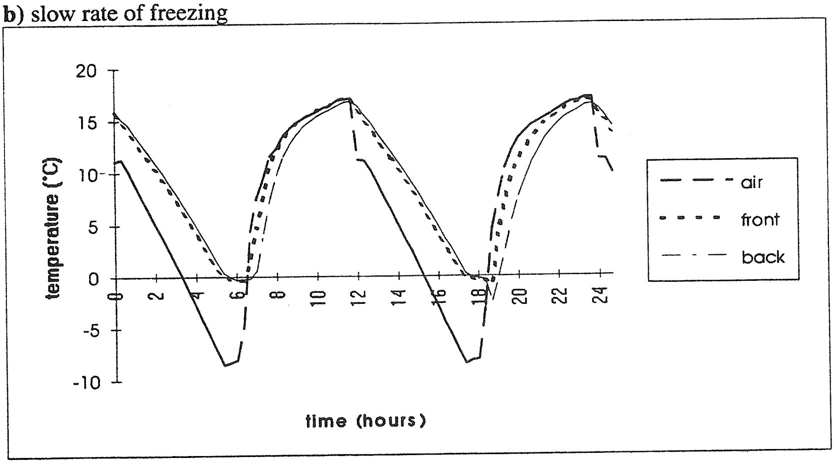


Fig. 6. Freeze-thaw cycle curves determined from thermocouple data obtained by continuous monitoring.

The resulting freeze-thaw damage to the mortar is illustrated in Fig. 7. Where failure occurred the surface of the mortar fell out as a layer up to 10 mm thick. More significantly, however, was the evidence that the expansion of the mortar was a much more sensitive indication of performance.

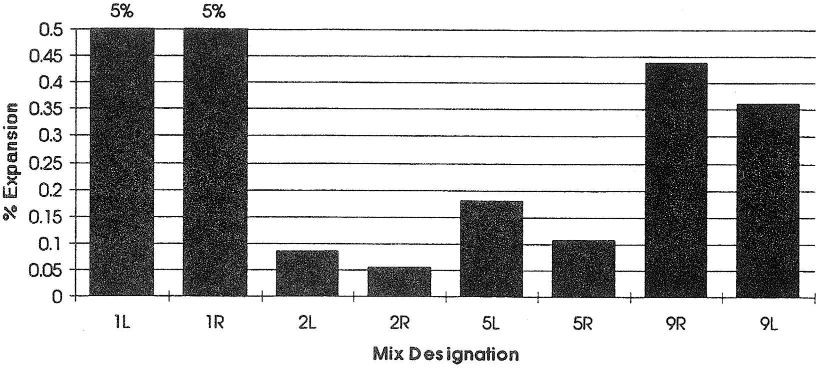


Fig. 7. Expansion data of mortar in stone walls after 134 cycles. The numbers refer to speicif mortar mixes and the letters "R" and "L" designate right and left joints on a stone wall.

The failure in Mortar 1 was catastrophic and the wall was removed after 72 cycles because the deteriorating mortar was clogging the pumps. The remaining mixes did not show any evidence of failure; however, expansion in excess of 0.2% for Mix 9 is considered significant. Note that the amount of expansion in mortar varied within a single wall. Perhaps degree of saturation due to the quality of the bond, or perhaps the wetting pattern on the face of the wall is significant.

Stone Walls, Fast Rate of Freezing.

The current investigation of the freeze-thaw durability of mortars, has continued with the use of stone walls. The mass of stone was reduced to increase the number of walls placed in the cabinet to 20. The cycle was a single fast rate and with 3 cycles in 24 hours. All other conditions remained the same. The reason for this change in cycling was to test the freeze-thaw durability of mortars under rigorous conditions, such as exposure to snow melt during a sunny day, and rapid freezing with the onset of night. This cycle is certainly not uncommon to the Parliament Buildings in Ottawa. The cycle is presented in Fig. 8. Of interest, is the long hold of the temperature at 0°C at the back of the mortar both during the freezing and thawing conditions.. This has not been seen in the previous cycles.

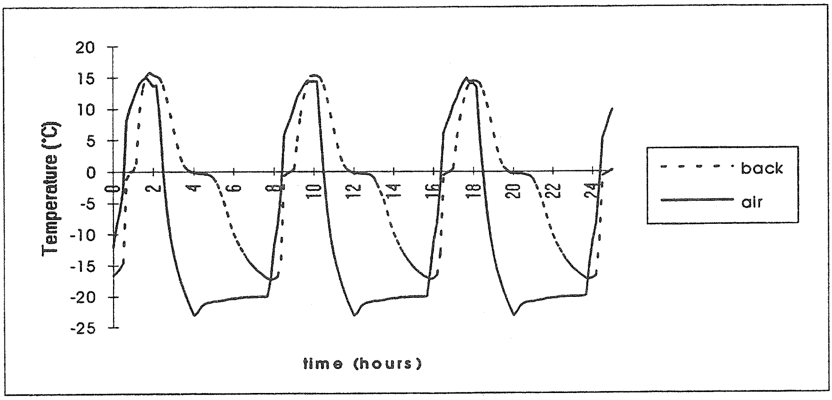


Fig. 8. Freeze-thaw cycle representing rapid rate of freezing

The same type of failure occurred in these samples as in the first test, although the rate at which failure occurred was much more rapid. Some mortars failed at only 17 cycles, others survived 125 cycles.

DISCUSSION

A framework for a unidirectional freeze-thaw durability test for mortars in masonry has been developed. The results differentiate the relative performance of a wide range of mortar mix designs. The style of apparent damage is consistent with that noted in the field. There remains, however, some work before this methodology can be used as a standard test. The following list is a summary of some of the questions which should be addressed:

- What cycle or combination of cycles best represent true field conditions?
- What type of conditioning should the walls undergo prior to cycling?
- How can the test results be related to service-life prediction?

CONCLUSIONS

The following conclusions appear warranted:

- rate of freezing and degree of saturation are important parameters to consider when designing a freeze-thaw test for masonry mortars.
- unidirectional freeze-thaw cycle testing results in damage more representative of field experience than onmi-direction freeze-thaw cycle testing.
- testing of masonry mortar is more realistic when it is placed between the masonry units.

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