Improvements to Water, Salt-Scaling and Freeze-Thaw Resistances Of Historic Mortar Replication Mixes

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Abstract

While the long-term destructive potential of liquid water in masonry assemblies is well known, the potential for disruption of saturated mortars exposed to freezing conditions can represent a more challenging and immediate problem. Highly porous and permeable mortars, valued in historic preservation work, also have the potential to become rapidly saturated. In horizontal traffic surfaces such as pavements and stairways, damages related to water ponding and saturation prior to freezing may be further exacerbated by the presence of de-icing salts whose crystallization may cause exfoliation, delamination and disruption of substrates.

Testing was undertaken to evaluate mortar admixtures in various historic mortar replication mixes incorporating Natural Cement, Natural Hydraulic Lime 3.5, Roman Cement and Portland Cement-Lime binders. Testing was based on a modified ASTM C672/C672M-12: Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals. The most effective treatment for improving freeze-thaw, water and salt-scaling resistances while maintaining high moisture vapour permeability was a proprietary cationic acrylic latex admixture at 75% concentration.

Introduction

Freeze-thaw resistance of mortar is commonly improved in one of three ways: air entrainment, use of water repellents, or polymer modification. Harder portland cement-lime mortars, such as ASTM C270-14a [1]. Types S and M by proportions, have been found to exhibit good freeze-thaw resistance both with and without air entrainment [2]. Mortars whose hardness, density, and/or modulus of elasticity are significantly higher than those of the original mortar are known to be incompatible with many types of historic masonry construction, however. The objective of this study was to provide practical guidance to promising approaches for improving performance of historic masonry mortars of various compositions.

Air entrainment is achieved by incorporating additives conforming to ASTM C226-12, Standard Specification for Air-Entraining Additions for Use in the Manufacture of Air-Entraining Hydraulic Cement, which create micro bubbles in the mortar. While it is commonly believed that the bubbles create void spaces into which ice or salt crystals can expand without disruption to the mortar, the effects of air entrainment are more complex and have been the subject of extensive research [3]. The size, distribution, and percentage of air voids are critical. Excessive air-void volume can negatively affect compressive strength, bond strength, and water absorption; inadequate air-void volume may prove ineffective in overcoming ice and salt-crystal expansion stresses.

Water repellents can effectively reduce water absorption into mortar from exterior exposure. As disruption will result only when freezing occurs while mortar is saturated, significant reductions in water absorption can improve freeze-thaw resistance. While a variety of water-repellent chemistries have been employed commercially, the most common types in use today are based on organosilane and siloxane prepolymers. Proprietary high-solids silane-cream water repellents are claimed to offer improved performance due to their heavier application and reduced volatility, allowing higher amounts of active treatment to be deposited more deeply within the mortar [4,5].

Polymer modification improves multiple key properties of mortar including bond strength, shrinkage, water absorption, and flexural strength [6]. At moderate polymer-binder ratios, they do not significantly reduce moisture-vapour permeability. Polymer additives increase freeze-thaw resistance by forming hydrophobic polymer-binder co-matrices. Many different polymer modifiers are commercially available, but the most effective ones do not substantially degrade when saturated with water or in long-term exposure to ultraviolet radiation in sunlight.

Of the available polymer modification chemistries, 100% acrylic admixtures are favoured for both their mechanical and colour stability. Most 100% acrylic admixtures are described by their manufacturers as being based on non-ionic polymer chemistry. In the early 1990s, a unique acrylic polymer, described by its manufacturer as being based on cationic polymer chemistry, became commercially available and was promoted as offering superior chemical and water resistance. While it was not disclosed how cationic chemistry related to the claimed performance improvements, internal testing confirmed the claim of superior water-resistance. This proprietary polymer was a component used in this study because of those properties [7].

Though primarily focused on polymer modification, the evaluations performed within this study included all three approaches to some extent. Although not intended to be an exhaustive academic examination of the many variables associated with each approach, the study’s comparisons of relative performance of representative examples were valuable in ranking the relative potential benefits of air entrainment, water repellents, and polymer modification in improving the freeze-thaw resistance of historic mortar replication mixes. Correlation with real-world experience was also a central focus in selecting methods and mortar formulations, and in evaluating results.

East Block: Parliament Hill, Ottawa, and St. Patrick's Basilica, Montréal

The initial impetus to undertake the study of polymer modification of masonry mortar was the premature freeze-thaw failure in early 2013, during the first winter after application, of an air-entrained ASTM C270 Type O repointing mortar on projecting elements of the northwest tower of the East Block on Parliament Hill in Ottawa (Figure 1). The mortar had been proportioned at 1 part ASTM C150 portland cement Type 1, 2.5 parts ASTM C207 hydrated Type SA air-entrained lime, and 8 parts ASTM C144 sand by volume (1:2.5:8). Air content was 12 to 15%. Failures did not occur on vertical surfaces.

Figure 1. East Block Parliament Hill, Ottawa, Ontario, built 1859-1866, the sloped elements (below the windows) of the northwest tower four years after repointing of the freeze-thaw damaged areas with polymer modified repointing mortar, 2017. Photo by Michael Edison.

Architect Fernando Pellicer of DFS Architecture in Montréal had previously undertaken more than 12 years of in situ comparative observations using polymer-modified and -unmodified mortars at St Patrick's Basilica in Montréal. In 2001 Pellicer wrote that "water infiltration and saturation of mortar joints in solid masonry walls has always been a concern, especially in northern climates where the action of freeze-thaw cycles is very destructive." He referred to "the potential benefits of polymer modified re-pointing mortars: Improved bond, flexural and compressive strengths, reduced water absorption and greater freeze-thaw resistance" as "a few of the positive points." He recognized, however, that "the challenge is to develop a polymer modified re-pointing mortar in which the positive aspects are retained to a sufficient degree and yet maintain an acceptable level of vapour transmission" [8].

In light of his observations over time at St. Patrick's Basilica, Pellicer concluded that the polymer-modified mortars generally remained in better condition than their unmodified counterparts and elected to consider use of polymer-modified mortar for repointing the damaged areas of the East Block tower. He chose a 50% dilution with water of a commercially available acrylic-latex modifier, Restoration Latex #1. The admixture was used with the same Type O mortar mix that had been employed for all the repointing work performed during the previous season.

In April 2013 DFS Architecture engaged the laboratory services of Edison Coatings, manufacturer of the polymer modifier, to evaluate the effects of polymer modification on the air-entrained Type O restoration mortar. Edison Coatings' lab tested modified mortar against an unmodified control, focusing on three key performance properties: compressive strength, water-vapour transmission, and cold-water absorption.

Mortars were mixed to a typical repointing Vicat consistency of 25±2 mm penetration, per ASTM C780-00, Standard Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry. Mortar cubes (50-mm) for compression testing were prepared and tested per ASTM C109/C109M-08, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). Unmodified mortar cubes were cured in a humidity chamber at 95 to 100% relative humidity for 18 days. Modified mortars were dry-cured in ambient laboratory air for 7 days to allow film formation, followed by 11 days curing in the humidity chamber. Dry-curing is aging without misting or further addition of water. The polymer modifier slows the rate of drying, retaining sufficient water in the mortar to promote cement hydration during the critical initial days of curing [9].

Results of compression testing indicated approximately 12% higher compressive strength for the polymer-modified mortar (Table 1). This difference can reasonably be attributed to the water-reducing effects of latex modifiers, whose surfactants allowed the 25 mm Vicat consistency to be achieved at a lower water-binder ratio.

Table 1. Compressive Strength results for polymer-modified vs. unmodified Type O mortars

Mortar Mix	Sample	Cure Method	Compressive Strength (psi)	Average (psi)
1:2.5:8 Non-Modified (cement:lime:sand)	4	18-Day Damp	800	758
	5	18-Day Damp	700	
	6	18-Day Damp	778	
1:2.5:8 Latex Modified (cement:lime:sand)	4	7 Air + 11 Damp	850	850
	5	7 Air + 11 Damp	850	

The purpose of this test was to determine whether polymer modification would lead to excessive strength increases, compromising the desire for low to moderate strength mortar. While compressive strength is not the only property of interest in evaluating mechanical performance, it is a convenient benchmark for other properties, such as flexural strength and modulus of elasticity, which tend to develop in proportion to compressive strength.

The 12% differential in compressive strength was deemed insignificant. Practical experience in reviewing tests of field-mixed mortars suggests variations greater than 12% from batch to batch are to be expected, even when using the same carefully measured mix design. Results for both mortars were also well within the range of typical strengths observed for cement-lime-sand mortars specified and prepared by proportions [10].

Water-vapour transmission testing was performed in accordance with ASTM E96-90, Standard Test Method for Water Vapor Transmission of Materials, Method B, Wet Cup. Mortar discs of uniform thickness were cast and cured in the manner appropriate to each mortar. Results indicated approximately 75% retention of water-vapour transmission rates in the modified mortar compared to the unmodified control (Table 2).

Table 2. Water Vapour Transmission Rates, polymer-modified vs. unmodified Type O mortars

Mortar Mix	Sample	Vapour Transmission (g/in^2/h)
1:2.5:8 Unmodified	1	0.0939
	2	0.1080
	3	0.0920
	Average	0.0979
1:2.5:8 Polymer Modified	1	0.0745
	2	0.0731
	3	0.0716
	Average	0.0730

This was considered more than adequate. Beyond the practical impact of inherent variability in mortar properties, precision of the ASTM E96 method is limited and significant coefficients of variation are reported in the standard for reproducibility and repeatability. Accordingly, it is impractical to closely specify or control mortar-water vapour permeability to the degree of precision that would make a 25% reduction the critical tipping point between compatibility. Mix designs should target larger differences between mortar and masonry unit or stone water vapour permeabilities to assure that the mortar is always more permeable.

Water absorption was evaluated in accordance with ASTM C67-12, Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile, Part 8 Absorption. 50 mm cubes were cast and cured as per the compression-testing regimen above, and were then immersed them in room-temperature water for 24 hours. Results indicated an approximate 80% reduction in water absorption for the modified mortar compared with the unmodified control (Table 3).

These results were taken as confirmation of Pellicer’s hypothesis. At the moderate polymer-binder ratio tested, polymer-modified mortar had the potential to improve freeze-thaw resistance without significant changes in mortar strength or permeability.

Subsequent to the presentation of these findings, the damaged areas of the East Block tower were repointed with the same polymer-modified air-entrained Type O mortar tested. The work was performed in spring 2013. To date, some six years later, there has been no reoccurrence of the freeze-thaw–related damage observed after the first year with the unmodified mortar that was otherwise of the same composition.

Table 3. Cold water absorption of polymer-modified vs. unmodified Type O mortars

Mortar Mix	Time, min	Cure Method	Water Absorption g/100 cm^2	Water Absorption, %
1:2.5:8 Unmodified (cement:lime:sand)	o	18-Day Damp	0	0
	15		31.56	3.37
	60		61.20	6.53
	120		81.44	8.69
	240		111.84	11.93
	360		132.48	14.13
	1440		138.20	14.74
1:2.5:8 Latex Modified (cement:lime:sand)	0	7 Air + 11 Damp	0	0
	15		3.32	0.38
	60		6.24	0.72
	120		8.20	0.94
	240		11.08	1.27
	360		13.84	1.59
	1440		15.96	2.87

Foley Courthouse, Albany, New York

Repointing mix design for the granite pavement at Foley Courthouse in Albany, New York, was initially based on a blend of ASTM C10 natural cement and ASTM C207 Type S lime. Although the original mix was placed in late fall and improperly cured, its immediate failure led to reconsideration of mix design and selection of a more robustly hydraulic mortar with proportions of 1:2 by volume of ASTM C10 natural cement and ASTM C144 aggregate. The failure in the first winter of this second pavement mortar led to initiation of a study by the authors of freeze-thaw resistance of historic mortar-replication mixes in pavement applications. Typical damages are shown in Figure 2.

The impermeable, poorly graded granite pavement system was susceptible to water ponding, mortar saturation, and consequential freeze-thaw damage. Initial research focused on trying to determine why the 1:2 mix design was vulnerable to freeze-thaw failure and to identify alternative mix designs that could potentially perform better.

A laboratory study was initiated based on a modified ASTM C666-03, Resistance of Concrete to Rapid Freezing and Thawing. The modification involved substitution of brick assemblies for the concrete prisms used as test specimens in the ASTM standard.

Three sets of brick and mortar assemblies were made, in which the mortar to be tested was placed between two common red bricks. The assemblies were believed to be more representative of the geometry and moisture dynamics for masonry mortar applications. The goal was to gauge relative freeze-thaw resistance properties of the mortars themselves, rather than focusing on the specifics of the Foley Courthouse pavement, granite pavement applications in general, or the more variable range of potential interactions with other substrates.

Figure 2. Foley Courthouse, Albany, New York, built 1932 to 1934. Some pavement mortar failures manifested themselves as a thin layer of dry, hardened mortar above a layer of wet, disaggregated mortar, presumably corresponding with the depth within the joint at which mortar was frozen while saturated. Photos by Chad Lausberg

Three mix designs were tested in volume proportions of 1:1, 1:1.5 and 1:2 ASTM C10 natural cement to ASTM C144 sand, respectively. All of the mortars were mixed in accordance with ASTM C305-11, Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency. All were mixed to a typical consistency for setting mortar, 45 mm ± 2 according to the Vicat cone penetrometer per ASTM C780-08, Standard Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry. The brick and mortar assemblies were cured in a curing chamber for 28 days at 95 to 100% relative humidity. After curing, the brick and mortar assemblies were placed in a shallow pan with 6.35 mm (1/4 inch) of water and subjected to 50 freeze-thaw cycles of 16 hours at -18°C (0°F) and 8 hours at 22°C (72°F).

When the 50 freeze-thaw cycles were complete, all of the mortars were found to be in perfect condition, exhibiting no scaling or other damage. Even the 1:2 mix that had failed in one season at Foley Courthouse was in perfect condition. These observations led us to conclude that ASTM C666 did not correlate well with real-world observations and that an alternative, more aggressive testing procedure was required. Although laboratory conditions were not a direct reproduction of the failed assemblies and exposures at Foley, a portion of each assembly was completely saturated when frozen and some degree of failure was expected. A meaningful test would not only reproduce some failure but would also exhibit some differentiation between different mortars.

More Stringent Testing Based on ASTM C672 (Modified)

A new study was then initiated utilizing a modified ASTM C672/C672M-12, Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals. Concrete paver and mortar assemblies were substituted for mortar prisms to more accurately represent geometry and moisture dynamics of the mortar joints in a pavement assembly. Assemblies were 330 mm x 330 mm (13 x 13 inches), creating 813 mm (32 lineal inches) of mortar joints. Edge dams were created with vinyl tile and polyurethane sealant to produce a ponded water condition. All of the mortars were mixed using the ASTM C305 procedure and adjusted to the same 45 mm ± 2 Vicat consistency. Joint widths were controlled at 1.26 cm (1/2 inch).

A wide range of mix designs was tested to obtain freeze-thaw performance trend information for potential restoration mortars (Table 4). Common binders like portland cement/hydrated lime, American natural cement, Roman cement, and natural hydraulic lime were proportioned with aggregates conforming to the requirements of ASTM C144-04, Standard Specification for Aggregate for Masonry Mortar at commonly used ratios. Portland cement conformed to the requirements of ASTM C150-07, Standard Specification for Portland Cement Type I. Hydrated lime conformed to the requirements of ASTM C207-06, Standard Specification for Hydrated Lime for Masonry Purposes Type S. Natural cement conformed to the requirements of ASTM C10-06, Standard Specification for Natural Cement. Natural hydraulic lime 3.5 conformed to the requirements of EN-459 1:2010 for natural hydraulic lime 3.5. These mix designs were then modified with different additives and treatments as noted, to determine whether and how they influenced freeze-thaw resistance.

Table 4. Mix Designs Tested for Freeze-Thaw Resistance, ASTM C672-Modified

Binder	Proportions (Type)	Modification	Cure Time (days)
Portland/Lime	1:0.25:3.75 (M)	None	7
Portland/Lime	1:0.25:3.75 (M)	100% Liquid Polymer	7
Portland/Lime	1:1:6 (N)	None	7
Portland/Lime	1:1:6 (N)	88C Silane Cream	7
Portland/Lime	1:1:6 (N)	75% Liquid Polymer	7
Portland/Lime	1:2.5:8 (O)	50% Liquid Polymer	7
Portland/Lime	1:2.5:8 (O)	75% Liquid Polymer	7
Portland/Lime	1:2.5:8 (O)	100% Liquid Polymer	7
American Natural Cement	1:1	None	56
American Natural Cement	1:1	89W Siloxane	56
American Natural Cement	1:1	12% Air	28
American Natural Cement	1:1	100% Liquid Polymer	28
American Natural Cement	1:2	100% Dry Polymer	28
American Natural Cement	1:2	50% Liquid Polymer	28
American Natural Cement	1:2	100% Liquid Polymer	28
Roman Cement	1:1	100% Liquid Polymer	28
NHL 3.5	1:2.5	None	28
NHL 3.5	1:2.5	88C Silane Cream	28
NHL 3.5	1:2.5	100% Liquid Polymer	28

The liquid polymer used in the study is a proprietary commercial cationic acrylic-latex modifier, the same as used in the East Block tower mortar evaluations. It is supplied by the manufacturer at 28% solids by mass. Test specimens designated as “100% Liquid Polymer” (Table 4) indicate use of undiluted, full-strength admixture with no additional water; 75% indicates dilution of 3 parts admixture and 1 part water; 50% indicates 1:1 dilution with water. All dilution rates are by mass. These dilutions were used to allow the optimum level of modification to be determined, the minimum amount needed to substantially improve performance without significantly reducing vapour permeability.

Unmodified control mixes for comparison were simply mixed with water as required to achieve the target Vicat consistency. Cure times were selected based on binder composition and characteristics. Because portland cement/lime-based mixes are known to cure and reach nominal full strength faster than natural cement and natural hydraulic lime, the portland cement/lime-mix designs were cured for 7 days, while the natural cement and natural hydraulic lime mixes were cured for 28 to 56 days.

All polymer-modified mortars were dry-cured, while unmodified mortars were cured in a humidity chamber at 95 to 100% relative humidity. After curing, the assemblies were flooded with 6.35 mm (1/4 inch) of 4% calcium-chloride solution and freeze-thaw cycles of 16 hours (ponded condition) at -18°C (0°F), followed by 6 hours at 22°C (72°F) and then 2 hours at 0°F (-18°C) wet, but without ponding. High permeability of the unfrozen assemblies causes the calcium-chloride solution to drain prematurely, so wet assemblies were frozen for 2 hours at -18°C (0°F) before ponding for the 16-hour cycle.

Salt scaling is defined as damage caused by freezing a saline solution on the surface of a concrete body [11]. ASTM C672 specifies scaling ratings from 0 to 5 (Table 5).

Table 5. ASTM C672 Scaling Ratings

Rating	Observations
0	No Scaling
1	Very Slight Scaling (3 mm [1/8 in] depth, max, no coarse aggregate visible)
2	Slight to Moderate Scaling
3	Moderate Scaling (some coarse aggregate visible)
4	Moderate to Severe Scaling
5	Severe Scaling (coarse aggregate visible over entire surface)

According to the standard, observations must be made every five freeze-thaw cycles or when a change has occurred. The standard also mandates that the surface be flushed thoroughly every five cycles and the calcium-chloride solution replaced, but this was done every cycle because of the highly permeable assembly design. One person made all observations and assigned ratings for every test sample as ratings are somewhat subjective and likely to vary between technicians. Testing continued for 50 cycles or until a Severe Scaling rating of 5 was reached, whichever occurred first.

Observations for mixes based on portland cement and hydrated lime binders are plotted in Figure 3. The poorer performing mixtures display curves that are more horizontal, indicating rapid progression toward a rating of 5, Severe Scaling. The better-performing mixtures display curves that are more vertical, many of them never reaching the 5 rating at the end of the 50-cycle testing regimen.

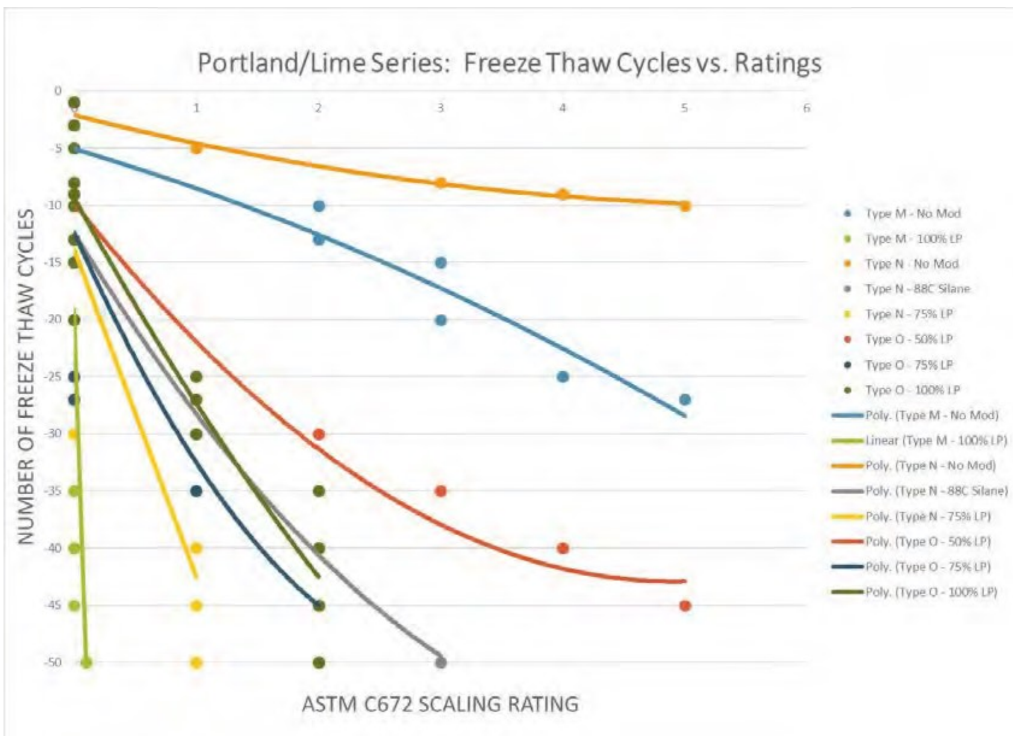

Figure 3. Portland cement/lime series: freeze-thaw cycles vs. scaling ratings

The results of testing showed a strong correlation between polymer modification and freeze-thaw scaling resistance. All of the polymer-modified mortars performed significantly better than the unmodified mortars. For Type O (1:2.5:8) mortars, the optimum level of polymer modification was achieved at 75% concentration, producing the same high degree of scaling resistance as the 100% (undiluted) specimen. Relatively high compressive-strength mortars with and without polymer modification generally performed better than lower strength mortars, as may be expected, but even Type M mortar performance improved significantly when polymer-modified.

One half of the unmodified Type N mortar panel was treated with a proprietary commercial high-solids silane-cream water repellent, Silan-Treat 88C. The performance improvement was significant, with the untreated side reaching failure with a scaling rating of 5 after just 10 cycles. The treated side of the same panel completed the full 50 cycles with only moderate scaling, a rating of 3.

Observations for mixes based on natural cement and hydrated lime binders are similarly plotted in Figure 4. Observations for the mixes based on natural hydraulic lime 3.5 are plotted in Figure 5.

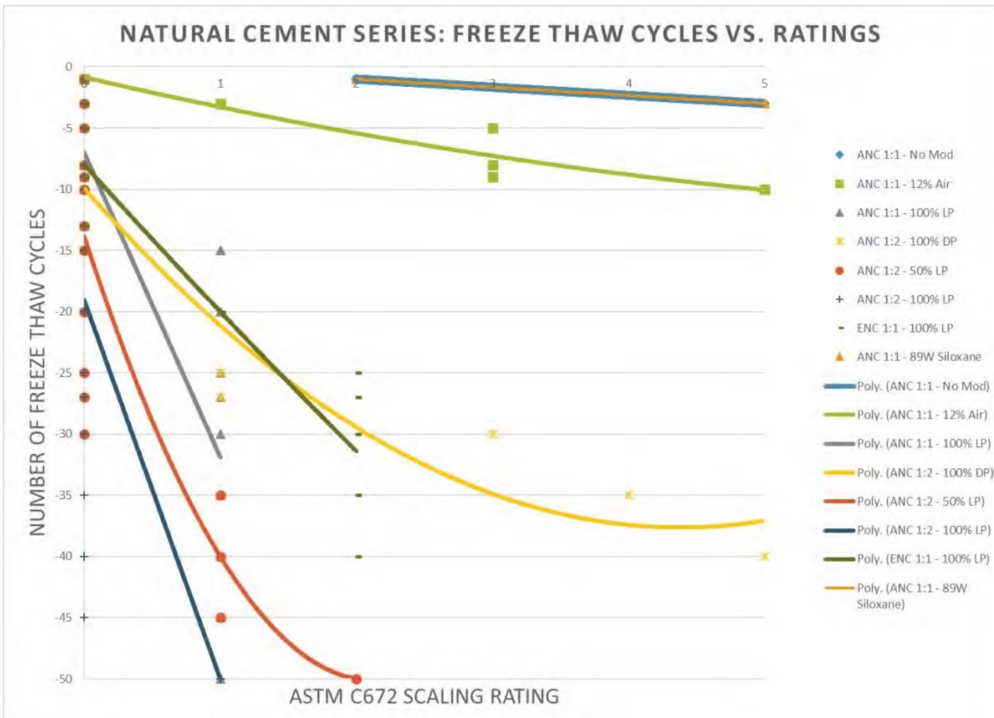

Figure 4. Natural-cement series: freeze-thaw cycles vs. scaling ratings

Similar to the results for portland cement/lime mortars, polymer-modified natural cement and natural hydraulic lime mixes were observed to perform significantly better than unmodified mixes. An air-entrained 1:1 natural cement-sand mix was found to perform only slightly better than the same mix without air entrainment. The non–air-entrained mix failed after 3 cycles, while the air-entrained mix endured 10 cycles. All polymer-modified mixes, regardless of composition or mix proportions, endured the full 50 cycles without reaching a scaling rating of 5.

One half of one of the natural-cement specimens was treated with a commercial 10% siloxane water-repellent treatment, Silox-Treat 89W. No improvement was observed with this treatment.

Half of one of the NHL 3.5 panels was treated with the high-solids silane-cream water repellent, Silan-Treat 88C. The untreated side failed in 13 cycles, while the treated side endured the full 50 cycles with a final rating of 4 (Figure 6).

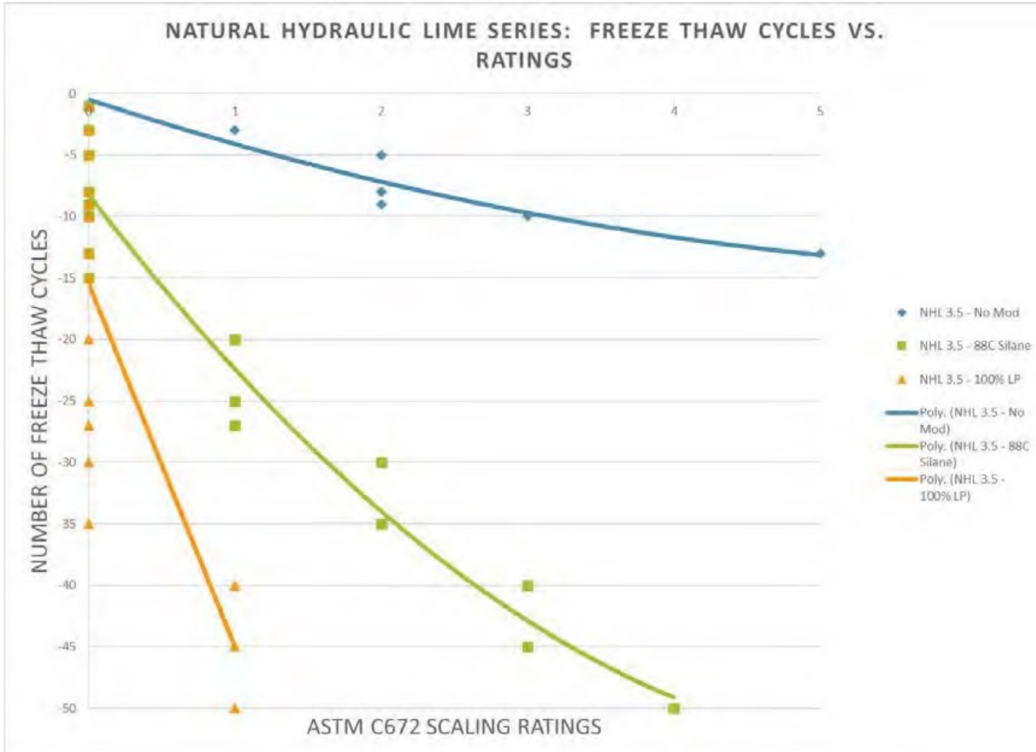

Figure 5. Natural hydraulic lime series: freeze-thaw cycles vs. scaling ratings

Figure 6. NHL 3.5 mortar with and without silane cream water repellent, after testing of 50 freeze-thaw cycles. The left side is treated with silane cream, the right side is untreated, 2017. Photograph by Chad Lausberg

A proprietary redispersable dry acrylic copolymer modifier was added to one of the natural-cement mixes. While scaling resistance improved significantly compared with the unmodified mix, it did not perform as well as the liquid polymer modifier tested at various concentrations. The dry polymer-modified mortar failed at 40 cycles, while even the 50% diluted liquid polymer version of the same mix endured the full 50 cycles with a final scaling rating of just 2. The 100% liquid polymer completed the 50-cycle test with a final scaling rating of just 1.

Effect of Polymer Modification on Mortar Density

In polymer-modified concrete applications, a primary objective is to reduce permeability to water and dissolved deicing salts. This is done to protect embedded reinforcing steel from corrosion. Reduced permeability is achieved by incorporating a defoaming agent, which has the effect of reducing air content and increasing density. Specifications typically require air content not to exceed 6.5% [12].

The improvements in water resistance observed in this study were not the result of increased mortar density caused by air reduction, however. Modification with the optimized polymer in this study actually resulted in significant density reductions.

For Type O mortar (1:2.5:8), based on portland cement and hydrated lime, density when mixed with water was 2.047. The same mortar, mixed with 75% polymer, had a density of 1.285, a reduction of roughly 37%. For 1:1 natural-cement mortar graded aggregate, density was 2.014 when mixed with water and 1.239 when mixed with 75% polymer, a reduction of roughly 38%. The changes are a result of higher air content.

Saturation Coefficients

All of the mortars tested for freeze-thaw resistance were also tested according to ASTM C67-12, Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile, Part 8 Absorption. All mortars were mixed using ASTM C305. Five mortar cubes for each mix design were prepared in accordance with ASTM C109/C109M-08, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). The cubes were cured using the same procedure as for the freeze-thaw testing. After curing, cubes were oven dried at 65.5°C (150°F) for 4 hours and weighed to obtain the initial dry weight. The cubes were then submerged in cold water at 22.2°C (72°F) for 24 hours and reweighed to obtain cold weight. The cubes were then submerged in boiling water for 1 hour at 100°C (212°F), allowed to cool to 22.2°C (72°F), and reweighed to obtain boiling weight. Saturation coefficient was then calculated based on the average values obtained for the quintuplicate samples, using the following formula:

$$\text{Saturation coefficient} = \frac{(\text{cold weight} - \text{dry weight})}{(\text{boiling weight} - \text{dry weight})}$$

Saturation coefficient is a value between 0 and 1 and relates to the absorption rate of water into a porous material. Values close to 1 correspond to a fast absorption rate, and values close to 0 correspond to a slow absorption rate. If the cold weight is close to the dry weight, the absorption rate is relatively slow, and the saturation coefficient will be low. If the cold weight is close to the boiling weight, the absorption rate is relatively fast, and the saturation coefficient will be high. High saturation coefficients indicate potential poor freeze-thaw resistance, as materials that are quickly saturated are more vulnerable to disruption upon freezing. For brick, a coefficient greater than 0.8 indicates unsuitability for exposure to severe weather.

Table 6 correlates the saturation-coefficient results obtained in the ASTM C67 absorption testing with the freeze-thaw performance results obtained in the ASTM C672 freeze-thaw testing.

Table 6. Saturation Coefficient (SC) Compared to Freeze Thaw Performance (Scaling Rating)

Mortar	Modification	SC	Cycles	Scaling Rating ASTM C672
Type M (1:0.25:3.75)	None	0.95	27	5
	100% LP	0.45	50	0
Type N (1:1:6)	None	0.90	10	5
	75% LP	0.27	50	1
Type O (1:2.5:8)	50% LP	0.28	45	5
	75% LP	0.18	50	2
	100% LP	0.09	50	2
ANC (1:1)	None	0.96	3	5
	12% Air	0.85	10	5
	100% LP	0.16	50	1
ENC (1:1)	100% LP	0.27	40	2
ANC (1:2)	100% DP	0.74	40	5
	50% LP	0.57	50	2
	100% LP	0.49	50	1
NHL 3.5 (1:2.5)	None	0.78	13	5
	100% LP	0.33	50	1

A red rating was assigned to mortars that failed (scaling rating of 5) before 15 cycles indicating poor freeze-thaw resistance. Red ratings correlate well with high saturation coefficients.

Yellow was assigned to mortars that failed before 50 cycles, representing mortars with freeze-thaw resistance that was superior to the poorest performing mortars but inferior to the best performing mortars. These results do not correlate particularly well with saturation coefficient. In the case of unmodified Type M mortar, the mid-range performance in spite of high saturation coefficients may be attributable to the generally better freeze-thaw resistance associated with relatively high compressive-strength mortars. The failure at 45 cycles of the Type O mortar modified with 50% diluted liquid polymer is an indication of sub-optimal modifier concentration, as the same mortar modified at higher levels of polymer concentration performed extremely well. The failure at 40 cycles of the mortar modified with dry polymer is an indication that the dry polymer is not as effective in improving scaling resistance as even the 50% diluted liquid polymer.

Green was assigned to mortars that remained intact after 50 cycles, indicating good freeze-thaw resistance. These correlated well with low saturation coefficients.

All of these mortars were polymer-modified, supporting the general indication that polymer-modified mortars exhibit superior freeze-thaw resistance by virtue of reduced saturation coefficient.

Conclusions

The goal of the program was to identify, rather than quantify with great accuracy, promising approaches to improving freeze-thaw resistance of various replication mixes for historic mortars. The ultimate proof of merit can come only through significant numbers of real-world applications and evaluation of their performance over time.

The ASTM C666 freeze-thaw resistance test, modified using masonry assemblies in place of mortar prisms, was found to correlate poorly with the real-world observations that led to initiation of these studies. Modified ASTM C672 scaling-resistance tests, on the other hand, correlated well with those observations.

Mortars modified with a proprietary liquid acrylic copolymer exhibited significantly better resistance to scaling and freeze-thaw exposures than their unmodified counterparts. This result was consistently observed across the full range of mortars tested, whether based on portland cement and hydrated lime, natural cement, or natural hydraulic lime. Non-hydraulic binders were not tested.

Compared with the levels of improvement achieved through liquid polymer modification, use of relatively high compressive-strength mix designs, air entrainment, dry polymer modification, and treatment with a 10% siloxane water repellent were relatively ineffective. A proprietary high-solids silane-cream water repellent produced significant improvements, however.

The optimum level of polymer modification for Type O portland cement-lime-sand mortar to significantly increase freeze-thaw resistance while maintaining other properties compatible with historic masonry was determined to be a dilution of 3 parts modifier to 1 part water by mass. This was the minimum level at which the full benefits of modification were obtained.

A number of in situ applications have been implemented over the past five years utilizing polymer modification and silane-cream treatment of various mortars in various cold weather locations. Future work will continue to track these applications and their performance.

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