8TH
CANADIAN
MASONRY
SYMPOSIUM

Jasper, Alberta
May 31 - June 3, 1998

RELATIONSHIP OF FREEZE-THAW DURABILITY OF MORTAR TO FLEXURAL BOND STRENGTH.

Margaret L. Thomson[1], Gary T. Suter[2], Lyne Fontaine[3] and A.H. Paul Maurenbrecher[4]

ABSTRACT

The durability of masonry under freeze-thaw conditions is a complex interaction of the mortar, stone and their environment. In testing, much attention is given to the durability of the mortar itself, but less to the mortar as part of a masonry system. This paper considers the durability of the mortar together with the stone, particularly the effect on the bond between the stone and mortar.

A total of 29 masonry wallettes and 5 stack bond masonry prisms were constructed for freeze-thaw testing together with companion stack bond prisms for evaluating flexural bond strength. The freeze-thaw testing was unidirectional. The freeze-thaw specimens showed three basic styles of expansion behavior:

- mortar failure,
- bond failure, and
- no failure

Early expansion and failure is related to mortar failure. Delayed expansion is related to bond failure. The prisms with the least amount of freeze-thaw expansion, also had the highest bond strengths.

It is recommended that durability testing of masonry, rather than its components, is critical.

---

[1] Ph.D., Technical Manager, Building Construction, Chemical Lime Company, Henderson, Nevada U.S.A. 89015, formerly Research Officer, National Research Council of Canada, Institute for Research in Construction, Ottawa, Canada.

[2] Professor, Department of Civil Engineering, Carleton University Ottawa, Ontario, Canada; and President, Suter Consultants Inc, Consulting Engineers Ottawa, Ontario.

[3] P. Eng., Senior Conservation Engineer, Architectural and Engineering Services for Environment Canada, Public Works and Government Services Canada, Ottawa, Canada.

[4] Ph.D. P.Eng., Institute for Research in Construction, National Research Council Canada, Ottawa, Canada

INTRODUCTION

Freeze-thaw damage to masonry is often related to the expansion of the mortar. Tension and compression stresses are developed, similar to those generated by later loading. It might be suggested, therefore, that bond strength may play an important role in the freeze-thaw durability of mortar.

Little work has been done to investigate the relationship of freeze-thaw durability to bond strength. This is a direct result of the limiting nature of the freeze-thaw testing procedures. For example, mortar cubes or cylinders are tested using ASTM C-666 and clay units are tested using ASTM C-67. This approach to testing masonry only gives part of the answer especially in the case of the mortar which is largely influenced by the masonry unit. The complexity of the interplay the mortar and masonry unit under freeze-thaw needs to be evaluated.

The Institute for Research in Construction at the National Research Council Canada, in conjunction with Public Works and Government Services Canada (Heritage Conservation Program) and Suter Consultants Inc. have been working to develop a durable mortar for the restoration of the Canadian Parliament Buildings. A uni-directional freeze-thaw durability test for mortar, developed for masonry wallettes, was used in this program (Thomson *et al.*, 1995). Performance is measured visually as well as a function of percent expansion across the front of the mortar joint. An expansion greater than 0.04% is considered a failure value for severe environments.

The objective of this paper is to make a first attempt of using laboratory test methods to investigate the nature of bond strength to the freeze-thaw durability of mortar using a variety of mortar mixes together with Nepean and Wallace sandstone.

TEST SPECIMENS AND PROCEDURES

Specimen Preparation, Curing and Testing

Nepean sandstone represents the bulk of the stone used in the construction of the older Parliamentary buildings in Ottawa. The stone is an orthoquartzite composed of detrital quartz with a quartz cement (locally quarried; grey-white with honey coloured discontinuous banding). The porosity is low (10%).

The Wallace sandstone is commonly used as trim (eg window sills & jambs). The stone is composed of detrital quartz and feldspar which is altered to clay. The cement is dominantly muscovite and clays with minor quartz. The porosity is moderate (13%).

Table 1 gives a summary of the stone properties.

A total of 36 mortar mixes are listed in Table 2. The mix designs are based on the volume ratio of 1 binder: 3 sand. Two stone types, seven binders (white masonry cement, white Portland cement, Type N hydrated lime, Type S hydrated lime, high calcium lime putty, hydraulic lime), and four locally available sands were used. These mortar mixes represented proposed mix designs for active restoration projects.

All of the mixing was completed by a skilled heritage mason. For the cement-lime putty mixes the aggregate and lime putty were combined in a tall pail and pounded using a well used, rounded head of an axe handle. This procedure is known as "knocking up the mortar." The cement-hydrated lime and masonry cement-hydrated lime mixes were prepared by mixing the dry ingredients prior to adding the water. Air entraining agent was added to the mixing water.

The consistency of the mortar was determined by the mason, who added water as needed. The target was a mortar which would be used for deep repointing of the sandstone masonry. Stone wallettes and stacked bonded prisms were built for frost durability and flexural bond strength testing (Fig 1). Wooden jigs were used to aid the mason in building the specimens. This allowed the mason to pack the joints as required. The stones were washed with water to remove the cutting powder and the water was allowed to drain off. The intent was to use the stones water saturated-surface dry. Joint thickness was maintained at 12 mm.

The specimens were built in a controlled environment laboratory. The masonry specimens, cubes and cylinders were cured under laboratory conditions. In the first week, the specimens were placed under plastic sheeting with damp rags to maintain the relative humidity close to 100%. After this initial curing period, the specimens were exposed to ambient laboratory conditions of 22±2°C and a relative humidity of 50±5% for at least 28 days.

Tests for Frost Resistance

IRC/NRC is in the unique position of having a Dutch developed freeze-thaw cabinet which conforms to the Dutch standard NEN 2872 for unidirectional freeze-thaw testing. For tests in this paper, the machine was modified to accept free standing wallets, and sprinkler pipes were installed to wet the specimens during the thaw cycle.

In order to measure expansion, which would act as an indicator of damage, measuring discs were glued to the face of the wallettes (Fig 1). The stainless steel discs are 6 mm in diameter with a drilled hole in the center, which is used to seat the conical points of a Demec gauge. Measurements were taken across the mortar joints using a 50 mm gauge. On a couple of specimens discs were placed on the stone only. There was insignificant movement associated with the stone during the test. Therefore, for the measurements across the mortar joints, all the change was assumed to be movement within the joint.

The specimens were placed in the cabinet and completely immersed in water for twenty-four hours. The backs and sides of the specimens were then jacketed with 10 mm extruded polystyrene and the edges were sealed with silicone, which was allowed to cure for 12 hours. During this curing period the specimens were kept at 100% relative humidity.

A rapid freeze cycle, considered representative of the damaging winter conditions experienced in Ottawa, was used to test the specimens. Thermocouples were imbedded during construction within 5 mm of the face and back of the wallettes. The front of the specimen follows much the same temperature profile as that of the air temperature, showing a 10 minute lag. The back of the specimen shows a plateau in the temperature profile at 0°C, which occurs during freezing of water. The freezing front moves from the face of the wallet through 90 mm in approximately 2 hours. The thaw cycle is accelerated by spraying of the specimens with water as soon as the air temperature rose above 0°C. The spraying lasts for the complete 2 hours of the thaw cycle, ensuring that the specimens do not loose any moisture (there may be a small gain in moisture).

The specimens were measured and assessed on every seventh day. After six days of freeze thaw cycling was completed (18 cycles), the specimens were conditioned for 12 hours by immersing them in water and then drained for 2 hours under conditions of 95% relative humidity. The joints were then measured and the cycling process recommenced 24 hours after the completion of the last.

Flexural Bond Strength

Six stone high, stacked bonded prisms were tested for flexural bond strength. Table 2 indicates the number of joints tested. The apparatus used is consistent with ASTM C 1072.

DISCUSSION OF RESULTS

The joint expansion data presented in Figure 2, shows three basic patterns:

- early expansion from the start of cycling, (Mix 5)
- delayed expansion and failure (Mix 28)
- minor expansion near the beginning with no further increase (Mix 27)

There is a relationship to the style of joint failure with the type of joint expansion. The early expansion appears to be related to the failure of the mortar. The mortar showed physical deterioration, forming a sand pile at the base of the specimen. For specimens showing delayed expansion, the deterioration showed as a surface spall then progressive deterioration into the joint. In a few cases the mortar showed no significant deterioration, but rather there appeared a bond failure at the stone/mortar interface.

Figure 3 shows the plot of flexural bond strength to percent expansion. Those mortars with the poorest freeze-thaw resistance also showed the poorest bond strength. Conversely, those mortars with the best freeze-thaw resistance showed the best bond strength.

The Wallace sandstone prisms have a lower flexural bond strength than the Nepean sandstone prisms. This is interpreted to be a real difference in bond behavior of the two sandstone. It suggests that where a minimum value of 0.57 MPa has been established for the Nepean sandstone, it is too high for the Wallace sandstone. A value of 0.2 MPa might be more appropriate. CSA mortar standard A179-94 requires a bond strength of not less than 0.2 MPa for a type N mortar (note the standard does not apply to stone units).

While this data is clearly not definitive it supports the need to view the freeze-thaw resistance of masonry as a system. The load imposed on masonry during freeze-thaw cycling is not a function of a single parameter. Mortars with associated good bond strength, show good freeze-thaw resistance.

CONCLUDING REMARKS

This investigation has provided strong support for testing of masonry rather than its individual components. Testing the performance of either the masonry unit or mortar can result in misleading information.

Failure due to freeze-thaw cycling can result from mortar failure or bond failure. Mortar failure appears to occur very rapidly, whereas bond failure is delayed. However, once bond failure occurs expansion is rapid.

ACKNOWLEDGMENTS

The authors are grateful to Mr. Herman Schultz (IRC) and Mr. Ken Trischuk (SCI) for their attention to detail. Mr. Roger Labe, our mason, provided a high degree of skill, practicality and contributed immensely to our understanding of stone masonry restoration. Mr. Marcel Joanisse, the chief mason to the Heritage Mason Group of Public Works and Government Services, recognized the importance of the project and provided not only the time of his staff and materials but also the vision as to where the project should go. The Parliamentary Precinct Dedicated Unit were, the ultimate clients for this project. They are thanked for their foresight to recognize the potential for this type of investigation in the restoration of heritage masonry.

REFERENCES

American Society Of Testing And Materials, ASTM C 67-94, Standard of Sampling and Testing Brick and Structural Clay Tile, ASTM, Philadelphia, PA.

American Society for Testing and Materials, C 110-94, Methods for Physical Testing of Quicklime, Hydrated Lime, and Limestone, Philadelphia, PA.

American Society for Testing and Materials, C 187-86, Test Method for Normal Consistency of Hydraulic Cement, Philadelphia, Pa.

American Society for Testing and Materials, C 230-90. Standard Specification for Flow Table for use in Tests of Hydraulic Cements, Philadelphia, PA.

American Society Of Testing And Materials, ASTM C 666-94, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, ASTM, Philadelphia, PA.

American Society Of Testing And Materials, ASTM C 1072-86, Method for Measurement of Masonry Flexural Bond Strength, ASTM, Philadelphia, PA.

Canadian Standards Association, A 179-94, Mortar and Grout for Unit Masonry, pp. 46, 1994

Netherlands Standard NEN 2872, Testing of Stony Materials --Determination of frost resistance of stony building materials--single sided freezing in fresh water environment. 1989. 9 p.

Thomson, M.L., Suter, G.T., and Fontaine, L., Freeze-Thaw Durability of Mortars in Historic Masonry: Test Methodologies. In: Proceedings of the Seventh Canadian Masonry Symposium, McMaster University, Hamilton, Ontario, June 1995, pp. 700-711.

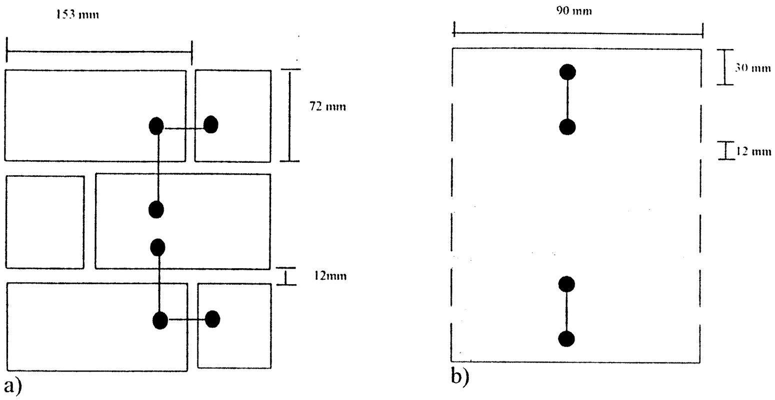

Figure 1 a) elevation of Nepean sandstone wallettes with Demec discs. Lines mark measurement direction. Thickness of wallettes is 90 mm.

b) elevation of stacked bond prisms. These prisms were used for flexural bond strength testing and for freeze-thaw testing. Prisms are 90 mm square.

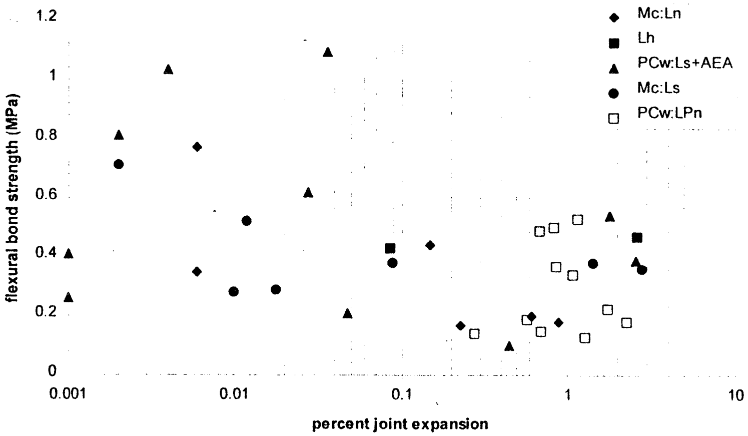

Figure 3 Relationship of flexural bond strength to percent expansion across the front lower joint of wallettes and prisms. Data points enclosed by open rectangles represent Wallace sandstone prisms.

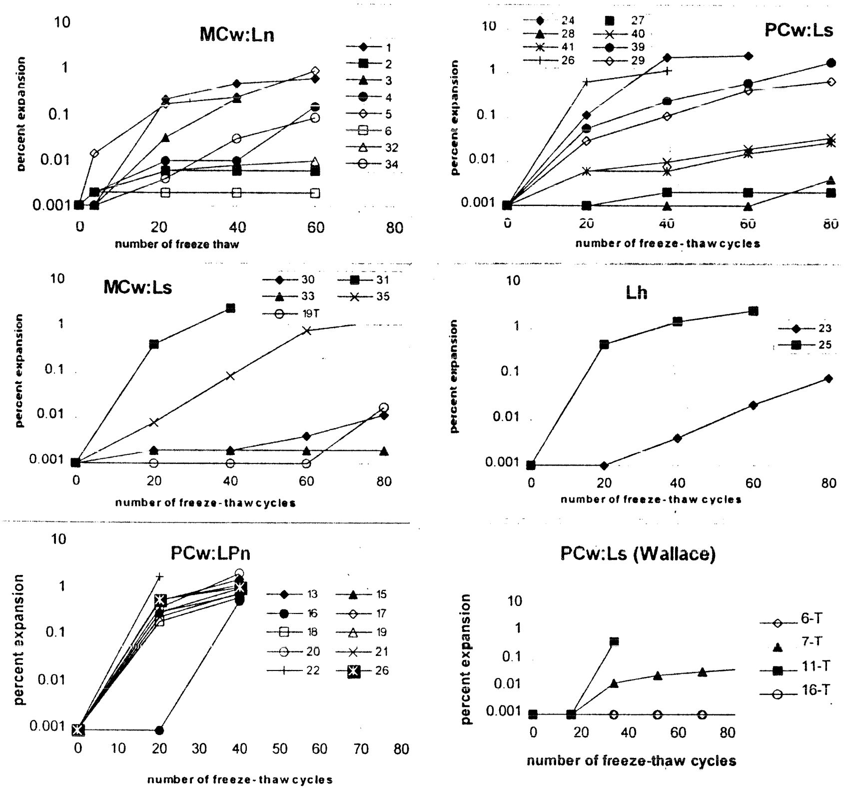

Figure 2 Percent expansion taken across the front bottom joint of the specimens (from start of first cycle). Reference to mix components and mix design number can be found in Table 2.

Table 1 Physical properties of Nepean and Wallace sandstone.

Stone	Bulk density (kg/m^3)	Porosity (vacuum sat.) (%)	Initial rate of absorption (g/1min/ 100mm^2)	Saturation coefficient	Thermal expansion (μm/m/°C)	Compressive strength (n=3, MPa)
Nepean	2336	9.9	0.22	0.48	12.5	100
Wallace	2299	13.5	0.24	0.64	11.5	87

Table 2. Mix Design, Plastic and Hardened Properties, Freeze-Thaw Expansion Data, Flexural Bond Strength Data.

Mix #	Mix Components	Volume Proportions	Water/ binder	Air (%)	Flow (%)	Vicat cone (mm)	Comp. Str. (MPa,)	Maximum expansion^{4} (%)	flexural bond strength, MPa (#jnts/COV)
1	Mcw: Ss	1:3⅛	0.66	n/m	n/m	n/m	12.0	0.590 (80	0.20 (5/76)
2	Mcw::Ss	1:3⅛	0.85	12	50	13	9.9	0.002 (80)	0.77 (5/21)
3	Mcw:Ln:Ss+Bc	1½:½:5+1¼	1.02	n/m	n/m	n/m	6.5	1.440 (80)	0.17 (5/28)
4	Mcw:Ln:Ss+Bc	1½:½:5+1¼	1.17	10	53	12	4.9	1.270 (80)	0.44 ((5/15)
5	Mcw+Bd:Ln:Ss+Bc	1½+$^{1}/_{10}$:½:5+1¼	1.02	n/m	n/m	n/m	7.5	0.890 (80)	0.18 (5/25)
6	Mcw+Bd:Ln:Sss+Bc	1½+$^{1}/_{10}$:½:5+1¼	1.17	12	64	12	4.7	0.016 (80)	0.35 5/32)
13	PCw:LPn:Ss+AEA	1:1:6	0.68	n/m	n/m	9.5	9.0	2.110 (55)	0.22 (5/17)
15	PCw+Bd:LPn:Ss+AEA	½+½:1:6	0.74	n/m	n/m	14.5	3.6	0.268 (40)	0.14 (5/10)
16	PCw:LPn:Ss+AEA	1:1¼:5¾	1.01	n/m	n/m	8.0	9.5	1.790 (80)	0.50 5/33)
17	PCw:LPn:Ss	1:2:9	0.84	n/m	n/m	7.5	3.9	0.776 (80)	0.18 5/39)
18	PCw:LPn:Ss+Bc	1:2:7+2	1.02	n/m	n/m	13	5.1	1.612 (40)	0.34 (5/18)
19	PCw+Bd:LPn:Ss+Bc^{2}	$^{1}/_{10}$+$^{9}/_{10}$:1$^{8}/_{10}$:7$^{7}/_{10}$	n/m	n/m	n/m	12	3.9	2.088 (40)	0.15 (5/17)
20	PCw:LPn:Ss	$^{1}/_{10}$:2:5	1.16	5	83	30	n/m	1.850(40)	0.13 (2/na)--**5**
21	PCw:LPn:Ss+Bc	1:2:8+1	0.97	n/m	n/m	13.0	4.4	0.668(40)	0.18 (5//32)
22	PCw:LPn:Ss	1:3:9	0.85	7	57	17	3.6	2.240 (17)	0.37 (5/18)
23	Lh:Ss	2:5	0.77	10	109	37	2.2	0.084 (80)	0.43 (5/61)
25	Lh:s+AEA	2:5	0.65	15	38	12	2.3	2.818 (80)	0.47 (5/61)
24	PCw:Ls:Ss+AEA+^{1}	1:3:9	0.79	10	16	7	5.20	2.582 (60)	0.39 (5/44)
27	PCw:Ls:Ss+AEA	¾:1½:5⅝	0.75	12	47	12	8.3	0.002 (80)	0.81 (5/19)
28	PCw:Ls:Ss+AEA	1:1:6	0.85	14	52	18	8.3	0.004 (80)	1.03 (5/36)
40	PCw:Ls:Ss+AEA	1:3:9	0.85	10	57	18	3.4	0.036 (80)	1.09 (5/28)
41	PCw:Ls:Ss+Magg^{3}+AEA	1:3:6+3	0.89	9	42	18	3.6	3.588 (80)	0.62 (5/29)
39	PCw:Ln:Ss+AEA	1:3:9	0.91	8	79	19	3.2	1.798 (80)	0.54 (5/30)
26	PCw:LPn:Ss+AEA	¾:1½:5⅝	0.79	8	40	15	2.8	2.202 (40)	0.53 (5//21)
29	PCw:LPn:Ss+AEA	1:1:5	0.85	8	54	18	4.9	1.120 (80)	0.49 (5/48)

Table 2 continued

Mix #	Mix Components	Volume Proportions	Water/ binder	Air (%)	Flow (%)	Vicat cone (mm)	Comp. Str. (MPa,)	Maximum expansion^4 (%)	flexural bond strength, MPa (#jnts/COV)
30	MCw+Bd:Ls:Ss+Bc	1½+$^1/_{10}$:½:5+1¼	1.09	17	33	17	3.9	0.012 (80)	0.52 (5/39)
31	MCw:Ls:Ss+Bc	1:1:5+1¼	1.17	16	n/m	17	1.7	2.798 (40)	0.36 (5/39)
33	MCw:Ls:Ss+Bc	1½:½:6¼	0.98	15	44	16	4.2	0.004 (80)	0.71 (5/33)
35	MCw:Ls:Ss	1:1:6¼	1.00	14	53	22	1.5	1.44 (80)	0.38 (5/27)
19T	Mcw:Ls:Sg	1½:½:6	0.58	14	65	24	5.5	0.018 (88)	0.29 (5/25)
32	MCw:Ln:Ss+Bc	1½:½:6¼	0.96	15	37	9	4.1	0.010 (80)	0.28 95/460
34	MCw:Ln:Ss+Bc	1:1:6¼	1.09	12	34	18	1.6	0.088 (80)	0.38 (5/56)
6T	PCg:PCw:Ls:Sg	¼:¾:2:7	0.63	11	79	24	7.9	0.001 (88)	0.26 (10/35)
7T	PCw:Ls:Sg	1:1:6	0.62	14	61	22	7.4	0.048 (88)	0.21 (9/64)
11T	PCw:Ls:Sg	1:2:7	0.72	10	67	23	?	0.451 (34)	0.10 (8/44)
16T	PCw:Ls:Sh	1:2:7	0.80	8	56	26	9.1	0.001 (88)	0.41 (10/39)

Binders	
PCw	white Portland Cement
MCw	white Masonry Cement
Bd	brick dust <75μm diameter
Ln	Type N lime
Ls	Type S lime
LPn	lime putty from high calcium quicklime
Lh	hydraulic lime

Aggregates	
Ss	Spratt sand custom sieved
Sg	Granmaitre sand
Sh	Parliament Hill sand
Bc	crushed brick custom sieved
Magg	crushed black marble sieved
AEA	air entraining agent

Notes
1 - 12 % carbon black added
2 - mix taken from active repointing site, proportions approx.
3 - black marble crushed and sieved to sand aggregate size
4 - bracketed number is number of cycles to maximum expan.
5 - bond failed with weight of apparatus. value of 0.13 MPa
6. mix designs 6T. 7T. 11T. and 16T used with Wallace

Standards for Testing
flow ASTM C 230
air content ASTM C110-94
vicat cone ASTM C 187
flexural bond strength ASTM C 1072