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LABORATORY STUDIES OF MORTAR FOR HISTORIC MASONRY: MECHANICAL PROPERTIES

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ABSTRACT

Over the past five years, a number of laboratory studies have been carried out to help define practical and durable mortars for the conservation of Canadian historic masonry assets. This paper provides an overview of the work performed on mechanical properties and specifically on the bond capacity between various mortars and masonry units.

INTRODUCTION

While Canada is rich in having many historic assets, these important assets frequently have suffered from too rapid deterioration due to inadequate and inappropriate maintenance measures. One key deterioration contributor has been non-durable mortar which either deteriorates due to freeze-thaw action or cracks, for example, at the mortar-unit interface thus destroying the bond.

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To help define practical and durable mortars for the conservation of Canadian historic masonry assets, Public Works Canada five years ago initiated a mortar laboratory study. Phase I work focused on the flexural bond capacity of five types of masonry cement based mortar in combination with three types of historic masonry units. Durability tests were also performed on the mortar.

A subsequent Phase II test program employed a total of 12 masonry cement based mortar mixes in an effort to establish refined mixes for the same three types of masonry units under flexural bond action. Uni-directional freeze-thaw tests were also carried out.

The Phase I and II test programs were pilot studies to point the way towards defining key parameters for more durable mixes. The results were used firstly, to carry out more detailed durability related research at the Institute for Research in Construction and secondly, to undertake a more comprehensive mortar study involving Portland cement-lime and masonry cement-lime mortars. This Phase III study deals in an integrated way with mechanical properties as well as durability performance of the mortars.

The paper provides an overview of the work carried out to date on mechanical properties. A companion paper at this conference deals with the durability research of mortars for historic structures.

PHASE I WORK

General
Phase I work served as an initial step in defining suitable masonry cement based mortars. The study focussed on the flexural bond capacity of five types of mortar in combination with three types of masonry units: sandstone, limestone and historic clay brick. All of these units came from historic assets in the Quebec City area. The five test mortars, all Type N, varied in terms of their proportions of masonry cement, latex additive, lime, flyash, and crushed brick as a partial substitute for sand. Prisms were constructed for each unit/mortar combination and bond capacities were determined at an age of about one month by means of the bond wrench method. While details for Phase I work are presented elsewhere (4), a summary of test parameters and results is given in the following sections.

Phase I Types of Mortar, Units and Specimens
Five types of mortar having a constant ratio of binder to aggregate of 1:3 were selected for testing. The basic thought was to test modified masonry cement based type N mortars which would provide a moderate level of compressive strength together with good bond capacities. To improve bond, additives consisting of latex, pozzolans and porous particles as a partial sand replacement were included in the test program as shown in Table 1.

Three types of masonry units were used; they were 30 x 90 x 95 mm units of clay brick (denoted as B), sandstone (S) and limestone (L). Key physical properties are given in Table 2 (5).

For each mortar type, test specimens consisted of three 50 mm cubes for mortar compressive strength testing, three 75 x 150 mm cylinders for mortar split-tensile strength testing, and two 7-unit high prisms for each masonry unit type for flexural bond testing.

Phase I Specimen Preparation, Curing and Testing
All masonry prisms were built by a skilled mason. It was agreed that the workability of each type of mortar should be adjusted until the mortar represented a reasonable mix for all three types of masonry units being used in the prisms. Since the sandstone and limestone units displayed much lower absorption characteristics than the brick units, the single mortar mix arrived at for each type of mortar tended to be somewhat too wet for the stone units and somewhat too dry for the brick units. Because of the relatively high absorption characteristics of the bricks, they were pre-wetted prior to prism construction. Flow and air content values for each mortar type are given in Table 3.

For the first seven days, all specimens were kept moist by means of wet burlap and polyethylene wrapping. After seven days the prisms were uncovered to cure further under laboratory room conditions while all mortar specimens were placed in a curing tank filled with a lime-saturated water solution. Since some of the mortar specimens still displayed very low strengths at that time, all specimens were immersed in the water without demoulding. Cubes and cylinders were demoulded at an age of about 13 days and again placed in the water tank. At an age of about 20 days, all mortar specimens were removed from the tank and left to cure under laboratory room conditions (approximately 20°C and 30% relative humidity) until testing time. Flexural bond strengths were determined by means of a bond wrench according to ASTM Standard C-1070-86(1). All testing took place at an age of about four weeks.

Phase I Test Results and Discussion
A summary of key test results is provided in Table 4; note that the averaged values for the mortar cubes and cylinders are based on three tests and those for bond capacities on five joints. The average bond capacities of Table 4 are also presented on Fig. 2. The following comments apply to the test results:

1. The mortar compressive strengths vary greatly. When the strengths are compared to the minimum strengths of 4.0 and 5.0 MPa for field prepared and laboratory prepared type N mortar according to CSA A179M-1976 (3), it is seen that the addition of latex in Type 2 produces too high a strength and the addition of flyash in Type 3 produces too low a strength.

2. Mortar split-tensile strengths also vary greatly and are ranked in the same order as the compressive strengths.

3. The highest bond capacities are achieved by the limestone units regardless of mortar type. The lowest bond capacities are produced by the sandstone units.

4. The use of latex in Type 2 significantly increases the compressive and tensile strengths of the mortar as well as the bond capacity of all unit types.

Table 1	Phase I Types of Mortar (proportions by volume except as noted)	
Type 1:	type N, masonry cement/sand	1/3
Type 2:	type N with latex additive, masonry cement/sand	1/3
Type 3:	masonry cement/lime/flyash/sand	1/1/25%/6
Type 4:	masonry cement/lime/flyash/sand	1 ½/½/25%/6
Type 5:	masonry cement/lime/crushed brick/sand	1 ½/½/1/5

Notes for Table 1:

1. Latex was "Sterncrete" manufactured by Sternson Limited. Latex and water were mixed half and half by volume.
2. Flyash was "Alfesil" manufactured by C.C. Chemicals Canada; 25% flyash represented percentage of combined weights of masonry cement and lime.
3. Crushed brick was "Centennial Red" manufactured by Canada Brick. Its gradation in the mortar mix was similar to the sand gradation.
4. The sand gradation fell within the limits specified by CSA A82.56M(2).

Table 2 Physical Properties of Phase I Masonry Units

Type of Unit	Compressive Strength (MPa)	48-Hour Water Absorption (%)	Initial Rate of Absorption (g/min/193.6 cm^2)
B	24.7	-	17.8
S	92.4	0.73	-
L	51.9	0.35	-

Table 3 Phase I Flow and Air Content for Each Mortar Type

Mortar Type	Flow (%)	Air Content (%)
1	92.0	12.5
2	73.5	14.5
3	79.6	10.0
4	83.4	10.0
5	59.0	14.0

Table 4 Phase I Test Results					
Mortar Type	**Compressive Strength (MPa)**	**Tensile Strength (MPa)**	**Tensile/ Compressive Strength (%)**	**Unit Type**	**Bond Capacity (MPa)**
1	9.9	1.17	11.8	B S L	0.34 0.30 0.72
2	13.9	1.59	11.4	B S L	0.53 0.49 0.94
3	3.2	0.23	7.2	B S L	0.33 0.15 0.52
4	8.1	0.69	8.5	B S L	0.38 0.21 0.72
5	6.3	0.58	9.2	B S L	0.48 0.19 0.62

Notes for Table 4:

Phase I Mortar Type

1 Type N
2 Latex additive
3 Flyash additive
4 Type 3 + increased masonry cement
5 Crushed brick aggregate

Unit Type

B = Brick
S = Sandstone
L = Limestone

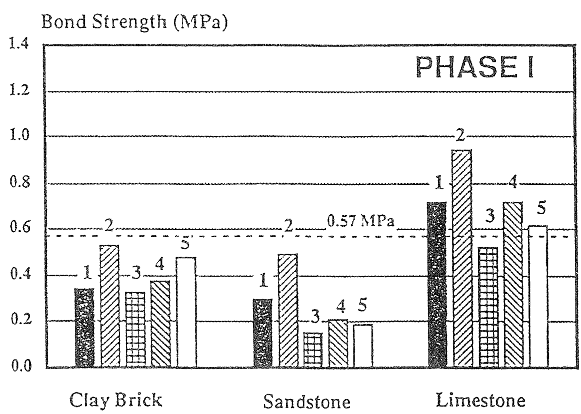


Fig. 2 Phase I Bond Capacities

5. The use of lime and flyash in Type 3 significantly reduces mortar compressive and tensile strengths but produces a good level of bond capacity at least for the limestone units. The increase in masonry cement and corresponding decrease in lime in Type 4 achieves bond capacity improvements for all unit types.

6. The use of crushed brick and lime in Type 5 produces moderate levels of mortar compressive and tensile strengths while achieving relatively good levels of bond capacity for brick and limestone units.

7. Assuming an allowable bond stress normal to bed joint for Type N mortar as 0.19 MPa (3) and a safety factor of 3 against this allowable value, a bond capacity of 0.57 MPa appears desirable. From the 0.57 MPa line shown in Fig. 2 it can be seen that only four limestone mortar combinations would be termed acceptable.

PHASE II WORK

General

For Phase I work, each batch of a given mortar type was adjusted in workability so as to achieve a compromise between the needs of the three types of units. Phase II work involved the testing of refined mortar mixes and adjusting the workability of each mix to suit the absorption characteristics of each type of unit. The detailed Phase II results have been published in a report (6).

Phase II Types of Mortar, Types of Units, Specimen Preparation, Curing and Testing

The Phase II test program again comprised the same three types of masonry units (brick, B, sandstone, S, and limestone, L) from the same historic assets as Phase I work. Four types of mortar per type of unit were selected for a total of 12 different mortars as shown in Table 5. The Phase II mortars are listed as B1 to B4, S1 to S4 and L1 to L4; in contrast, the Phase I mortars are referred to as Type 1 to 5 as indicated in Tables 1 and 5.

Using the same types of specimens (mortar cubes, mortar cylinders and masonry prisms) as for Phase I work, the same skilled mason built the prisms for flexural bond testing. The workability of each mortar mix was left to the judgement of the mason. Table 6 shows the flow and air content values of each mortar mix.

The Phase II curing and testing conditions were very similar to those for Phase I. Again, testing took place at an age of about four weeks.

Phase II Test Results and Discussion

A summary of key test results for Phase II work is provided in Table 7; the following comments apply to the bond strength results of Table 7:

Table 5 Phase II Types of Mortar (proportions by volume except as noted)			
BRICK			
B1	MC/S	2/5	
B2	MC/L/F/S	1.75/0.25/20%/5	
B3	MC/L/CB/S	2.75/0.25/1/4	
B4	MC/L/CB/S	1.5/0.5/1/4	
SANDSTONE			
S1	MC/S	2/5	
S2	MC/F/S	2/20%/5	
S3	MC/CB/S	2/1/4	
S4	MC/L/CB/S	2/10%/0.5/4.5+20%latex	
LIMESTONE			
L1	MC/S	1/3	
L2	MC/L/F/S	1.75/0.25/25%/6	
L3	MC/L/F/CB/S	1.5/0.5/15%/1/4	
L4	MC/L/CB/S	1.75/0.25/1/4	

For comparison,
Phase I mortars:

Type	Proportions
1 MC/S	1/3
2 MC/S	1/3/50% latex
3 MC/L/F/S	1/1/25%/6
4 MC/L/F/S	1.5/0.5/25%/6
5 MC/L/CB/S	1.5/0.5/1/5

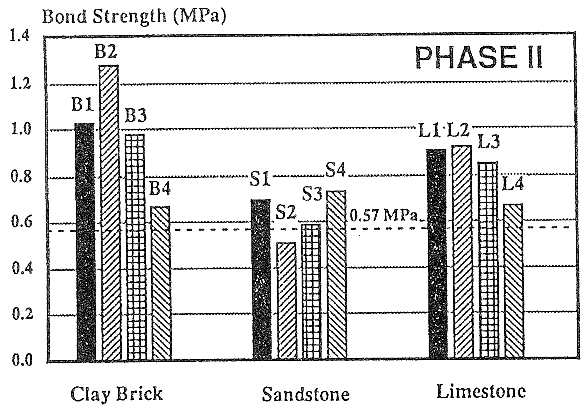
Legend

MC	=	masonry cement
L	=	lime
F	=	flyash % = % of binder weight (MC+L)
CB	=	crushed brick
S	=	sand
20% latex	=	20% of liquid volume is latex

Table 6 Phase II Flow and Air Content for Each Mortar Mix

Mortar Type	Flow (%)	Air Content (%)
B1	65	12.4
B2	69	12.4
B3	42	10.5
B4	55	11.6
S1	53	13.0
S2	36	9.0
S3	21	11.2
S4	35	10.2
L1	40	13.0
L2	36	11.4
L3	32	10.0
L4	23	10.3

Table 7 Phase II Test Results



Mortar Type (proportions by volume)

B1	MC/S	2/5
B2	MC/L/F/S	1.75/0.25/20%/5
B3	MC/L/CB/S	1.75/0.25/1/4
B4	MC/L/CB/S	1.5/0.5/1/4
S1	MC/S	2/5
S2	MC/F/S	2/20%/5
S3	MC/CB/S	2/1/4
S4	MC/F/CB/S	2/10%/0.5/4.5/20% latex
L1	MC/S	1/3
L2	MC/L/F/S	1.75/0.25/25%/6
L3	MC/L/F/CB/S	1.5/0.5/15%/1/4
L4	MC/L/CB/S	1.75/0.25/1/4

Mortar Type	Flow (%)	Air Content (%)	Compressive Strength (MPa)	Tensile Strength (MPa)	Tensile/ Compressive Strength (%)	Bond Capacity (MPa)
B1	65	12.4	13.6	2.09	15.4	1.03
B2	69	12.4	8.5	1.21	14.2	1.28
B3	42	10.5	5.7	0.96	16.8	0.98
B4	55	11.6	4.1	0.65	15.8	0.67
S1	53	13.0	15.3	1.76	11.5	0.70
S2	36	9.0	14.5	1.99	13.7	0.51
S3	21	11.2	10.4	1.96	18.9	0.59
S4	35	10.2	13.7	2.25	16.4	0.73
L1	40	13.0	8.0	1.45	18.2	0.91
L2	36	11.4	8.3	1.45	17.6	0.92
L3	32	10.0	5.4	0.99	18.4	0.85
L4	23	10.3	9.0	1.21	13.5	0.67

1. The refined mortar mixes of Phase II provide major improvements in bond capacity especially for the brick and sandstone prisms that previously had performed poorly. Again using 0.57 MPa as a measure of minimum required bond capacity, all Phase II results, with the exception of S2, meet this requirement.

2. With reference to the 0.57 MPa line, Phase II mortars B1, B2, B3 and L1, L2, L3 provide very good levels of bond capacity; all other mortars with the exception of S2 can be termed as satisfactory. S2 is about 10% below the line.

3. There is no ready correlation between bond capacity and mortar compressive/split-tensile strengths. For instance, for S1 to S4 both the mortar compressive and split-tensile strengths are very high, yet the bond capacities are just slightly above the 0.57 MPa line except for S2 which is below the line.

4. What might be termed the "best" Phase II mortar performance, in terms of combining a relatively low but adequate compressive strength with a relative high bond capacity, is achieved by B3, B4 and L3; with compressive strengths of 5.7, 4.1 and 5.4 MPa, they provide bond capacities of 0.98, 0.67, and 0.85 MPa respectively.

PHASE III WORK

General

The Phase III mortar test program was designed to provide input into the conservation work for masonry structures on the Parliamentary Precinct in Ottawa. The principal objective of the program was to study the plastic and mechanical properties of various mixes to determine suitable repointing mortars for Nepean and Ohio sandstone masonry. Only the Nepean sandstone mortar work, which made up the bulk of the test program, will be discussed in this paper. Phase III results have been published in a report (7).

Phase III started with the preparation of a series of trial mortar mixes to determine plastic properties. The main work consisted of constructing and testing a variety of mortar specimens and Nepean sandstone masonry prisms to determine mechanical properties of the hardened mortar.

Phase III Types of Mortar

Two basic mortar types were used throughout: masonry cement based mortars and Portland cement/lime based mortars. Mortar proportions corresponded to type N or weaker mixes. Besides the use of either masonry cement or Portland cement, key material variables were the type of lime (hydrated lime types N and S, lime putty, and hydraulic lime), and the possible presence of crushed brick and brick dust.

A series of trial mixes were made to test their plastic properties and help select suitable mixes for later specimen construction. Fourteen masonry cement mixes and twelve Portland cement/lime mixes were made in total. For different water/binder ratios, the following plastic properties were determined: air content, flow, Vicat rod and cone penetration, and slump.

For specimen construction and mechanical properties testing, a total of 34 mixes were employed as follows: 14 masonry cement mixes which ranged in proportions from simple mixes (for instance, masonry cement/sand = 2/6.25 or masonry cement/lime/sand = 1/1/6.25) to complex mixes (for instance, masonry cement/lime/sand/crushed brick/brick dust = 1.5/0.5/5/1.25/0.1); and 20 Portland cement mixes which ranged in proportions also from simple mixes (for instance, Portland cement/lime/sand = 0/2/5 or 1/3/9 + air entrainment) to complex mixes (for instance, Portland cement/lime putty/sand/brick dust = 0.1/1.8/7.2/0.9).

Phase III Types of Specimens, Specimen Preparation, Curing and Testing

The types of specimens prepared for each mortar mix were identical to earlier work (mortar cubes and cylinders for compressive and split-tensile strength testing of the mortar, and masonry prisms for flexural bond testing) with one exception: additional mortar cylinders were produced for stress-strain testing of the mortar; the latter enabled determination of the mortar's modulus of elasticity. For many of the mixes and especially the slower hardening Portland cement/lime mixes, a sufficient number of specimens were prepared to enable testing at ages of both 28 and 90 days.

All masonry prisms were built by a skilled heritage mason; the workability of each repointing mix and therefore the amount of water added to each mix was left to the judgement of the mason. In general, prisms were constructed with pre-wetted but surface dry stone units; this was done to simulate field repointing conditions.

Curing involved moist curing within a polyethylene enclosure for fourteen days and then leaving the specimens to harden further under laboratory conditions of about 50% relative humidity and 20°C temperature until the testing time at 28 or 90 days. Flexural bond strengths were determined in a bond wrench apparatus as in earlier work.

Phase III Test Results and Discussion

During the second half of 1994 and the early part of 1995, hundreds of tests were performed to define the mechanical properties for the 34 mortars. Since the work had not been completed at the time of writing of this paper, it is only possible to provide tentative answers as to which of the 34 mixes proved to be most suitable for the repointing of Nepean sandstone masonry. The tentative recommendations include two mortar mixes of which one mix is a masonry cement based mortar and the other a Portland cement/lime based mortar. The mix proportions are masonry cement/lime/sand = 1.5/0.5/6.25 and Portland cement/lime/sand = 1/3/9 with air entrainment to achieve 10 to 12% air content in the plastic state. For both mixes, type S hydrated lime appeared to be best. These tentative recommendations were reached by assessing all the mechanical properties according to these performance criteria: the mortar compressive strength should be fairly low but not too low (in the range of 2 to 5 MPa), the mortar split-tensile/compressive strength ratio should be reasonably high (greater than 15%), the initial tangent modulus of the mortar should be fairly low but not too low (in the range of 2000 to 5000 MPa), and the bond strength should be satisfactorily high (greater than 0.6 MPa). All of these strength and stiffness requirements pertain to 28-day ages of specimens. The performance criteria essentially ensure that the repointing mixes are fairly soft mortars with a measure of "give" and reasonably high tensile properties to resist cracking both within themselves and at the critical bond interface between mortar and stone units.

The full evaluation of the Phase III results including the freeze-thaw durability testing of suitable companion specimens by the Institute for Research in Construction, Ottawa, Canada, will be carried out in the near future.

CONCLUDING REMARKS

All too often in the past, mortars used in the maintenance and conservation of historic masonry assets have failed after only a relatively brief period in service. The paper has outlined recent Canadian mortar studies performed to develop more durable mortars to withstand the relatively harsh Canadian climatic conditions.

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