CORE CONSOLIDATION OF HERITAGE STRUCTURE MASONRY WALLS & FOUNDATIONS USING GROUTING TECHNIQUES - CANADIAN CASE STUDIES

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ABSTRACT

Damage to masonry walls due to deterioration of their rubble core can be a major concern and, in the event that consolidation techniques are determined to be necessary, it is important that the selected strategy should consider the need to maintain the existing aesthetic quality of the masonry, as well as its structural integrity - both during and after the grouting operations. In particular, it is generally recognized that a restored structure should be able to adequately accommodate stresses created by differential movement of components during changes in temperature and dynamic loading conditions. The techniques that are available for core consolidation are discussed, together with Canadian case studies which illustrate specific strategies that were designed to arrest deterioration while providing improved durability and adequate movement accommodation. The many factors that were considered during the development of the grouting strategies are evaluated, including minimum intervention, structural stability, investigation methods, desirable properties of grouting materials and the impact of placement techniques. Also reviewed is the use of modern non-destructive methods that were used to evaluate the condition of the hidden core and determine the location of voids. A cement-based cellular foam grout that best matched the criteria of desired properties and performance requirements will also be examined.

Key words Consolidation; Cellular Foam Grout; Core Rubble Grouting; Foamed Grout; Heritage Structures; Ground Penetrating Radar; Impact-Echo; Investigation; Lime; Masonry; Non-Destructive Testing; Stone Walls; Restoration; Stabilization

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INTRODUCTION

The exterior masonry walls of many older Canadian buildings were traditionally constructed using dimension stone units built as double wythes with rubble filled inner cores - for at least the foundation portion. During construction the inner cores were filled with stone off-cuts, rubble etc., bound with weak, lime-based grouts or mortars. Unfortunately, lime binders frequently fail to adequately carbonate before the mortar joints deteriorate sufficiently to allow water to penetrate the core and initiate degradation. Voids can form as the grout or mortar disintegrates and subsequently washes out of open joints or accumulates as a loose powder at lower levels. Over many years, the masonry walls can become further destabilized as the loosely bound rubble becomes mobile and further voids form. Often the loading conditions and differential movement are sufficiently accommodated by the weakened masonry - but, sometimes, the change in distribution of loads can cause concentration of stresses which, in turn, can cause bulging, displacement and/or cracking of masonry units.

Although grouting voids within the inner core rubble to stabilize masonry walls is a long established practice, methods have changed over the years - and these have ranged from historic gravity grouting utilizing hand placement techniques through to the use of modern pumping techniques that include hand and power-operated diaphragm pumps, aerated pressure systems and vacuum systems. [1]

KEY CONSIDERATIONS

The author believes the following represent the key factors that affect the success of a grouting operation and should be considered during the development of masonry core consolidation strategies:-

- Investigation and evaluation
- Grout mixture composition
  - Fluid properties
  - Physical hardened properties
- Grouting methodology
  - Mixing equipment
  - Pumping equipment
  - Pumping pressures
  - Grout confinement
- Method of maintaining masonry integrity

Perhaps the most important consideration is the selection of an experienced specialist grouting company that has a suitably trained workforce and the special equipment necessary for the production and placement of the grout in an effective and safe manner. This, of course, can be a problem where experienced contractors are not available locally - or when prequalification of contractors or sub-contractors is not possible. However, it is undesirable for this type of work to be carried out by companies with little or no experience or expertise.

Investigation and Evaluation

Before it can be determined whether or not core consolidation is necessary, it is important that the causes of any masonry damage are fully investigated and identified. The investigation should include research into the history of the structure to determine whether events in the past may have had an adverse impact on the condition of the masonry. (Case Study One provides an example.) If possible, details concerning previous restoration work should be evaluated - particularly if this included core consolidation work or below grade waterproofing. If possible, the investigation should attempt to quantify the volume of hidden voids and their locations - although grouting often takes place by pumping the maximum volume of grout to "refusal" through uniformly spaced injection tubes (ports).The investigator should also consider the likely impact that changes in masonry properties can have after consolidation work has taken place. (For example, potential changes in the way in which differential movement is accommodated between components.)

Grout Mixture Composition

Many different materials have been used for consolidation grout mixtures and experts' opinions have varied widely regarding what makes the best composition. Some of the materials that have been incorporated into grouts - or have comprised the grout mixture - include, but are not limited to:-

- Lime Mixtures
- Cement/Lime Mixtures
- Lime/Pozzolan Blends
- Cellular Foamed Cement Grouts
- Portland Cement Mixtures
- Cement/Pozzolan Blends
- Bentonite or Gelling Agents

Traditionally, consolidation grouts were based on lime, and even today this binder is still preferred by many experts. Naturally occurring pozzolanic materials and crushed clay brick have been reported to provide beneficial flow, anti-segregation/bleeding and strength development properties when blended with hydrated lime,[2] although man-made supplementary cementing materials such as fly ash and silica fume have also been used or investigated.[1, 4] Fly ash has been reported to provide beneficial properties when used with both Portland cement and lime, but was found to be less beneficial when used with lime alone. However, some considerable variation between mixes were also reported, together with increases in long term strength. [3] The use of Portland cement as the primary binder can contribute to greater than desirable strength and shrinkage - unless special admixtures or techniques are used. Bentonite has been used to reduce strength and to provide improved resistance of the grout to bleeding and segregation.[1, 3] The introduction of soluble salts from the use of normal grey Portland cement can be detrimental, although this concern can be reduced or eliminated by utilizing white cement. However, there is always a danger that water injected with the grout can mobilize salts within the masonry that could migrate to the exterior surfaces. The use of cellular foamed cement grouts will be discussed in Case Study One.

Whichever grout mixture is selected, the following properties are generally recognized as being critical:-

Plastic Grout Properties

- High Fluidity - to provide adequate flow while using low pump pressures;
- Good Penetrability - to fill small gaps and interconnected voids;
- Low Segregation/Settlement - to maintain plastic volume and consistency;

Hardened Grout Properties

- Low Shrinkage - to maintain volume without development of stress or loss of bond and to reduce moisture penetration through post-shrinkage cracks/gaps;
- Strength Considerably Lower than the Masonry Units - to absorb stresses rather than transfer them to masonry units;
- Compatibility with Masonry Units - to provide adequate composite movement accommodation, similar moisture vapour transmission properties and low mobility of soluble salts;
- Adequate Durability - by providing freeze/thaw stability and low permeability.

The desired strength of the grout will depend on the properties of the masonry units. Very little published data is available in this regard, although design compressive strengths of less than 2 N/mm^2 (300-psi) @ 28-days have been reported by some researchers (2) while others report strengths that range from 3 to 6.5-N/mm^2 (450 to 950-psi) (4)

CASE STUDIES

The factors that should be considered during the development of restoration strategies can perhaps best be reviewed by examining three Canadian case studies.

Case Study One - Owens Art Gallery, Mount Allison University, New Brunswick

The Owens Art Gallery is the oldest university art gallery in Canada. (See Photograph 1.) Originally named The Owens Museum of Fine Arts, it was officially opened on May 28th 1895 to accommodate the School of Fine Arts and Applied Arts within Mount Allison University in Sackville, New Brunswick. The building was constructed using a light olive sandstone stone obtained from quarries within the nearby community of Rockport.

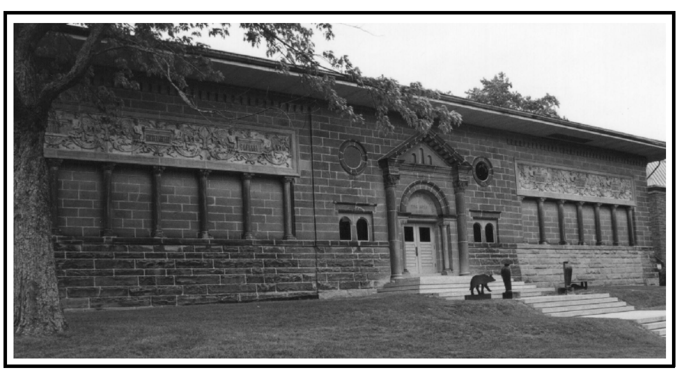


Photo. 1. Owens Art Gallery, Sackville, New Brunswick

Original construction documents were not available at the time of the investigation of the damage that became apparent during the mid 1990's, but a review of photographs taken during the original construction work confirmed that the foundation walls were constructed as a double wythe with an interior rubble core. Research also confirmed that roof re-construction work was carried out during the early 1970's and subsequently this was proved to have contributed to major damage of the masonry and, in particular, the inner core rubble. It also seems likely that the roof re-construction work caused an increase in the distribution of loads to the outer wythe and this caused cracking and damage to both units and joints.

By 1996, the deterioration and damage caused by the infiltration of moisture through cracks and joints - and the subsequent destabilizing of the inner core rubble - had become extensive. In particular, displacement of stones became evident. (See Photograph 2.) It also appears that the changes in the load distribution through the masonry caused columns supporting the friezes that adorn the front elevation to become over-loaded and this resulted in further damage. (See Photograph 3.)

Photos 2 & 3: Examples of damage caused by the deterioration of inner core rubble

The pre-project investigations comprised:-

- Non-destructive testing to confirm the presence and extent of hidden voids, including impact-echo testing, and fibre-optic inspections; (See Photos 4 & 5)
- A structural evaluation to provide data required for the restoration strategy.

The structural evaluation comprised:-

- A visual inspection of the interior roof construction;
- Removal of a selected masonry unit to confirm the nature of the various wall constructions;
- Pull-out testing to confirm the strength of the proposed masonry tie system;
- A structural analysis carried out by a professional engineer.

Photos 4 & 5: Using impact-echo (left) and fibre optics to investigate the condition of the inner core.

The structural analysis confirmed the optimum requirements for accommodating horizontal thrust forces during grouting - and thus the design requirements for the tie diameter, length and spacings based on the proposed maximum pump pressures of 0.03N- (5-psi) and a fluid grout density of 12 KN/m^3 (80-pcf). The maximum desirable lift of grout at any one time was determined to be 700 mm (28-in) for the lower portion of the walls and 500-mm (20-in) for the upper portions. In addition, the structural analysis confirmed that the loading condition on the walls - when acting as a full composite thickness with concentric loading conditions - was quite low. The structural analysis also confirmed the over-stressing of the columns and this determined the need for temporary relief of their loads during the restoration work.

The confirmed low loading on the composite masonry walls indicated that acceptable performance could be gained once the walls had been adequately tied and the inner core rubble stabilised. The structural analysis determined that the use of shear-development anchors to develop load support across the full thickness of the walls was not necessary.

The restoration strategy that was developed from the information provided by the investigation process can be summarised as follows:-

- The relief of load and temporary support of the columns on the south walls during the anchoring, grouting and repointing work; the arrangement consisted of pre-fabricated steel frames between the columns and the use of hydraulic jacks to deflect the loads from the columns; the total required displacement after settlement of the jacks was calculated to be between 0.3 mm and 0.5 mm (0.012 and 0.020-ins); deflection gauges were installed to facilitate monitoring of the load relief and they were held in position until the loads were replaced;
- Below grade waterproofing to contain the grout and improve durability;
- Installation of helical stainless steel masonry ties between the two outer wythes to provide temporary restraint during grouting, and to improve the composite action of the masonry;

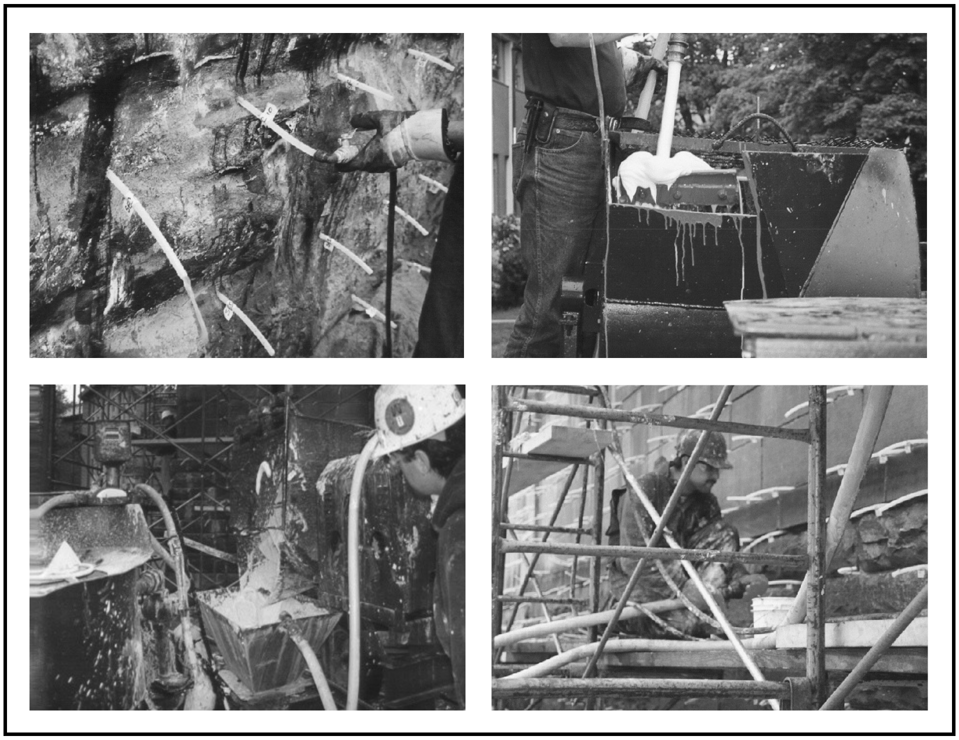
- Repair of damaged units using a proprietary mortar designed for heritage structure applications;
- Raking out deteriorated or inappropriate mortar and other materials within the mortar joints and back-pointing with a lime/cement based mortar to contain the grout during restoration work. The front of the joints were left open for about 25-mm (1-in) to facilitate final repointing;
- Water-flushing the inner core rubble using warm water and low pressure to remove any disintegrated binder so that the grout could subsequently be pumped at reduced pressures. (See Photograph 6.) Two way radios were used between the operator and a watch-person within the gallery to ensure that leakage to the interior did not cause damage to finishes, etc.
- Grouting of the voids within the core with a cellular foamed cement grout designed to be compatible with the requirement for consolidation and stability without excessive stiffness;
- Repointing the balance of the masonry unit joints;
- Correction of other deficiencies that could have affected the performance of the structure, such as improvement of storm-water drainage and flashings.

Some five years later, the restoration work appears to have been successful in accommodating differential movement, arresting the deterioration of the art gallery and restoring the masonry to a durable condition.

<u>Cellular Foamed Cement Grout.</u>

Cellular foamed cement grout was selected because of the author's previous experiences gained within the mining industry and principally because of its lightweight, low strength properties - as well as its inherent ability to absorb stress. These properties have been well-documented - together with the grout's ability to deform considerably under load at a constant yield stress and redistribute damaging point load stresses.[(5)] (These unique properties also present opportunities for seismic retrofit applications for historical structures.) The density of the hardened cellular foam grout can be varied by adjustment of the quantity of foam introduced into the base grout, as well as by incorporating a filler, such as sand. Generally, densities less than 400-Kg/m^3 (25-pcf) produce unstable hardened material, while the benefit of foaming becomes diminished once densities exceed about 1600-Kg/m^3 (100-pcf). For neat cement grouts this range of densities will generally produce 28-day compressive strengths between 1.5-N/mm^2 and 14-N/mm^2 (200 and 2000-psi) with a relatively reasonable linear relationship.

The liquid cellular grout, which was designed to have a wet density between 720 and 800-Kg/m^3 (45 and 50-pcf), was produced by blending a foam into a 0.45 water/cement ratio grout. A methylcellulose-type admixture was mixed within the cement/water grout to provide thixotropic properties to the plastic grout and minimize leakage to the interior through cracks, gaps, etc. 28-day compressive strengths were typically between 5 to 7 N/mm^2. (725 to 1015 psi) To produce the foam, a proprietary surfactant-type admixture was diluted in water and forced through a nozzle under pressure using a purpose designed pump. A high-shear colloidal mixer was used to mix the cement/water grout which was then transferred into a standard spiral-blade mortar mixer. After the foam had been blended into the grout, (See Photographs 7 & 8) the final mixture was injected into the core using a standard Moyno pump fitted with 50-mm (2") diameter lines. (See Photograph 9.) The nozzle end was fitted with a pressure gauge and a return line to permit the nozzleman to control the flow of grout and pumping pressures. Above grade level the grout contained white cement to reduce the level of soluble salts that could subsequently leach to the surface and contaminate the masonry units. An estimated 25 cu.m. (900 cu.ft.) of grout was injected into the inner core rubble voids, which represented approximately 7.5% of the total volume of masonry.



Photos 8: (Top Left) Flushing the core with warm water. Photo 9: (Top Right) Pumping foam into mortar mixer. Photo 10 (Bottom Left) Transferring cellular grout to pump hopper. Photo 11: (Bottom Right) Injecting cellular grout into inner core rubble.

As already discussed, when utilising consolidation grouting techniques, a major concern is the introduction of moisture that may cause leaching of soluble salts and staining or damage of masonry surfaces. However, a major advantage of cellular foamed cement grout is the low volume of water used - in the order of 50% of that used for traditional grouts. Provided that the water/cement ratio used for cellular grout approaches the figure generally considered to be necessary for optimum hydration - about 0.42[6] - the amount of free water that will not be used in the hydration process is not significant. (Conversely, it is important that the water/cement ratio used is not less than about 0.40, or the cement hydration process may consume water from the foam - resulting in unstable bubbles.) In fact, although there were a few areas that remained damp for a while - mainly in shaded areas - the masonry dried very well and no detrimental effects were observed.

A further major advantage provided by cellular foamed grout is the reduced weight of material that is injected into the masonry - theoretically less than the original rubble binder. The dry weight can be designed to be at least 1000-Kg per cubic metre (1700-lb per cubic yard) less than a traditional lime or lime/cement grout.

Case Study Two - Saint Louis Convent, Waterloo, Ontario

Constructed in 1895, Saint Louis Convent in Waterloo is a brick masonry structure supported on a double wythe foundation wall. Over the years, excessive step-cracks occurred within the brick masonry walls at many locations - usually adjacent to windows. (See Photograph 12.) Lack of available funds precluded a detailed investigation but a preliminary visual study indicated that the most likely cause of the cracking was differential settlement/movement of the foundation walls - most likely due to destabilisation of the inner core rubble. This could be confirmed by the condition of the masonry at and just below grade level, the knowledge that the below grade portions of the walls had not been waterproofed, and the presence of debris within the basement that was most likely disintegrated core rubble binder. The poor condition of the below grade foundation walls was confirmed during the subsequent restoration work. (See Photograph 13.)

The restoration strategy consisted of the following:-

- To provide the required restraint during grouting and a better composite action between the two wythes, helical stainless steel ties were installed into the basement interior. In view of the tough nature of the mainly granite stones, the ties were epoxy-resin grouted "front and back".
- The below grade portion of the foundation wall masonry was exposed, waterproofed and back-filled - both to contain the grout and to provide improved protection.
- The masonry joints within the above grade portion of the foundation walls were cut-out and repointed using a prepackaged lime-based heritage restoration mortar. (Hard cement-based mortar was also removed from the face of the stone masonry units.)
- Holes were drilled into the inner core rubble from the inside. Warm water was used to flush out disintegrated binder from the core, and the voids were grouted using similar techniques to those already described for the previous case study. Almost 6.0 cu.m. (200 cu,ft,) of grout was calculated to have been injected, which represented about 10% of the total volume of masonry.
- The cracks within the brick masonry walls were "stitched" using the helical stainless steel masonry ties. The ties were "dry-fixed" into smaller diameter pilot holes first drilled to the required depth. The holes were drilled at 45°angles through the mortar joints to intersect the cracks roughly at their mid-point.
- The open joints within the brick masonry were then cut-out and repointed using a prepacked heritage restoration masonry mortar, selected to blend with the existing mortar.

After two severe winters and extreme changes in temperature over very short periods, no further cracks have become visible and repaired cracks have remained unchanged.


Photo 12: (Left) Cracks caused by deterioration of inner core rubble. Photo 13: (Right) Condition of below grade foundation wall.

Case Study Three - Heritage Complex - Brampton, Ontario

Now a museum and part of the Heritage Complex in Brampton, the County of Peel Jail was constructed in 1866. (See Photograph 14.) After the jail was closed in 1977 a new museum archives building was constructed with portions of the perimeter courtyard wall becoming the exterior walls. In the Summer of 2000 it was decided that the exterior masonry should be repointed.

During the old mortar cutting out operations loose stones and the presence of disintegrated mortar indicated that the inner core rubble was in a poor condition and further investigation was determined necessary. (See Photograph 15.) The investigation consisted primarily of a survey using Ground Penetration Radar (GPR) techniques which revealed the presence of considerable voidage. It is believed that this was the first time that the technique has been used for this purpose in Canada and the results provided by computer-generated contour mapping of the results were extremely valuable. (See Fig. 1.) The mapping of the voids and suspected loosely bound rubble facilitated the installation of the injection ports and the concentration of grout at key locations.

Helical stainless steel masonry ties were first installed to provide restraint against grouting pressures and to improve the composite action of the restored masonry. Tests were first carried out to ensure adequate pull-out load could be achieved. (See Photograph 16.) The grout and grouting techniques were similar to those described for the previous case studies. (See Photograph 17.)

About 2 cubic metres (70 cubic feet) of grout was used - approximately that calculated to be required from the data provided by the GPR survey - representing about 6% of the total masonry volume. Good flow within the rubble was achieved through interconnected voids and positive contact was made between most of the ports. (See Photograph 18.)

Photo 14 (Top Left) Former County of Peel Jail - the grouted courtyard wall is to its left. Photo 15 (Top Right) Example of inner core rubble deterioration after removal of stone masonry unit. Figure 1 (Middle Left) Computerized contour image produced by GPR - The darker areas represent solid masonry. Photo 16 (Middle Left) Pullout testing a masonry tie. Photo 17: (Bottom Left) Pumping cellular grout through an injection port. Photo 18 (Bottom Right) Contact is made between ports.

CONCLUSIONS

In an ideal world, restoration strategies should be designed to include the least intrusive methods and they should be reversible. Wherever possible, they should also attempt to use traditional materials that are similar to those used for the original construction - and compatible with the masonry in terms of movement accommodation, etc. However, although competent design and practices can almost always ensure that grouting operations do not impact on the aesthetic quality of the building fabric, these philosophies are difficult to observe when the original materials did not prove to be adequately durable and the techniques to be employed are unavoidably permanent. It is therefore the author's opinion that the use of cellular foamed cement grout provides an acceptable compromise - particularly in view of the sacrificial and beneficial properties that the material provides.

There are many heritage structures and older buildings that are no doubt suffering from the effects of deteriorated inner core rubble - most of them probably remain undiagnosed, with deterioration proceeding at an accelerated rate. Often, restoration strategies address the result of the problems without fully understanding the cause. Consolidation and stabilisation of the walls using grouting techniques should be an essential part of a restoration strategy for these buildings - provided that the original cause/s of accelerated deterioration - water infiltration through joints above and below grade, cracks, poor waterproofing and flashing details, etc., - are also addressed.

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