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STRENGTHENING AND REPAIR OF MASONRY UNDER COMPRESSIVE LOAD AND TESTING OF EDCC-STRENGTHENED PRISMS

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ABSTRACT
Compressive strength is perhaps the most important property of masonry. Due to the weak bond between masonry units and mortar, structural masonry walls have low tensile and shear strength. Hence, the design of masonry structures is effective for situations where compression is the limiting case. Hollow masonry walls are usually strengthened with grout, whether or not they are also reinforced. Grouting is relatively easy to do during construction but it is difficult to implement for repair of masonry, because of having to drill into the wall to access the hollow cores. In several parts of the world, numerous masonry buildings require repair due to inappropriate design or execution work and uncertainty in the quality of the material used. In many of these cases increasing compressive strength of the masonry is an issue. An overview of the main existing techniques to increase masonry compressive strength is presented. The initial phase of an experimental program on hollow concrete block walls strengthened by rendering with Eco-Friendly Ductile Cementitious Composites (EDCC) is also presented, including 16 compression tests of three course prisms.

KEYWORDS: *compressive strength, repair, structural masonry, strengthening*

INTRODUCTION
Masonry buildings can require strengthening or repair due to inappropriate design, poor execution of the work and/or uncertainty in the quality of the material used. In many of these

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cases increasing the compressive strength of the masonry is an issue. Like concrete, masonry is a low-tensile strength material and compressive strength is its main property. Unreinforced masonry is a composite material where the low bond strength between block and mortar makes it a non-tensile strength material in many practical applications. On the other hand, masonry is very effective when compression is the main load-demand. However, in some cases, masonry also needs compression-strengthening, either for very high-demand compression load, or when high-strength blocks are not available. As grouting is difficult to implement for the repair or strengthening of masonry, because of having to drill into the wall to access the hollow cores, alternative techniques need to be developed. Rendering with Eco-Friendly Ductile Cementitious Composites (EDCC) is one of them and this method has some advantages over the other techniques. For example, application is straightforward and there is less environmental impact. EDCC is a new repair material developed at the University of British Columbia [1, 2]. After a review of the main existing repair and strengthening techniques against compressive loading, the initial phase of an ongoing experimental program at the University of Calgary is presented, including compression tests of hollow concrete block prisms strengthened with EDCC.

STRENGTHENING AND REPAIR TECHNIQUES FOR STRUCTURAL MASONRY UNDER COMPRESSIVE LOADING

Grouting

Grout is a high slump, pourable mixture of cement, aggregates and water used to fill vertical or horizontal voids in the masonry. Usually grout is combined with steel reinforcement in order to improve the tensile and shear strength of the masonry. Camacho et al. [3] performed compression tests on concrete block walls (900 mm wide, 1000 mm high and 140 mm thick) varying the block compressive strength and grouting conditions (Figure 1). Material properties and test results are summarized in Table 1.

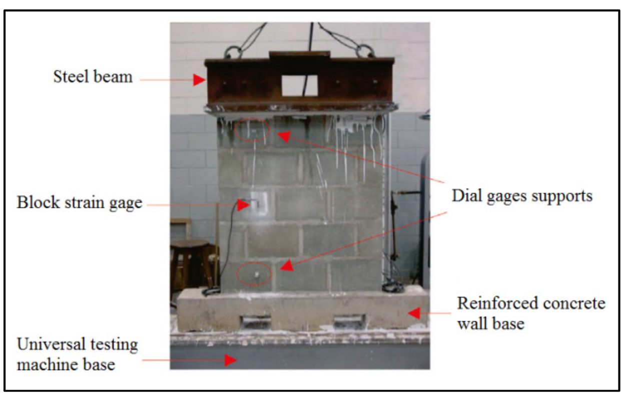

Figure 1: Grouted wall testing scheme (adapted from Camacho et al. [3])

Table 1: Material properties and compression test results of Camacho et al. [3]

Type	Description	Value (MPa)
Material property 1	Average compressive strength of W1 wall blocks*	8.64
Material property 2	Average compressive strength of W2 wall blocks*	15.76
Material property 3	Average compressive strength of the bed joint mortar	6.10
Material property 4	Average compressive strength of the grout	17.73
Compression test 1	W1 wall (without grout, without reinforcement)	4.39
Compression test 2	W1 wall (with grout, without reinforcement)	7.86
Compression test 3	W1 wall (with grout and 0.15% reinforcement ratio)	9.32
Compression test 4	W1 wall (with grout and 0.40% reinforcement ratio)	9.50
Compression test 5	W1 wall (with grout and 1.00% reinforcement ratio)	9.11
Compression test 6	W2 wall (without grout, without reinforcement)	8.19
Compression test 7	W2 wall (with grout, without reinforcement)	15.17
Compression test 8	W2 wall (with grout and 0.15% reinforcement ratio)	13.93
Compression test 9	W2 wall (with grout and 0.40% reinforcement ratio)	15.86
Compression test 10	W2 wall (with grout and 1.00% reinforcement ratio)	17.31
Note: * = calculated with gross area.		

Comparing the strengths of ungrouted W1 and W2 walls (tests 1 and 6) with their grouted equivalents (tests 2 and 7) shows the grouting to increase compressive strength by 79% and 85%, respectively. Compared to the W1 grouted wall (test 2), the introduction of reinforcement enabled an average compressive strength increase of 19% (tests 3 to 5). While the highest reinforcement ratio (1.0%, test 5) induced the lowest increase (16%), it should be noted that the differences between the different reinforcement ratios are not significant in the sense that the variation is within the normal variability of masonry. Similarly, compared to the W2 grouted wall (test 7) the introduction of reinforcement caused an average compressive strength increase of 3% (tests 8 to 10), but the lower reinforcement ratio (0.15%, test 8) induced a drop of 8%. So this research shows that grouting has a significant effect on wall compressive strength but that the effect of reinforcement on compressive strength is limited. According to Parsekian, Hamid and Drysdale [4], several factors can influence the grouting technique: incomplete grout vibration, grout shrinkage, incompatibility of the stress-strain diagram between the block and the grout and geometric factors. Concerning the reinforcement, the absence of stirrups can explain the limited effect on compressive strength.

Fibre reinforced polymers

Fibre reinforced polymers (FRP) have key advantages for masonry repair, such as strength-to-weight ratios exceeding significantly those of conventional civil engineering materials and a high degree of chemical inertness in most environments [5, 6]. For wall masonry repair work, FRP can be used in the forms of mesh, sheet, strip or bar. Chagas and Moita [7] investigated the rehabilitation of damaged concrete masonry walls using carbon fibre reinforced polymers (CFRP) and glass fibre reinforced polymers (GFRP) meshes. The walls were 800 mm wide, 1000 mm high and 140 mm thick. Three specimens, considered as the reference specimens, were subjected to axial compressive loading up to their collapse in order to induce damage to the walls. Seven other specimens were submitted to axial compressive loading of 75% of the average collapse loading of the reference walls (which resulted in a load of 320 kN). These seven specimens were then strengthened with FRP systems applied on both main wall surfaces. To provide a high bonding base coating for the FRP systems and soften wall surface irregularities, two epoxy layers were applied between the walls and the FRP systems (dented primer and putty, respectively). The FRP meshes were glued to the walls between two epoxy based saturant resin layers (i.e. one between the wall and the FRP mesh and one on top of the FRP mesh). The material properties and test results are summarized in Table 2.

Table 2: Material properties and compression test results of Chagas and Moita [7]

Type	Description	Value (MPa)
Material property 1	Average concrete block compressive strength (gross area)	5.64
Material property 2	Average compressive strength of the bed joint mortar	6.49
Material property 3	Compressive strength of the epoxy based saturant resin	86.20
Material property 4	Tensile strength of the CFRP one-directional fabric mesh	3800.00
Material property 5	Tensile strength of the GFRP two-directional fabric mesh	1517.00
Compression test 1	Average compressive strength of the reference walls (without FRP retrofitting)	3.82
Compression test 2	Damaged wall retrofitted with CFRP mesh	5.27
Compression test 3	Damaged wall retrofitted with CFRP mesh	5.31
Compression test 4	Damaged wall retrofitted with GFRP mesh	4.02
Compression test 5	Damaged wall retrofitted with GFRP mesh	4.62
Compression test 6	Damaged wall retrofitted with CFRP mesh (but without the putty layer)	3.96
Compression test 7	Damaged wall retrofitted with GFRP mesh (but without the putty layer)	4.46
Compression test 8	Damaged wall retrofitted with GFRP mesh (but without the putty layer)	5.71
Note: FRP systems applied on both main wall surfaces.		

As compared with the reference walls (test 1), CFRP and GFRP systems caused average compressive strength increases of 38.5% (tests 2 and 3) and 13% (tests 4 and 5), respectively. Moreover, the authors noticed that the retrofitted walls showed load-displacement and stress-strain curves similar to those obtained from the reference walls. Without the putty layer, the CFRP system caused an insignificant increase of only 4% (test 6) (within the normal variability of masonry). In contrast, with GFRP system, the same situation created an average increase of 33% (tests 7 and 8). According to the authors, the above results confirm that the bonding between the FRP external reinforcement and the substrate is a key issue. Figure 2 shows the tested wall retrofitted with CFRP, corresponding to “Compressive test 3” in Table 2.

Figure 2: Tested wall retrofitted with CFRP and corresponding to "Compressive test 3" in Table 2 (Chagas and Moita [7])

Cement mortar overlays

Oliveira and Hanai [8] tested concrete walls reinforced with different overlay conditions. The walls were 390 mm wide, 810 mm high and 140 mm thick. The different mortar overlays were applied on both faces. Figure 3 shows the illustration of two connector types (A and B) used in the research.

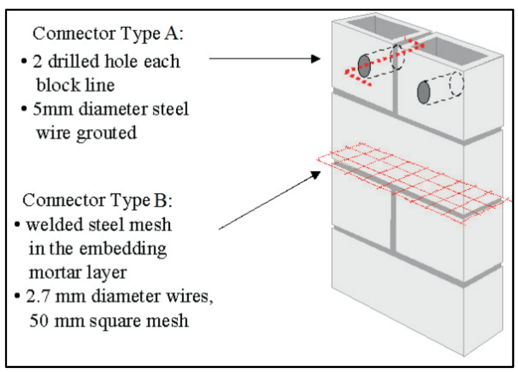

Figure 3: Illustration of connectors Type A and B (adapted from Oliveira and Hanai [8])

Material properties and test results are summarized in Table 3. According to the authors, application of mortar overlays increases the wall strength, but not in a uniform manner. The efficiency in strengthening walls loaded in axial compression is not proportional to the overlay mortar strength (test 2, +22% and test 3, +18%) because the strength of the composite is affected by the failure mechanisms of the walls. Steel mesh reinforced overlay in combination with high strength mortar showed better efficiency (test 4, +43%): the steel mesh mitigated the damage effects in the block wall and in the overlay itself. The use of type B connectors did not create a significant increase in wall strength (compare test 4 with test 5), while there was a 9% drop in wall strength with type A connectors (compare test 4 with test 8). The use of polypropylene fibres provoked a 10% drop in wall strength (compare test 1 with test 6), whereas the use of steel fibres caused only a 2% drop in wall strength (compare test 3 with test 7). Again, these differences are within the typical variability of masonry, and suggest the fibres were having little to no effect.

Table 3: Material properties and compression test results of Oliveira and Hanai [8]

Type	Description	Value (MPa)
Material property 1	Average concrete block compressive strength (gross area)	9.00
Material property 2	Bed joint mortar compressive strength	11.00
Material property 3	“Weak” mortar compressive strength	3.00
Material property 4	“Strong” mortar compressive strength	23.00
Compression test 1	Wall without overlay	7.27
Compression test 2	Wall coated with the “weak” mortar	8.88
Compression test 3	Wall coated with the “strong” mortar	8.61
Compression test 4	Wall coated with the “strong” mortar and steel welded square mesh (2.77 mm diameter)	10.40
Compression test 5	Wall coated with the “strong” mortar, steel welded square mesh (2.77 mm diameter) and type B connectors*	10.44
Compression test 6	Wall coated with the “weak” mortar and polypropylene fibres (25 mm long)	6.52
Compression test 7	Wall coated with the “strong” mortar and steel fibres (30 mm long)	8.41
Compression test 8	Wall coated with the “strong” mortar, steel welded square mesh (2.77 mm diameter) and type A connectors**	9.49
Note: * = type B connectors (i.e. 160 mm wide strips of welded meshes, placed in the mortar bed joints). ** = type A connectors (i.e. 5 mm steel wires passing through cylindrical grouted holes).		

Engineered Cementitious Composite (ECC) overlays

According to Lin et al. [9], Engineered Cementitious Composites (ECC) form a recent class of civil engineering materials designed to obtain higher toughness and ductility than those of conventional materials. A typical ECC mix contains water, cement, randomly distributed discontinuous fibres and some common chemical additives [9]. So it should be noted that tests 6 and 7 (Table 3) of Oliveira and Hanai [8] research could had been presented in this section. Kyriakides and Billington [10] tested 30 clay masonry prisms (6 groups of 5 specimens each) varying the ECC strengthening design. The prisms were 272 mm high, 196 mm wide and 94 mm thick. When used, ECC layers were applied approximately 13 mm thick on only one face of the prism. Also ECC contained 8 mm long polyvinyl alcohol (PVA) fibres at 2% by volume. The testing scheme of each group of prism is presented in Figure 4.

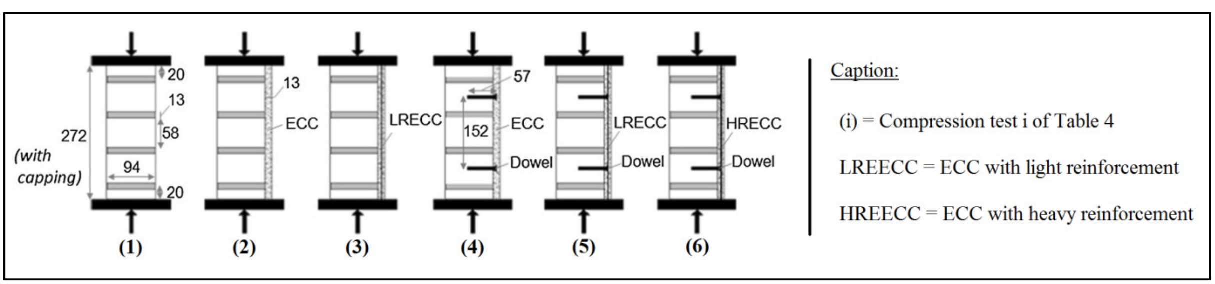

Figure 4: Tested scheme of prisms strengthened with ECC (Kyriakides and Billington [10])

Material properties and test results are summarized in Table 4. When compared with plain prisms (test 1), the ECC layer (test 2) increased the compressive strength by 45%. The introduction of the light steel reinforcement (test 3) created an increase of only 33%. According to the authors, this difference in strength could be explained by the system used to fix the grid on the prism surface and the lack of ECC between the prism surface and the grid in some spots (especially at the crossing points of the grid). Compared with the test 2, the dowel system (test 4) caused a compressive strength decrease of 18%. The authors mentioned that installation of the dowels may have weakened the bricks in the prisms. When compared with plain prisms (test 1), the ECC layer combined with dowels and light steel reinforcement (test 5) or heavy reinforcement (test 6) resulted in decreases in strength of 5% and 6%, respectively. These results confirmed the observations made with tests 3 and 4, but again are within the variability one expects of masonry.

Table 4: Material properties and compression test results of Kyriakides and Billington [10]

Type	Description	Value (MPa)
Material property 1	Average solid clay brick unit compressive strength	79.30
Material property 2	Average bed joint mortar compressive strength	10.43
Material property 3	Average ECC compressive strength (containing PVA fibers)	61.40
Material property 4	PVA fibers nominal strength	1,620.00
Material property 5	Yield strength of the steel reinforcement (grid)	345.00
Compression test 1	Average strength of plain prisms (not strengthened)	20.06
Compression test 2	Average strength of plain prisms strengthened by ECC layer	29.04
Compression test 3	Average strength of plain prisms strengthened by ECC layer and light reinforcement[1]	26.66
Compression test 4	Average strength of plain prisms strengthened by ECC layer and steel anchors (dowels)	23.77
Compression test 5	Average strength of plain prisms strengthened by ECC layer, light reinforcement[1] and steel anchors (dowels)	19.00
Compression test 6	Average strength of plain prisms strengthened by ECC layer, heavy reinforcement[2] and steel anchors (dowels)	18.76
Note: 1 = steel grid of 38 mm x 38 mm. 2 = steel grid of 25.4 mm x 25.4 mm.		

ONGOING EXPERIMENTAL PROGRAM AT THE UNIVERSITY OF CALGARY

Background

Eco-Friendly Ductile Cementitious Composites (EDCC) form a new class of materials to be applied on masonry structures. These materials are characterized by their simplicity of use, low costliness and sustainability. They can be understood as a subdivision of ECC materials (presented in the previous section) in which Portland Cement is substantially replaced by industrial by-products (e.g. fly ash) or totally replaced by alternative binders (e.g. geopolymer cements). Canadian and Brazilian universities are collaborating on the structural testing and numerical modelling of EDCC (Table 5). Applications of EDCC can be the retrofitting of historic or modern masonry.

Table 5: Co-operation between Canadian and Brazilian universities studying EDCC applications for masonry structures

University (location)	Main field of study for the co-operation
University of British Columbia (Vancouver, British Columbia, Canada)	EDCC development, characterization and testing
University of Manitoba (Winnipeg, Manitoba, Canada)	Durability testing of masonry strengthened by EDCC
University of Calgary (Calgary, Alberta, Canada)	Structural testing of modern masonry strengthened by EDCC
Federal University of São Carlos (São Carlos, São Paulo, Brazil)	Structural testing and numerical modelling of modern masonry strengthened by EDCC

The three next sections present an initial campaign of tests made with concrete prisms strengthened by EDCC against compressive loading at the University of Calgary.

Experimental program

16 concrete masonry prisms were tested under compressive loading. Specimens consisted of three course prisms made with concrete masonry units (nominal dimensions: 400 mm wide, 200 mm high and 200 mm thick) and type S mortar. Three groups of specimens were tested (named A, B and C). Group A consisted of 6 plain specimens, Group B consisted of 5 specimens with 5 mm thick EDCC strengthening and Group C consisted of 5 specimens with 10 mm thick EDCC strengthening. When used, the EDCC was applied on both main surfaces of the prisms.

Material properties

Properties of the materials forming the different specimens were determined according to the CSA S304-14 [11] standard recommendations and are summarized in Table 6. The EDCC material is described in Kaheh et al. [12, 13].

Table 6: Properties of materials forming the concrete prisms and EDCC

Property (unit)	Value
Average concrete block unit compressive strength (MPa)	16.1 (6.9%)*
Average bed joint mortar compressive strength (MPa)	12.0 (4.5%)*
Average EDCC compressive strength (MPa)	45.0**
Average EDCC minimum compressive strain capacity (%)	3.0**
Average EDCC density (kg/m^3)	1985**
Note: * = coefficient of variation. ** = results available in Kaheh et al. [12, 13].	

Compressive test results

The compressive test results are presented in Table 7.

Table 7: Compressive test results of plain and EDCC strengthened prisms

Test	Group	Specimen	Strength (MPa)
1	GA[1]	1	11.96
2	GA	2	13.13
3	GA	3	12.36
4	GA	4	11.65
5	GA	5	11.86
6	GA	6	14.23
Average compressive strength of GA: 12.53 MPa (7.8%)*			
7	GB[2]	1	19.69
8	GB	2	18.10
9	GB	3	17.98
10	GB	4	15.75
11	GB	5	16.25
Average compressive strength of GB: 17.55 MPa (9.0%)*			
12	GC[3]	1	13.75
13	GC	2	18.54
14	GC	3	13.69
15	GC	4	17.59
16	GC	5	15.56
Average compressive strength of GC: 15.83 MPa (13.9%)*			
Note: 1 = group of specimens without EDCC strengthening (GA). 2 = group of specimens strengthened with 5 mm EDCC overlay (GB). 3 = group of specimens strengthened with 10 mm EDCC overlay (GC). * = coefficient of variation.			

As compared with non-strengthened prisms (Group A), the use of EDCC with 5 mm thick (Group B) and 10 mm thick (Group C) increased the average compressive strength by 40% and 26%, respectively. The coefficients of variation ranged from a low of 7.8% with Group A to the high of 13.9% with Group C. As regards qualitative results, the integrity of EDCC layers was relatively well preserved, even after the specimens ruptured. Also, no detachment was observed between the EDCC and the block units during the tests (Figure 5).

Figure 5: Concrete masonry prism strengthened by EDCC layers (5mm thick)

Hence, these first results show that overlaying with EDCC can have a significant positive influence on prism compressive strength and the procedure seems to be a viable repair/strengthening technique (with an optimum EDCC thickness lower than 10 mm). Other tests will be done in order to confirm or not these conclusions.

CONCLUSIONS

The overview of masonry strengthening techniques against compressive loads established that, excluding grouting, only techniques using pourable mixtures applied to the external surfaces of the masonry have been found in the available literature. The four following conclusions can be drawn about the techniques mentioned:

1) ECC overlays offer the higher increases in compressive strength (45%);

2) Steel grid reinforcement put into cement mortar or ECC overlay gave an increase up to about 40% but the grid fixing system must be realized carefully;

3) CFRP and GFRP meshes provided increases of 38% and 33%, respectively, but to get these results each FRP type needs a specific preparation of the masonry surface;

4) Special anchoring systems (e.g. dowels) requiring drilling into the masonry and intended to improve the bond between the strengthening material and the masonry surface do not bring satisfactory results.

In addition, the following conclusions can be drawn from the results of the compressive tests on concrete prisms strengthened by EDCC overlays (as part of an ongoing experimental programme at the University of Calgary):

1) 5 mm thick EDCC overlays increased compressive strength by 40%;

2) EDCC layers remained substantially intact during the test, even after the specimens ruptured. No important detachments were observed between the EDCC and the block units;

3) The optimum EDCC thickness is lower than 10 mm.

Others tests will be done to confirm or not the above mentioned conclusions.

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