12th Canadian Masonry Symposium
Vancouver, British Columbia, June 2-5, 2013

PRELIMINARY INVESTIGATION OF STEEL FIBRE REINFORCED GROUT AS INFILL REINFORCEMENT FOR MASONRY BLOCK WALLS

R.T. Harris[1], S. Lissel[2] and R. Laing[3]
[1] MSc Student, Department of Civil Engineering, University of Calgary, Calgary, AB, T2N 1N4, Canada, rtharris@ucalgary.ca
[2] Associate Professor, Department of Civil Engineering, University of Calgary, Calgary, AB, T2N 1N4, Canada, sllissel@ucalgary.ca
[3] Undergraduate Student, Department of Civil Engineering, University of Calgary, Calgary, AB, T2N 1N4, Canada,

ABSTRACT

Results of a preliminary study examining the potential of steel fibre reinforced grout as a method of masonry wall reinforcement are presented, along with a brief literature review outlining past applications of steel and other fibres to masonry walls. Various fibre lengths including 13 mm straight, 30 mm hooked and 60 mm hooked are used in the grout mixes, with the aim to produce a self-consolidating grout that could be cast into the cores of concrete block walls for in-plane strengthening. Grout tensile strength is evaluated from flexural tensile tests performed on 150 x 150 x 450 mm beams according to ASTM C1609. Compressive properties are determined through direct, uniaxial compression tests performed on 100 mm diameter cylinders. Slump flow test results are also reported.

KEYWORDS: reinforced grout, steel fibres, material testing

INTRODUCTION

Unreinforced masonry walls perform poorly in seismically active areas, often leading to structural collapse in significant seismic events. Although modern design standards require the use of steel rebar in new construction, older buildings or non-structural walls may not adhere to these requirements. Cost effective methods to strengthen unreinforced walls to meet minimum seismic requirements are very desirable. Many strengthening methods have been proposed such as external fibre-reinforced polymer (FRP) sheets, retrofits using embedded FRP or conventional steel rebar, and post-tensioning. These methods often impact the appearance of the wall, and can be quite complicated to implement successfully, requiring special equipment or careful preparation of the wall prior to application.

The eventual goal of this research is to develop a form of infill reinforcement where a relatively inexpensive material is pumped or poured into the internal cores of the concrete block wall to provide the necessary reinforcement. Ideally, the material would be cheap, very fluid before hardening and require minimal skill to mix and install, while satisfying the strength and ductility demands required in a seismic retrofit. Although this work focuses on a retrofit application for concrete block walls, it would be equally applicable to new construction or any other masonry application where there is a significant void within an existing wall; hollow multi-wythe brick walls for example. Currently, two reinforcement materials are being examined; a polyurethane resin and steel fibre reinforced grout (SFRG). This paper outlines the development of a self-consolidating steel fibre reinforced grout with strength and working properties appropriate for use in such a retrofit.

PREVIOUS USE OF FIBRES

This section focuses on the application of fibre-reinforced grout specifically to masonry, an area in which previous work is very limited. To our knowledge, no previous work directly testing the in-plane strength of masonry walls reinforced with steel fibres has been reported.

Hervillard [1] tested masonry piers filled with polymer fibre reinforced grout under axial load. For concrete block, the use of polymer fibres was shown to increase the strain at 50% of the peak stress. This improvement in post-peak behaviour was attributed to improved confinement of the grout cores from the addition of fibres. Fibres did not improve the tensile strength of the grout and at high fibre contents there were grout consolidation issues, with the vibration rod leaving voids within the grouted core for several specimens. A synthetic stress-strain curve was then generated and used to predict the behaviour of masonry shear walls. The resulting model was able to predict the moment-curvature behaviour of walls adequately, with better results observed for high aspect ratio walls.

Snook et al. [2] tested polymer fibre reinforced grout in cantilevered wall specimens under quasi-static, fully reversed cyclic loading. A constant axial load was applied. Walls were reinforced with conventional steel reinforcement, with the fibres added to enhance confinement. Walls were 1.32 m or 2.13 m high, and 1.41 m long. Failure of the wall was said to occur when the load dropped to 20% of the peak load, with load applied in displacement controlled cycles with three cycles at each displacement. The addition of polymer fibres was found to increase drift at peak and failure loads (improve ductility), and increase overall energy absorption. Fibres were more effective than steel plates or seismic combs in both respects. An improvement in wall shear strength was also observed with reduced cracking for fibre-reinforced walls.

Oliveira and Bernardo [3] tested self-consolidating steel fibre grout reinforced walls under out of plane loading. In this case, it was combined with conventional reinforcement and fibre dosages of 0%, 0.5%, 1.0 % and 1.5% were used. The fibres used were DRAMIX ZP 306 hooked end steel fibres, with an aspect ratio of 48. These fibres are 30 mm long, have a diameter of 0.62 mm, and a tensile strength of 1270 MPa. The resulting grout mixes had slump flows in excess of 750 mm, and did not suffer from any problems with segregation. A superplasticizer was required to achieve these working properties. In the hardened state, the grouts had compressive strengths from 26 to 28 MPa, and peak flexural tensile strengths from 2.98 MPa to 12.12 MPa, as determined from un-notched 100 x 100 x 450 mm prisms under three point loading. The out of plane bending capacity of 0.2 m thick, 1.0 m wide, 1.4 m high walls was tested through 4-point bending tests. The testing aimed to evaluate wall strength and ductility for the different fibre dosages. Three levels of conventional reinforcement were combined with the fibre reinforced grout. The first contained the minimum level of reinforcement according to the 2005 Eurocode 6 Masonry design guidelines. The second contained reinforcement such that a balanced flexural failure condition was achieved. Finally, the third arrangement was over-reinforced, with a brittle compression dominated failure predicted. In all three scenarios, the wall was partially grouted; three of the five available cores were grouted, with the other two remaining empty. Four walls were tested for each of the three reinforcement arrangements, one for each fibre dosage. Results indicated that the addition of steel fibres increased flexural capacity by 25% to 105% for the first two reinforcement arrangements, where the tensile capacity of the reinforcement played a significant role in governing failure of the wall (steel area under the balanced condition). For the over-reinforced wall the fibre reinforced grout did not significantly increase the wall capacity.

Oliveira and Bernaedo also used design guidelines developed by RILEM TC-162- TDF for steel fibre reinforced concrete [4] to predict theoretical wall capacity. This design procedure is based on the definition of an equivalent rectangular stress block that defines the contribution of the steel fibres and is analogous to most current design standards for reinforced concrete. This approach was found to significantly underestimate the strength of the wall in many cases, with experimental values 1.03 to 2.61 times that predicted, although the least accurate predictions were often for the walls without any fibres . The approach tended to be more accurate for the walls with low levels of conventional reinforcement and higher fibre dosages.

The work by Oliveira and Bernaedo clearly demonstrates that steel fibres can be used in a self-consolidating grout mix to improve flexural strength, and increase wall ductility. Flexural strength can also be reasonably predicted using design equations developed for steel fibre reinforced concrete.

GROUT MIX PROPORTIONS

Mix proportions are based on that given by Berndt [5] and several steel fibre reinforced concrete mixes by Grunewald [6]. These were modified to suit material availability. A Masterbuilder's Glenium 7101 superplasticizer was used. Type CL fly ash and Type GU cement manufactured by Lafarge were used in the grout mixes.

Five grout mixes were developed. They can be broadly classified into coarse and fine grouts. The fine grouts use a maximum aggregate size of 2.36 mm, while the coarse grouts have a maximum aggregate size of 14 mm. No special effort was made to grade the aggregate to suit the requirements of any masonry grout standard such as ASTM C404 [7], which specifies a maximum aggregate size of 12.5 mm for coarse grout and 9.5 mm for fine grout. The coarse grouts in this study are comparable to a coarse grout according to ASTM C404 as the content above 12.5 mm for the coarse aggregate used is less than 1% by weight. The fine grout in this study uses much smaller aggregate than required by a fine grout in ASTM C404 in order to make it more suitable for this application. For a retrofit application where access to the top of the wall may be limited, a fine grout is preferred as the smaller aggregate could be pumped through a small (~25 mm) hole drilled through a face shell, whereas coarse grouts or a fine grout according to ASTM C404 would require the removal of a face shell.

DRAMIX fibers manufactured by Bekaert were used. Three fibre lengths were used in the grout mixes tested, 13 mm for the fine grouts, and 30 mm and 60 mm for the coarse grouts. The 13 mm steel fibres are straight, brass coated, unbundled fibres with a diameter of 0.16 mm (81 aspect ratio). The 30 mm and 60 mm fibres are bundled, hooked fibres and have an aspect ratio of approximately 80. The batches are designated FG for fine grout, CG for coarse grout, together with a number corresponding to the fibre length. Since grouts were tested in two iterations, the revised mixes based on the results of the first are also followed by the letter R. For example, the revised fine grout, using 13 mm fibres is designated as FG13R, while the first is simply FG13. Since it would be useful to be able to simply add fibres to a pre-bagged grout mix, an attempt was also made to produce a SFRG using premixed, bagged grout with 30 mm fibres and the addition of a superplasticizer. However, this resulted in a zero slump grout, indicating that more significant changes are required to achieve a self-consolidating SFRG from a bagged grout mix. Since it did not satisfy workability requirements, this mix was excluded from further testing. Mix proportions for the five grouts are displayed in Table 1.

Table 1: Grout Batch Proportions

	FG13	FG13R	CG30	CG30R	CG60
Fibre Type	DRAMIX OL 13/0.16 Straight	DRAMIX OL 13/0.16 Straight	DRAMIX 80/30 BP Hooked	DRAMIX 80/30 BP Hooked	DRAMIX 80/60 BP Hooked
Fibre Length (mm)	13	13	30	30	60
Fibre Volume Fraction (%)	1.0	1.05	0.75	0.78	0.75
Fibre Content (kg/m^3)	80	84	60	63	60
Max Aggregate Size (mm)	2.36	2.36	14	14	14
Cement Content (kg/m^3)	412	410	367	380	367
Water Content (kg/m^3)	323	263	223	211	273
Fly Ash Content (kg/m^3)	176	175	217	174	217
Coarse Aggregate, 2.36-14 mm (kg/m^3)	-	-	481	504	481
Fine Aggregate, 0.150-2.36 mm (kg/m^3)	1259	1318	1032	1080	1032
Superplasticizer (L/m^3)	0.0	1.1	2.6	2.7	0.5
Water/Cement Ratio	0.55	0.45	0.38	0.38	0.47

GROUT WORKING PROPERTIES

As mentioned previously, for this application, the grout should be self-consolidating. To be classified as self-consolidating according to ASTM C476 [8], the slump flow should be between 610 and 760 mm. Slump flow was measured according to ASTM C1611 [9], using a conical mould. Average values for each mix are presented in Table 2, as well as noted observations of bleeding or segregation issues for the mix.

Table 2: Trial Batch Slump Flow and Workability Issues

	Average Slump Flow (mm)	Mix Observations
FG13	960	significant bleeding and segregation
FG13R	490	no issues
CG30	750	slight segregation
CG30R	500	no issues
CG60	770	moderate segregation, slight bleeding

Only mix CG30 satisfies the requirements of ASTM C476 for self-consolidating grout, while FG13 and CG60 exceed the upper value of 760 mm. More significantly, CG30, FG13 and CG60 all had some issues with segregation, with a visible concentration of steel fibres at the centre of the puddle. The revised mixes, FG13R and CG30R, did not suffer from any workability issues, but the slump flows of 490 mm and 500 mm respectively fall below the recommendations of ASTM C476. For a retrofit application without rebar, this lower slump flow should not be a problem, and in this testing neither revised grout had difficulty consolidating in the 150 x 150 x 450 mm moulds used for the flexural test, or the 100 mm diameter cylinders used for compression testing. The 60 mm fibre mix did not consolidate well in the 100 mm diameter cylinders, and it was decided 60 mm fibres would be too long to be successfully applied as infill reinforcement.

GROUT COMPRESSIVE STRENGTH

Grout compressive strength is of secondary importance to the grout's tensile behaviour in this application, but the fibres are expected to provide confinement and improve the compressive behaviour as well. Tests were performed on 100 mm diameter, 200 mm tall cylinders, with load applied at a rate of approximately 0.25 MPa/s in accordance with the procedure of ASTM C39 [10]. Both load and strain were recorded to determine the entire stress-strain behaviour of the grout and five cylinders were tested for each mix. The loading rate was established based on the elastic behaviour of the specimen, and was not changed as the specimen failed. Two linear displacement transducers and the apparatus shown in Figure 1 were used to determine strain.

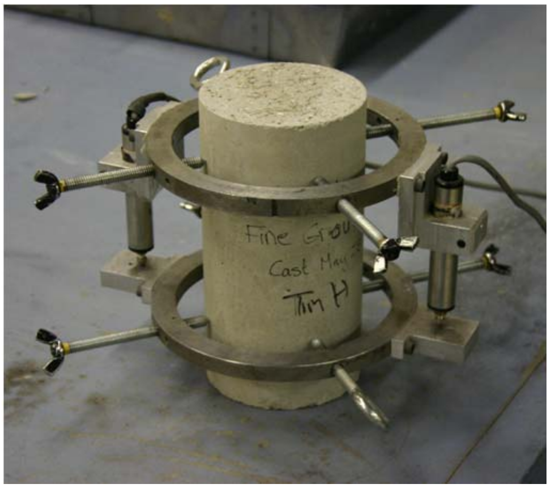

Figure 1: Compression Test Apparatus for Determining Strain

For the sake of brevity, the complete stress-strain behaviour for each grout is not reported here, but a summary of relevant values are reported in Table 3.

Table 3: SFRG Strength and Ultimate Strain in Compression

	Strength		Peak Strain		water/cement ratio
	Mean (MPa)	C.O.V%	Mean	C.O.V%	
FG13	34.44	6.5	0.0030	12.3	0.55
FG13R	45.30	7.6	0.0036	11.9	0.45
CG30	47.46	6.8	0.0045	6.7	0.38
CG30R	49.89	9.0	0.0035	22.3	0.38
CG60	30.58	15.0	0.0031	16.1	0.47

All mixes far exceed the minimum requirements for grout [8]. The strength values generally correlate to what is expected from the water to cement ratios – the lowest ratio gives the strongest grout – but the grout using 60 mm fibres appears unusually weak. This is a result of poor consolidation of the 60 mm fibres in the mould. Since a block core size greater than 100 mm is not too common, it is clear that 60 mm fibres are not suitable for this application. Stronger grouts also tended to have a higher peak strain, although peak strain showed relatively high variability compared to strength.

GROUT TENSILE STRENGTH

Flexural tensile strength was determined using a 150 x 150 mm beam under third point loading over a 450 mm span. The test procedure was based on ASTM C1609 [11]. The apparatus used is shown in Figure 2. Specimens were tested at ages of between 27 and 29 days. The load deflection curves for each mix are shown in Figures 3 to 7.

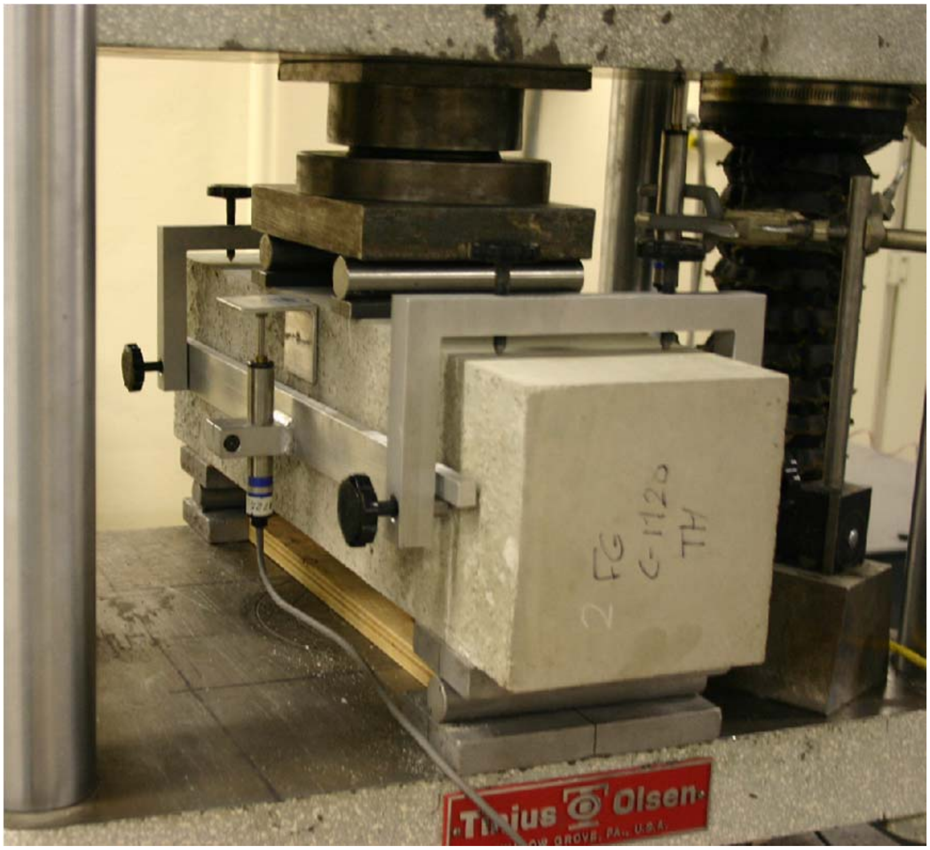

Figure 2: Flexural Test Setup

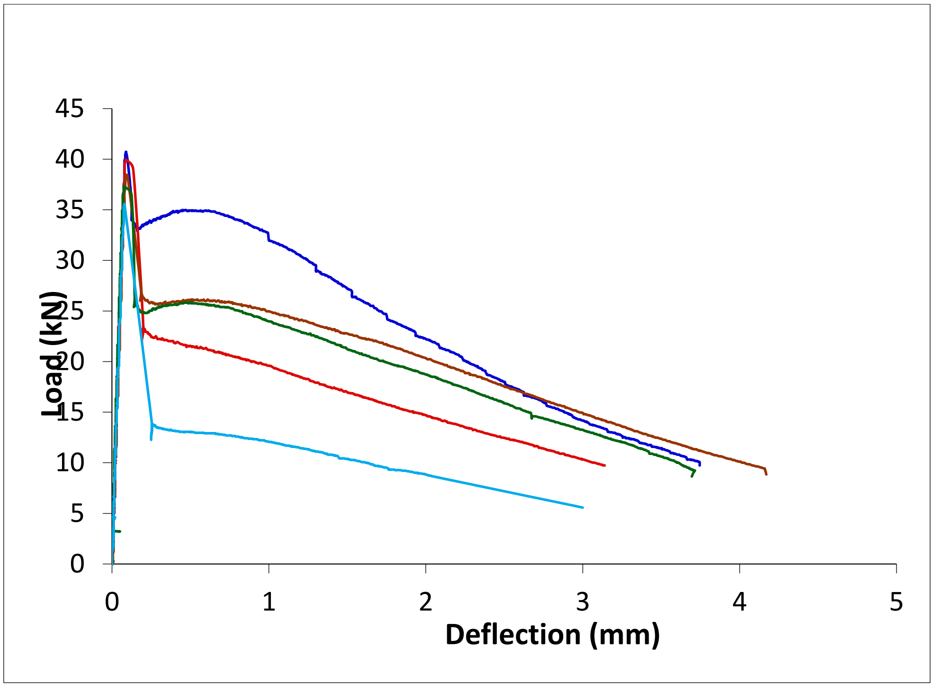

Figure 3: FG13 Under Third Point Loading (5 Specimens)

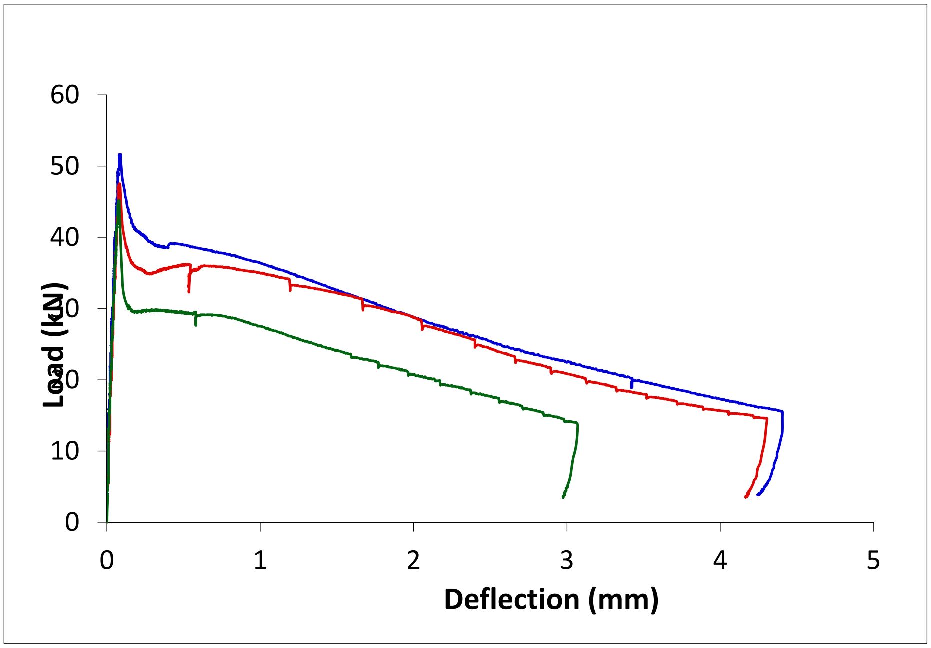

Figure 4: FG13R Under Third Point Loading (3 Specimens)

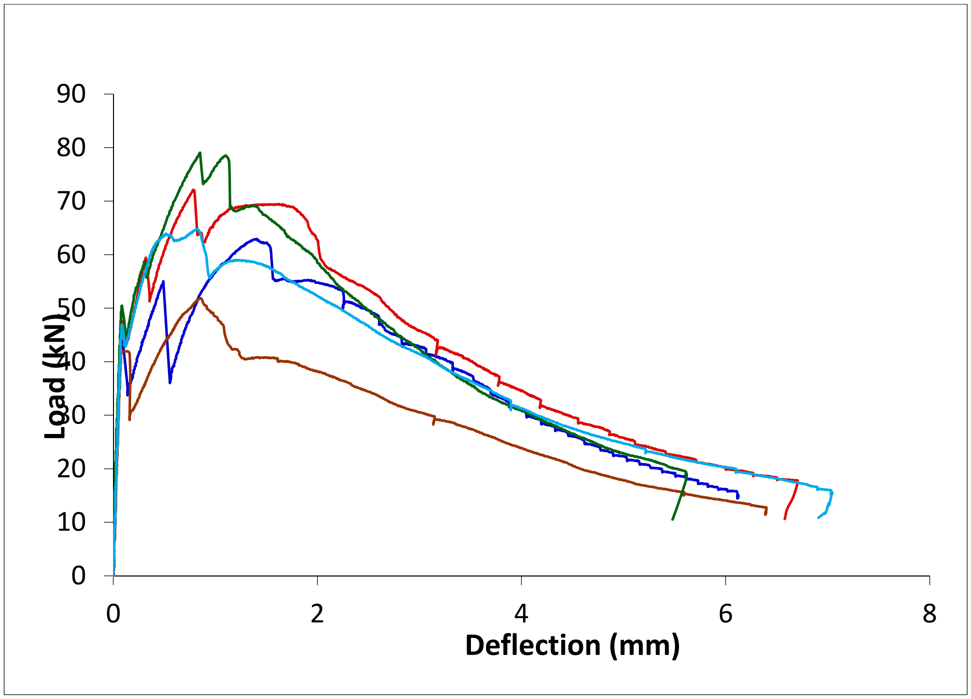

Figure 5: CG30 Under Third Point Loading (5 Specimens)

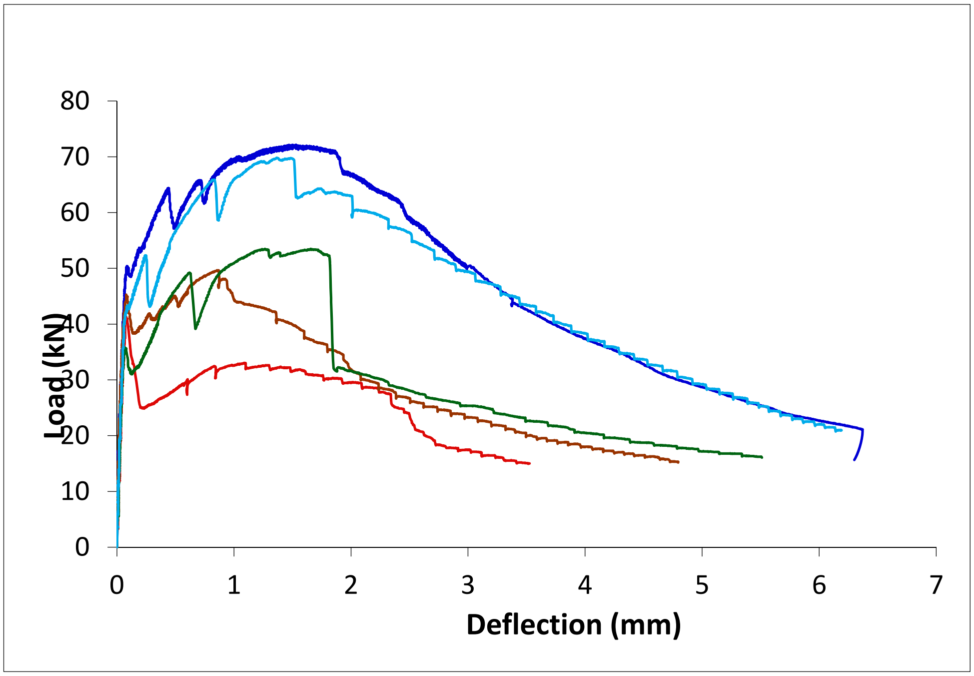

Figure 6: CG30R Under Third Point Loading (5 Specimens)

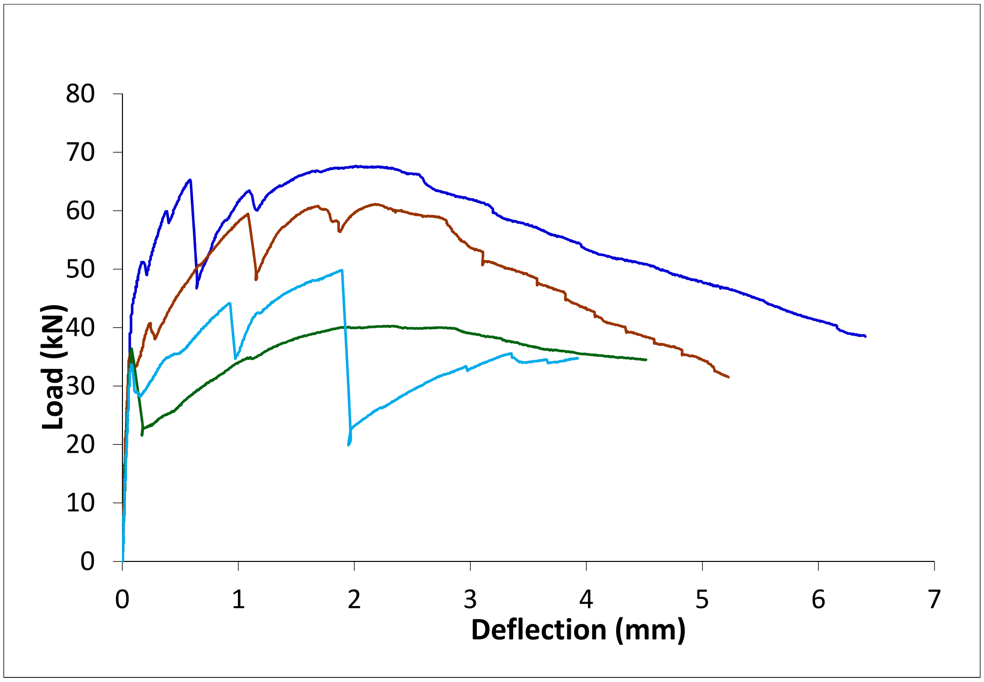

Figure 7: CG60 Under Third Point Loading (4 Specimens)

FG13 was the weakest grout with an average peak load 38.4 kN. The peak load was achieved at the first point of cracking, and the fibres did not provide sufficient capacity to maintain this load, with a rapid drop in load following this crack. Post peak behaviour varied widely with the weakest specimen supporting a load of 5.6 kN at a deflection of 3 mm (L/150), and the strongest supporting 14.9 kN. Segregation and the resulting uneven distribution of fibers is a likely cause of this variability. The revised mix FG13R reached a higher average peak load of 48.1 kN, but showed similar post peak behaviour. Note that in Figure 4, the results from only 3 specimens are shown due to a problem in the testing of the other two.

The 30 mm fibre coarse grout CG30 showed the most consistent behaviour, reaching an average peak load of 66.1 kN. As can be seen in Figures 5 and 6, the strength continued to increase beyond the point at which the first crack occurred. The peak occurred after the initial crack formed. The fibres clearly improved the strength and toughness of the beam, with an average residual strength of 40.6 kN at a deflection of 3 mm. The revised 30 mm fibre grout displayed a lower average peak strength of 57.3 kN, and was less consistent. It is not clear what the cause of this might be, but clumping of the fibres in the mix may have contributed. In this case, although easier to work with, the revised grout did not perform as well as the initial mix.

The 60 mm fibre grout results were widely variable, but an average peak strength of 54.7 kN was achieved. The 60 mm grout is notable in that it achieved this strength with a relatively low grout compressive strength. The 60 mm grout showed ideal behaviour, as shown in Figure 8, with the formation of multiple cracks along the length of the beam, and the final failure occurring by crushing of the grout. Despite this, its working properties would make it difficult, if not impossible, to apply to masonry.

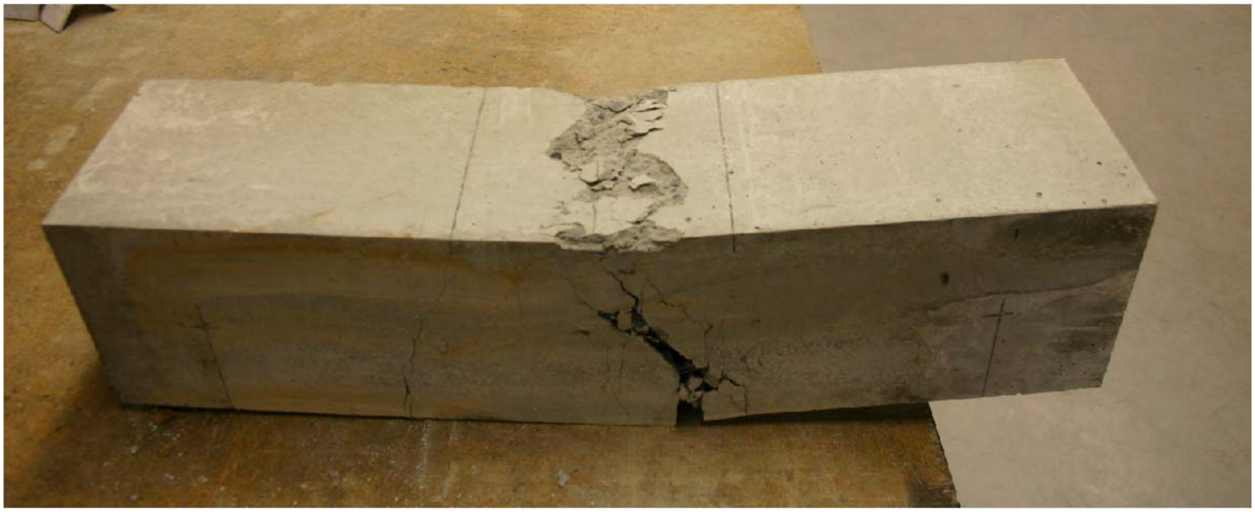

Figure 8: Ideal Failure, CG60 Specimen 1

The extreme tension fibre stress at cracking and at peak is calculated using uncracked section properties, as outlined in ASTM C1609 [11] such that:

$$f = \frac{PL}{bd^2} \tag{1}$$

Where f is the desired stress (cracking or peak), L is the beam span = 450 mm, b is the width of the beam, P is the applied load, and d is the depth. Although this does not reflect the true behaviour of the beam after cracking, it is a standard measure that can be compared to other values in literature. The toughness T_{150} is calculated as the area under the load-deflection curve up to a deflection of L/150. Grout flexural tensile strengths and toughness are displayed in Table 4.

Table 4: Flexural Tensile Test Results

	Cracking Stress		Peak Stress		L/150 Stress		Flexural Toughness (T_{150})	
	Mean (MPa)	C.O.V%	Mean (MPa)	C.O.V%	Mean (MPa)	C.O.V%	Mean (J)	C.O.V%
FG13	4.91	5.4	4.91	5.4	1.49	32.8	59	29.1
FG13R	6.02	6.6	6.02	6.6	2.40	22.6	86	15.8
CG30	5.79	6.5	8.25	14.9	5.07	13.8	158	16.0
CG30R	5.32	12.0	7.04	22.5	4.07	46.2	135	33.2
CG60	4.89	20.5	6.82	22.4	5.84	20.5	140	28.0

CG30 performed best in most respects. It had the highest average peak strength and the highest toughness. It also has the lowest coefficient of variance for post peak, L/150, stress.

CONCLUSIONS

Five steel fibre reinforced grout mixes were tested to determine their compressive strength, flexural tensile strength, and slump flow. The CG30 grout was found to meet the slump flow requirements for a self-consolidating grout according to ASTM C476. It also had high strength and peak strain in compression with quite low variability (COV ≈ 6.7% in both cases). Most importantly, with a peak tensile strength of over 8 MPa and a residual strength of 5 MPa, the CG30 grout could contribute significant in-plane strength to a wall. Future research will focus on determining whether this grout can improve the strength of otherwise unreinforced masonry assemblages.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of the Natural Science and Engineering Research Council (NSERC), and the generosity of Bekaert for donation of the steel fibres.

REFERENCES

1. Hervillard, T.P.C. (2005). “Effectiveness of polymer fibres for improving the ductility of masonry structures” (Master’s Thesis). Washington State University.

2. Snook, M., McLean, D., McDaniel, C., Pollock, D. (2005). “Effects of confinement reinforcement on the performance of masonry shear walls”. 10th Canadian Masonry Symposium.

3. Oliveira, L.A.P, Bernardo, L.F.A (2010). “Influence of self-compacting steel fibre reinforced concrete infill on the flexural strength and ductility of masonry walls”. Retrieved from http://thesis.ubi.pt/upload/820/oliveira_bernardomip.pdf

4. Rilem TC 162-TDF Committee (2003). “Test and design methods for steel fibre reinforced concrete $\sigma-\varepsilon$ design method. Final Recommendation.” Materials and Structures, Rilem, 36, 560-567.

5. Berndt, M.L. (2010). “Strength and permeability of steel fibre reinforced grouts.” Construction and Building Materials, 24, 1768-1772.

6. Grunewald, S. (2004). “Performance-based design of self-compacting fibre reinforced concrete.” [Thesis]. Delft University, Delft, Netherlands.

7. ASTM Standard C404 – 11. (2011). “Standard specification for aggregates for masonry grout.” ASTM International, West Conshohocken, PA.

8. ASTM Standard C476. (2010). “Standard specification for grout for masonry.” ASTM International, West Conshohocken, PA.

9. ASTM Standard C1611/1611M – 09b. (2009). “Standard method for slump flow of self-consolidating concrete.” ASTM International, West Conshohocken, PA.

10. ASTM Standard C39/C39M – 11a. (2011). “Standard test method for compressive strength of cylindrical concrete specimens.” ASTM International, West Conshohocken, PA.

11. ASTM Standard C1609/C1609M – 10. (2010). “Standard test method for flexural performance of fiber-reinforced concrete (using beam with third-point loading).” ASTM International, West Conshohocken, PA.