10th Canadian Masonry Symposium, Banff, Alberta, June 8 – 12, 2005

EFFECTIVENESS OF POLYMER FIBERS FOR IMPROVING DUCTILITY IN MASONRY

Thomas Hervillard[1], David McLean[2], David Pollock[3] and Cole McDaniel[4]
[1]Graduate Student, [2]Professor, [3]Associate Professor, [4]Assistant Professor
Department of Civil and Environmental Engineering
Washington State University, Pullman, WA 99164-2910 USA

ABSTRACT

This study investigated the stress-strain behaviour of fiber-reinforced masonry prisms subjected to compressive loading. Thirty masonry prisms were tested: fifteen of concrete blocks and fifteen of hollow clay bricks. The cells of the masonry prisms were grouted solid, with one-third of the piers containing grout with no fibers, one-third with grout containing fibers at 2.97 kg/m^3 (5 lbs/yd^3), and one-third with grout containing fibers at 4.76 kg/m^3 (8 lbs/yd^3). The prism specimens were loaded in compression to failure under a controlled rate of displacement. Test results show that, for concrete masonry, the use of fibers within the grout increases the strain capacity. For clay masonry, the addition of fibers did not significantly increase strain capacity.

KEYWORDS: ductility, concrete blocks, clay bricks, fibers, compression behaviour

INTRODUCTION

The strength design provisions in the 2002 MSJC *Building Code Requirements for Masonry Structures* [1] establish maximum reinforcement limits for use in masonry structures. These limits on tensile reinforcement are based on material strain capacities and specified drift limits and are intended to provide ductile response. The effect of the new provisions has been to restrict the use of masonry systems for many traditional applications. Previous research has demonstrated that steel confinement plates and seismic reinforcement combs can be placed in the masonry mortar joints to increase the masonry compressive strain capacity and thereby improve ductility. The goal of the present research is to investigate the effectiveness of adding polymer fibers into the grout as a technique for improving the ductility of masonry.

The research presented in this paper investigated the effects of fiber reinforcement on the compressive stress-strain behaviour of concrete masonry prisms. Compression tests were performed on fully-grouted hollow clay brick and fully-grouted concrete block masonry prisms. Polymer fibers were mixed into the grout of the prisms at two different dosages: 2.97 kg/m^3 (5 lbs/yd^3) and 4.76 kg/m^3 (8 lbs/yd^3). The prisms were tested under displacement control in order to obtain the full stress-strain curves. An understanding of the stress-strain behaviour of confined masonry under axial compression is needed to guide the development and application of confinement reinforcement within the flexural compression regions to improve the performance of masonry shear walls under seismic loading.

PREVIOUS RESEARCH

Priestley and Elder [2] investigated the compression stress-strain characteristics of grouted concrete block masonry with steel confinement plates in the mortar bed joints. The prisms were tested in a servo-hydraulically controlled universal testing machine operated under controlled rates of ram travel. Stress-strain relationships were obtained by making two adjustments to the displacement data. The first adjustment was made to account for the testing machine stiffness for both the rising and declining slopes of the load-displacement curve. The second adjustment was made to determine strains in the damaged region and was applied only to the descending portion of the load-displacement curve. Priestley and Elder observed that prism courses confined by the upper and lower testing machine platens remained intact during unloading, and that these undamaged courses expanded into the damaged central prism courses as unloading progressed. Recovered displacements from the confined end courses were computed assuming a linear elastic behaviour and added to the displacement measurements in order to calculate strains in the damaged region. The damaged region was defined after testing based on physical observations of crushing within a course. The researchers concluded that the confinement plates effectively changed the failure mechanism and improved the ductility of concrete masonry prisms.

Hart et al. [3] conducted a study of confinement reinforcement in concrete masonry prisms using seven different types of steel confinement reinforcement. Two of these types were the steel plate similar to that used earlier by Priestley and Elder [2] and an open steel mesh referred to as a seismic comb. Displacement-controlled compression testing was performed to obtain the stress-strain behaviour of each masonry prism. Hart et al. concluded that all prisms tested with confinement, when compared to prisms without confinement, had greater displacement ductility and exhibited a decreased slope of the descending branch portion of the compressive stress-strain curve for concrete masonry.

Malmquist [4] investigated the use of confinement plates and seismic reinforcement combs in concrete block and hollow clay brick masonry prisms. The prisms were loaded to failure in compression under a controlled rate of displacement. Results showed that the use of confinement reinforcement in the mortar bed joints of masonry increased the strain capacity above that of unconfined masonry. Strains at 50% of peak stress were 30% and 50% greater for clay brick and concrete block masonry, respectively, when confinement reinforcement was provided. Improvements from the two types of confinement reinforcement were approximately the same.

Strain values for confined concrete masonry at various limit states from these three previous studies are given in Table 1.

Table 1 - Strain values for confined concrete masonry

	Peak stress	50% peak stress	20% peak stress
Concrete Masonry w/ Plates			
Priestley and Elder	0.0020	0.0074	0.0120
Hart et al	0.0019	0.0065	0.0135
Malmquist	0.0023	0.0055	0.0122
Concrete Masonry w/ Combs			
Hart et al	0.0016	0.0055	0.0140
Malmquist	0.0019	0.0060	0.0112

PREPARATION OF TEST SPECIMENS

A total of 30 prisms were tested: fifteen were constructed of concrete block masonry and fifteen of hollow clay brick masonry. All prisms were fully grouted. For each material type, five prisms were constructed without fibers, five with polymer fibers added to the grout at a dosage of 2.97 kg/m^3 (5 lbs/yd^3), and five with fibers at a dosage of 4.76 kg/m^3 (8 lbs/yd^3). Nominal dimensions of the prisms were 14 cm (5.5 in.) wide by 29 cm (11.5 in.) long by 81 cm (32 in.) high. The hollow concrete block masonry units were made from medium density concrete according to ASTM C90 [5] with a net-to-gross-area ratio of 0.56. The hollow clay brick units conformed to ASTM C652 specifications [5] with a net-to-gross-area ratio of 0.63. Table 2 summarizes average compressive strengths for the concrete blocks, clay bricks, grout (following ASTM C1019 requirements [5]) and mortar (ASTM C 270 [5]).

Table 2 – Compressive strengths (1 MPa = 145 psi)

	Strength (MPa)
Concrete block	17.20
Clay brick	32.35
Grout	56.00
Mortar	29.90

The fibers used in this investigation were synthetic fibers made of two types of polymers: polypropylene and polyethylene. The fibers were engineered to enhance the ductility of concrete and to control the widening of small cracks within hardened concrete. The modulus of elasticity of the fibers was matched to the elastic modulus of concrete paste while the geometry of the fibers was optimized to obtain a good bond between the fibers and the concrete matrix. The fibers do not increase the tensile strength of the concrete. The fibers were mixed directly into the grout and did not require any special handling. Table 3 lists properties of the fibers.

Table 3 – Fiber properties

Specific gravity	0.92
Absorption	None
Modulus of Elasticity	9.5 GPa (1,378 ksi)
Tensile strength	620 MPa (90 ksi)
Melting point	160°C (320°F)
Ignition point	590°C (1,094°F)
Alkali, Acid and Salt	High

All tests prisms were constructed by qualified masons. Bagged Type S mortar was used. Each prism was constructed on a leveled plywood board placed inside a large plastic bag used to retain moisture during curing. Grouting of the prisms was performed the day following the laying of the blocks and hollow bricks. The grout used was a bagged coarse grout conforming to ASTM C476 [5]. Grout was placed in the cells of the prisms in two lifts and received a single pass per lift from a 25 mm (1 in.) diameter vibrator to achieve consolidation. For the specimens with fibers, the fibers were added to the grout during the mixing process. No special handling, mixing or consolidation procedures were used for the grout containing the fibers. After the vibration of the grout, the tops of the prisms were leveled and the prisms were contained in the plastic bags and allowed to cure indoors for a minimum of 28 days. Figure 1 shows a picture of the prisms during construction.

Following construction, the ends of the prisms were capped with gypsum plaster. The prisms were set onto a layer of the plaster spread onto a glass plate to form bottom caps. The top cap was created by pressing and leveling a glass plate onto a layer of plaster spread over the top of the prisms. Figure 2 shows a picture of the capped prisms.

Figure 1 – Prism construction

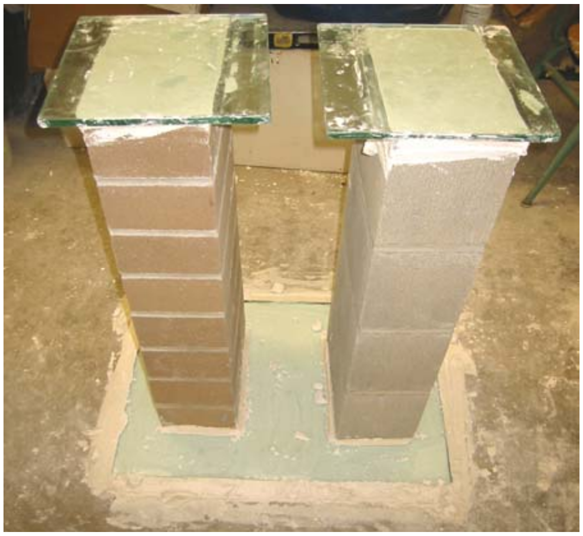

Figure 2 – Prism capping

The specimens were labeled as follows: material type = CON for concrete block and CLA for hollow clay brick; amount of fibers = N for no fibers, F1 for fibers at a dosage of 2.97 kg/m^3 (5 lbs/yd^3), and F2 for fibers at dosage of 4.76 kg/m^3 (8 lbs/yd^3); and specimen number, with five specimens per parameter set. For example, CON-N-4 was the fourth specimen of the set of concrete block masonry prisms with no fibers added to the grout.

TEST SETUP

The prism specimens were tested in compression using a 1780-kN (400-kip) Universal testing machine (UTM) at Washington State University. This machine has a two-screw load frame with a single cylinder ram acting on the lower platen. The machine is a servo-hydraulic system that was operated in displacement control at 0.13 cm/min (0.05 in/min). Ram stroke was recorded by a linear variable differential transformer (LVDT) mounted centrally on the back edge of the lower platen. Displacement measurements recorded by the UTM LVDT included the testing frame flexibility.

A spherical bearing plate was used as the upper platen for testing and served to accommodate slight differences in alignment of the upper and lower surfaces of the prisms. Total prism displacement was recorded using four displacement potentiometers placed beside the four corners of the test prism, measuring between the lower platen and upper spherical bearing plate.

A fifth potentiometer, measuring between the upper and lower platens at approximately mid-depth of the prisms, was used to control the displacements input to the prisms. Test data was recorded on a personal computer at a rate of 5 Hz.

TEST RESULTS

Loading of a prism specimen to failure typically was completed in less than 3 minutes. During testing, pieces of the masonry were often ejected from the prisms in an explosive manner. Prisms made of concrete blocks generally exhibited a more gradual failure compared to failure in the brick prisms. Before collapsing, a crunching sound was audible for most of the prisms. Prisms without fibers typically developed vertical splitting and face shell spalling during testing. Damaged regions developed over a large portion of the specimen length and typically included damage to the grout cores. Failure in the prisms with fibers tended to extend over a smaller portion of the specimen length. In most cases, the fiber-reinforced grout cores remained intact even after the masonry had spalled away. Figures 3 and 4 show typical failures in the clay and concrete prisms, respectively.

Figure 3 - Clay prism after testing

Figure 4 – Concrete prism after testing

For several specimens, material ejected from the specimen during loading impacted the strings of the potentiometers and compromised readings from these instruments. Two displacement data sets were available to compute prism strain values. The UTM LVDT lower platen displacement record provided one basis to formulate strain values. However, these values needed adjustment to account for the UTM stiffness, similar to the adjustment made by Priestley and Elder [2] described previously. A second basis to obtain strain values was to use the average of the four-potentiometer readings that reflect prism stiffness only. Using the load data record and these two bases for calculating strain values, the UTM machine stiffness was determined by considering the machine stiffness and prism stiffness acting in series. Knowing the machine stiffness for each prism test allowed the UTM LVDT strain to be corrected by subtracting machine stiffness from the stress-strain curves during prism loading and adding the stiffness when unloading.

Figure 5 shows a comparison plot of stress-strain curves obtained from both sets of displacement data (curve 1 is based on the UTM LVDT readings; curve 2 is based on output from the four potentiometers) and the corrected UTM LVDT stress-strain curve (curve 3) for a prism test. The corrected UTM LVDT strain curve essentially reproduces the four-potentiometer strains. For five prism tests, spalling of the masonry impacted the potentiometers, and the corrected UTM LVDT strains were used to obtain stress-strain behaviour for these specimens.

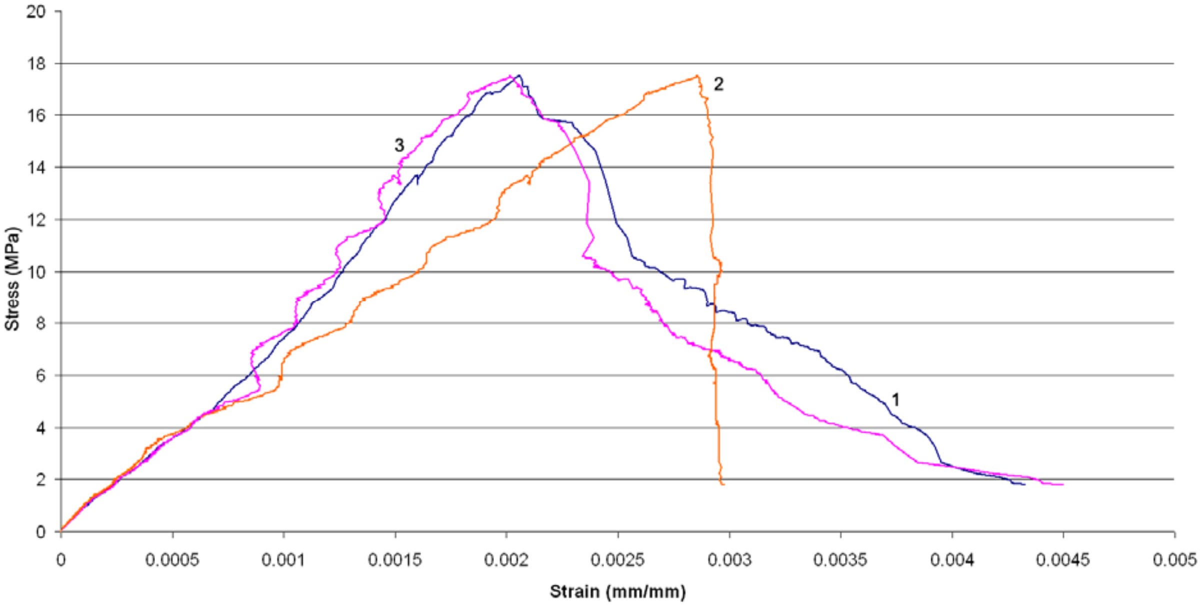

Figure 5 - Stress-strain curves adjusted for machine stiffness (1 MPa = 145 psi)

An additional correction to the prism strain computation was made to account for the confinement provided by the upper and lower platens bearing on the prism ends, similar to the procedures used by Priestley and Elder [2]. Observations made during testing as well as photographs of each prism were used to define the region over which damage occurred. Undamaged prism material was assumed to unload according to the initial prism stiffness and contribute added strain to the damaged prism region. Corrected damaged zone strain values were computed and plotted with the uncorrected average total strains, as shown in Figure 6.

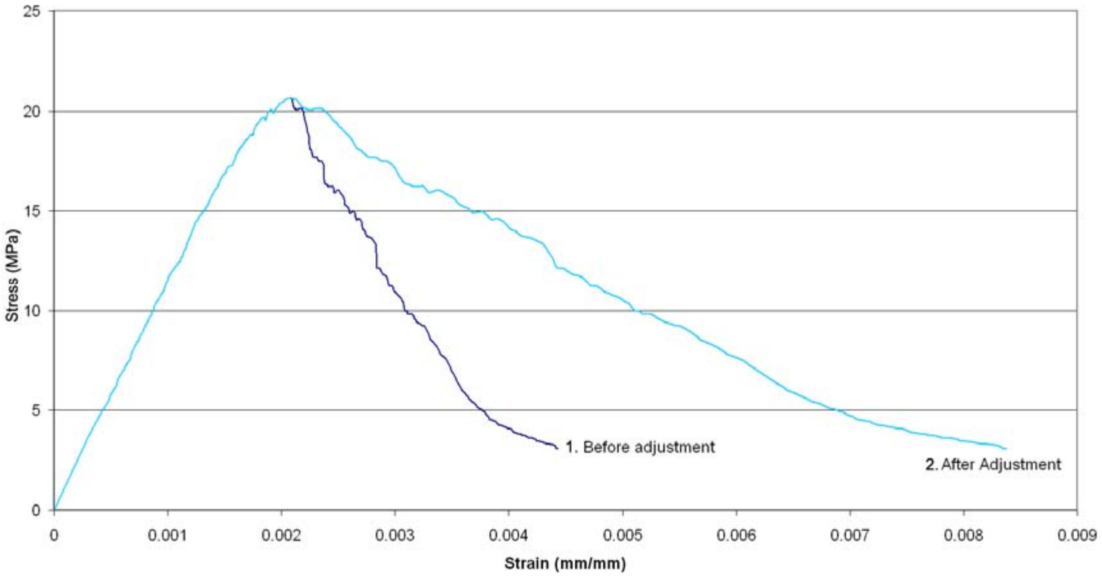

Figure 6 - Stress-strain curve adjusted for undamaged regions (1 MPa = 145 psi)

Average stress strain curves obtained for different amounts of fiber and material type are given in Figures 7 and 8. Average values of peak stress, strains at peak stress and strain at 50% of the peak stress for the prism tests of this study are summarized in Table 4.

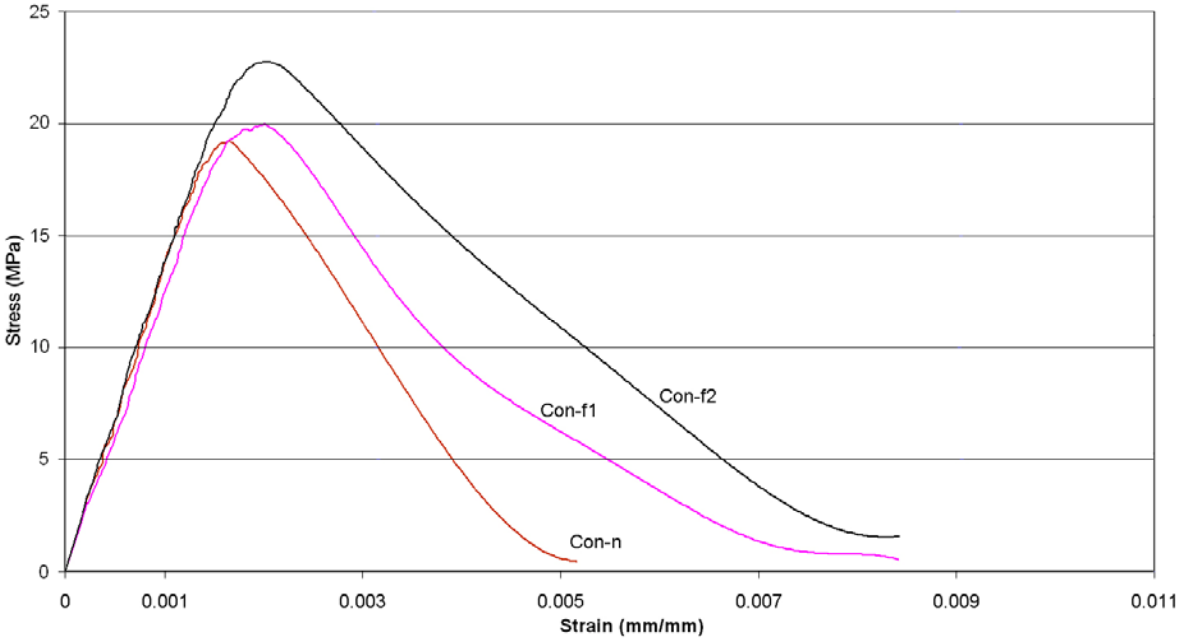

Figure 7 – Average stress-strain curves for concrete block masonry (1 MPa = 145 psi)

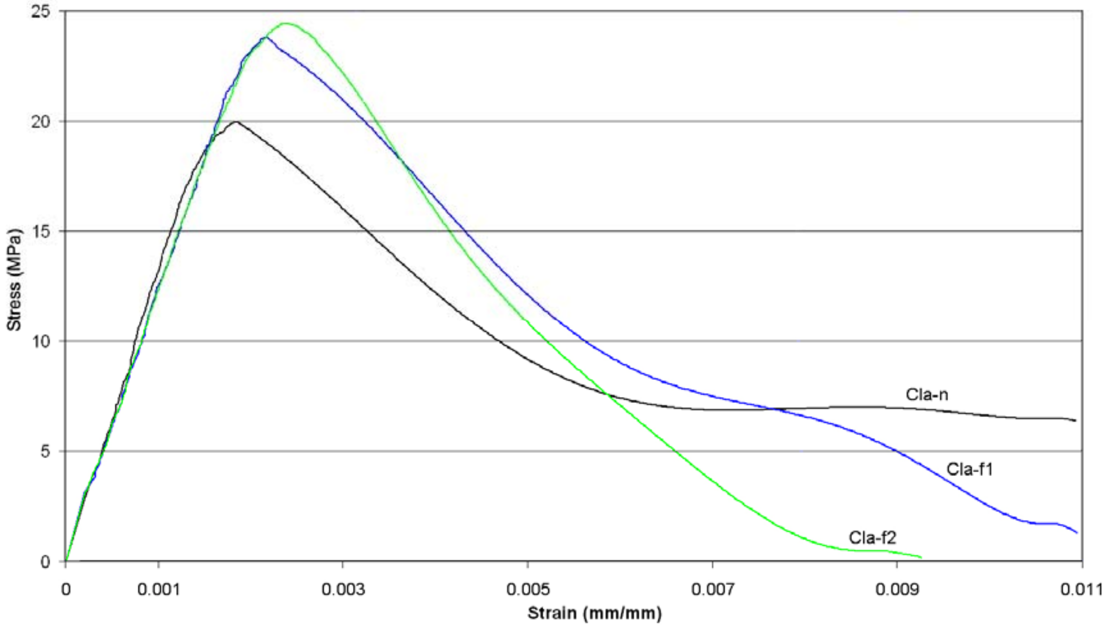

Figure 8 – Average stress-strain curves for hollow clay brick masonry (1 MPa = 145 psi)

Table 5 - Average test results (1 MPa = 145 psi)

	Peak stress (MPa)	**Strain at peak stress**	**Strain at 50% peak stress**
Concrete Block Masonry			
No fibers	18.48	0.0016	0.0032
Fibers @ 2.97 kg/m^3 (5 lbs/yd^3)	20.00	0.0019	0.0039
Fibers @ 4.76 kg/m^3 (8 lbs/yd^3)	21.65	0.0019	0.0047
Hollow Clay Brick Masonry			
No fibers	20.79	0.0018	0.0045
Fibers @ 2.97 kg/m^3 (5 lbs/yd^3)	23.99	0.0022	0.0053
Fibers @ 4.76 kg/m^3 (8 lbs/yd^3)	24.44	0.0022	0.0050

Considering average values, greater strain capacity is evident due to the addition of fibers in the grout for both materials types. Increasing the dosage of fibers in the grout resulted in greater strain capacity in the concrete masonry prisms; however, there was a slight decrease in strain capacity in the prisms with the higher dosage of fibers in the clay masonry. In the concrete masonry, strains at 50% of peak stress were between 28% to 47% greater due to the addition of fibers in the grout. Improvements in strains at 50% of peak stress for clay masonry were less, ranging from 11% to 18%. For concrete masonry, the improvements in strain capacity from the addition of fibers are comparable to those that have been reported in previous tests with other forms of confinement reinforcement [2, 3, and 4]. For clay masonry, the improvements in strain capacity obtained by adding fibers to the grout were less than those obtained using other forms of confinement reinforcement [4].

STATISTICAL ANALYSES

Due to the limited number of tests in this study, it was necessary to use statistics to evaluate the significance of the findings. An analysis of variance (ANOVA) was performed using SAS [6] to determine if the amount of fibers had a statistically significant effect on peak stress values, strains at peak stress, and strains at 50% of the peak stress for both materials. For both analyses, a 90% confidence level was used.

For the clay masonry prisms, the ANOVA results given below indicate that the addition of fibers had a significant effect on the values of peak stresses and on the corresponding strains but not on the values of strain at 50% of the peak stress.

CLAY	Peak stress	Strain at peak stress	Strain at 50% of the peak stress
Significance	YES	YES	NO

A Duncan's grouping for the clay masonry results, given below, shows that the results for peak stresses are considered identical for the two percentages of fibers used (group A), but they are significantly different from the results obtained with no fibers (group B). The conclusion is the same for strains at peak stresses. Duncan's grouping for strains at 50% of the peak stress is not considered because no significance of the amount of fibers was obtained for those strains.

CLAY	Peak stress	Strain at peak stress	Strain at 50% of the peak stress
F2	A	A	A
F1	A	A	A B
No Fibers	B	B	B

For the concrete masonry prisms, the ANOVA results given below show that the addition of fibers had a significant effect on the values of peak stress and strain at 50% of peak stress but not on the strain at peak stress.

CONCRETE	Peak stress	Strain at peak stress	Strain at 50% of the peak stress
Significance	YES	NO	YES

A Duncan's grouping for the concrete masonry results, given below, shows that only the results from groups "F2" and "No Fibers" are considered significantly different.

CONCRETE	Peak stress	Strain at peak stress	Strain at 50% of the peak stress
F2	A	A	A
F1	A B	A B	A B
No Fibers	B	B	B

CONCLUSIONS

Results from this study indicate that the use of polymer fibers mixed into the grout is effective at increasing the strain capacity in concrete masonry. Improvements in strain capacity from the addition of fibers in concrete masonry are comparable to those reported in previous tests using other forms of confinement reinforcement. Improvements in strain capacity from the addition of fibers for clay masonry were less than those obtained for concrete masonry and less than has been reported for other forms of confinement reinforcement. The diminished improvements for the clay masonry may be due to the lack of confinement to the units provided by the fibers coupled with the greater net area and strength with the hollow clay bricks when compared to the corresponding properties for the concrete blocks.

Increasing the amount of fibers in the grout improved the strain capacity in the concrete masonry. However, larger amounts of fibers in clay masonry appeared to have no beneficial effects.

The findings of this study were based upon a limited number of tests. It is recommended that additional tests be conducted investigating the effectiveness of adding fibers to the grout to verify the findings of this study. It is also recommended that the effects of the fiber reinforcement within the grout in masonry shear walls be investigated.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided for this project by the Northwest Concrete Masonry Association, the Masonry Industry Promotion Group of Spokane Washington, and the W.R. Grace & Co. – Conn.

REFERENCES

1. Masonry Standards Joint Committee, *Building Code Requirements for Masonry Structures (ACI 530-02/ASCE 5-02/TMS 402-02)*, 2002.
2. Priestley, M.J.N. and Elder, D.M. (1983). "Stress-Strain Curves for Unconfined and Confined Concrete Masonry," *ACI Journal*, 80(3), pp. 192-201.
3. Shing, P.B., E.W Carter and J.L Noland (1993) ."Influence of Confining Steel on Flexural Response of Reinforced Masonry Shear Walls." *The Masonry Society Journal*, Vol. 11, No. 2 February.
4. Malmquist, Kirk J., "Influence of Confinement Reinforcement on the Compressive Behavior of Concrete Block Masonry and Clay Brick Masonry Prisms", M.S Thesis, Washington State University, June 2004.
5. American Society for Testing and Materials (ASTM). (2003) *Annual book of ASTM Standards*, West Conshohocken, PA:
    - C90-03 Standard Specification for Loadbearing Concrete Masonry Units, Vol. 04.05
    - C270-03b Standard Specification for Mortar for Unit Masonry, Vol. 04.05
    - C476-02 Standard Specification for Grout for Masonry, Vol. 04.05
    - C652-04 Standard Specification for Hollow Brick (Hollow Masonry Units Made From Clay or Shale), Vol. 04.05
    - C1019-03 Standard Test Method for Sampling and Testing Grout, Vol. 04.05
6. SAS System 9.00, 2002, SAS Institute Inc., Cary, NC, USA.