8TH CANADIAN MASONRY SYMPOSIUM

Jasper, Alberta
May 31 - June 3, 1998

ADVANCED CONCEPTS FOR MASONRY REINFORCEMENT

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ABSTRACT

Three new masonry reinforcing techniques were investigated during this study: the use of a grout containing steel fibers, the use of preplaced steel fibers which are then grout injected within the cells, and the use of fiber-composite reinforcement in grouted cells. Five-unit-high prisms were fabricated using these new reinforcement techniques and the prisms were then tested in flexure.

The performance of beams constructed using several of the new reinforcing techniques is comparable with that of a conventionally reinforced masonry beam. The new techniques have potential applications in new construction and in the upgrade of existing unreinforced (or under reinforced) masonry structures.

INTRODUCTION

Cost effective methods for reinforcing existing masonry buildings are needed to bring a large inventory of structures into compliance with new seismic requirements. Although several methods are available for external reinforcement, methods of internally reinforcing the cells in hollow-unit clay or concrete masonry buildings would be less invasive and more cost effective.

Three methods of reinforcement were investigated: grout containing short steel fibers, preplaced steel fibers grouted in place, and the use of braided composites such as Kevlar and carbon fiber. The reinforcement methods were investigated in two test series. The Series I tests compared beams containing grout mixed with steel fibers with unreinforced and conventionally reinforced beams. The Series II tests investigated preplaced steel fibers which were then grout injected and the use of braided composite reinforcement.

BACKGROUND

A number of researchers have investigated alternative reinforcement methods for concrete and clay masonry. Several methods use external reinforcement such as ferrocement and fiber-composite materials. A summary, presented by Prawel (1986), discussed the work of others in seeking external reinforcement methods using cement-based layers containing steel reinforcement. A more recent study conducted by the Swiss Federal Laboratory for Materials Testing and Research (Schwegler 1994) investigated the use of carbon fiber and polyester sheet goods which were bonded to the surface of masonry walls. Both references report improved strength and ductility using external reinforcement to upgrade existing masonry construction.

In many cases, it is not feasible or practical to apply external reinforcement to existing masonry structures due to the unit type, equipment attached to wall surfaces, existing surface treatments, and for architectural (aesthetic) reasons. Providing a simplified method for strengthening existing hollow-unit masonry construction would be very beneficial as government agencies strive to comply with new regulations regarding upgrade of facilities in seismically active regions.

In addition, alternative reinforcement techniques are needed in new masonry construction. The masonry industry is struggling with an under-experienced work force, and many projects have demonstrated problems with improperly placed reinforcing bars. Vertical and horizontal reinforcement slows wall construction and in many cases requires the mason to thread units over vertical bars projecting from foundations and lower walls. By separating the unit placement and installation of reinforcement into two separate operations, the construction sequence is simplified and the mason's productivity is increased.

LABORATORY TESTS - SERIES I

An initial test program was conducted with the objective of investigating the feasibility of pumping a fiber-reinforced grout into the hollow cells within an existing unreinforced concrete masonry wall. Introducing such a fiber-reinforced grout would increase wall flexural and shear resistance without altering the external appearance. In addition, the reinforced grout could be introduced by pumping it through holes approximately 75 mm (3 inch) in diameter located at the base of the wall. Variables investigated in the initial study were the mix design of the masonry grout containing steel fibers, the mixing and handling properties of such a grout and the flexural strength and deformation of beam sections containing this grout.

Grout Mix Design

The grout mix used conforms to specifications outlined in ASTM C 476, *Standard Specification for Grout for Masonry*. This mix design is for a coarse grout and employs a volumetric ratio of 1 part cement to 3 parts sand to 2 parts gravel having a 9.5 mm (0.375 inch) diameter maximum aggregate size, with a water/cement ratio of 0.7. Four grout prisms cast using this mix design attained an average compressive strength at 33 days of 32.8 MPa (4,760 psi). The average modulus of rupture for two grout prisms tested in flexure using ASTM C 78, *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)* was 3.15 MPa (457 psi).

For the fiber-reinforced grout, Dramix© wire type ZL 30/50 supplied by Bekaert, was added to the grout mix described above at a rate of approximately 48 kg per cubic meter (80 pounds per cubic yard or 2% by weight) of grout. The slump of the grout prior to the addition of the steel fibers was 235 mm (9.25 inches) and was 220 mm (8.75 inches) after adding the fibers. Compression tests performed 37 days after casting on four fiber-reinforced grout prisms averaged 28.0 MPa (4060 psi). The average modulus of rupture for two prisms tested in flexure (ASTM C 78) was 4.06 MPa (589 psi).

Two separate batches of grout were made, one for the plain grout and rebar reinforced specimens and one for the fiber reinforced grout specimens. A fluidifying admixture having expansive properties (SIKA Grout Aid - Type II) was used at a rate of 1% of cement weight in both grouts.

Flexure Specimen Preparation

The flexure specimens were constructed as a series of 5-high stack bond prisms using concrete masonry units, cut in half such that the full thickness of the web was intact. A prism building jig was used to assure that the prism had uniform thickness mortar joints and straight sides. The mortar used was an ASTM C 270 Type S mortar having a volumetric ratio of 1 part cement, 0.5 parts lime and 4.5 parts sand. The flexural specimens were allowed to cure for 3 to 5 days prior to grouting.

The slump of the grout which did not contain fibers was measured as 230 mm (9 inches) and was then transferred to a small wheelbarrow and placed in the large flexure specimens using a shovel. The grout was consolidated using a 19 mm (0.75 inch) diameter concrete vibrator. The grout was reconsolidated after approximately 5 minutes and additional grout added to completely fill the grout space.

The grout containing fibers was mixed to an initial slump of 235 mm (9.25 in.) after which the steel fibers were added slowly by hand. Fibers were added to a final rate of approximately 48 kg mass per cubic meter (80 pounds per cubic yard) of mix. A slump of 220 mm (8.75 in.) was then measured.

The flexural beam specimens were air cured in the laboratory for a minimum period of 28 days.

Flexure Specimen Tests

Flexure specimen tests were carried out using a deflection-controlled beam testing machine. Load was measured using an external load cell with an indicator dial. Deflection was measured using 2 LVDTs mounted on both sides of the specimen, at center-span, where maximum deflection occurred. In addition, a dial gage was used to measure deflection on one side of the specimen at midspan as a back-up. Load, LVDT deflection and dial gage deflection data were recorded by hand.

Discussion of Results

Data for all flexural specimens is shown in Table 1. Typical load versus center deflection curves for the unreinforced, conventionally reinforced, and fiber reinforced specimens are shown in Fig. 2.

The two flexural beam specimens without any reinforcing steel performed in the expected brittle manner for this type of masonry. Behavior was essentially linear until cracking occurred at the ultimate load. The initial crack propagated through the section causing complete failure of the member.

The three specimens reinforced with a metric #10 (#3 inch-pound bar size) reinforcing bar behaved as expected with essentially linear behavior up to the occurrence of yielding of the reinforcing, Fig. 2. After yielding, the curves are characterized by a relatively short range of yield behavior followed by a gradual increase in applied load with increasing deformation.

Two of the three specimens containing the fiber-reinforced grout showed an initial linear range followed by a gradual softening behavior up to peak load, Fig. 2.

Significant energy absorption capacity is present in each of three load-deformation curves for the fiber reinforced grout specimens. Test data show that the use of fiber-reinforced grout can provide structural performance comparable to a conventionally reinforced cell, albeit at a small reinforcement ratio. Subsequent tests were conducted to determine if grouts with a higher fiber content and different types of reinforcement would improve flexural performance.

LABORATORY TESTS - SERIES II

An additional eight flexural beam specimens were constructed using techniques similar to those described above but with several key distinctions. Four of the specimens contained steel fibers which were preplaced in the cells followed by injection of a cementitious grout to encapsulate the fibers. This permitted a higher fiber content in the reinforced cell than in Series I specimens. The remaining four were reinforced with fiber-composite tubes: specimen K2 used a 51 mm (2 in.) braided Kevlar tube, K2.5 used a 63.5 mm (2.5 in.) braided Kevlar tube, C3 used a 76.2 mm (3 in.) carbon fiber tubes, and C5 used a 127 mm (5 in.) carbon fiber tube. Each of the fiber-composite reinforced specimens was grouted with a fine silica sand grout. Center point load deflection data were obtained from the specimens during flexural testing.

Grout Mix Design

The grout used in this series of tests was a fine, sanded grout containing (by weight) 1 part Type III cement, 2 parts fine silica sand (Unimin Type 7030), 0.15 parts hydrated lime, 0.3 parts Type F fly ash, and 0.75 parts water. In addition, a grout expansion admixture was used at a rate of 1% and a super-plasticizer was added at the rate of 2% (both by weight).

An alternative scheme for introducing a higher steel fiber content into the cell was developed based upon the concrete industry's usage of pre-placed aggregate concrete. This technology has been termed "SIFCON" for "Slurry Infiltrated Fiber CONcrete" in previous investigations and relies on pre-placing the fiber reinforcement into the masonry cell followed by injection of a fine, cement-based grout to act as a binding matrix surrounding the fibers. Two small cylindrical specimens were reinforced and grouted as a trial prior to building full size prisms. Fibers were poured into the container and grout injected, from the bottom upwards, to fill intermediate void spaces. A coarse (sanded) grout and a finer cement slurry were used in these trials. Cutting the cylinders open exposed the dense fiber matrix. The fine cement grout had excellent penetration into the fiber matrix and was used for the full-size specimens

SIFCON Flexural Specimen Preparation

Dramix© wire fibers, type ZL 30/50 supplied by Bekaert, were placed into the hollow cells prior to grouting at an average rate of 10.5 kg (23.1 pounds) for each prism. This dosage rate corresponds to a fiber content of 27 percent, by weight, or approximately 595 kg per cubic meter (1000 pounds per cubic yard) of grout. Compared with the initial tests, which used fibers at a rate of 2 percent by weight, this represents a substantial increase in the steel content of each specimen. A masonry prism filled with fibers, before grouting, is shown in Fig. 4. Fibers were placed by hand into each cell at a slow rate, to prevent balling or clumping.

Small-diameter holes were drilled into each mortar joint for injection of a cement-based grout to encapsulate the steel fibers. Preliminary tests showed that a sanded grout had some difficulty in penetrating the dense steel matrix and hence a highly fluid cement-water slurry was used. The grout formulation used here was comprised simply of Type III Portland cement, water (w/c = 0.5) with 2 percent plasticizing admixture and 0.5 percent Sika Grout-Aid to provide some expansive properties to the grout.

Grout was injected into the prisms at a pressure of 55 to 70 kPa (8 to 10 psi). Injection progressed smoothly, however, it was noted that the mix will require optimization for future trials. The grout was too fluid, injecting very easily, but leaked out of very small holes in mortar joints. A grout formulated to contain a fine sand (No. 50 mesh and smaller) should be added to future mixes to provide proper injection and fiber encapsulation properties.

<u>Fiber-Composite Specimen Preparation</u>

Several fiber-composite reinforcement methods were investigated based on commercially available braided forms and types of fabric. Both aramid (Kevlar) and carbon fiber reinforcements were available in braided form with sufficient cross sections for reinforcing the flexure specimens.

The two aramid reinforcements used were an Arasox 63.5 mm (2.5 inch) diameter medium fabric and a 51 mm (2 inch) diameter heavy fabric manufactured by Atkins & Pearce. The net area of the braided tubes were 44.5 mm^2 (0.069 $in.^2$) for the 63.5 mm and 59.4 mm^2 (0.092 $in.^2$) for the 51 mm. Using the ratio of the moduli of elasticity for the two materials of 0.586 results in an equivalent steel reinforcement approximately equal to a #2 (inch pound bar size) reinforcing bar for the two specimens.

Two carbon fiber reinforcements were used. A 76.2 mm (3 inch) diameter Gammasox and a 127 mm (5 inch) diameter Megasox braided tube were obtained from Atkins & Pearce. The net areas of the carbon fiber tubes were 92.3 mm^2 (0.143 $in.^2$) and 111 mm^2 (0.172 $in.^2$), respectively. The 127 mm tube is nearly the equivalent of a metric #13 (#4 inch-pound) steel reinforcing bar considering the modular ratio of 1.103. The 76.2 mm reinforcement falls midway between being equivalent to a metric #10 or #13 (#3 or #4 inch-pound) reinforcing bar.

The prisms were reinforced during the grouting process. One end of the tubular reinforcement was closed and weighted by inserting a small concrete core into the reinforcement and then clamping the reinforcement to the core with a hose clamp. The reinforcement was then dropped into the interior of the cell (closed end down, as shown in Fig. 5), centered, and filled with grout. Additional grout was pumped into the cell, outside the tubular reinforcement, to completely fill the cell and confine the fabric reinforcement. The prisms were allowed to cure for a minimum of 28 days in laboratory air prior to flexural testing.

Flexure Specimen Tests

Flexure specimen tests were conducted using a deflection-controlled beam testing machine. Load was measured using an external load cell with an indicator dial. Deflections were measured using a dial gage on the underside of the specimen at midspan. Load and deflection were recorded manually at 890-1330 N (200-300 pound) intervals until failure. Specimens were loaded until complete breakage occurred. The ultimate strength was determined from the maximum load achieved for each specimen. In addition, flexural toughness was calculated according to ASTM C 1018, *Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)* for each of the prisms in both test series.

Discussion of Results

Results for the Series II flexural beam specimens are also listed in Table 1. Representative load versus center span deflection response of SIFCON reinforced, carbon fiber reinforced, and aramid fiber reinforced beams are shown in Fig. 3. The data shows several interesting results. First, the steel-fiber reinforced specimens performed well with most specimens still carrying significant loads at midspan deflections of 3.81 mm (0.15 inches). The steel-fiber flexural specimens were all constructed with a fine unsanded grout compared to the coarse grout (ASTM C 476) used in the Series I tests. The coarse grout used for Series I tests had tested compressive strengths in excess of 27.6 MPa (4000 psi), whereas the fine grout used for Series II tests had a typical 28 day compressive strength of 22.1 MPa (3200 psi). The use of a fine grout was necessary in these tests to encapsulate the preplaced steel fibers using grout injection techniques. When comparing results of the two experimental phases, one must take into account that the Series I test series used a grout with a compressive strength of about 30 percent greater than the secondary test series specimens. Optimization of the grout formulation for use with these reinforcement materials would be expected to further increase performance.

Second , a large increase in toughness resulted from the introduction of the composite fiber reinforcements into the flexural specimens. Most notably, the specimens K2 and CF3 continued to carry significant loads at midspan deflections of 19.9 mm (0.784 inches) and 14.8 mm (0.584 inches), respectively. The calculated toughness (using ASTM C1018 method) does not consider the area under the load displacement curve beyond 10.5 times the first-crack deflection so that the numerical value tends to understate the toughness. In fact, aramid specimen K2 performed to 87 times the first-crack deflection and carbon-fiber specimen CF3 performed to 22.5 times the first-crack deflection.

CONCLUSIONS

Several advanced reinforcement systems were investigated as a means to simplify construction of reinforced structural masonry. Fiber reinforced grout concepts were evaluated as a means to increase flexural capacity of new reinforced and existing unreinforced masonry buildings. The results of this study suggest that use of fiber reinforced masonry grout has potential as a reinforcement method. Specific results supporting this conclusion are:

1. A number of fiber reinforced grouts were successfully mixed having suitable compressive and flexural strengths. This grout was produced having slump in the 8 to 10 inch range recommended for masonry grout.
2. The steel fiber grout produced had good workability and was easily handled, placed and consolidated using conventional methods.
3. The ultimate load resistance for the fiber reinforced specimens equaled or exceeded the load resistance of specimens conventionally reinforced with a metric #10 (#3 inch-pound) bar for deformations in the 0.00 to 1.27 mm (0.00 to 0.05 inch) deflection range.
4. The fiber reinforced specimens exhibited considerable ductility and energy absorption capacity, comparable to conventionally reinforced specimens.
5. The preplaced steel fibers generally rested in a horizontal position, transverse to the longitudinal axis of the beam. An alternate fiber configuration or placement scheme which would preferentially orient fibers along the longitudinal axis would be desirable to fully utilize the individual fiber strengths.
6. Use of grout-filled aramid and carbon fiber socks provide another means to reinforce hollow masonry construction. Placement of the lightweight reinforcement is simple and could be used for both increasing the flexural performance of both new and existing masonry wall systems.
7. Masonry reinforced with aramid and carbon fiber performed in a similar manner to conventionally reinforced masonry.
8. Optimization of the grout formulation for use with advanced reinforcement schemes would be expected to further increase performance.

The advanced reinforcement techniques would be easy and cost effective to implement in the field for repair or strengthening of existing walls. The strengthening technique would require removal of a face shell at the top of a wall, feeding in fibers or socks, followed by injecting a grout through the height of the wall. Alternatively, where less reinforcement is required, a low-fiber content grout could be pumped into the wall.

The fiber reinforcement methods discussed here are also applicable to new construction. As the masonry industry struggles with an under-experienced work force many projects have experienced improperly placed or missing reinforcing bars. In addition, vertical and horizontal reinforcement slows wall construction and in many cases requires the mason to thread units over vertical bars projecting from foundations and lower walls. By incorporating the reinforcement into the grout as short, discrete fibers, the construction sequence is simplified and the mason's productivity is increased. Fiber reinforced grouts, placed and consolidated correctly, offers a simple method to reinforce walls which is applicable in all but the most structurally demanding situations.

POTENTIAL FUTURE RESEARCH

Research topics related to use of advanced masonry reinforcement techniques may include:

- Alignment techniques for steel (or synthetic) fibers to provide a preferential orientation to the fibers within the grout matrix, increasing the effectiveness of included steel reinforcement.
- Field techniques for strengthening existing structures.
- The results reported herein are based on only a few grout mix designs. Additional studies are needed to improve the mix design in terms of strength, workability and cost.
- The flexural beam tests were conducted on specimens 40 inches long. Flexural and placement tests should be conducted on story-height wall sections.
- The flexural test loadings were all monotonic. Reversed loading tests are needed to evaluate the shape of the hysteresis curve under reversed loading and to investigate the effect of multiple loading cycles on the response.
- Design and economic studies are needed to evaluate the applicability of this technique when applied to actual buildings located in Seismic Zones 2, 3 and 4.

ACKNOWLEDGMENTS

This work was completed under Grant Number CMS-9200605 from the National Science Foundation.

This research was accomplished with the assistance of many talented individuals. Dr. Richard Atkinson and Dr. Jim Noland were responsible for the genesis and much of the work on this research. Dean Frank, Robert van der Hoeven, and Shawn Albert of Atkinson-Noland & Associates were responsible for specimen fabrication, data acquisition and data reduction.

1. Prawel, S.P., Reinhorn, A.M., and Kunnath, S.K., "Seismic Strengthening of Structural Masonry Walls with External Coatings." Proceedings of the Third U.S. National Conference on Earthquake Engineering, Charleston, S. Carolina, August, 1986.

2. Schwegler, G.,"Verstärken von Mauerwerk mit Faserverbundwerkstoffen in seismisch gefährdeten Zonen." Swiss Federal Laboratories for Material Testing and Research, Report No. 229, 1994, p. 44.

Table 1. Results of flexural tests on masonry beam specimens.

Test Series	Modulus of Rupture MPa (psi)	Toughness Index I5	Toughness Index I10	Toughness Index I20
I - Unreinforced	2.62 (380)	0	0	0
I - No. 3 Grade 60 reinf.	3.03 (440)	5.1	10.7	22.5
I - Steel fiber, low fiber content (pumpable)	4.07 (590)	4.0	7.7	17.7
II - Steel fiber, high fiber content (SIFCON)*	2.00 (290)	4.0	7.5	12.6
II - Kevlar, 2" dia. tube*	2.52 (365)	4.8	8.2	10.6
II - Kevlar, 2.5" dia. tube*	2.55 (370)	3.8	7.7	15.1
II - Carbon, 3" dia. tube*	2.72 (395)	3.4	6.7	13.9
II - Carbon, 5" dia. tube*	2.93 (425)	3.1	7.2	15.0

* Note. Series II specimens used a grout with compressive strength of 22.1 MPa (3200 psi), whereas the Series I specimens used grout with compressive strength of 27.6 MPa (4000 psi).

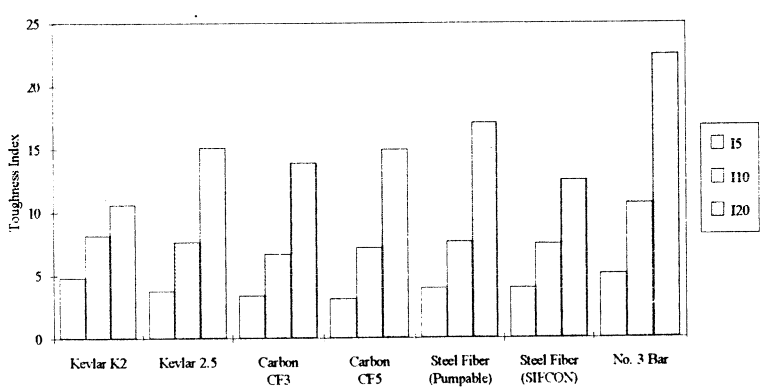

Figure 1. Toughness indices for all flexural beam specimens.

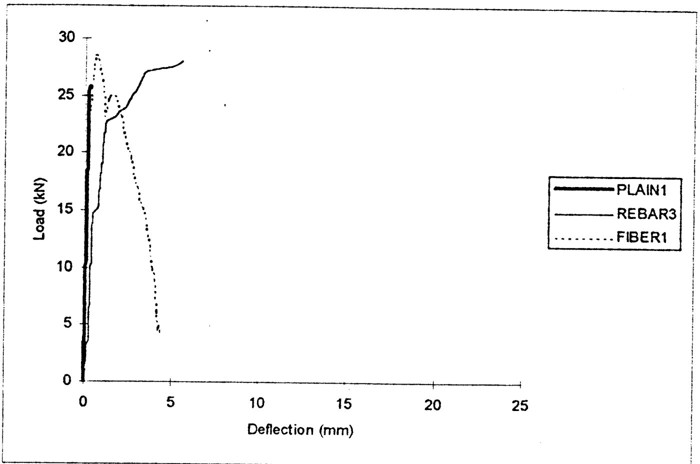

Figure 2. Load-displacement plot for representative Series I prisms. PLAIN1 was an unreinforced prism, REBAR3 was a conventionally reinforced prism, and FIBER1 was a prism reinforced with grout containing steel fibers.

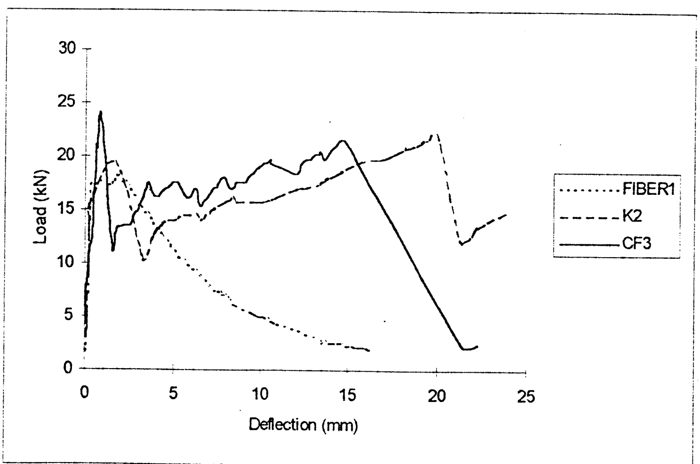

Figure 3. Load-displacement plot for representative Series II prisms. FIBER1 was a SIFCON-method reinforced prism, K2 was a prism reinforced with a 51 mm Kevlar tube, and CF3 was a prism reinforced with a 76.2 mm carbon fiber tube.

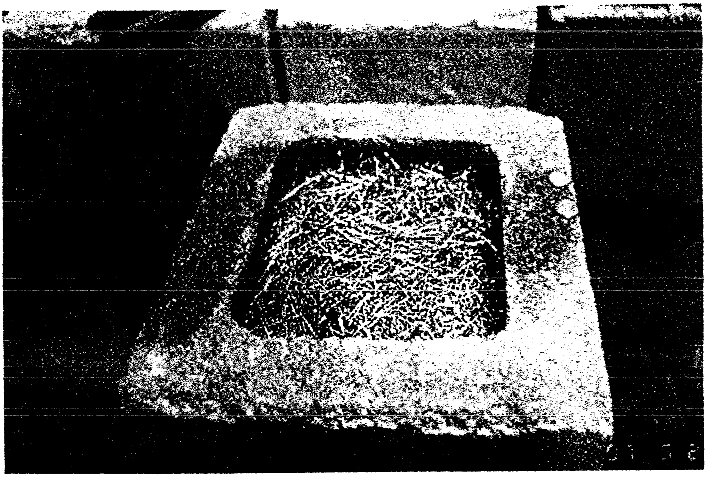

Figure 4. Masonry prism filled with steel fibers prior to grout injection.

Figure 5. Kevlar reinforcing being placed in masonry prism.