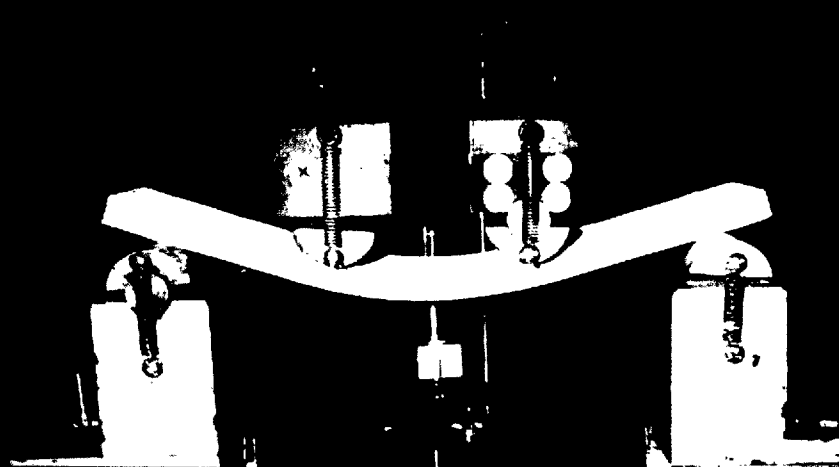


High-Performance Fiber-Reinforced



Concrete Thin Sheet Products

**Alva Peled
Surendra P. Shah
Nemkumar Banthia**
Editors

High-Performance Fiber-Reinforced Concrete Thin Sheet Products

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PREFACE

There have been worldwide advances in the development of high-performance fiber-reinforced thin products for a variety of applications, including curtain walls, pipes, and roof tiles, and for repairing and retrofitting existing structures. Different methods of manufacturing, such as extrusion and pultrusion, have been recently developed using various fibers, such as glass and wood, and synthetic fibers, such as carbon and PVA. Recognizing the importance of these products, commercial developments are currently taking place in Europe, Australia, Pacific Rim countries, and the U.S.. Since these developments are expected to materialize in the coming century, there is a need to review the state of the art and reflect on the future.

The proceedings are the result of the effort of ACI Committee 549, Ferrocement and Other Thin Reinforced Products. Original papers for this symposium were presented at the ACI Convention in Chicago, Ill., March 1999. The papers were reviewed in accordance with ACI policy.

The proceedings deal with different aspects of high-performance fiber-reinforced thin products: the extrusion process; the pultrusion technique for producing high-performance thin products; long-term durability of glass fibers; PVA fibers; long-term durability of nonwoven and woven glass fibers; integral formwork panels made of glass roving; permanent formwork with carbon fibers; hybrid laminate composites with various types of meshes and discontinued fibers; and the effect of low contractile admixture in glass fiber concrete.

The editors gratefully acknowledge ACI Committee 549, the reviewers, the authors, and the ACI staff who have made this volume a timely contribution to the awareness and growth of high-performance fiber-reinforced thin products.

Editors

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Surendra P. Shah
Nemkumar Banthia

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Effect of Fiber Length in Extruded and Cast Cement Composites

by A. Peled, Y. Akkaya, and S. P. Shah

Synopsis:

The influence of fiber length on tension and flexural behavior of extruded and cast cement composites was examined for PVA (hydrophilic) fibers and polypropylene (hydrophobic) fibers. The fiber-matrix interface, fiber surface, and microstructure of the composite cross-section were characterized by SEM. Opposite trends were obtained for the cast and extruded composites with increasing fiber length. For the extruded composites, decreasing fiber length increased flexural and tensile response, whereas for the cast composites increasing the fiber length increased the flexural and tensile response. These differences were found to be a result of differences in fiber-matrix bond properties and fiber distribution. The extruded composites showed a stronger fiber-matrix bond compared to the cast composites. This led to differences in the fiber failure mechanism: fiber rupture of the 6mm fibers in the extruded composite, and fiber pullout of both fiber lengths in the cast composites and for the 2mm fibers in the extruded composites.

Keywords: reinforcement; cement composite; extrusion; fiber length; PVA fibers; polypropylene fibers; bond; fiber-matrix interface

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INTRODUCTION

In general, fibers are incorporated in the brittle cement matrix to control cracking, to provide high ductility and improved impact resistance, to increase tensile and flexural strengths and to provide a strain-hardening type of response (1). Fiber reinforced concretes (FRC) can be categorized into two classes by their tensile responses: low-performance FRC and high performance FRC (HPFRC). Conventional FRC mainly exhibits an increase in ductility of the composite compared to the plain matrix; whereas HPFRC exhibits a substantial strain-hardening type of response, leading to a large improvement in both strength and toughness of the composite compared with the plain matrix. Fibers can improve the matrix tensile strength, if they can effectively bridge matrix microcracks. The effectiveness of the fiber-bridging action depends on the length, diameter, and distribution of fibers, as well as matrix properties. Fibers that bridge microcracks create closing pressures that suppress crack growth (2,3).

Fiber length affects the contribution of the fiber to the strength and toughness of the composite (1,4). A minimum (critical) length should be considered when discussing fiber length effects. This critical length is the minimum length required developing the full strength capacity of the fiber. Composites with fiber lengths lower than the critical length fail without fiber

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fracture during fiber pullout, since the fiber is not long enough to generate sufficient bond to fracture. In this case the failure is governed by debonding or matrix fracture. In composites with fiber length greater than the critical length, fiber strength can be attained and the failure is governed by fiber fracture. In general, a continuous increase in fiber length is advantageous for generating high strength. However, when toughness is considered, an increase in length over the critical length can be detrimental. The critical length of the fiber is controlled by the fiber-matrix bond (4). When the fiber-matrix bond increases the critical length decreases.

The present work was conducted to study the effects of fiber length on the flexural and tension behavior of extruded cement composites. Extrusion is a technique that has been shown to impart high performance characteristics to fiber reinforced cementitious materials (5). In the extrusion process a highly viscous plastic-like mixture is forced through a rigid opening (a die) having geometry of a desired cross-section. The advantage of using extrusion in cement product processing is that fibers can be aligned in the load-bearing direction, the matrix and fiber packing can be optimized to achieve low porosity, and the bond between fiber and matrix can be improved. During the extrusion processing the viscosity (rheology) of the material is a controlling factor. The mixture must be sufficiently plastic (soft) to flow under pressure and pass easily through the die, but on the other hand, it must be rigid enough to resist deformation and retain the extruded cross section after it exit from the die. If the rheology of the material is not close to ideal, it can reduce composite performance. Fiber length can change the viscosity of the fresh mixture and influence the performance of the composite.

The influence of fiber length on flexural and tensile behavior of extruded cement composites was examined for PVA (hydrophilic) fibers and polypropylene (hydrophobic) fibers. For comparison the effect of fiber length was also examined for composites produced with the conventional casting process, using the same PVA fibers as for the extrusion composites.

EXPERIMENTAL

Materials and Processing

The effect of fiber length was examined on two different production processes, extrusion and cast, and two fiber types, PVA and polypropylene. The fiber lengths examined were 2, 4, and 6mm for the PVA fibers and 13, and 19mm for the polypropylene fibers. Both fiber types and all fiber lengths were examined in the extrusion process. For the cast process only PVA fibers having lengths of 2 and 6 mm were examined. The properties of the PVA fibers are: 1900 MPa tensile strength, 41 GPa modulus of elasticity, and 14 microns diameter. The tensile strength of the polypropylene fibers is 700 MPa.

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The basic extruded material composition by volume was: 3% fibers, 12% silica fume, 1% superplasticizer and 1% methylcellulose for helping the extrusion process, with a water/cement ratio of 0.3. In the case of the cast composites in order to increase the fluidity of the fresh mixture, the 1% by volume methylcellulose was replaced with superplasticizer, keeping the same water/cement ratio of 0.3 as for the extruded composites.

The preparation of the mixtures for both cast and extruded composites was as follows for both fiber types: first the liquid phase was mixed together with the fibers to get a proper dispersion of the fibers in the composite, and then the solid materials were incorporated in the mixture. All the components were mixed together for about 10-15 minutes. Sheet specimens were produced for both the cast and extrusion processes; the specimens were 4mm thick and 25mm wide.

After production, the specimens were cured under a plastic sheet. After one day the specimens were demolded (in the case of the cast specimens) and cured at 100% RH at 90°C for 2 days. After storing for another 24 hours in 50% RH at room temperature the specimens were dried at 105°C for 24 hours and tested in flexure.

Extrusion and Test Methods

Extrusion--A small-scale extrusion rheometer was used at a rate of 0.5 mm/sec to evaluate the rheology of the different batches. A ram type extruder was used for this purpose; in a ram extruder a piston is used to apply pressure to the material in the barrel in order to force it through a die.

Flexural test--A three-point flexural test was carried out to characterize the flexural behavior of the composites. The span was 101.6mm (4inch). The three point bending test was conducted using stroke control at a rate of about 0.7 mm/min. The test results presented are for an average of 6 specimens. Typical stress-deflection curves representing the composites flexural behavior were chosen for comparison.

Tension test--For the PVA fiber composites (cast and extruded) without sand, in addition to the flexural tests, tension tests were performed for un-notched specimens at a rate of 0.02mm/min. A gage length of 12.7 mm (0.5inch) was used for controlling the test by using the average measurement from two CMOD gages. The specimens were 152.4 mm long and tested in the longitudinal direction of the specimen (the extrusion direction). The tensile strength and the area under the stress-strain curves (toughness) up to 1.2×10^{-4} strain were calculated. The test results presented are an average of 5 specimens. Typical representative stress-strain curves were chosen for comparison.

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Microstructure characterization--Fragments of specimens of the PVA fiber composites obtained after tension and flexural tests were dried at 60°C prior to being gold-coated for observation in a scanning electron microscope (SEM), in an attempt to characterize the fiber-matrix interface, the fiber surface, and the microstructure of the composite cross-section. The tensile zone was mainly observed with the flexure specimens. The observations were conducted on the composite fracture surface and on the polished surface of tensile composites. Examination of the top views and side views of the fracture surface were obtained. The side view was mainly used to observe the protruded length of the fiber, which remained on top of the fracture surface after the tension test. This was used to characterize the fiber failure mechanism. In the case of the polished specimens, the polishing was done along the specimen length, exposing the wide side of the composite, in order to observe the orientation of the fibers. Also another set was polished across the width of the specimen in order to observe the distribution of fibers at a cross section near the fracture zone.

MECHANICAL BEHAVIOR

Effect of fiber Length

The effect of fiber length on tension and flexural behavior of extruded composites can be seen in Figure 1 for PVA fiber composites and for polypropylene fiber composites. Table 1 presents the average tensile and flexural strengths and composite toughness for the PVA fibers. It can be clearly seen that for both fiber types decreasing the fiber length significantly enhances the tensile and flexural response of the extruded composites. The improvement is in both strength (tensile and flexural) and toughness. About a four-fold enhancement was obtained in the ductility of composite with 2mm PVA fibers compared to composites with 6mm fibers (flexural composites). A strain hardening response can be seen for the PVA fiber composites. The figure also shows the substantial improvement achieved with the PVA fibers on composite flexural behavior compared with the plain matrix.

This is in contrast to the extruded composites in the cast systems, where increasing the fiber length improves the composite flexural and tensile response (Figure 2 and Table 1). Here about a two-fold improvement in the ductility of the flexural composite and 60% increase in the flexural strength values were obtained for composites with 6mm long fibers compared to those with 2mm long fibers. This influence of fiber length was obtained when fibers fail by pullout for both fiber lengths. Longer fibers lead to a high energy, requirement to pull out the fiber, and this results in a high tensile and flexural response.

This contradictory trend in the cast and extruded composites indicates that short fibers are advantageous when using the extrusion technique, whereas

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long fibers are advantageous when using the cast technique. In general, short fibers are easier to handle during mixing; result in less broken fibers (mainly when brittle fibers were used), and are more easily dispersed in the composite (fewer fiber bundles).

Effect of Processing

Figure 3 compares the tensile response of cast and extruded composites with PVA fibers for 2mm fiber length and for 6mm fiber length. The extrusion process significantly improves the tensile response of composites containing 2mm fibers (Figure 3a). For composites containing 6mm fibers, the cast composite exhibits higher ductility and toughness, whereas the extruded composite shows more brittle behavior with higher composite tensile strength (Figure 3b). The high ductility of the cast composite with 6mm fibers suggests that the fiber failure mechanism is governed mainly by fiber pullout, whereas the brittle behavior and the high strength of the extruded composite suggests fiber rupture (4).

Comparison between the tensile behavior of the extruded composite containing 2mm fibers and the cast composite containing 6mm fibers shows a substantial strain hardening response of the extruded composites (Figure 4). This means that the extrusion technique enables reduction of the fiber length to as low as 2mm and at the same time achievement of a significant strain hardening response of the composite, which cannot be obtained when the conventional cast technique is used, even with a 6mm fiber length.

MICROSTRUCTURE

Fiber Failure Mechanism

Figure 5 shows a side view of a fracture surface after a tensile test for extruded and cast composites with 2 and 6mm fiber lengths. This view shows the length of fibers protruding from the matrix surface after the test. Assuming similar fiber-matrix bond for both fiber lengths (i.e. the same critical fiber length), one would expect to obtain a longer protruded length for the long fibers (6mm), if both fiber lengths (2 and 6mm) were completely pulled out during testing.

In the extruded system, the protruded length of the 6mm fibers is less than that of the 2mm fibers (Figures 5a and c). Thus fiber fracture rather than fiber pullout is indicated as the failure mechanism for the 6mm fibers. The long protruded length exhibited with the 2mm fibers is a result of fiber pullout.

For the cast composites a longer protruded length is obtained with the 6mm fibers compared to the 2mm fibers (Figures 5b and c). This indicates a

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failure mechanism controlled by the fiber pullout process for both fiber lengths in the cast composites.

It can be concluded that for the extruded system, the fiber pullout process is the failure mechanism for the 2mm fibers and fiber fracture is the dominant failure mechanism for the 6mm fibers. In the cast system, a fiber pullout process is the failure mechanism for both fiber lengths. The pullout mechanism can lead to an enhanced ductile behavior of the extruded composite with the 2mm fibers and the cast composites with 6mm fibers (Figures 1 and 2).

Fiber-Matrix Bond

Observations of the fiber-matrix interface and the surface of the fiber itself were conducted, in an attempt to characterize the fiber-matrix bond of cast and extruded composites:

- a) Fiber-matrix interface--Figure 6 shows SEM micrographs of PVA fiber embedded in the cement matrix for extruded and cast composites. A large gap between the fiber and the matrix and a porous matrix around the fiber can be seen in the cast composite (Figure 6b). A much more compacted matrix around the fiber can be seen in the extruded composite (Figure 6a), i.e. stronger fiber-matrix bond.
- b) Fiber surface--Figure 7 shows SEM micrographs of the PVA fiber surface after a flexure test. These observations were made for the 2mm fibers, since in both processing methods (extruded and cast) these fibers exhibited fiber pullout failure. Significant long fibrils and a rough fiber surface can be seen in the extruded composite (Figure 7a). Very fine fibrils and a much smoother fiber surface can be seen in the cast composite (Figure 7b). The long fibrils and the roughness of the extruded fiber surface indicate an aggressive pullout process with high friction between the fiber and the relatively dense matrix of the extruded composite.

Figure 8 shows a top view of a fracture surface after testing. The figure shows a large amount of long fibrils lying on top of the fracture surface of the extruded composite made with 2mm fibers (Figure 8a). Such fibrils were not observed in the case of the extruded composite with 6mm fibers (Figure 8b) and with the cast composite (Figure 8c). This indicates once again the higher pullout resistance of the 2mm fibers in the extruded system. This figure also shows a longer protruded length of the 2mm fibers, compared with the 6mm fiber in the extruded composites. Note that the protruded length of the cast specimen with 2mm long fiber is quite long.

Based on the entire set of observations it is concluded that the extrusion process improved fiber-matrix bond compared with cast composites. This strong bond can be obtained, since in the extrusion process the materials are

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formed under high shear and high compressive forces during production. A strong fiber-matrix bond leads to a shorter critical fiber length. Fibers with a greater length than the critical length are long enough so that the failure is governed by fiber fracture. The embedded length of the 6mm fibers in the extruded composites exceeded the critical length, thus fiber fracture rather than fiber pullout is the failure mechanism for composites made with those fibers. This can explain the contradictory influence of fiber length on mechanical behavior obtained with the cast and the extruded composites when increasing fiber length (Figure 1 and 2).

Fiber Dispersion

Figure 9 shows the distribution of the fibers in the extruded composite cross-section for the different fiber lengths. It can be seen that the 2mm fiber dispersed more homogeneously in the composite than the 6mm fibers. More fiber clumps can be seen in the case of the 6mm fibers. The better dispersion of the 2mm fibers in the extruded composite contributes to the high tensile and flexural response of this composite (Figure 1).

Higher tensile strength was obtained with the extruded composite with 2mm fibers, compared to the extruded composite with 6mm fibers (Figure 1 and Table 1). This was so even though the failure of the 6mm fiber was governed by fiber fracture, which should lead to brittle composite behavior but with high strength. The more uniform dispersion of the 2mm fibers in the extruded composite appears to contribute to this behavior.

CONCLUSIONS

- 1) In the extruded composites decreasing fiber length improves the mechanical behavior (tensile and flexural) of the composite. This trend was obtained for different fiber types: PVA and polypropylene.
- 2) In the case of the cast composites increasing fiber length increases the mechanical behavior (tensile and flexural) of the composite. Based on microstructure characterization, the fiber pullout process is the fiber failure mechanism for both fiber lengths. A longer fiber length (6mm) required more energy to pull out, leading to the higher strength (flexural and tensile) and toughness of the composite.
- 3) The extrusion process improves the fiber-matrix bond compared with cast composites. Extruded composites made with a 2mm long fiber showed a superior strain hardening response compared to cast composites made with 6mm fibers.
- 4) The difference in the fiber-matrix bond between extruded and cast composites resulted in different fiber failure mechanisms:

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- a) Fiber pullout occurred in the case of the extruded composites with 2mm fibers and in case of cast composites with both fiber lengths, and
 - b) Fiber fracture in the case of extruded composite with 6mm fiber.
- 5) With the extrusion technique it is possible to reduce the fiber length to as low as 2mm and at the same time achieve a significant high strain hardening response of the composite, which cannot be achieved when the conventional casting technique is used, even with a 6mm fiber length.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the Illinois Clean Coal Institute and the project manager Dr. Daniel D. Banerjee,

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Table 1: Flexural and tensile strengths and toughness of the extruded and cast composites containing PVA fibers.

Processing	Fiber Length (mm)	Flexural Strength (MPa)	Tensile Strength (MPa)	Toughness (Area under the curve up to 1.2×10^{-4} strain)
	Plain Matrix	13.8	---	---
Extrusion	2	33.8	9.1	96
	4	29.7	8.3	77
	6	25.0	7.3	49
Cast	2	20.1	2.8	29
	6	29.2	5.3	59

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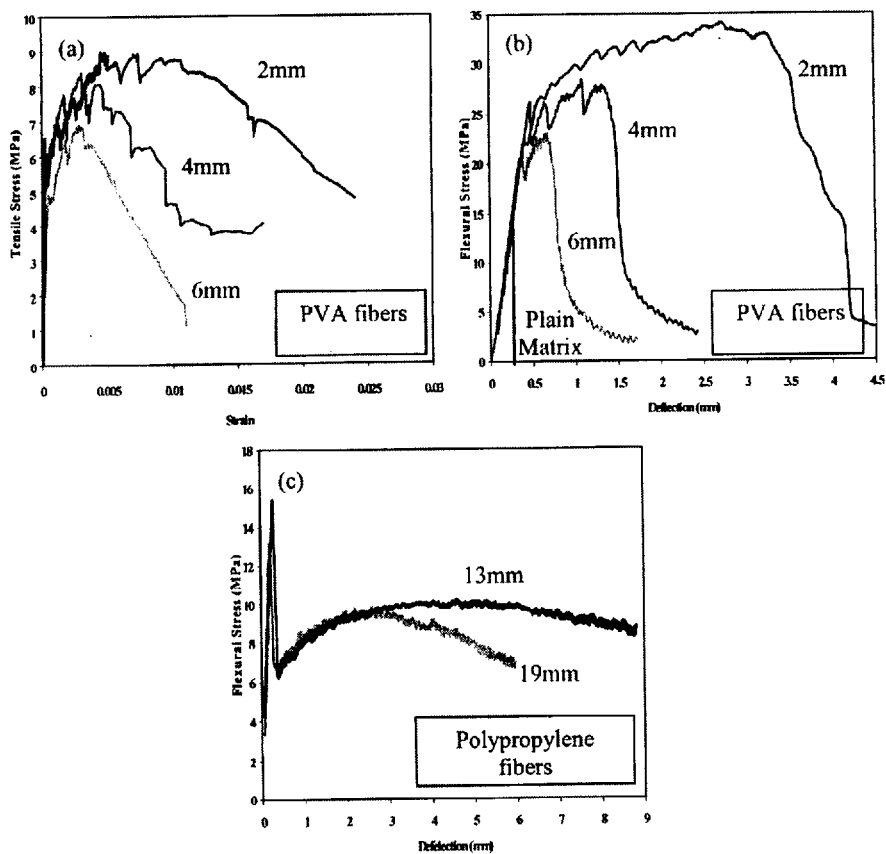


Figure 1: Effect of fiber length on extruded composites: (a) tensile response of composite with PVA fibers without sand, (b) flexural response of composites with PVA fibers, (c) flexural response of composites with polypropylene fibers.

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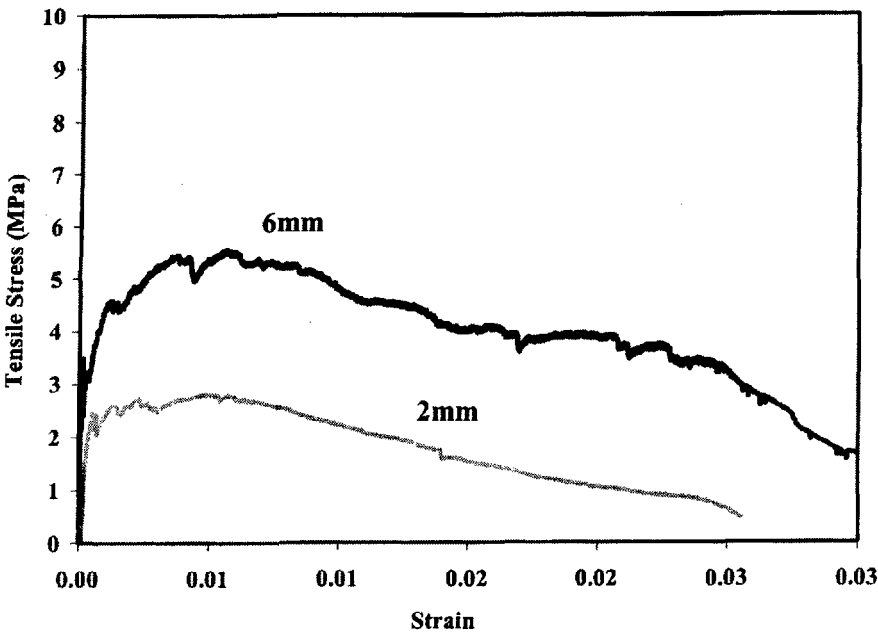


Figure 2: Stress-strain curves of cast composites containing PVA fibers with 6mm and with 2mm lengths.

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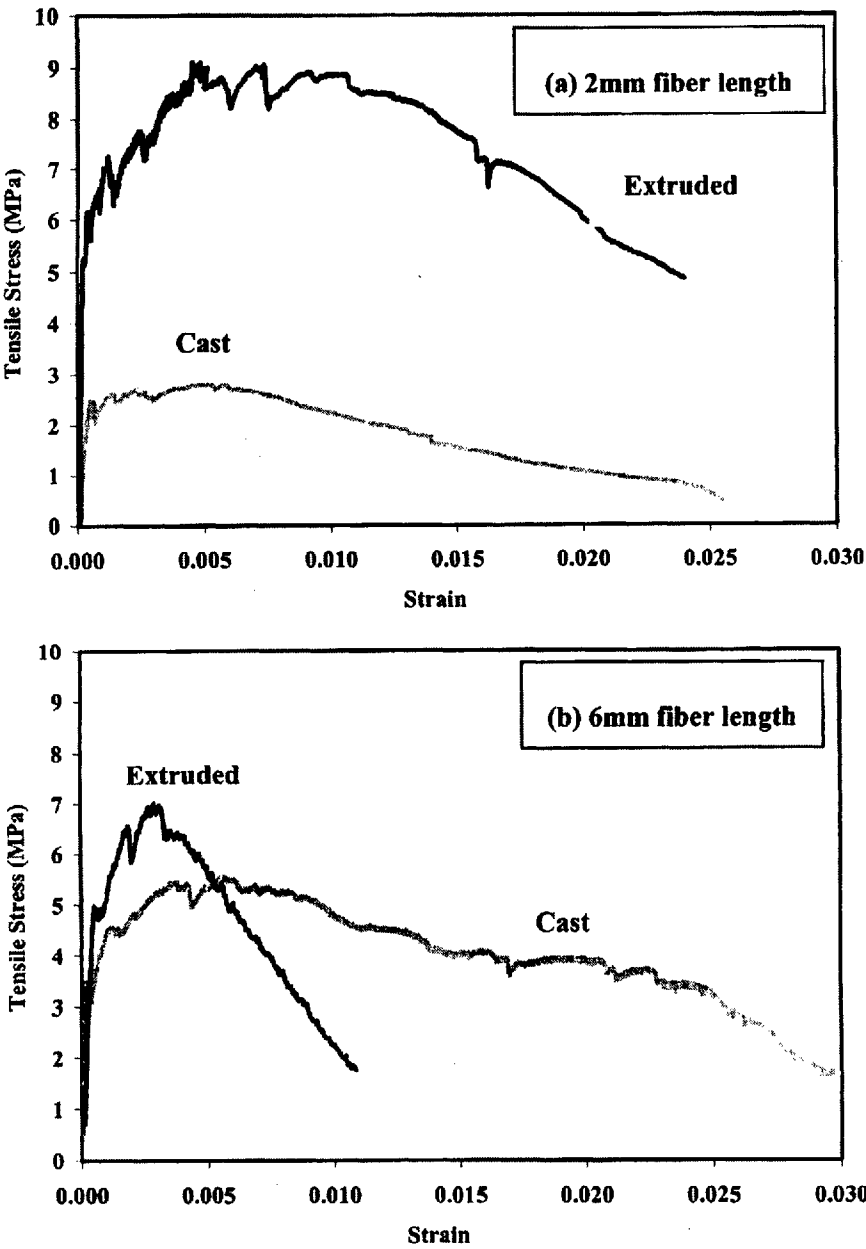


Figure 3: Comparison between the stress-strain curves of cast and extruded composites: (a) composites containing fibers with 2mm length, (b) composites containing fibers with 6mm length.

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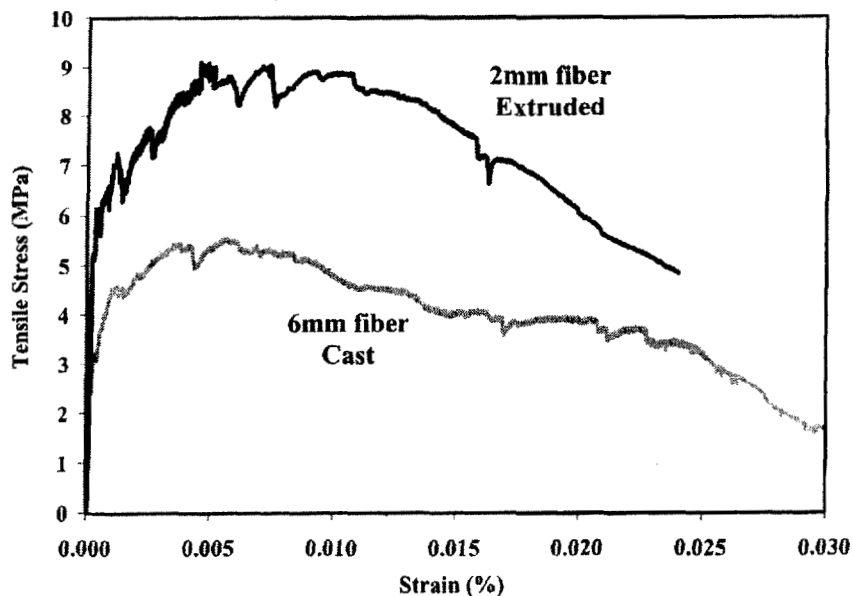
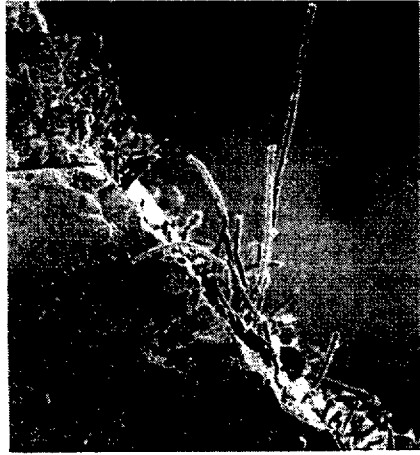


Figure 4: Stress-strain curves for cast composites with 6mm fiber length and extruded composites with 2mm fiber length.

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(a)



(b)



(c)



(d)

Figure 5: Side view of a composite fracture surface: (a) extruded composite with 2mm fibers, (b) cast composite with 2mm fibers, (c) extruded composite with 6mm fibers, (d) cast composite with 6mm fibers.

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(a)



(b)

Figure 6: PVA fiber embedded in the cement matrix (x6000): (a) extruded composite, (b) cast composite.

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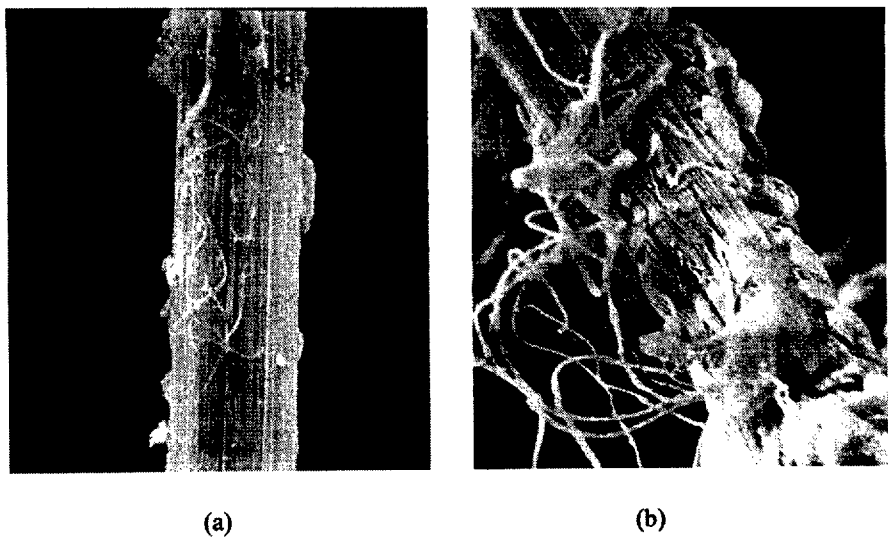


Figure 7: 2mm PVA fiber surface after flexure test of the composite for different processing (x2000): (a) cast, (b) extruded.



(a)



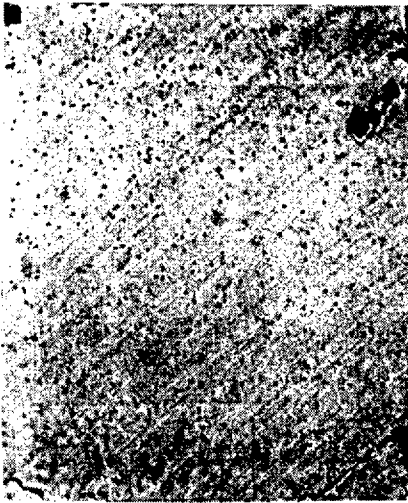
(b)



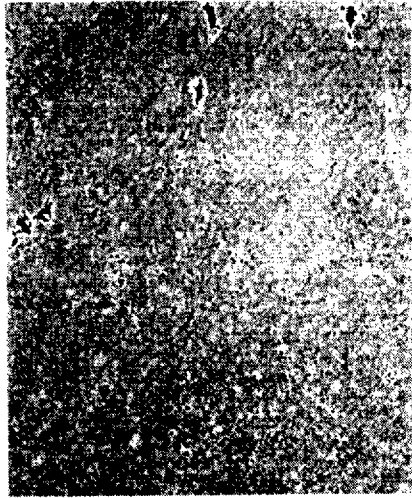
(c)

Figure 8: Top view of composite fracture surface (x200): (a) extruded composite with 2mm fibers, (b) extruded composite with 6mm fibers, (c) cast composite with 2mm fibers.

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(a)



(b)

Figure 9: Distribution of PVA fibers in extruded composites cross-section for the different fiber lengths (x50): (a) 2mm, (b) 6mm.

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CFRC Permanent Formwork for the Steel Free Bridge Deck

by N. Banthia, C. Yan, A. A. Mufti and B. Bakht

Synopsis:

The steel free bridge deck slab technology has seen its real-life applications in a span of less than ten years from its initial conception. Indications are that more and more bridges will be built using this concept around the world, especially in places where corrosion of reinforcement is a serious concern.

In this paper, results of an experimental project carried out at the University of British Columbia, where a full scale bridge deck was tested with carbon fiber-reinforced cement (CFRC) permanent formwork, are described. The bridge deck had 0.4% of fibrillated polypropylene fiber-reinforcement but no traditional steel reinforcement. The carbon fiber used in the formwork was a pitch-based fiber with a moderately high modulus of elasticity and tensile strength. The deck slab was tested at various locations under a simulated concentrated wheel load and the load versus deflection characteristics were recorded. While the bridge deck failed, as expected, in a punching shear mode at a load several times higher than the design load, the bond between the CFRC formwork and the concrete deck was identified as a weak link in the system.

Keywords: carbon fiber-reinforced cements; permanent formwork; steel-free bridge deck

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Aftab A. Mufti is a Professor of Civil Engineering at Dalhousie University, Canada and Director of the Nova Scotia CAD/CAM Centre in Halifax. He has been involved in structural engineering research for more than 35 years, and is one of the inventors of the concept of the steel-free bridge deck. He is a recipient of several awards.

Baidar Bakht is Vice President of JMB Structures Research, Inc. He is Adjunct Professor at Dalhousie University and University of Toronto and has 30 years of research experience in structural engineering. He is the author of over 150 technical papers and six volumes.

INTRODUCTION

Historically, reinforced concrete deck slabs of girder bridges have been designed as flexural elements where the steel reinforcement is expected to carry flexural stresses arising from the traffic loads. This approach requires a large amount of steel as reinforcement, and given the severe corrosion problem in our harsh environments, this poses a critical durability concern. In fact, the problem is so severe that by one estimate, more than 40% of the existing bridge deck area in the continental US will require replacement in the next decade or so (1,2). Apart from the insurmountable financial burden on the infrastructure, the user costs associated with disruptions to traffic are incalculable.

It is known now, however, that the amount of steel provided can be reduced considerably if one allows the development of arching action in the deck. Indeed, in some codes (3) a significant reduction in the steel reinforcement is allowed, where it is believed that the concentrated loads are carried by the slab to the girders by means of shallowly-sloped compressive struts.

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More recently, it has been shown that if the two flanges of the girders supporting the deck are tied together to fully resist the lateral forces produced by the arching action, then the reinforcing steel can be removed entirely. Removal of traditional steel, however, means that some alternate form of reinforcement is required to provide resistance against thermal and shrinkage cracking. This was achieved by providing polypropylene fiber reinforcement in concrete (4,5,6). The steel-free bridge deck technology, described above has seen its real-life applications in a span of less than ten years from its initial conception, and indications are that more and more bridges will be built using this concept around the world.

While placing the steel-free deck, the removal of traditional form-work is an inconvenience, and the construction efficiency can be significantly enhanced by providing a permanent formwork system which does not need removal and thus becomes an integral part of the structure. In addition to contributing to construction ease, if a high performance material is chosen for the permanent formwork, the performance of the bridge deck itself may be improved by resisting the longitudinal cracks that are formed at the soffit of some steel-free deck slabs. In the project described here, the use of carbon fiber reinforced concrete (CFRC) was investigated as the material in permanent formwork for the steel-free bridge-deck. As is well known (7,8), CFRC is a material with significantly improved strength, toughness, impact resistance, fatigue endurance and durability over plain concrete, and hence a suitable candidate for the permanent formwork.

EXPERIMENTAL PROGRAM

CFRC Permanent Formwork Panels

The mix designs for the permanent formwork panels are given in Table 1. A typical panel and its dimensions are shown in Figures 1 and 2, respectively. The panels were cast at a pre-cast plant in Armstrong BC and shipped to Vancouver after 28 days of curing. Two of the panels were subjected to a line-load in a test frame and tested to destruction. The load vs. deflection curve for the panels is given in Figure 3. It can be seen in this figure that the panel has a large capacity to absorb energy after the load has increased beyond the limit of proportionality (8).

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The PFRC Deck

The 2.33 m x 6.0 m long bridge deck assembly is shown in Figures 4 and 5. As can be seen, the assembly comprised two steel girders (W610x241) spaced 2 m c/c, supported on 6 m long 101.6 mm diameter rollers on the strong floor of the laboratory. Angle sections (100 x 100 x 10 mm) acting as straps were welded to the girders at a spacing of 1 m along the span (Figure 6). The carbon fiber reinforced cement permanent formwork panels were placed on the girders over an edge support of 50 mm, and the polypropylene fiber reinforced concrete (PFRC) deck was poured on top. Series of studs, welded to the girder along the length and embedded in the PFRC deck, transferred the horizontal shear force between the deck slab and the girders.

The polypropylene fiber reinforced concrete (PFRC) used in the deck had a compressive strength of 35 MPa and had fibrillated polypropylene fibers at a volume fraction of 0.4%. A typical load-displacement curve (ASTM C1018-97) for the PFRC is shown in Figure 7. The material developed a flexural toughness factor of 2.25 MPa.

Deck Testing

The load on the deck was applied in succession at locations 1, 3 & 5 shown in Figure 5 by using a loading frame shown in Figure 4. A view of the deck under load is also shown in Figure 8. Load was applied using a loading pad 508 mm x 254 mm in size with a 1.4 MN loading jack. During a test, displacement of the load point and the applied load were recorded simultaneously at a frequency of 1 Hz. The load was applied at a rate of 1 mm/min.

RESULTS

Loading at Location 1

The load at location 1 was cycled three times between 0 and ~500 kN, followed by a monotonic increase to about 740 kN at which point the bond between CFRC formwork and the PFRC deck was noticed to have failed (Figure 9). The test was stopped, and the underside of the deck was examined thoroughly for assessment of damage. Subsequently, the loading was continued at the same location and the deck was found to fail in a punching shear mode at a load of about 700 kN (Figure 10).

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Loading at Location 3

The load at location 3 was also cycled three times between 0 and ~500 kN, followed by a monotonic increase to about 600 kN (Figure 11) at which point, once again, the deck failed in a punching shear mode (Figure 12).

Loading at Location 5

At location 5 the load was cycled twice between 0 and ~800 kN, followed by a monotonic increase to about 1160 kN (Figure 13) at which point, once again, the deck failed in a punching shear mode.

DISCUSSION

It is clear from the tests describe here that the proposed system of CFRC permanent formwork in conjunction with a PFRC deck is more than capable of supporting the required factored design load of about 200 kN (e.g., Canadian Highway Bridge Design Code). Clearly, there are some issue to be resolved, including the lack of perfect bond between the cast-in-place deck slab and the formwork, which possibly caused a premature failure during loading at location 1. The CFRC used in the permanent formwork can be further optimized.

Need also exists to understand the fatigue endurance of the proposed deck assembly. Some such tests are currently underway.

ACKNOWLEDGEMENT

The authors are highly indebted to the Canadian Government's Department of External Affairs and Foreign Trade (DFAIT) for the financial support received for this project under the Japan Science and Technology Fund (JSTF). Valuable advice of Prof. Taketo Uomoto of Tokyo University is also thankfully acknowledged. Finally, continued support of Natural Sciences and Engineering Research Council is appreciated.

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Table 1. Carbon Fiber Reinforced Cement Mix Design and Properties

Cement (ASTM Type 1)	870 kg/m ³
Silica Fume	130 kg/m ³
Water	350 kg/m ³
Fine Aggregate	1000 kg/m ³
Superplasticizer	21.75 liters/m ³
Carbon fiber	2% by volume
Compressive strength	66.12 MPa
Flexural strength	15.39 MPa
Flexural toughness	1.24 N-mm/mm ²
Flexural toughness of plain matrix (for comparison)	0.075 N-mm/mm ²

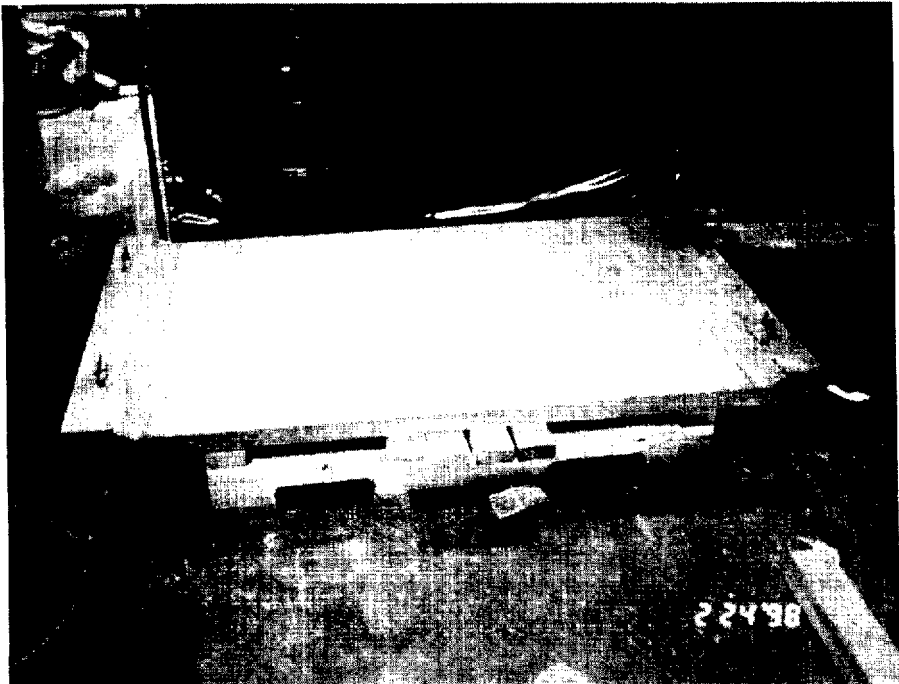


Figure 1-A CFRC Permanent Formwork Panel

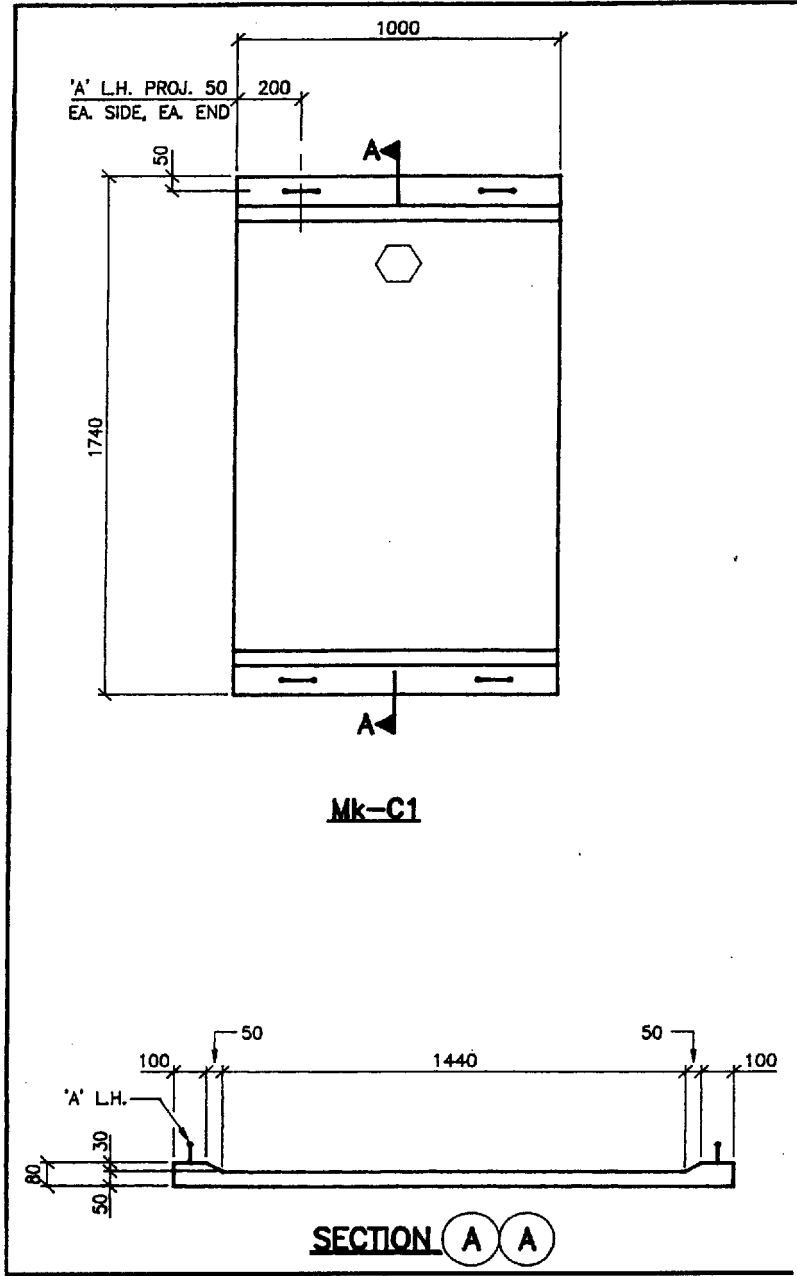


Figure 2 - Dimensions of the CFRC Permanent Formwork Panel

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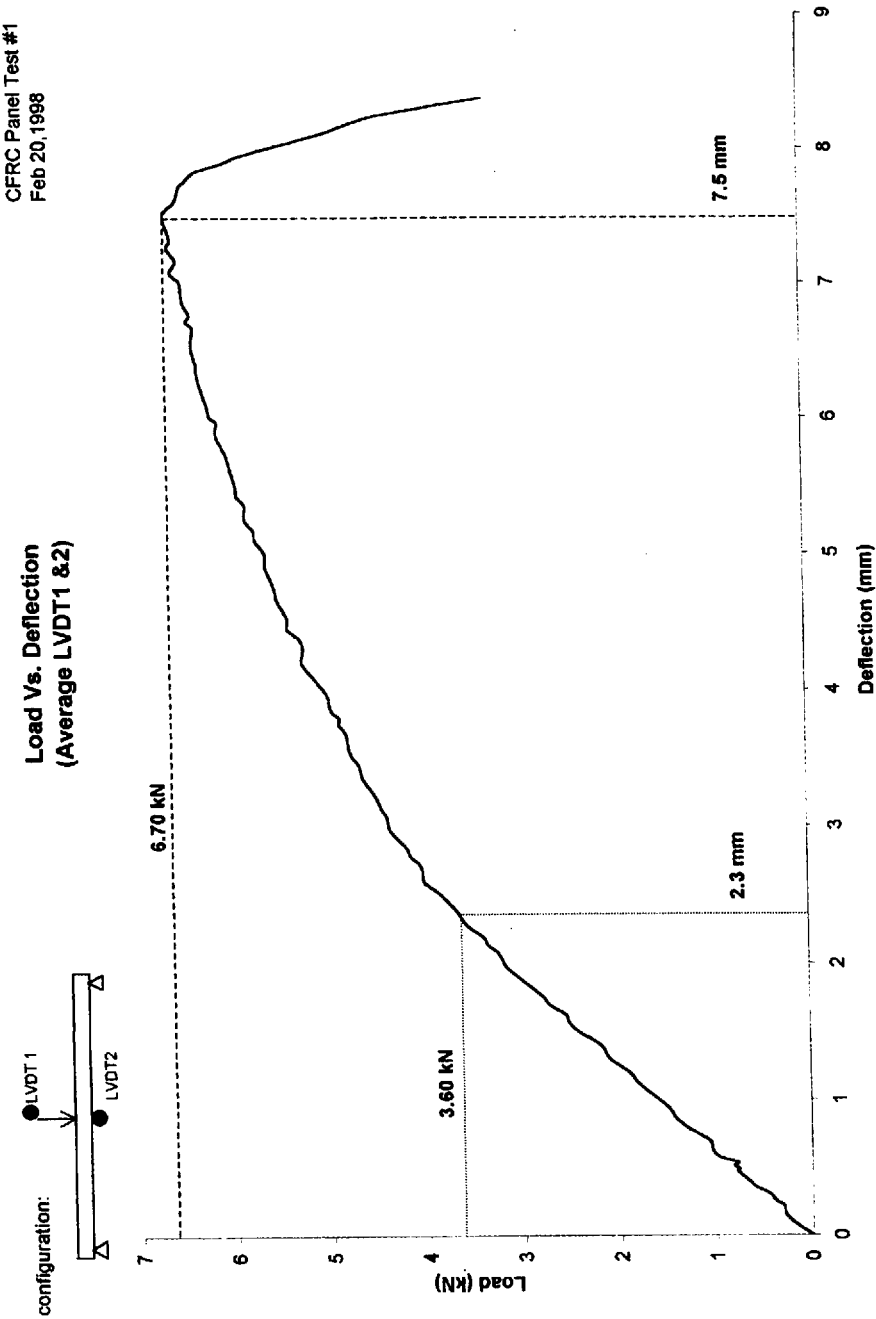


Figure 3 - Load vs. Deflection Response of the CFRC Permanent Formwork Panel. Notice the non-brittle response and the energy absorption capacity.

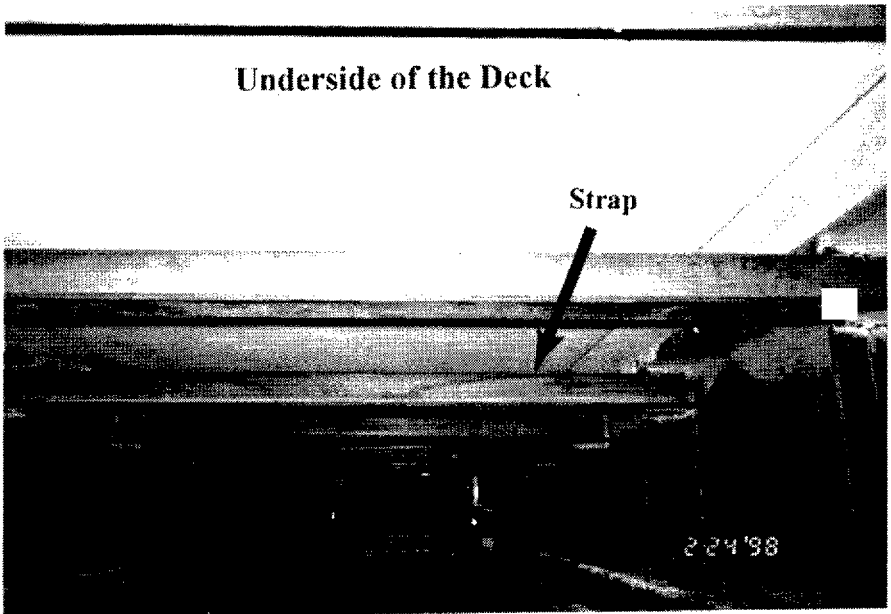


Figure 6 - Underside of the Deck showing the Straps
Welded 1 m c/c.

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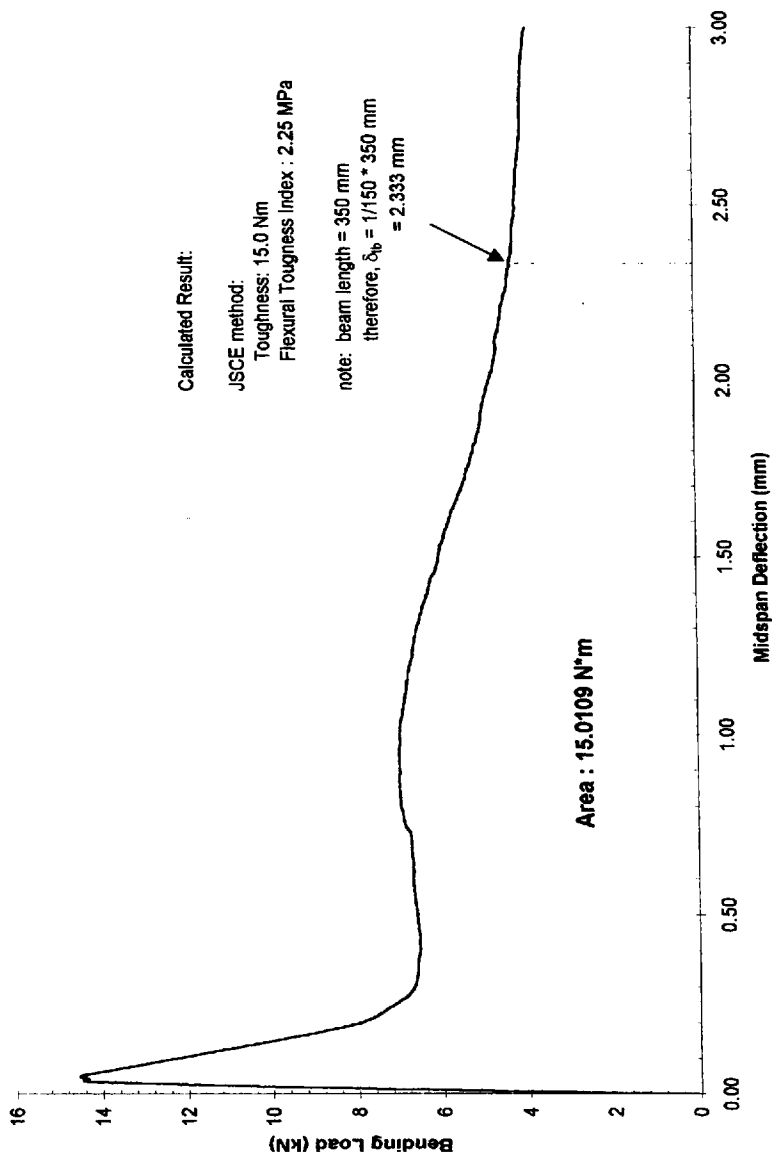


Figure 7 - Load-Displacement Curve for Polypropylene Fiber Reinforced Concrete (ASTM C101896).

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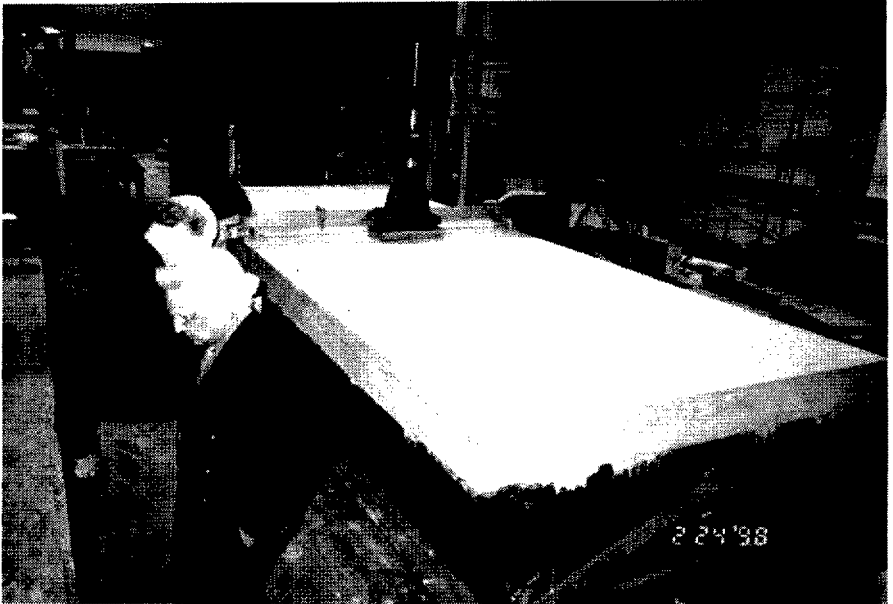


Figure 8 - Bridge Deck under Load.

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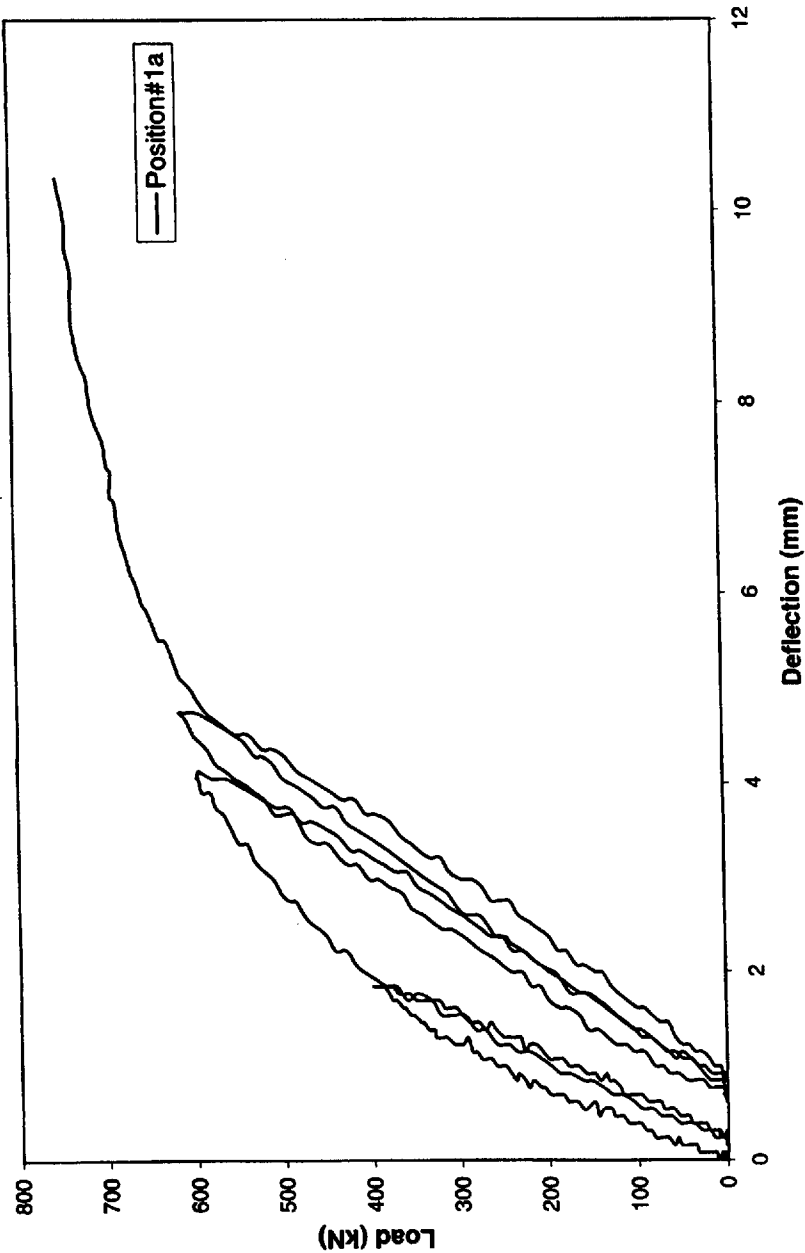


Figure 9 - Load-Displacement Curve (Location 1)
First Loading.

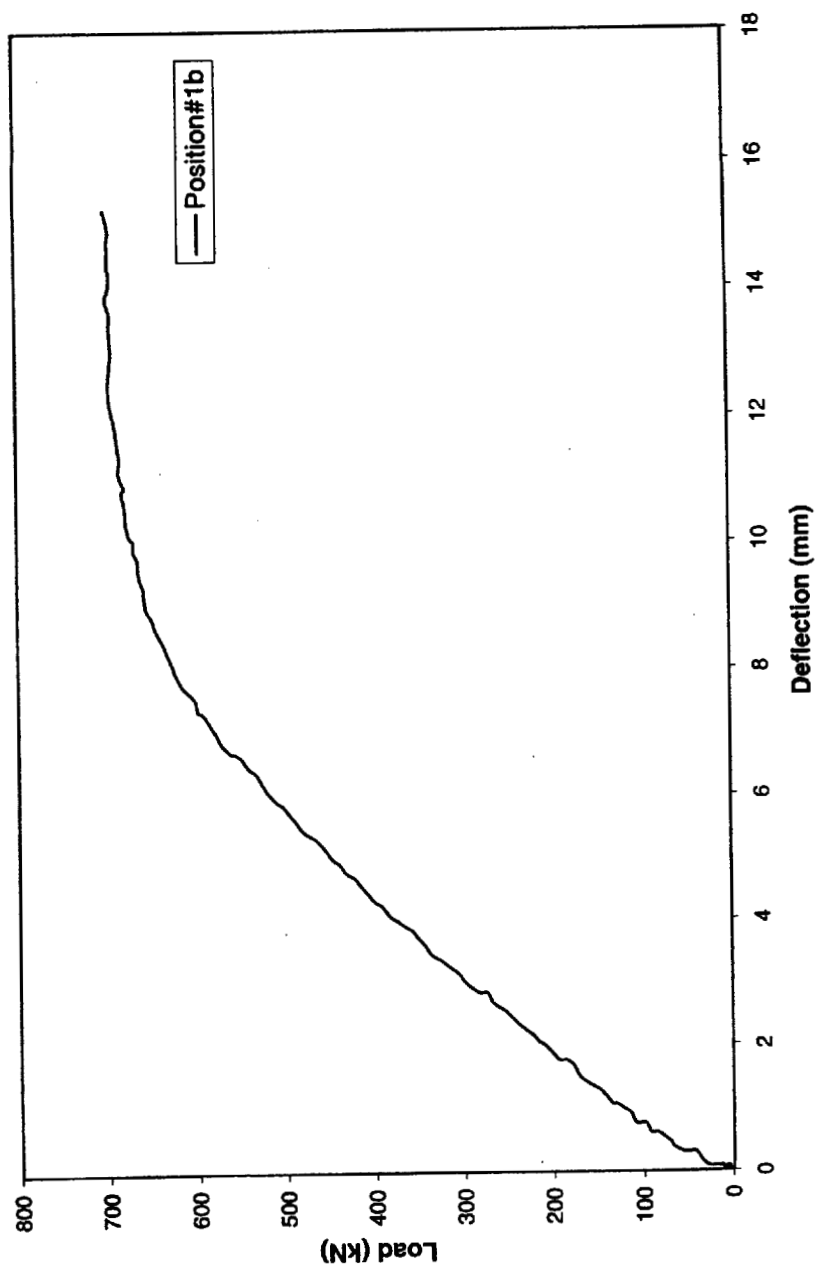


Figure 10 - Load-Displacement Curve (Location 1)
Second Loading.

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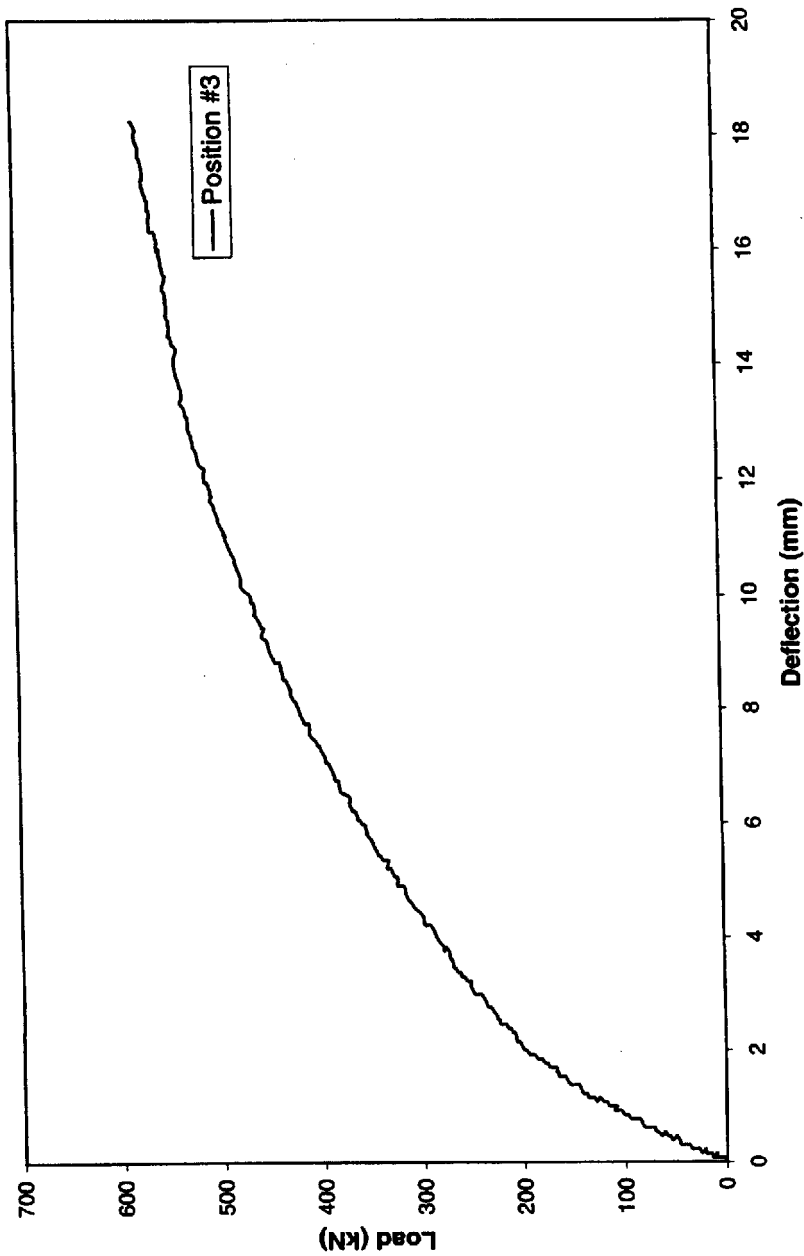


Figure 11 - Load-Displacement Curve (Location 3).

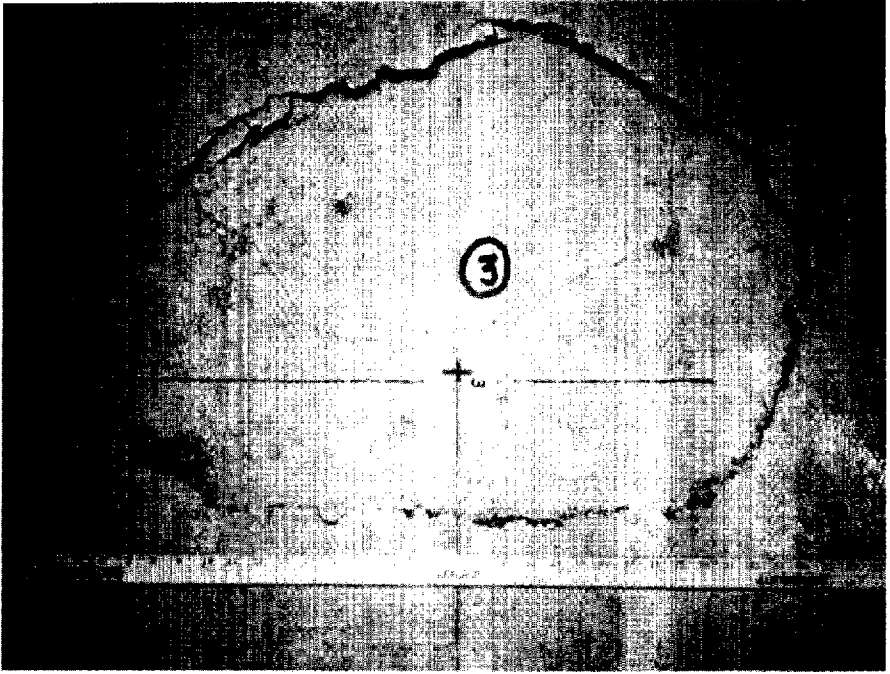


Figure 12 - Plan View of the Deck Showing Punching Failure at Location 3.

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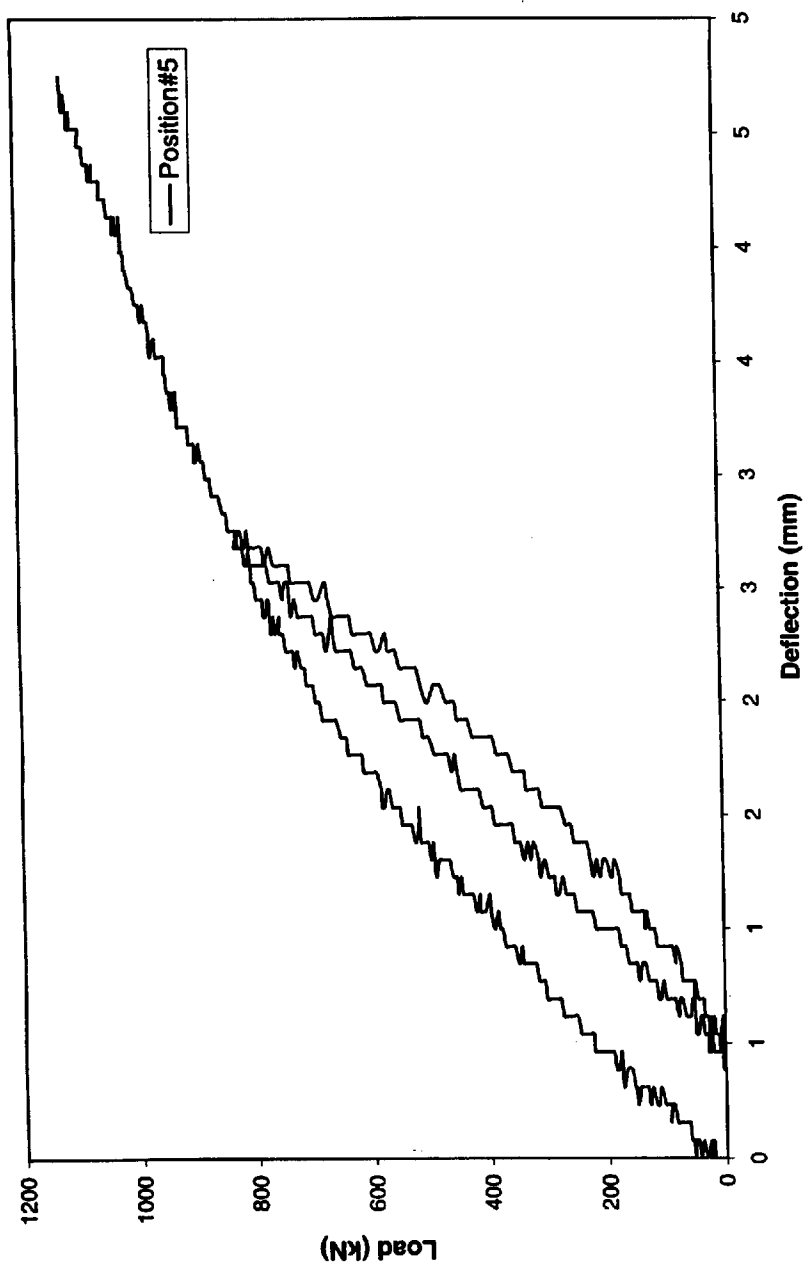


Figure 13 - Load-Displacement Curve (Location 5).

Effect of Material Constituents on Performance of Fiber-Reinforced Cementitious Thin Sheets

by Y. Shao, R. Srinivasan, and S. P. Shah

Synopsis:

The effect of material constitutes on the on the performance of fiber-reinforced cementitious thin sheets was studied in order to examine the possible trade-off between cost and performance in cement-based building product development. A variety of materials were incorporated into fabricating cementitious thin sheets. The variables included types of fibers (glass, polyethylene terephthalate, polyolefin, or polyvinyl alcohol), types of sand (marble, silica or fly ash) and percent content, mixing method (dispersive or non-dispersive), latex types, (MMA or SB), cement types (Type I or Type III), mineral additives (metakaolin or silica fume) and curing conditions (moisture or steam). Twelve batches of thin sheets with 3% fibers by volume for each were prepared by extrusion processing and three-point bending tests were conducted to evaluate the strength and toughness. The purpose of the study was to establish several mix designs for extrusion production of high-performance fiber-reinforced cementitious thin sheets at compatible cost.

Keywords: fiber cement composites; glass fiber; PET fiber; polyolefin fiber; PVA fiber; latex; sand content; additives; mixing; curing

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INTRODUCTION

The use of fiber reinforced cementitious thin sheets in North America construction industry is still relatively new. Compared to the other composite board products, such as particleboard, medium density fiberboard (MDF), oriented strand board (OSB) and hardboard, which have been used over the past 40 years, the cementitious thin sheet products are still in their infancy. The move towards lightweight construction in a factory environment permits improved quality control, reduced labor costs and more cost efficient design. It is predicted that an increasing market share for fiber cement products will be seen early in the next millennium (1).

In manufacturing the fiber cement thin sheets, Hatschek process is most commonly used. As the asbestos replacement, only the cellulose fibers can be used as the alternative process water carrier (2). Recent research has re-evaluated the extrusion processing as an alternative to Hatschek in fabricating high performance cement-based products (3). In contrary to Hatschek process, extrusion is a dough process that uses only small quantities of water. The technique enables use of almost all types of fibers and matrix, and this allows a wide range for trade-off affecting both performance and cost.

This paper reports on the effort to study the influence of material constituents on the performance of fiber-reinforced cementitious thin sheets fabricated by extrusion. Studied were the effects of different fiber types, different sand content and types, different latex types, different cement types, and different mineral additives. Effects of different curing conditions and

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different mixing methods were also examined. Mechanical properties of the thin sheets were evaluated through the three-point bending tests. The flexural strength and toughness measurements were correlated with the changes in material constituents in each batch. The goal of the present research was to determine the relationships between the performance and the constituents in high performance fiber-cement thin sheet that was economically feasible and technically available for mass production.

EXPERIMENTAL

Sample Preparation

The material compositions of twelve mix designs for different fiber-cement thin sheets are shown in Table 1. Fiber volume ratio of all batches were fixed at 3%. The control mix design (#16) used type I Portland cement, polyvinyl alcohol (PVA) fibers, sand to cement ratio 0.65, metakaolin to cement ratio 0.2, latex (solid) to cement ratio 0.14, and high range water reducer to cement ratio 0.01. Metakaolin was chosen as the mineral additive in the mix design other than silica fume, because of its favorite white color to achieve the light color of the final products. The liquid latex used had several functions. It worked as a dispersant for fiber distribution, as a wetting agent for fibers to attain better bond with cement matrix and as a water proofing membrane to enhance the resistance of the final product to the water permeability. Extrusion process was used to fabricate the thin sheets. Since extrusion was a dough process, the extrudability of a material was adjusted by using appropriate amount of water. It was noticed that the viscosity of an extrudable mix was almost a constant, no matter what the constituent materials were incorporated with. Therefore, the water to cement ratio in the mix design was an indicator of the influence of material constituent change upon the workability. The extrusion process required a process aid to help achieve a dough mix. It was accomplished by using the methylcellulose at a cellulose to cement ratio of 0.01, and was constant for all batches.

Four different types of fibers were employed in the extrusion production of cementitious thin sheets. They were polyethylene terephthalate (PET) fiber, polyvinyl alcohol (PVA) fiber, polyolefin (PO) fiber and AR glass fiber. The mechanical and physical properties of the fibers are listed in Table 2. Except that the PVA fibers were hydrophilic, all the other three depicted a hydrophobic behavior. PET fibers were made from the recycled plastic beverage bottles. AR glass fibers were alkali resistant bundled fibers. There were 102 filaments in one strand. PO fibers were monofilament fibers with the longest fiber length among the four.

Three types of fine aggregates were used as filler to reduce the total cement content and to improve the shrinkage resistance of the final products. They were marble sand, silica sand and class F fly ash. Here the fly ash was used

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as a filler in the mix, rather than the cementitious material. The average particle size of the fly ash was 30 μm . For marble sand and silica sand, a particle size distribution was obtained through sieve analysis. By a series of experiments, it was found that the combination of 75% of sand retaining on 150 μm sieve and passing 300 μm , and 25% retaining on 75 μm sieve and passing 150 μm provided a good extrudability, i.e. an easy flow in extrusion die, a smooth surface of extrudate, and a straight edge without defect.

Two types of latex were experimented in this project: styrene-butadiene (SB) latex and methyl-methacrylate (MMA) latex. The former was formulated to generate a polymer film during the air drying inside concrete, while the latter was to form a powder in the same air drying process. The powder form of MMA latex was able to be transferred into a film form if the material was heated to a temperature of about 150 $^{\circ}\text{C}$. MMA latex was specially developed for concrete products where the autoclaving or steam curing were to be used. Compared to SB latex, MMA latex was relatively not sticky and easier to work with. The development of MMA latex was still in experimental stage. The liquid latex contained nearly half solid polymer and half water with a very small quantity of antifoaming agent. The ratio of solid polymer to cement was kept 0.14 for all the batches, with a HRWR (high range water reducer) to cement ratio 0.01 for water reduction. A batch (#41) only using silica fume plus HRWR, without latex and metakaolin, was also prepared to study the combined effect of mineral additives and chemical additives. For the MMA latex modified thin sheets, the difference between moisture curing and steam curing at 80 $^{\circ}\text{C}$ for 30 minutes was explored.

The mixing procedure was developed typically for fiber-cement extrusion. The details were reported elsewhere (4). In the typical dispersive mixing that was used in most batches, the fibers were first mixed with liquid latex to get dispersed and coated by the polymer, and then the other dry components were added together with the required water and HRWR. The so-called non-dispersive mixing method was also experimented in this research to demonstrate the effect of mixing procedure. In non-dispersive mixing, fibers were added at the very last stage after the dough was formed. The distribution of the fibers was achieved through kneading the dough with the fibers and was not expected to achieve a uniform dispersion. In this way, fibers underwent the minimal mixing action, and thus carried a minimum possible damage. The study was also intended to examine how incomplete dispersion of fiber in fiber-cement thin sheets might affect the performance.

Evaluation of Mechanical Properties

Mechanical properties of extruded thin sheets were evaluated by a three-point bending test. The specimen size was 150 mm long by 76 mm wide by 6 mm thick. The span was 101 mm. The tests were carried out on MTS machine

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with a displacement control at a loading rate of 0.04 mm/s. All specimens from different batches were tested at the age of 7 days, since the previous study had shown that strength and toughness of extruded thin sheets at 7-day had already reached that of 28 days (3). The specimens were cured in a moisture room with a 95% relative humidity for six days, and dried in an environmental chamber with a 50% relative humidity for one day before testing. The drying process was to let latex to form a thin film. At least three samples were tested for each batch at the specified age. The complete flexural stress versus deflection curves, as well as the strength and the area under the curves, were used to investigate the influence of the material constituents and processing parameters on the performance of fiber reinforced cementitious thin sheets.

RESULTS

Effect of Types of Fibers

Fig. 1 shows the typical flexural stress - deflection curves of fiber-cement thin sheets reinforced by four different fibers with the same matrix material. The marble sand was used at a sand to cement ratio of 0.65. To keep the consistent viscosity of an extrudable mix, water to cement ratio (W/C) was adjusted accordingly (Table 1). PO fiber required the least water content, while PET fiber consumed the most. The flexural strength was not necessarily proportional to the water to cement ratio. Rather, it was dependent on the fiber strength. The glass fiber led to the highest strength in thin sheets, followed by PVA fiber, PO fiber and PET fiber. Although the PVA fibers were five times stronger than PO fibers, the first crack strengths of the two thin sheets were pretty close. The toughness of the material was represented by the postpeak behavior. The glass fiber thin sheets exhibited a strain softening type of response, whileas the PVA fiber composites demonstrated a postpeak strain hardening behavior. Both PO fiber and PET fiber thin sheets underwent sudden load drop, but maintained a large postpeak deflection which was attributed to the process of fiber stretching and fiber pullout. It was the long fiber length in PO fiber thin sheets that contributed to the large postpeak deflection. It seemed that the hydrophilic PVA fibers had better bond with cement, generating a postpeak strain hardening response with a distributed multiple matrix microcracking and without sudden load drop. This ductile behavior was important in the applications where the impact resistance of the thin sheets was required.

Effect of Sand Content

The effect of sand content on strength and toughness of thin sheets was studied by using three sand to cement ratios: $S/C = 0, 0.33$ and 0.65 . The typical flexural stress and deflection curves of the sheets from the three batches are plotted in Fig. 2. PVA fibers of 3% by volume were employed in all batches. It was obvious that the higher the sand content, the lower the peak load and the less the toughness, although the strength at the initial drop were about the same. The behavior was indicative of a weak postpeak response of the composite in the

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presence of the sand. As was noticed, the bond between fiber and matrix played a critical role in postpeak response of a composite, if the fiber length was a constant. The presence of sand in the matrix reduced the cement content and thus weakened the interfacial bond of fiber with the matrix. Nevertheless, the use of the sand with certain size distribution was helpful to achieve the extrudability at a lower water to cement ratio.

The comparison of three different fine aggregates: marble sand, silica sand and fly ash, is presented in Fig. 3 with a sand/cement ratio 0.65 and a fiber volume ratio 0.03. Silica sand performed slightly better than the marble sand in terms of the strength and toughness of the thin sheets. However, the fly ash didn't behave satisfactorily as a fine aggregate. Because of the small particle size, fly ash batch consumed a large quantity of water to keep the consistent viscosity for processing, leading to a reduced strength. It seemed that use of fly ash as fine aggregate in extrusion process was not appropriate.

Effect of Mineral and Chemical Additives

The basic constituent materials used in this study were metakaolin as mineral additive for its favorite white color, plus latex and high range water reducer as chemical additives. The fiber-cement thin sheets with these constituents were also compared with that made of silica fume plus HRWR, which turned out to have a dark color. The result is shown in Fig. 4. They were the composites with 3% PVA fibers and having no sand. Taking the percent of cement as the reference, batch #20 contained 20% metakaolin, 14% solid latex and 1% HRWR, while batch #41 used 18% silica fume and 3% HRWR. Apparently, the silica fume batch had lower ultimate strength and less ductility, although the prepeak behavior was not much different in the two mix designs. It was the enhanced bond of the fiber with the matrix by the help of latex that contributed to the better postpeak performance in the latex bonded thin sheets.

Effect of Types of Latex

Fig. 5 compares the flexural responses of the thin sheets containing two different latexes: SB latex and MMA latex. They had same fiber content (3%) and same silica sand to cement ratio (0.33). No significant difference in their mechanical properties was observed after six days cured in moisture chamber and one day dry at 50% relative humidity.

Steam curing was also adopted as special curing for Batch #38 with MMA latex in order to form the water proofing film in cement thin sheets at an elevated temperature. Steam curing was carried out after the samples were hardened during a 24-hour initial curing. The thin sheet were then placed in a steam chamber at a temperature of 80 °C for 30 minutes steam curing. After cooling down, the samples were left in the moisture room for further curing, as was done for all the other batches. The comparison between the steam cured and the moisture cured was shown in Fig. 6. Steam cured thin sheets exhibited an