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Some Developments in Polypropylene Fibers for Concrete

By Antoine E. Naaman, Surendra P. Shah, and James L. Throne

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Synopsis: The main purpose of this project was to explore the feasibility of using newly developed polypropylene (PP) fibers as reinforcement for portland cement concrete and to compare their reinforcing effectiveness with asbestos, glass and steel fibers. The PP fibers used were made of a high tensile strength (up to 80 ksi), high modulus (up to 10^6 psi), high stretch ratio (up to 12 to 1) polypropylene ribbon yarn supplied by AMOCO Synthetic Fabrics. The fibers were cut from a continuous strand obtained by properly twisting two PP ribbon yarns together. Twisting led to a substantial increase in the bonding properties of the fibers (mechanical bond) and their rigidity considered important during mixing. Different fabrication procedures and mortar mixes are described. Salient results of an extensive series of tests on flexural beams and pull-out tests to improve bonding properties are reported. Because steel, glass, asbestos and polypropylene have substantially different specific gravities, performance comparison is made not only on the basis of volume fraction of fibers but also weight fraction and related costs. It stresses the potential merits of using PP or equivalent organic fibers in concrete matrices and suggests exciting research directions to pursue.

Keywords: asbestos; bonding; costs; cracking (fracturing); fiber reinforced concretes; flexural strength; glass fibers; metal fibers; plasticizers; polypropylene fibers.

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INTRODUCTION - OBJECTIVE

In the early sixties, Goldfein (1) tried polypropylene (PP) fibers as concrete reinforcement in the construction of blast resistant structures for the U.S. Corps of Engineers. The addition of small amount of PP fibers (less than 0.5% by volume) led to a substantial increase in the ductility and impact resistance of the composite. His work provided an incentive to Shell Chemicals to develop their "caricrete" material which essentially consists of polypropylene fiber films and concrete (2). Common applications of PP fiber reinforced concrete include pile caps, pipes and coastal land-fill structures (3,4).

PP fibers have some unique properties that make them very compatible for mixing with concrete matrices. They are chemically inert and very stable; they have a hydrophobic surface hence do not absorb part of the mixing water; they are light; they can achieve a relatively high tensile strength; and they can be fabricated in many forms at unit costs competitive with if not cheaper than other types of fibers. Some of their shortcomings include a relatively low modulus of elasticity, a low melting point, combustibility and poor bond with the cement matrix.

When compared to other fiber reinforced cement composites, discontinuous PP fiber cement composites have shown so far two distinctive characteristics in their load-deflection response under loading: the load-deflection curve drops substantially after first matrix cracking and a large increment of deflection (hence crack width) is needed before the resistance to applied load picks up again (Fig. 1, curve a). This behavior is believed

due mainly to the low elastic modulus and bonding properties of the fibers and the relatively small volume fraction of fibers used in the composite. The above described drawbacks were overcome in part by Hannant, et al. (5) who used continuous nets of polypropylene fibrillated films in cement boards. PP fibrillated films offer relatively high strength (up to 100 ksi (700 MPa)) and high elastic modulus (more than 1000 ksi (7000 MPa)). Two additional observations can be made from their study in comparison to earlier ones: a relatively high volume fraction of reinforcement (up to 7%) was used and the bond was substantially improved mechanically because continuous nets of film were used instead of discontinuous fibers. Surprisingly, these two characteristics can also be used to describe ferrocement (see definition in Ref. 6). The study reported in (5) showed that a substantial improvement in the post-cracking response of the composite can be achieved. Combined with the addition of superplasticizers to reduce water content in the cement matrix and improve the cracking strength, a load-deflection response similar to curve b in Fig. 1 can be obtained. However, the main drawback of using PP fibrillated films is the difficulty of fabrication of the composite whereas the continuous nets have to be placed in large numbers of layers and properly penetrated by the matrix. In a recent investigation, Dave and Ellis used the spray technique combined with suction de-watering to produce PP fiber cement composites with up to 8% volume fraction of fibers (7). They still observed a substantial drop in the load-deflection response after cracking (Fig. 2) and a similar behavior was reported in (8).

In 1978 AMOCO Chemicals sponsored a cooperative research study with the first two authors to explore the feasibility of using PP fibers in cementitious matrices and to compare their reinforcing effectiveness with other common types of fibers such as asbestos, glass and steel fibers. One of the major objectives of the project was to develop a PP fiber and a cement composite to achieve a load-deflection response in flexure with the following characteristics (Fig. 1, curve b): high cracking strength, little or no drop in load at cracking, multiple cracking at increasing deflections, a post-cracking response with a relatively high slope (modulus) and high strength. This paper attempts to summarize the highlights of the study and its main findings. A comparison of the main mechanical properties and relative costs of commonly used fibers is given next to provide some necessary background.

COMPARATIVE PROPERTIES OF FIBERS

Detailed information on the important properties of fibers most commonly used in cementitious matrices can be found in (9). Table 1 attempts to present a fact sheet about the four types of fibers used in this study: polypropylene, glass, steel and asbestos fibers. Several observations are in order:

1. Although the strengths of these fibers are comparable for all practical purposes (often the full strength is not utilized in the composite), their elastic moduli are substantially different. In particular, the elastic modulus of polypropylene is about eleven times smaller than that of glass and thirty times smaller than that of steel. Hence to develop the same contribution in resisting applied loads, polypropylene fiber reinforced composites will deform (or stretch) much more than composites using steel, glass or asbestos fibers. Note that the contribution of the fibers to the tensile strength of the composite is itself limited by the bond strength that can develop at the interface between the fiber and the concrete; that is why the tensile strength of the fiber is seldom fully utilized.

2. To describe fiber content, the volume fraction of fibers in the composite is used instead of the weight fraction. The optimum fiber content varies with the type of fiber and is mostly limited by practical considerations related to ease of dispersion, segregation and the like. It is known, for instance, that an increase in steel fiber content may lead to balling, segregation and non-uniform distribution. In a similar manner, an increase in glass fiber content may lead to a very harsh mix, an increase in entrapped air, a reduction in density and a deterioration of properties.

3. The specific gravity of steel is about nine times that of polypropylene. The specific gravity of glass or asbestos is about three times that of polypropylene. Hence for the same volume fraction of fibers in a given composite, the weight of steel fibers would be nine times that of polypropylene and the weight of glass fibers would be three times that of polypropylene. As fibers are bought on a weight basis, polypropylene may have a substantial cost advantage.

4. In order to illustrate a possible cost comparison between various fibers, Table 2 is proposed. It assumes current market prices in the U.S. (1981) for steel, glass and asbestos fibers and a range of prices for polypropylene. The comparison is based on the same volume fraction of fibers in a typical composite. For instance, if the cost of polypropylene is 1.2$/lb, then using steel fibers or glass fibers to supply the same volume content as polypropylene would cost three times more than using polypropylene fibers. Another way to interpret the data of Table 2 is related to performance. For instance, if the cost of polypropylene fibers is $1.2/lb and if for the same volume content the composite performance is lesser than that using glass fibers, then one can attempt to use in the composite up to three times more polypropylene than glass and still be cost effective. A wide range of unit costs was assumed for polypropylene fibers in Table 2 to reflect various degrees of difficulty in manufacturing (such as twisting and drawing at high ratios) and to account for the uncertainty associated with a small scale production.

EXPERIMENTAL PROGRAM AND TESTING PROCEDURE

Because the main objective of the study was to improve the composite behavior (Fig. 1, curve b) by continuously learning from previous work and building up on it, a wide variety of ideas was explored. An extensive series of tests on flexural beams (more than one hundred series) and fiber pull out (to determine bond properties) was undertaken in addition to a limited number of tensile tests on standard ASTM briquettes. The flexural beams included a group reinforced with continuous meshes of polypropylene fabrics (not described here because of space) and a group reinforced with discontinuous fibers. The latter group comprised PP, glass and steel fiber reinforced mortar beams as well as asbestos cement beams cut from commercially available sheets (trade name Transite by John Mansville).

Fiber Properties

The glass fibers used in this investigation were cut from strands (Table 1) in 1 in. (25.4 mm) length. They were supplied by Corning Glass. The steel fibers were brass coated cut from wires with the following properties: length = 0.75 in. (19 mm) and diameter = 0.016 in. (0.41 mm) (supplied by National Standard Company). Various types of PP fibers with various properties were tried. They mostly included the following: 400 D (Denier; a Denier is the mass in grams of 9000 meters of yarn) monofilament fiber, 500 D one-ply twisted ribbon yarn with a number of twist per inch varying from about 1 1/2 to 6 and 2 x 500 D two-ply twisted ribbon yarn with about 3 to 6 twists per inch and draw ratios (or stretch ratios) varying from 6 to 1 to 12 to 1. Because in a first phase of the investigation the two-ply twisted fibers led overall to the best results a larger number of tests were carried out using these fibers. They had the following properties: draw ratio more than 8 to 1, tensile strength about 85 ksi (586 MPa), an initial modulus of elasticity of the order of 980 ksi (6760 MPa) and an average elongation at failure of 21%. All PP fibers were cut to about 1 in. (25 mm) length.

Mixing Procedure

Two main mixing methods were followed in this study: premixing the fibers with the mortar matrix and using a premixed mortar to impregnate a 3-D mat of fibers.

In the premixing method, the non-fiber components (cement, sand, water and superplasticizer) were mixed first using a sufficient proportion of water (in which the superplasticizer was already diluted) to render the fresh mix liquid-like. Then the

fibers were slowly added until the mix lost most of its fluidity. The remaining fibers and water were then slowly added trying to keep a balance between harsh mix, fiber content and water content. This procedure was mostly necessary when the total volume content of fibers was relatively large while the water content was relatively small. To understand the above procedure, it is important to keep in mind the difference in specific gravity between the fibers and the mortar matrix which has a density $\gamma \simeq 2.1$ to 2.4. If the mortar is too liquid, PP fibers ($\gamma = 0.91$) tend to float while steel fibers ($\gamma = 7.86$) tend to sink. In either case, uniform dispersion of the fibers is lost and the composite properties will greatly vary. Because of this element it is necessary to maintain a mix with sufficient workability.

An additional mixing element was found to be important in this investigation and is described as the "apparent or bulk volume" of the fibers in relation to the volume of mortar. The "apparent volume" of the fibers can be described as the volume they occupy if they are placed by dispersing in a container. It is substantially different from the "solid volume" of fibers. The apparent volume is related not only to the fiber packing but also to their shape, diameter and length. The shape of the fiber itself may be such that it entraps air, hence occupying a larger volume than theoretically predicted.

Another method of obtaining the composite (different from the premixing method) was also used in this project. It can be described as the "impregnation" method. In this method, a fiber mat (Fig. 3) is preplaced in a mold and the premixed mortar matrix is then applied, accompanied by vibration to insure a better penetration. The advantage of this technique is that the mortar or paste can be optimally designed independently of the fiber type and content. Disadvantages include a higher probability of entrapping air and the tendency of the mat to float during vibration, hence requiring better control of fabrication.

Mortar Mixes

Three different mortar mixes were mainly used in this investigation. They are described in Table 3. The richer mix (Mix III) had a smaller proportion of fine sand (all passing ASTM sieve No. 40). It was designed to achieve mostly a high first cracking strength. A superplasticizer (Melment) was used to increase fluidity during mixing, hence allowing a reduction in water content and a strength increase in the hardened matrix. In most series of tests involving high volume fractions of fibers, all components were precooled to about 40°F (5°C) prior to mixing to delay the hydration reactions and keep the mix as workable as possible for the time period needed to prepare the specimens.

Forming - Fabrication

Specimens were poured in plexiglass molds according to one of the following three procedures: using horizontal molds (the width - length plane is horizontal), vertical molds (the width - length plane is vertical) or a horizontal bed equipped with a vibrator-screeder. In this latter case sheets of dimensions 12 x 36 x 1/2 in. (305 x 915 x 12.5 mm) were prepared from which specimens of dimensions 12 x 3 x 1/2 in. (305 x 76 x 12.5 mm) were later cut for testing. All flexural specimens had the same dimensions.

The mold bed with the vibrator-screeder was built to simulate the possible production of manufactured sheets by spreading the composite and applying a high level of vibration and compaction. The procedure seems promising and the composite obtained is only limited by the amount of fibers that can practically be premixed. The same bed with the vibrator-screeder was also used in combination with a pre-placed fiber mat and impregnated by a mortar matrix. Provided the mat has the proper characteristics, the procedure did not offer any difficulty. However, the composite obtained from the mat did not (in general) show better properties than that obtained by premixing, perhaps because of a higher amount of entrapped air and insufficient penetration by the matrix of the volume enclosed by the individual twisted fibers.

All specimens were generally taken off the molds 24 hours after pouring and kept at 100% relative humidity and 72°F for one week to one month before removal and testing.

Testing Procedure

All testing was performed using an "Instron" Universal testing machine. For the flexural beams a four-point loading arrangement with a 10 in. (254 mm) span and a 4 in. (102 mm) constant bending moment zone was selected. The rate of stroke was 0.5 in/min (12.5 mm/min). The load-deflection response was automatically plotted on an x-y recorder. The beams were generally loaded to failure or 0.5 in. (12.5 mm) deflection whichever occurred first. The pull-out tests were run using the half portion of an ASTM standard briquette in a manner similar to earlier tests described in (10).

SUMMARY OF RESULTS

Following is a global summary of salient results achieved to date.

PP Fiber Bond

The efficiency of fiber reinforcement depends not only on the mechanical properties of the fibers but also on the bond at the interface between the fibers and the matrix. Untreated PP is known to have poor bonding properties. To improve its bond with concrete, the following approaches were tried: treating the fiber surface to become hydrophilic, adding buttons at the ends of the fibers (Fig. 4) and twisting the fibers (Fig. 5). The last two approaches add essentially to the mechanical bond and led to the best results (Figs. 6 and 7). The bond of PP fibers was improved from a value of about 80 psi (0.55 MPa) to a value of about 500 psi (3.45 MPa). Two-ply twisted fibers were selected as economically most feasible and because their immediate fabrication was within the capability of AMOCO Fabrics. Twisting had also the advantage of producing a rigid fiber system which kept its straight shape during mixing and was found desirable for the composite post-cracking strength and modulus. One hundred pounds of twisted fiber strands were fabricated by AMOCO Synthetic Fabrics (2 x 500 D ribbon yarn, 3 to 6 twists per inch, draw ratio of 8 to 1). Fibers about 1 in. (25 mm) long were cut from the above strands by various techniques, mixed with concrete in various amounts and tested. Their reinforcing effectiveness was compared with that of glass, steel and asbestos fibers and is described next.

Flexural Tests

In analyzing the flexural test results an attempt was made to achieve the highest possible performance for each fiber composite. In the case of asbestos cement, a manufactured product considered best in its category (Transite by John Mansville) was used. It contains 15 to 18 percent by volume of asbestos fibers and achieved an average modulus of rupture of about 4500 psi (31 MPa). For the other composites, particular attention was placed at improving first cracking strength, the post-cracking behavior (modulus, multiple-cracking), the strength or the stress at about 0.5 in. deflection and the general shape of the load-deflection curve (sharp drop at first cracking, slope).

Typical results are shown in Figs. 8 and 9. It can be generally observed that although a high modulus of rupture can be achieved with asbestos cement through a manufactured process, the failure behavior is brittle and no post-cracking response seems to exist. The response of the other composites (lab produced) suggests that PP fiber composites compare very well with steel and glass fiber composites for the modulus of rupture, especially if the weight percentage of fibers is considered instead of the volume (Fig. 9). Moreover, the response of the PP fiber reinforced mortar beams after first cracking and their multiple

cracking characteristics was outstanding in comparison to the other composites as seen in Figs. 10 and 11. A rapid comparison of areas under the load-deflection curves and weight fractions of fibers (Fig. 9) suggests that PP fibers increase the toughness (or energy absorbing capability) of mortar substantially more than steel, glass or asbestos fibers.

The flexural test results using discontinuous PP fiber mats were not as good as those obtained from premixing the fibers. This is mainly due to the poor penetration of the matrix through the mat and around its individual fibers. A comparison of load-deflection curves of two series of tests using a fiber mat with that of a series using premixed fibers is shown in Fig. 12. Research is being continued to improve the performance of the mat system.

SUMMARY OF PERFORMANCE AND CONCLUSIONS

The performance of PP fibers and PP fiber reinforced cementitious composites as derived from this study is qualitatively described in the following items. The background to some of the conclusions is not documented here because of space limitations.

1. The best bonding properties of PP fibers with concrete were obtained by improving the mechanical bond, namely adding end buttons to the fibers or twisting them. Twisting was easier to achieve in a short time from a production viewpoint.
2. Although the bond strength of a single-ply twisted fiber was equivalent to that of a two-ply twisted fiber, the mixing performance of the two-ply twisted fiber was superior because the fiber was more rigid and kept its straight shape during mixing.
3. Everything else being equal, PP fibers with a high draw ratio (hence high strength and modulus) led to a better composite performance than PP fibers with a small draw ratio. The ultimate tensile strain of the fibers was always sufficient and was never fully utilized in the composite.
4. Using the two-ply twisted fibers (1 in. long, 2 x 500 D, 3 to 6 twists per inch), the optimum composite performance was achieved by premixing the fibers in amounts of about 4 to 5% by volume. It was not practical to mix a larger volume.
5. The addition of latex to the composite did improve the first cracking strength of the composite and allowed the addition of a higher volume fraction of fibers (10% higher than the mix without latex). This improvement was judged insignificant when compared to the additional cost of latex.
6. Everything else being equal, composites made with fibers premixed in the concrete matrix were superior to those made with a fiber mat impregnated by the matrix. This is perhaps due to the higher amount of air entrapped (when 3-D mats are used)

during fabrication and the lack of penetration by the matrix of the twisted portions of the fibers.

7. Small diameter fibers (such as 2.8 D, 12 mm long used in some European applications) are too thin (fine) to be practically mixed in proportions of more than about 2% by volume of the concrete matrix. This is because they have a tremendous surface area to be wetted (bonded) by the matrix and when mixed they occupy a very large apparent volume. The use of these fibers may be limited to applications requiring a small volume fraction of fibers (pile caps) or non-conventional mixing procedures.

8. Now that the goal of developing a discontinuous PP fiber reinforced cementitious composite with high mechanical performance seems within reach, attempts should be made to develop an efficient and economical production procedure for sheet-like applications such as those utilizing asbestos cements.

ACKNOWLEDGEMENT

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Table 1 Comparison of Typical Fiber Properties

	Specific Gravity	Tensile Strength ksi (MPa)	Young's Elastic Modulus 10^6 psi (GN/m^2)	Elongation at Failure %	Common V_f %	V_f % This Study	Common Diameter, Equivalent Diameter or Denier[a]
Polypropylene (This study)	0.91	85 (586)	0.98 (6.8)	21%	less than 2%	2 to 6%	Single Filament or Staple: 2 to 2000 D[a] Bundle: Any diameter
Glass (204 filament strand)	2.7	up to 180 (1241)	11 (76)	≈ 3.5%	4 to 6%[b]	2 to 3%	Strand: 0.0044 x 0.026 in. (0.11 x 0.66 mm) Equivalent Diameter: 0.012 in. (0.30 mm)
Steel	7.86	100 - 300 (700 - 2100)	30 (207)	≈ 3.5%	less than 2%	2 to 3%	Diameter: 0.005 to 0.040 in. (0.12 to 1 mm)
Asbestos a. Chrysotile b. Crocidolite	2.55 3.37	Fiber Bundle: 30 - 260 (210 - 2000) up to 500 (3500)	23 (159) 28 (193)	2 to 3% 2 to 3%	7 to 18%	15 to 18% "Transite"[c]	510 to 76000μ in. (13 to 1930 μm) 2500 to 50000μ in. (63 to 1270 μm)

[a]Denier = mass in grams of 9000 m of yarn. [b]By the spray technique. [c]Manufactured by John Mansville.

Table 2 Relative Cost Comparison Between Various Fibers Assuming Same Volume Fraction (U.S. Costs 1981)

Assumed PP Cost $/lb	Fiber Cost Ratio for Same V_f			
	PP*	Glass $1.2/lb	Steel $0.4/lb	Asbestos $0.25/lb
0.60	1	6	6	1.2
1.2	1	3	3	0.6
1.8	1	2	2	0.4
2.4	1	1.5	1.5	0.3

*Read data in the following two ways: 1. If the unit cost of PP is $1.2/lb, then for the same volume fraction of fibers, the cost of steel or glass will be three times (3) the cost of polypropylene (1). 2. If the unit cost of PP is $1.2/lb and if the performance of PP fiber reinforced concrete is less than that of glass or steel fiber reinforced concrete, then one can put up to three times more volume fraction of PP fibers to improve composite performance and still be cost effective.

Table 3 Typical Mortar Mix Proportions Used

	Mix Proportions by Weight		
	Mix 1	Mix 2	Mix 3[d]
Cement[a]: C	1	1	1
Sand: S/C	1[b]	1[b]	0.4[c]
Water: W/C	0.50	0.40	0.32
Superplasticizer/C (Melment)	0.023[e]	0.023	0.023

[a]Cement mostly ASTM, Type III.

[b]Graded Ottawa silica sand, ASTM C-109.

[c]Fine Ottawa silica sand all passing sieve #40.

[d]All components were cooled (about 40°F) prior to mixing.

[e]Used up to above amount only if necessary.

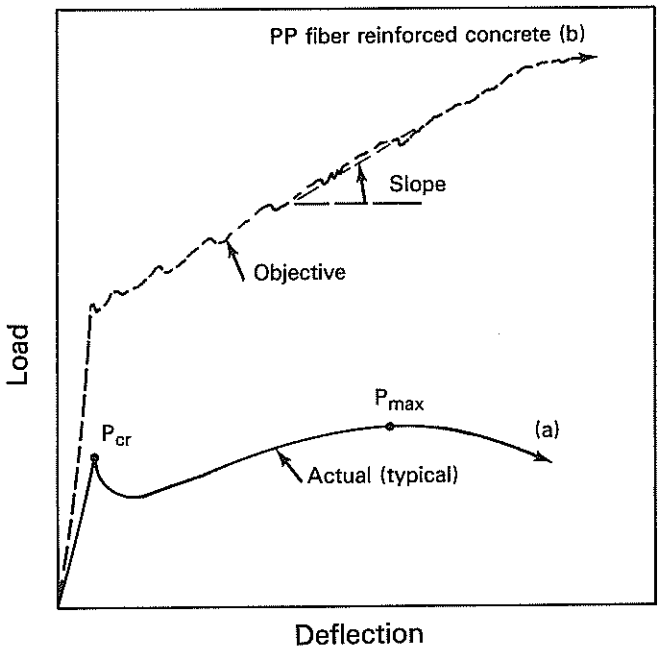


Fig. 1--Load-deflection response of PP fiber-reinforced cement composites: actual and objective

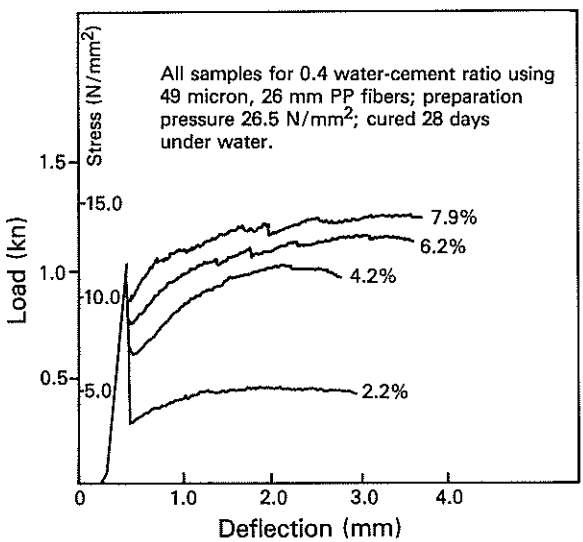
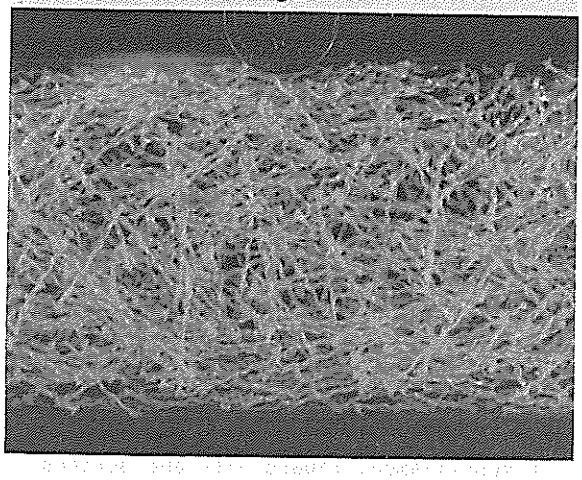
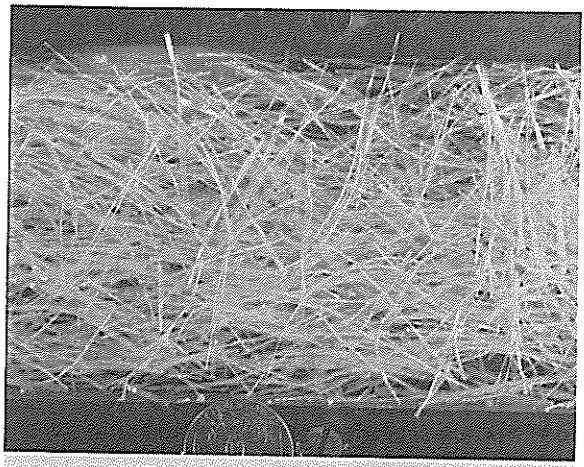


Fig. 2--Typical load-deflection curves of PP fiber-

FD-21 - FIBER MAT - V_f = 6.78% - 2 PLY TWIST





FD-13 - FIBER MAT - V_f = 2.86% - 1 PLY TWIST

Fig. 3--PP fiber mats preplaced in molds

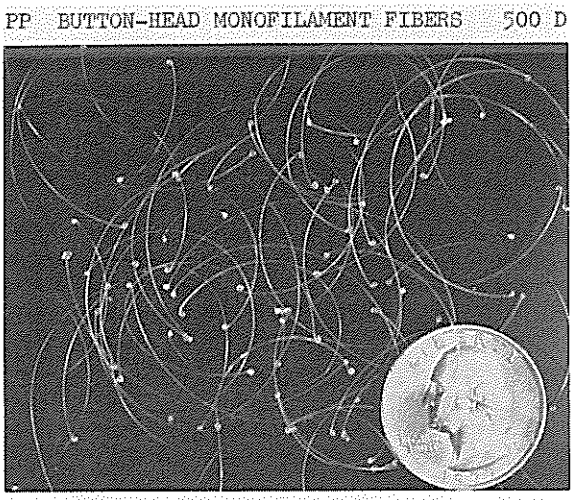


Fig. 4--PP monofilament fibers with end buttons (400 D)

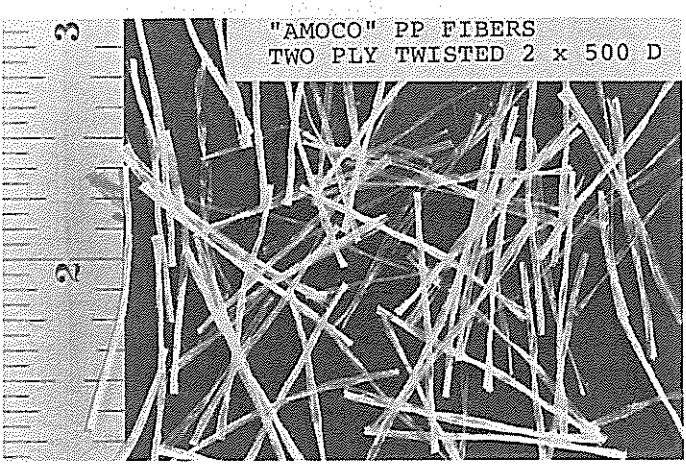


Fig. 5--PP two-ply twisted fibers (2 x 500 D)

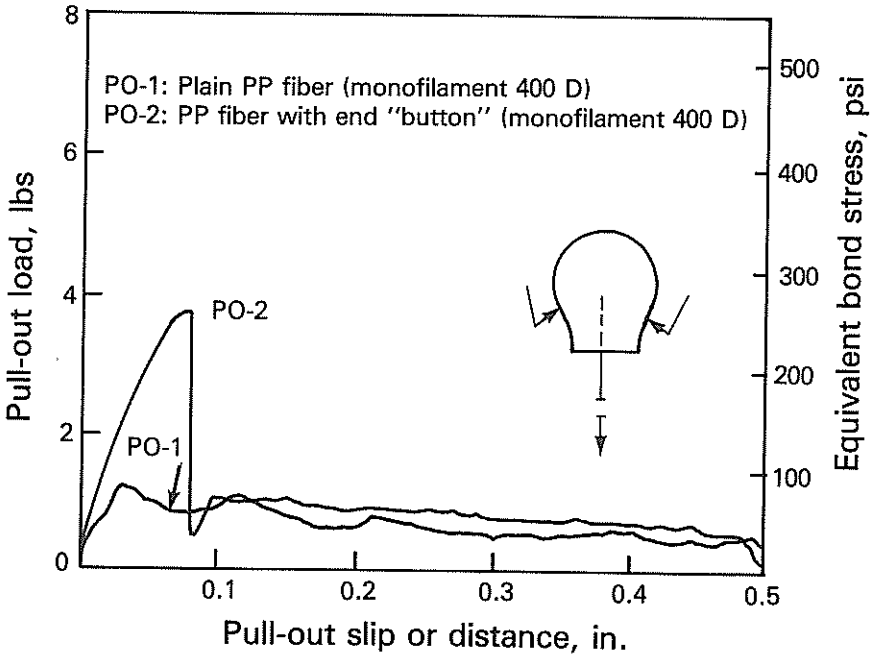


Fig. 6--Effect of end button on the pullout response of PP monofilament fibers (mortar mix No. 2)

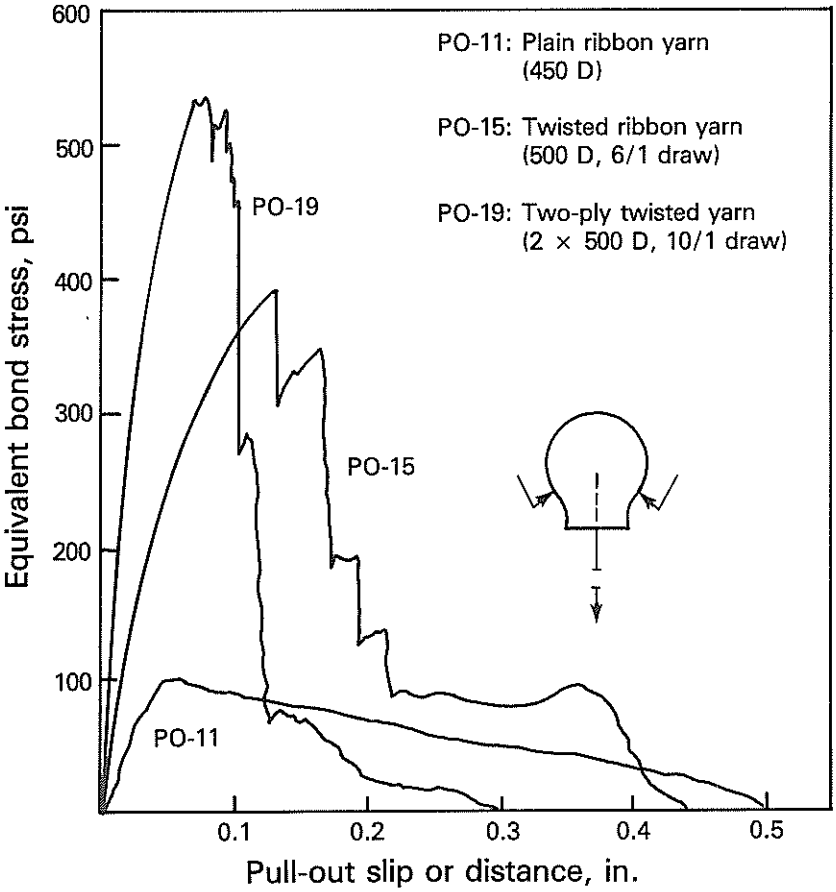


Fig. 7--Effect of twisting on the pullout response of PP ribbon fibers (mortar mix No. 2)

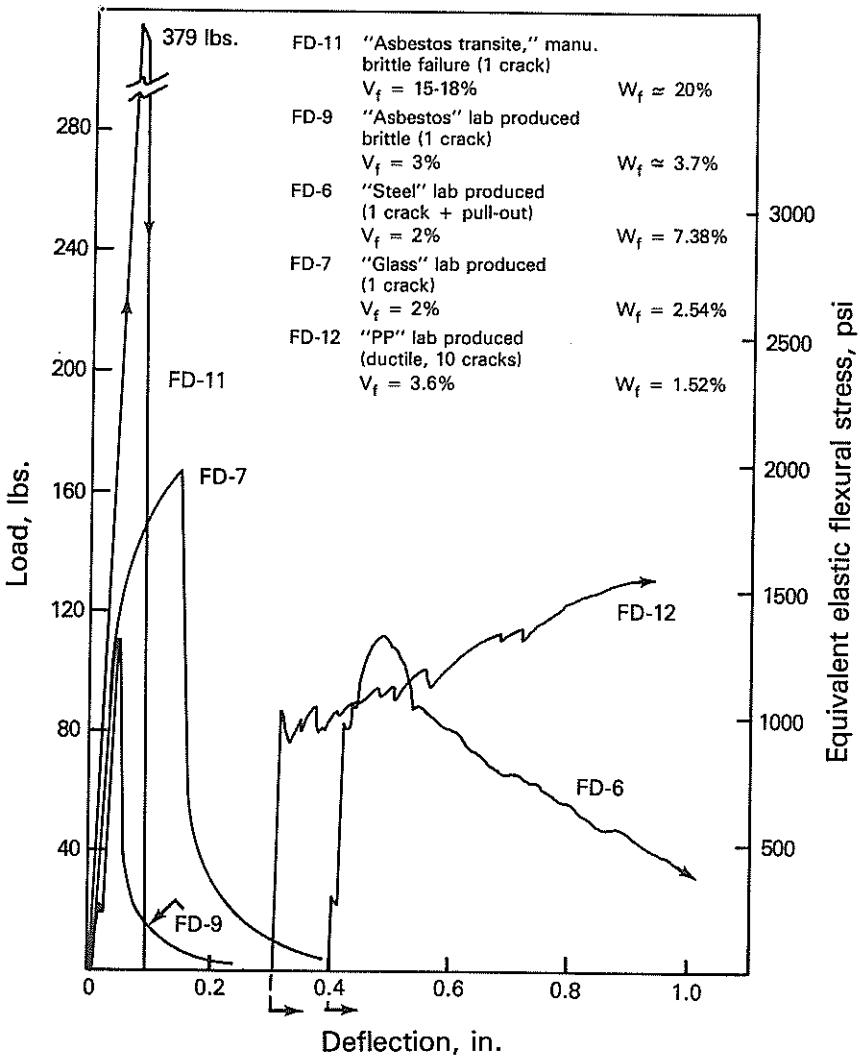


Fig. 8--Comparison of the load-deflection response of various fiber-reinforced cementitious composites (mortar mix No. 1)

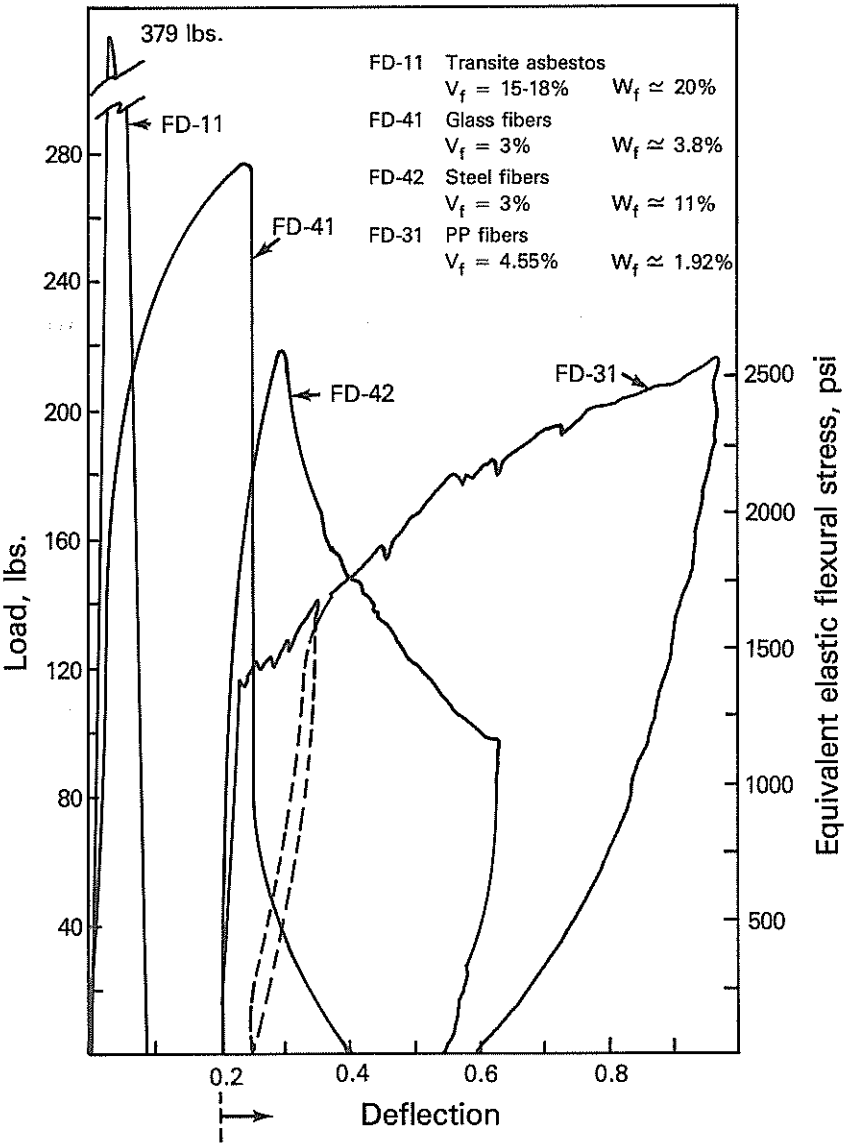
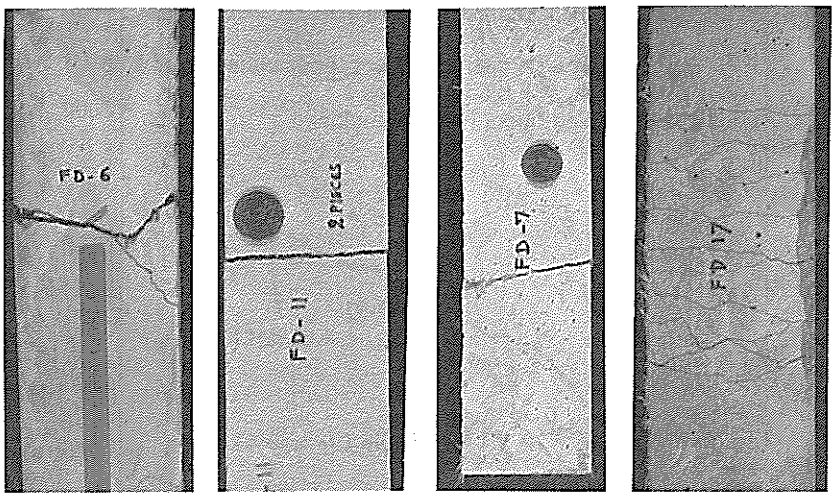


Fig. 9--Best performances achieved using steel, glass and PP fibers and their comparison with that of "Transite" asbestos cement (mortar mix No. 3)



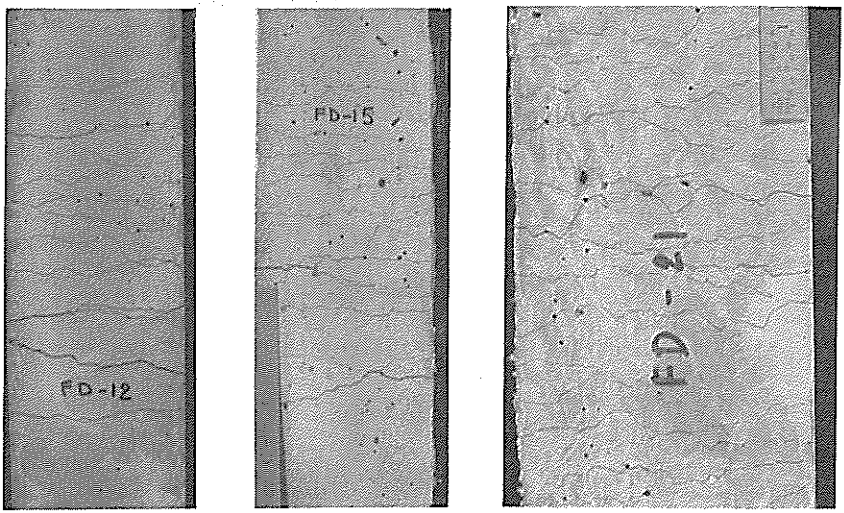
STEEL FRC
V_f = 2%

ASBESTOS TRANSITE
V_f=15-18%

GLASS FRC
V_f = 2%

PP TWO-PLY TWISTED
V_f = 2.13%

Fig. 10--Typical flexural cracking characteristics of various fiber reinforced cementitious composites



PP 1 PLY TWIST
6/1 DRAW
V_f= 3.62%

PP 2 PLY TWIST
8/1 DRAW
V_f = 2.5 %

PP MAT 2 PLY TWIST
6/1 DRAW
V_f = 6.78 %

Fig. 11--Typical multiple cracking in flexure of PP fiber-reinforced mortar

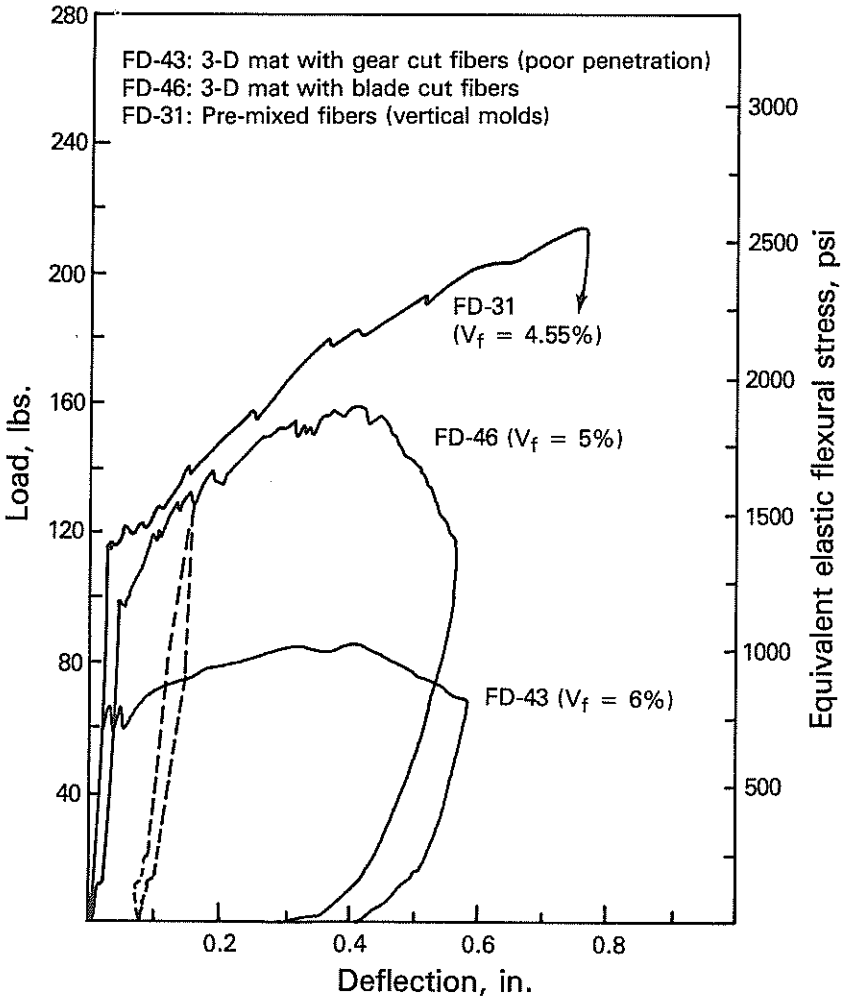


Fig. 12--Comparison of load-deflection curves using PP 3-D mats or premixed fibers