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A Comparative Study of Concretes Reinforced with Carbon, Polyethylene, and Steel Fibers and Their Improvement by Latex Addition


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Mortars containing carbon, polyethylene, and stainless steel fibers at the same volume fraction and with similar fiber diameters were compared in terms of tensile, compressive, and flexural properties. Carbon fibers, though having the lowest tensile modulus, strength, and elongation at break among the fiber types, gave mortar of the highest tensile strength and lowest cost; polyethylene fibers, due to their high ductility, gave mortar of the highest flexural toughness; and steel fibers gave mortar of the highest flexural strength. The tensile, compressive, and flexural strengths and flexural toughness were all increased by latex addition for any fiber type.

Keywords: carbon; concretes; fibers; latex (plastic); mortars (material); plastics, polymers, and resins.

INTRODUCTION

Concrete reinforced with short fibers has received considerable attention recently due to the high toughness and increased tensile and flexural strengths provided by the fiber addition. The fibers used are mainly steel fibers,[1-3] carbon fibers,[4-7] and polymer fibers.[8,9] Among the polymer fibers, polyethylene fibers have attracted most attention due to the outstanding toughness of concrete reinforced with them.[8,9] Carbon fibers also have attracted attention due to their ability to provide concrete that can sense strain or stress without the need for embedded or attached sensors, such as optical fibers.[7,10] Steel fibers remain one of the most commonly used fibers for reinforcing concrete. Due to the recent progress mentioned previously, a systematic study is needed to compare the mechanical properties of concretes reinforced with steel, carbon, and polyethylene fibers. Although these concretes have been studied separately by previous workers, their comparison at the same mix proportions, fiber volume fraction, processing conditions, and mechanical testing conditions has not been made previously. Thus, an objective of this paper is to compare these concretes systematically in terms of tensile, compressive, and flexural properties as well as cost.

Latex-modified concretes have received considerable attention recently due to their high flexural strength, high compressive strength, high toughness, and low permeability.[11-15] The combined use of carbon fibers with latex-modified concrete further increases flexural strength and toughness while decreasing compressive strength and chemical attack resistance slightly, compared to concrete containing latex but no fibers.[5,6,16] The effect of latex addition on concretes containing steel or polyethylene fibers has not been reported previously. Because latex-modified concretes are expensive, the further addition of fibers is more acceptable economically than the addition of fibers to concrete without latex.[5] Therefore, this paper compares latex-modified mortars containing steel, carbon, and polyethylene fibers, in addition to assessing the effect of latex addition in each type of fiber evaluated.

RESEARCH SIGNIFICANCE

This paper provides a comparative study of the tensile, compressive, and flexural properties and the cost of mortars containing various types of short fibers (steel, carbon, and polyethylene) at the same fiber volume fraction and fiber length and subjected to the same mixing procedure.

EXPERIMENTAL METHODS

Materials

Properties of the steel, carbon, and polyethylene fibers are shown in Table 1. The polyethylene fibers used were the highest grade polyethylene fibers available, whereas the carbon fibers used were the lowest grade carbon fibers available. These choices are the same as in previous work in recent years. The steel fibers used in previous work are most commonly of 500-μm diameter (resembling toothpicks in

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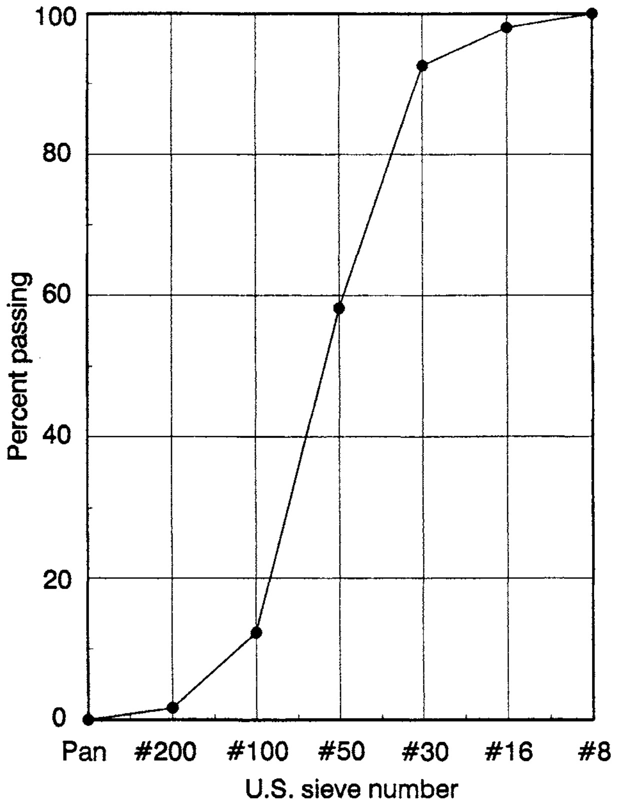

Fig. 1—Particle size analysis of sand

size) and are available in the form of stainless steel fibers ($1.00/lb) and carbon steel fibers ($0.45/lb).[3] In contrast, the steel fibers used in this work were 60 μm in diameter. This choice of steel fibers was based on the need to compare the effectiveness of steel, carbon, and polyethylene fibers of comparable sizes in reinforcing concrete. Steel fibers used in previous work include smooth (straight) and deformed (bent or corrugated) ones. In this work, smooth steel fibers were used. Carbon and polyethylene fibers also were smooth, since comparison among the fibers is an objective of this work.

Table 1 shows that the carbon fibers have the lowest tensile modulus, strength, and elongation at break among the three fiber types. Polyethylene fibers have much higher tensile modulus, strength, and elongation at break than the carbon fibers, but they are more expensive per unit weight as well as per unit volume. The diameter is larger for polyethylene fibers than carbon fibers. The steel fibers have even higher modulus than the polyethylene fibers, but their tensile strength and elongation at break are lower than that of the polyethylene fibers. The diameter and price of steel fibers

Table 1—Properties of steel, carbon, and polyethylene fibers

	Steel	Carbon	Polyethylene
Type manufacturer	Stainless 434, International Steel Wool Corp., Springfield, OH	Isotropic pitch, Ashland Petroleum Co., Ashland, KY	High modulus, Allied-Signal, Inc., Petersburg, VA
Trade name	—	Carboflex	Spectra 900
Length, mm	5	5	5
Diameter, μm	60	10	38
Density, g/cm^3	7.7	1.6	0.97
Modulus, GPa	200	48	117.3
psi	2.9×10^7	6.7×10^6	1.7×10^7
Elongation at break	3.2 percent	1.4 percent	5-8 percent
Tensile strength:			
MPa	970	690	2588
psi	1.4×10^5	1.0×10^5	3.8×10^5
Volume electrical resistivity, Ωcm	6×10^{-5}	3×10^{-3}	—
Price, $/lb	6.40	9	22
Price, $/cm^3	0.11	0.032	0.047

Table 2—Mix proportions for specimens with and without latex

Specimen type	Volume percent fibers	Water-cement ratio		Sand-cement ratio
		Without latex	With latex	
Compressive	0.37	0.30	0.30	1
Tensile	0.53	0.32	0.23	0
Flexural	0.35	0.32	0.23	1

are the highest among the three fiber types. All fibers have the same length of 5 mm.

The cement was portland cement (Type I). The sand was natural sand, with the particle size distribution shown in Fig. 1. The sand-cement ratio, water-cement ratio, and fiber volume fraction are shown in Table 2. Sand was used in specimens for compressive and flexural testing, but not used in specimens for tensile testing because of the small cross-sectional area of the dog-bone-shaped tensile specimens (30 x 20 mm in the narrow part of the dog bone shape). No coarse aggregate was used in any specimen. For each specimen configuration (compressive, tensile, flexural), the fiber volume fraction was the same for all fiber types. The water-cement ratio was chosen to maintain the slump around 170 mm. The latex was styrenebutadiene; it was used in the amount of 20 percent by weight of cement and was used along with an antifoam that was in the amount of 0.5 percent by weight of latex. The latex, antifoam, and carbon fibers were first mixed by hand for about 1 min. Then this mix, along with cement, water, and sand (if applicable), were mixed in a mixer with a flat beater for 5 min. After pouring the mix into oiled molds, a vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1 day and then allowed to cure at room temperature in air for 7 days.

Table 3—Tensile properties

Fiber type	Mix type	Strength: MPa, percent	Strength: psi, percent	Modulus: GPa, percent	Modulus: psi, percent	Ductility, percent
Steel	Without latex	1.94 (± 3.2)	281 (± 3.2)	9.03 (± 1.5)	1.31×10^6 (± 1.5)	0.0146 (± 0.2)
	With latex	2.32 (± 1.5)	336 (± 1.5)	5.69 (± 3.3)	8.25×10^5 (± 3.3)	0.0306 (± 0.7)
Carbon	Without latex	2.45 (± 8)	355 (± 8)	10.7 (± 5.3)	1.55×10^6 (± 5.3)	0.0097 (± 2.3)
	With latex	3.15 (± 2.4)	457 (± 2.4)	7.3 (± 1.8)	1.06×10^6 (± 1.8)	0.0413 (± 0.8)
Polyethylene	Without latex	2.13 (± 2.7)	309 (± 2.7)	12.8 (± 2.3)	1.86×10^6 (± 2.3)	0.0173 (± 0.5)
	With latex	2.38 (± 2.4)	345 (± 2.4)	21.2 (± 4.7)	3.07×10^6 (± 4.7)	0.0112 (± 0.3)
No fibers	Without latex	0.88 (± 4.7)	128 (± 4.7)	10.9 (± 3.1)	1.58×10^6 (± 3.1)	0.004 (± 1)
	With latex	3.03 (± 4.5)	439 (± 4.5)	11.5 (± 2.1)	1.67×10^6 (± 2.1)	0.0352 (± 1.2)

Testing procedure

Specimen dimensions depended on deformation mode—compressive, tensile, or flexural. They were all in accordance with ASTM standards for mortars. For all the tests, six specimens of each type were used.

For compressive testing according to ASTM C109-80, specimens were prepared by using a 2 x 2 x 2-in. (5.1 x 5.1 x 5.1-cm) mold. Compression testing was performed using a hydraulic material testing system (MTS). The crosshead speed was 1.27 mm/min.

Dog-bone-shaped specimens of the dimensions shown in Fig. 2 were used for tensile testing. They were prepared by using molds of the same shape and size. Tensile testing was performed using a screw type mechanical testing system. The crosshead speed was 1.27 mm/min.

During compressive or tensile loading up to fracture, strain was measured by the crosshead displacement in compressive testing or by a strain gage in tensile testing.

Flexural testing was performed by three-point bending (ASTM C348-80), with a span of 140 mm (5.5 in). The specimen size was 40 x 40 x 160 mm. Flexural testing was performed using a screw type mechanical testing system. The crosshead speed was 1.27 mm/min. Flexural toughness was calculated from the area under the stress-displacement curve.

Results

Table 3 shows tensile properties. Among the three types of fibers, carbon fibers gave the highest tensile strength, whether latex was present or not; steel fibers gave the lowest tensile strength. Latex addition increased tensile strength with all fibers. Fiber addition increased strength with all fibers when latex was absent, but when latex was present it slightly increased strength in the case of carbon fibers and decreased strength in the cases of polyethylene fibers and steel fibers. Polyethylene fibers gave the highest tensile modulus, while steel fibers gave the lowest modulus whether latex was present or not. Latex addition increased the modulus in the case of polyethylene fibers, but decreased the modulus in the cases of carbon fibers and steel fibers. Fiber addition had little effect on the modulus in all fibers when latex was absent, but when latex was present it increased the modulus in the case of polyethylene fibers and decreased the modulus in the cases of carbon fibers and steel fibers. Polyethylene fibers gave the highest tensile ductility (elongation at break) when latex was absent, but gave the lowest ductility when latex was present. When latex was present, carbon fibers gave the highest ductility. Latex addition increased ductility in the cases of carbon fibers and steel fibers, but decreased ductility in the case of polyethylene fibers. Fiber addition increased ductility with all fibers, whether latex was present or not; however, the effect was much larger when latex was absent.

Table 4 shows tensile, compressive, and flexural strengths (tensile strength values are the same as those in Table 3.) Among the three types of fibers, steel fibers gave the highest compressive strength and polyethylene fibers gave, by far, the lowest compressive strength when latex was absent, but when latex was present polyethylene fibers gave the highest compressive strength and steel fibers gave the lowest. Latex addition increased compressive strength in the case of all fibers, particularly in the case of polyethylene fibers. Fiber addition decreased compressive strength with all fibers when latex was absent; when latex was present, it decreased compressive strength negligibly in the cases of polyethylene fibers and carbon fibers, and decreased compressive strength more significantly in the case of steel fibers.

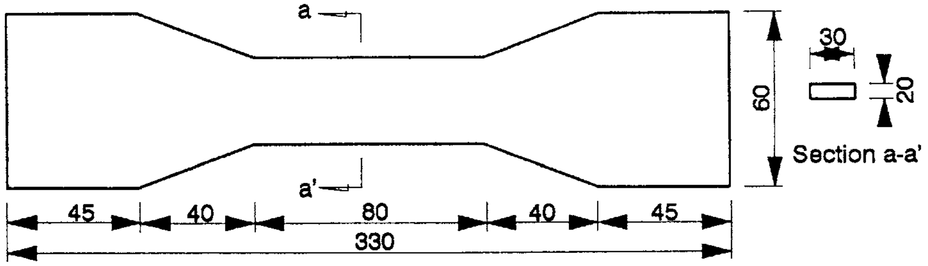

Fig. 2—Geometry of tensile test specimens (numbers in mm)

Table 4—Tensile, compressive, and flexural strength

	Strength, MPa, percent					
	Without latex			With latex		
Fiber type	Tensile	Compressive	Flexural	Tensile	Compressive	Flexural
Steel	1.94 (± 8)	34.8 (± 9)	5.50 (± 15)	2.32 (± 3.7)	35.5 (± 6.7)	9.68 (± 9.8)
Carbon	2.45 (± 8)	31.6 (± 9)	3.71 (± 21)	3.15 (± 2.4)	37.8 (± 4.1)	8.24 (± 9.2)
Polyethylene	2.13 (± 7)	26.4 (± 10)	5.32 (± 14)	2.38 (± 4.5)	38.7 (± 3.2)	7.33 (± 8.6)
No fibers	0.88 (± 4.7)	35.6 (± 9)	4.36 (± 2.2)	3.03 (± 4.5)	38.6 (± 3.3)	6.02 (± 4.8)

Table 5—Flexural toughness

	Flexural toughness, MPa.mm	
Fiber type	Without latex	With latex
Steel	0.638	1.000
Carbon	0.475	0.856
Polyethylene	1.305	1.318
No fibers	0.223	0.500

Among the three types of fibers, steel fibers gave the highest flexural strength, whether latex was present or not. Carbon fibers gave the lowest flexural strength when latex was absent; polyethylene fibers gave the lowest flexural strength when latex was present. Latex addition increased flexural strength with all fibers. Fiber addition increased flexural strength in the cases of steel fibers and polyethylene fibers, whether latex was present or not. In the case of carbon fibers, fiber addition decreased flexural strength when latex was absent but increased flexural strength when latex was present.

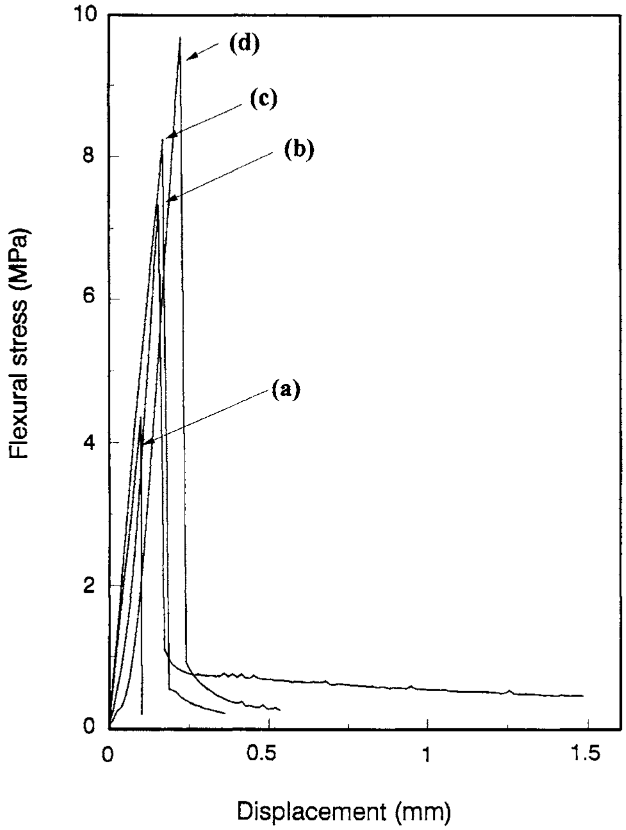

Fig. 3—Plots of flexural stress versus displacement during three-point bending: (a) without latex or fibers; (b) with latex and polyethylene fibers; (c) with latex and carbon fibers; (d) with latex and steel fibers

Table 5 shows flexural toughness. Among the three types of fibers, polyethylene fibers gave the highest flexural toughness and carbon fibers gave the lowest toughness, whether latex was present or not. Latex addition increased the toughness with all fibers, though the increase is slight in the case of polyethylene fibers. Fiber addition increased toughness with all fibers, whether latex was present or not.

Fig. 3 gives the plots of flexural stress versus displacement for plain mortar (without latex or fiber) and three types of fiber reinforced latex modified mortars. The high flexural toughness in the mortar with polyethylene fibers is due to the long tail of its curve after the peak in the curve. Because of the low stress level at the tail, the tail is a situation that does not allow structural load-bearing usage of the concrete. Thus, the flexural toughness of polyethylene fiber reinforced concrete is not as attractive as what the flexural toughness value alone indicates.

Fracture surface examination shows that the average length of fiber pullout was much larger for polyethylene fibers than carbon or steel fibers. This reflects that polyethylene fibers are more ductile than both carbon and steel fibers (Table 1) and are better dispersed than steel fibers (as observed in the mix and in the fracture surface, and as attributed to differences in surface energies among the fibers), thus resulting in the highest flexural toughness among the three types of fibers.

As suggested by the observed effect of latex addition on flexural toughness (Table 5) and supported by visual observation during mixing, latex was less useful for polyethylene fibers than carbon or steel fibers. This probably is related to the difference in the ease of dispersion among the different fiber types.

DISCUSSION AND CONCLUSION

The following conclusions may be drawn from Tables 3 to 5. The main attraction of carbon fiber addition is the resulting high tensile strength. The main attraction of steel fiber addition is the resulting high flexural strength. The main attraction of polyethylene fiber addition is the resulting high flexural toughness. With all fibers, latex addition is beneficial to all properties except the tensile modulus. In the case of polyethylene fibers, latex addition increases compressive strength and tensile modulus greatly, though it increases flexural toughness only slightly. In the cases of steel fibers and carbon fibers, latex addition decreases the modulus and greatly increases flexural toughness. Latex addition is beneficial to all properties, even when fibers are absent.

Carbon fibers have the lowest tensile modulus, strength, and ductility among the three fiber types (Table 1). Nevertheless, they provide mortar of the highest tensile strength, whether latex was present or not, and mortar of the highest tensile ductility when latex was present. In addition, they provide mortar of the lowest electrical resistivity,[17] even though they are less conductive than the steel fibers (Table 1). That the steel fiber reinforced mortars (whether with or without latex) had much higher electrical resistivity than the carbon fiber reinforced mortars (whether with or without latex) at the same fiber volume fraction of 0.53 percent and subjected to the same mixing procedure was confirmed in a companion work by the authors. The high tensile strength and low resistivity of carbon fiber reinforced mortars are partly because of the small diameter of the carbon fibers. Nevertheless, these observations suggest that the fiber-matrix bonding is strongest and/or the fiber dispersion is the best in the case of carbon fibers. In the presence of latex, steel fibers gave the lowest tensile and compressive strengths, but the highest flexural strength; in particular, steel fibers gave lower tensile and compressive strengths and lower flexural toughness than polyethylene fibers, yet they gave higher flexural strength. The origin of the high flexural strength provided by steel fibers is not clear. The high flexural toughness provided by polyethylene fibers is associated with the long tail in the flexural stress-versus-displacement curve (Fig. 3) and is due to the combination of high ductility and good dispersion of these fibers.

Comparison between carbon and polyethylene fibers shows the following differences:

1. Carbon fibers were much less expensive than polyethylene fibers.

2. Carbon fibers exhibited much lower tensile strength, modulus, and ductility than polyethylene fibers.

3. Carbon fibers gave mortar of higher tensile strength, lower modulus, higher flexural strength, and lower flexural toughness than polyethylene fibers at the same volume fraction.

4. Modulus of mortar reinforced with carbon fibers (whether with or without latex) was similar to that of plain mortar, whereas the modulus of latex-modified mortar reinforced with polyethylene fibers was much higher than that of plain concrete.

5. Latex addition increased the tensile ductility and flexural toughness of mortar containing carbon fibers, but not (or essentially not) for mortar containing polyethylene fibers.

6. Without latex, compressive strength was lower for concrete reinforced with polyethylene fibers than that reinforced with carbon fibers.

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