

FINAL REPORT

**Treatment of Wood Pulp Fibers
to Control Shrinkage Cracking in Concrete**

Phase III: Field Demonstration in Test Slabs

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1.0 Summary of Technology

A simple and economical method for improving pulp fiber dispersion in cement-based materials was developed by Dr. Hiroki Nanko at IPST and Dr. Kimberly Kurtis at Georgia Tech. Described in U.S. Patent 6966038, this technology involves treating pulp fibers with a cationic starch to allow for adsorption of silica-rich particles, such as fly ash. The combined physical and chemical changes to the pulp are believed to account for the significantly improved dispersion of fibers treated in this manner in cement-based composites (i.e., pastes, mortars, and concretes), as compared to untreated pulp fibers which tend to ball and clump in these applications. Laboratory and field work, performed by this team, has demonstrated that reinforcement of cement-based materials with treated pulp fibers can produce 400% greater toughness and improved crack resistance, while retaining good strength properties.

One target application for the technology is the use of treated pulp fibers to control plastic (early age) shrinkage cracking in concrete. This type of cracking typically occurs in the first 12-24 hours of age and sections with large surface area to volume ratios (i.e., flatwork such as pavements, bridge decks, driveways, slabs, etc.) tend to be more prone to plastic shrinkage cracking. Given the economic advantages embodied with the use of pulp fibers over synthetic polymeric fibers currently commonly used for plastic shrinkage crack control, it is anticipated that the market for fiber reinforced concrete could be enlarged. No negative consequences of the inclusion of pulp fibers in concrete for control of early age cracking are anticipated, based on research by this team and in the published literature.

2.0 Summary of the Potential Market

- Currently ~5% of all concrete produced in the U.S. is fiber reinforced (the specific proportions may vary by market). However, the increased cost of polymeric fiber reinforced concrete, which is typically a 10-15% premium over ordinary concrete, is believed to limit the market potential.
- Currently, 16-18 million pounds of polymeric fibers – primarily polypropylene – are used annually for early age shrinkage crack control in concrete.
- It is estimated that perhaps 15% of all concrete would benefit from fiber reinforcement. This represents a tremendous potential market, given that 12B tons of concrete are produced worldwide *each year*.
- It is believed that pulp fibers could provide an economical alternative to polymeric fibers for shrinkage crack control; this could be the technology that allows the fiber reinforced concrete market to reach its potential of 15% of all concrete produced. (See detailed analysis in Sections 3.0 and 4.0)
- In addition, pulp fiber reinforcement may offer some improvements. Pulp fibers are 5 to 10 times shorter than typical polymeric fibers used for this application. For a given fiber volume fraction, then, a greater number of shorter fibers would be present. This suggests that crack arrestment may occur prior to the crack coalescence and formation of macrocracks, a significant advantage, as crack width is linked with concrete permeability (which allows for faster penetration of aggressive agents such as chlorides, sulfates, alkalis and water). Additionally, it is believed that pulp fibers may release moisture, held in their structure, to produce an “internal curing” effect, which also is beneficial in terms of reducing shrinkage and cracking.

3.0 Assessment of Market Value

Polymer, glass, and steel fibers are commonly used in concrete, with polymer fibers being the most widely used. One of the largest producers of polymer fibers for concrete is Amoco. Amoco produces polymer fibers at an unknown cost but sells them – according to an analysis performed in 2001 - for \$1-1.50/lb to WR Grace, a leading admixture producer for the concrete industry. WR Grace passes these fibers at \$2.50-3.50/lb. onto concrete readymix producers, which are a rather fragmented industry. Readymix producers will then charge whatever the local market will bear for fiber-reinforced concrete. Current market value for polymer fiber reinforced concrete is about 10-20% more than for normal concrete, or an additional \$5-20/cu.yd.

Pulp fibers produced would offer a significant economic advantage over the widely used polymer fibers. We believe that the total cost to produce the modified fibers, including the pulp, fly ash, cationic starch, and processing itself, at a cost of \$0.50-0.66/lb. Such an advantage may be enough to tremendously expand the use of fiber-reinforced concrete.

It is reported that 12 billion tons or 24 trillion pounds of concrete are placed annually worldwide. If we assume a typical unit weight for concrete of 145 lb./cu. ft., this translates to 165 billion cu. ft./year or 6 billion cu. yds./year. If we assume that pulp fibers are used in *only 1%* of the concrete consumed each year, at a fiber addition rate of only 1.5% by volume or 1% by mass, this amounts to nearly 1 million cu. yds. or over 1 million tons of pulp fiber consumed each year. If we assume that *15%* of the concrete placed each year contains 1.5% pulp fiber by volume, *over 15 million tons of pulp fiber would be consumed each year for this application alone.*

4.0 Anticipated Costs to Produce and Ship Treated Fibers

Below is a simple analysis to anticipate the costs to produce the treated fibers, using the process developed by Kurtis and Nanko, which involves treatment with cationic starch (corn or potato starch) and fly ash. The treated fiber is subsequently dewatered to a moisture content of ~50%, as indicated below.

Material cost: \$ 494/t of dry pulp

Materials: Pulp + Fly ash (100% to pulp) + Cationic (corn) starch (1% to pulp)

- Pulp (Bleached Kraft): \$ 470/t
- Fly ash: \$ 20/t
- Cationic starch: \$ 0.20/lb (\$ 440/t)

Shipping cost: \$ 120/t of dry pulp

Pulp (1t) + Fly ash (1t) + Water (1t)

TOTAL COST: \$ 614/t, (pulp price + \$144)/t

5.0 Demonstration of Technology

Prior reports have described results obtained through laboratory testing. The focus here will be on a recently completed field demonstration, performed at Lafarge's Research Complex in Atlanta, Georgia. Seven 15x15 ft. concrete slabs, 5 in. thick, were cast from seven mixtures, which varied in the type of fiber reinforcement use (i.e., polypropylene or treated pulp fiber) and their fiber volume fraction. The polypropylene fiber used is a standard product in the concrete industry (Grace Microfiber, which is a 19 mm monofilament fiber), and it was used at standard dosage rates of 0.5, 1.0, and 1.5 lbs./cu. yd. concrete. The polypropylene fiber concrete has been denoted as "OF" (ordinary fiber) and the pulp fiber concrete as "PF". The volume fractions have been designated as low (0.06%), medium (0.12%), and high (0.18%) or A, B, and C.

Slabs were cast September 7, 2005, which was selected as the weather was advantageous for producing cracking in concrete. Conditions were sunny, 75-85°F, relative humidity of 35-50%, with winds of 10-15 mph. Additionally, the concrete mixture design was tailored to make cracking likely, by using a high cement content, low water-to-cement ratio, and small aggregate size. The formwork and subgrade were kept dry and no plastic sheeting was used either below the slabs or on top, for curing, to maximize moisture loss and cracking. Finally, the slabs were only roughly finished and were floated only, rather than using a broomed finish. This left the surface "open" and allowed for more moisture loss. Thus, the conditions were optimized to produce a "worst case scenario" for plastic shrinkage cracking. A photograph of the slabs is shown in Figure 1.

The age when cracks were first observed in each of the seven cases is recorded in Figure 2. In the case of the 0.18% polypropylene fiber slab, which was placed last, the lack of site lighting after dusk likely delayed the observation of the first crack, which would likely have been visible earlier. Figure 3 shows the total crack surface area at 20 hours of age, by which time plastic shrinkage cracking is presumed to have ceased. The data shows 10x more crack surface in the control slab (Figure 4) than in any of the fiber-reinforced slabs. The treated pulp fibers have performed comparably to the polymeric fibers.

It is worth noting that in general the cracks observed in the pulp fiber reinforced slab were shorter and narrower (Figure 5) than those observed in the polymer fiber reinforced slabs, suggesting that pulp fibers may act to arrest cracks before they grow or coalesce into macrocracks, which have a greater negative influence on concrete impermeability and, hence, durability.



Figure 1. View of seven slabs, as finished.

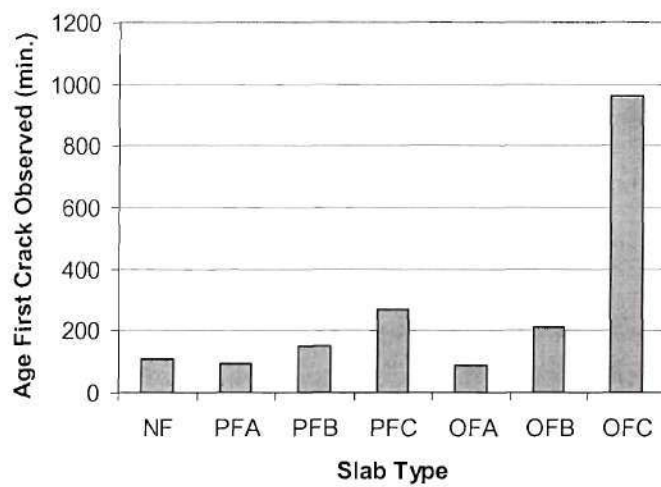


Figure 2. Age at first crack observation for each of the seven cases.

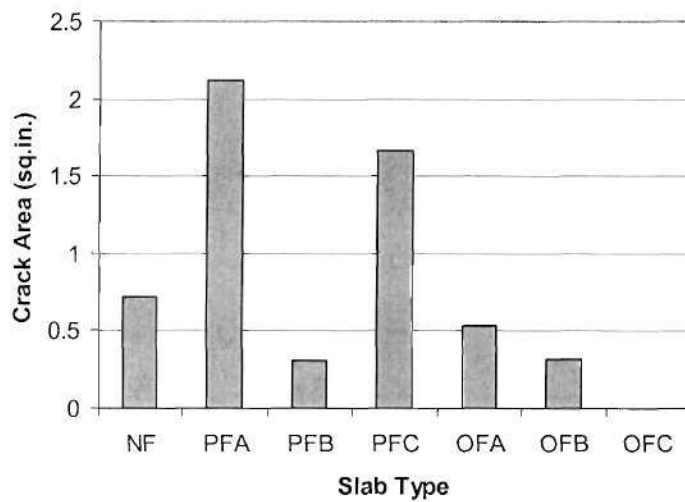


Figure 3. Measurements of crack surface area at 20 hours of age, for each of the seven cases.

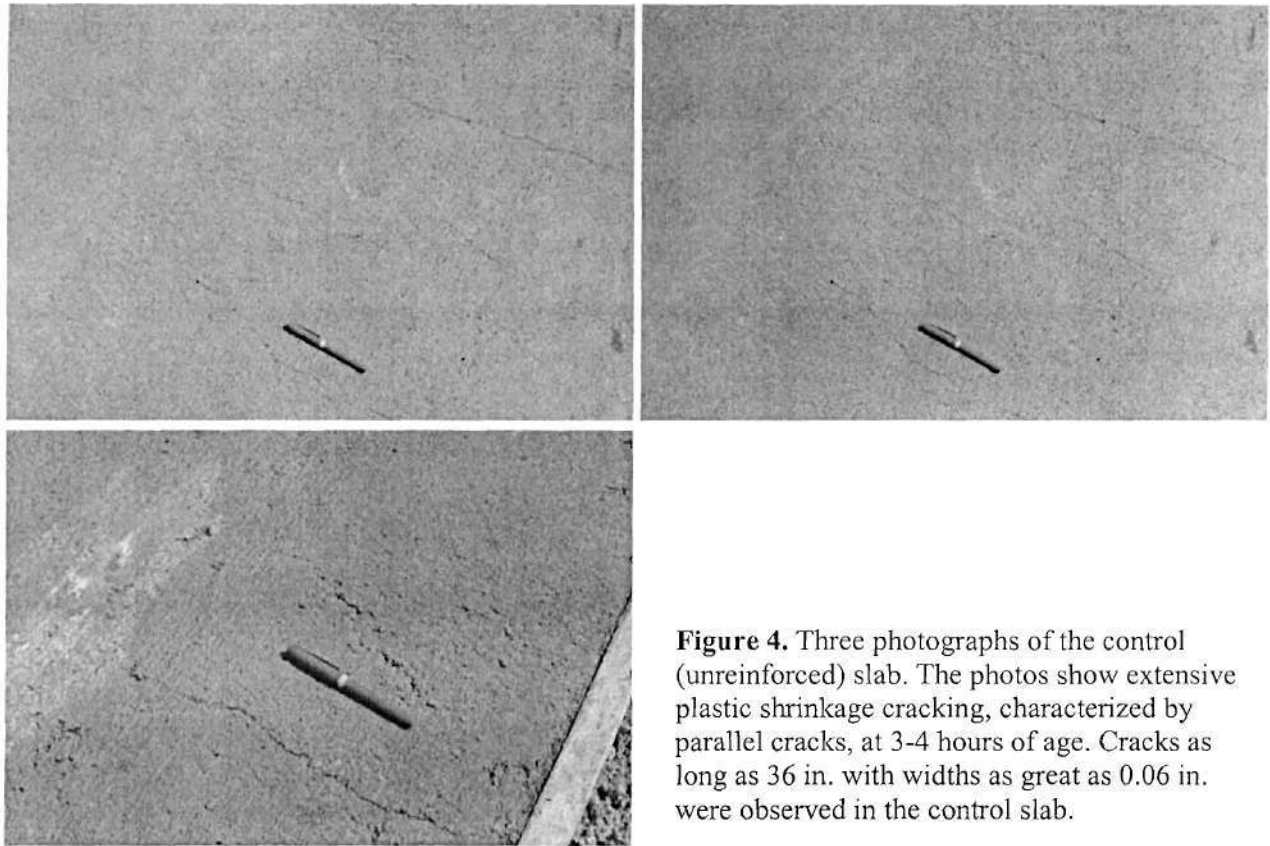


Figure 4. Three photographs of the control (unreinforced) slab. The photos show extensive plastic shrinkage cracking, characterized by parallel cracks, at 3-4 hours of age. Cracks as long as 36 in. with widths as great as 0.06 in. were observed in the control slab.

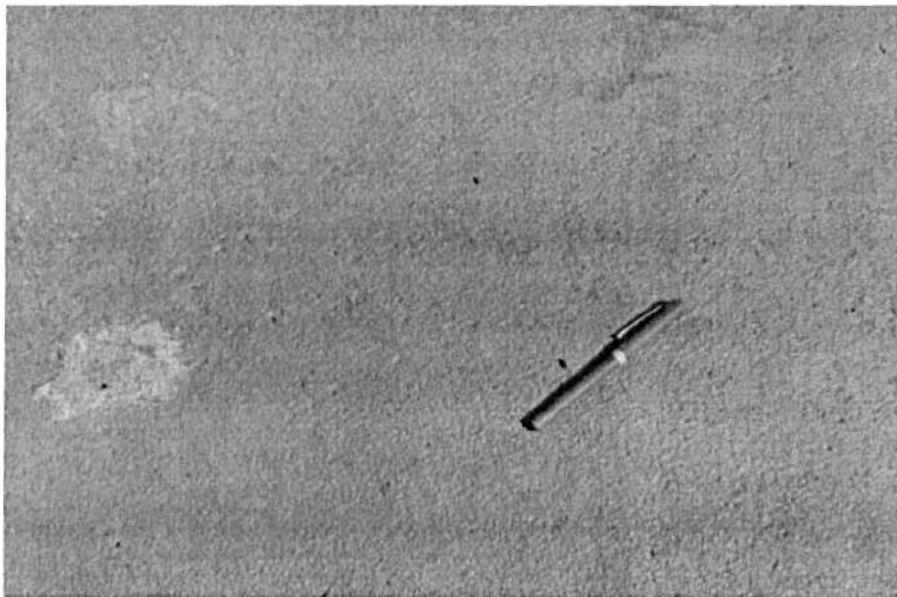


Figure 5. A nearly hairline crack is just visible in the low volume fraction (0.06%) pulp fiber slab, at ~3 hours of age.

In addition, compressive strength of four replicate 4x8" cylinders, cast on site, was measured at 28 days, according to ASTM C 39 procedures. Test results are reported in Figure 6 for polypropylene fiber concrete, denoted OPX (depending on volume fraction), and pulp fiber concrete (PFX), as compared to unreinforced controls (NF or "no fibers"). These data show a good relationship between the compressive strength of the pulp fiber concrete and the unreinforced concrete, suggesting no negative effect on strength by their addition.

It should be noted that additional water was added to all of the concrete, because of the hot and windy conditions. The most water (18 gallons) was added to the first fiber-reinforced concrete produced – PFA. For comparison, only 6 gallons were added to the "control" concrete. Subsequently, measures were taken to adjust the superplasticizer dosage in the fiber reinforced concretes, both PF and OF, but some additional water was typically required. The greater rate of water addition in the PFA concrete likely accounts for the slightly lower observed strength. However, the significantly lower strength of the OFC concrete is more likely due to poor fiber dispersion. Fiber clumping was visible at the fractured surfaces, as the water addition rate in this concrete was comparable to the control.

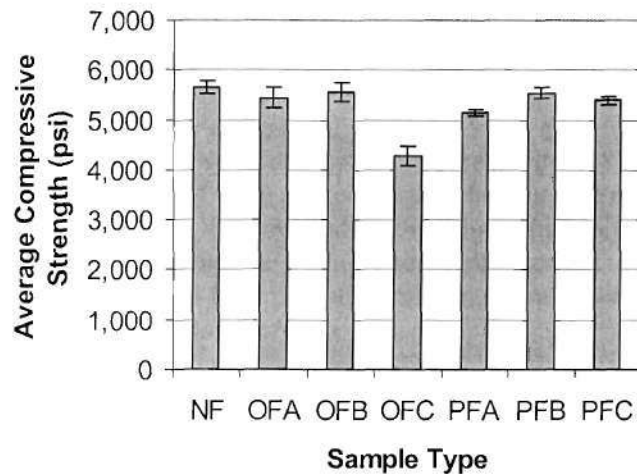


Figure 6. 28-day compressive strength data, with standard deviation bars, for unreinforced (NF), polypropylene fiber reinforced (OF), and pulp fiber reinforced (PF) concrete cast from the field batches.