

Comparison of UltraFiber 500® Alkali Resistant Cellulose Fiber versus Synthetic Polypropylene Fiber for Secondary Reinforcement in Concrete

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OVERVIEW

The successful introduction of a new alkali resistant virgin cellulose fiber for secondary reinforcement in concrete has generated questions and some misconceptions in the marketplace. This technical report answers these questions and addresses the misconceptions.

The use of un-processed, cellulose based fibers for reinforcement in building materials dates back well over 2,000 years. In the modern era, engineered processed cellulose fibers are used extensively in cementitious building materials and in concrete applications. UltraFiber 500® was developed based on a virgin, purified form of cellulose manufactured from one of the longest, thickest cellulose fibers found in nature. These properties make it ideal for the harsh demands of today's modern concrete applications. Research and independent testing have verified the performance attributes provided by UltraFiber 500® for: plastic shrinkage crack control, temperature crack control, increased impact resistance, improved freeze/thaw resistance, control of explosive fire spalling, improved concrete hydration, improved strength properties, reduction in water permeability, reduction in water absorption, and improved concrete durability.

A thorough assessment of the attributes of cellulose fibers proves that they offer new performance dimensions to the fiber reinforced concrete (FRC) market. The distinct differences in the physical properties of cellulose fiber offer performance features that are superior to and cannot be matched by synthetic polypropylene fibers.

FIBER PROPERTIES

Cellulose fibers and synthetic polypropylene fibers vary tremendously in their fiber properties.

Polypropylene Fiber

Polypropylene (PP) fibers are one of many synthetic end products of the fossil fuels industry. They are either extruded as monofilament or produced as fibrillated tapes in many different shapes and sizes. The first PP fibers to enter the FRC market were side products from textile mills. These PP fibers were called "fibrillated" because of the interconnecting strands between the fibers (most commonly used as carpet backing fibers in the textile industry). Years later, polypropylene

producers began offering individual monofilament fibers in various lengths and deniers. Over the years, the PP fibers have become shorter and thinner in an attempt to reduce the problems they present when placing and finishing concrete.

Polypropylene fibers are completely hydrophobic meaning that they will absorb no moisture. As a result, PP fibers do not assimilate well in the concrete paste, and petrography proves that they do not bond well within the cement paste and create additional voids.



FIGURE A: Synthetic Polypropylene in Concrete (Note: Micro-voids around fiber and lack of paste/fiber bonding)

Some producers coat their fibers with a surfactant to provide some short-term pseudo-hydrophilicity to reduce fiber balling in the concrete. This coating is soon washed off during the concrete mixing process and has been shown to increase air content.

To be anchored into the concrete, polypropylene fibers depend solely on frictional forces and aggregate gripping since there is no surface bonding between the fiber and the paste. This is why PP fibers must be long so that gripping and interlock can take place. Without that, performance benefits would be substantially reduced.

Cellulose Fiber

The term "cellulose fiber" represents a class of fibers that originate from wood and plant materials and they vary tremendously in size, denier, shape, purity, and fiber strength. One commonality of these fibers is that they all contain some

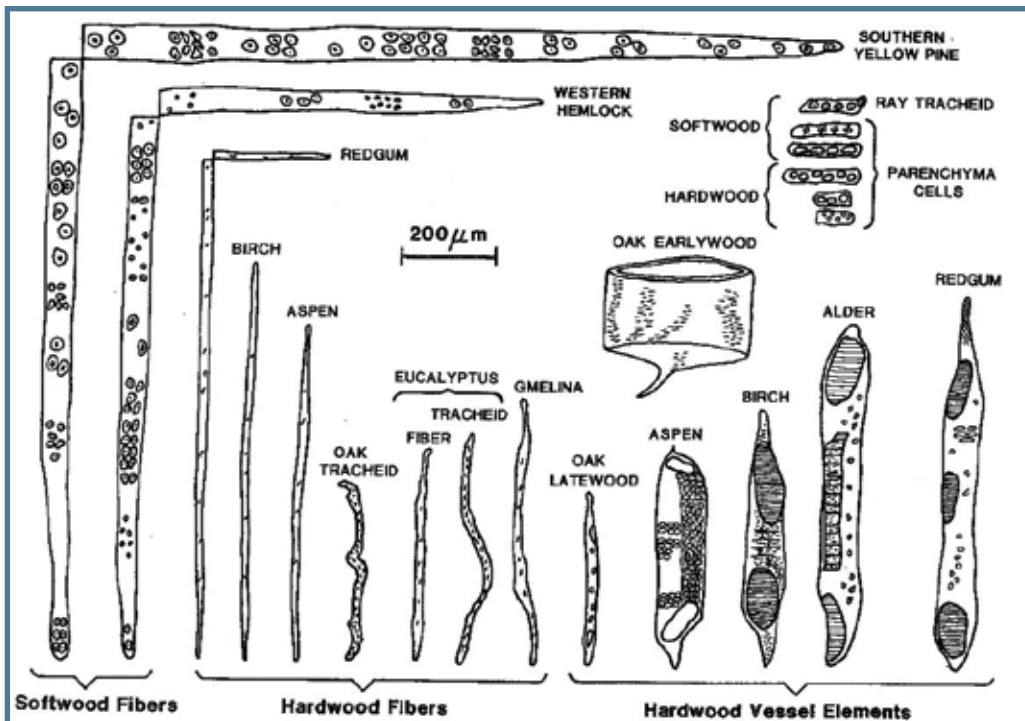


Figure B: Sketch of Wood Based Cellulose Fibers

cellulose which is an organic polymer of glucose. On a molecular level, cellulose can vary substantially in the degree of polymerization and in the crystalline structure. All cellulose fibers are not created equal. Figure B shows a class of cellulose fibers processed from trees. Note the tremendous variance in size, shape, and appearance. Cellulose fibers can be liberated from wood materials through numerous processing methodologies. In these processes, the less stable and weaker components of the wood can be completely removed leaving only purified cellulose fiber remaining. Some processing conditions purify the cellulose fibers to higher degrees of stability and chemical resistance than others.

Numerous and varied forms of cellulose fiber have been used as a reinforcing fiber in building materials dating back well over 2,000 years. Their crack control and reinforcing properties were recognized by pre-modern societies. In the last 50 years, numerous forms of engineered processed cellulose fibers are used as a major component in highly durable building materials used worldwide.

To meet the demands of today's modern concrete industry, UltraFiber 500® was developed based on a virgin, purified form of cellulose fiber made from one of the longest and thickest cellulose fibers found in nature. The select plantation trees used to manufacture UltraFiber 500® contain the longest and thickest cellulose fiber in North American and are similar to the Southern Yellow Pine fiber shown in Figure B.

Unlike polypropylene fibers, cellulose fibers are highly hydrophilic and will absorb moisture. UltraFiber 500® can absorb up to about 85% of its weight in moisture. This hydrophilic characteristic promotes outstanding bonding between cellulose fiber and the cement paste (see Figures C and D).

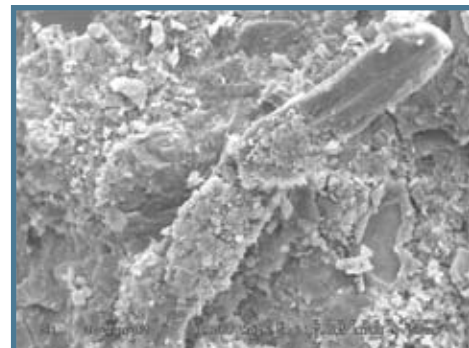


FIGURE C: Cellulose Fiber Bonded Into Concrete

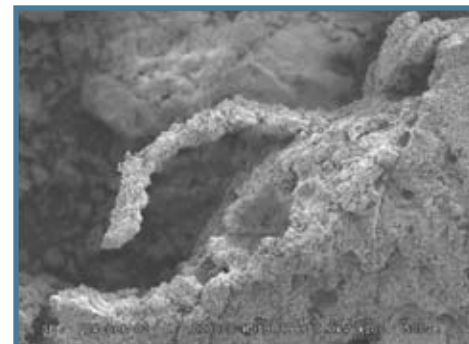


FIGURE D: Cellulose Fiber Bonded With Cement Paste

As it cures, this bonding intensifies, hardens, and becomes more fully hydrated from internal curing provided by the moisture that is given up by the fiber to unhydrated cement.

Since UltraFiber 500® is bonded and fully anchored within the concrete paste, it does not require a fiber length as long as polypropylene requires to provide excellent performance properties. Furthermore, the intense bonding reduces microscopic voids and openings within the concrete as observed from hydrophobic fibers like synthetic polypropylene.

Fiber Property Comparison

Compared to typical synthetic polypropylene fibers, UltraFiber 500® cellulose fiber has greater fiber tensile strength and higher elastic modulus than polypropylene fibers (ACI SP182-8). The fine diameter and short fiber length provide exponentially higher fiber counts, closer fiber spacing, and higher specific surface area versus polypropylene fibers (ACI 544.1R-96). Cellulose is slightly heavier than water (1.1 g/cm³) while synthetic PP fibers are lighter than water (0.9 g/cm³). Hydrophilic cellulose fibers acclimate much better within the paste than light, hydrophobic synthetic PP fibers. Because of their hydrophilic nature, cellulose fibers more easily disperse within the concrete in typical industry concrete mixing processes. Good fiber dispersion within the concrete is important for uniform performance throughout the concrete. The hydrophobic nature of PP presents a challenge to good mixing and good fiber distribution without the occurrence of fiber clumping and balling that reduces the in-place concrete performance and finishability. Table 1 below summarizes some of the key fiber property differences:

Table 1: Fiber Property Comparison

Fiber Attributes, units	UltraFiber 500®	Typical PP
Avg. Length, mm	2.1	16
Denier, g/9,000m	2.5	6
Projected Diameter	18	30
Max. Moisture Uptake, wt. %	85	0
Fiber Count, fibers/lb.	720 x 10 ⁶	44 x 10 ⁶
Apparent Density, g/cm ³	1.10	0.91
Surface area, cm ² /g	25,000	1,500
Avg. Fiber Tensile, KSI	90 - 130	30 - 70
*Fiber Spacing µm	640	950

* Dosage @ 1.5lbs/yd³

FIBER PERFORMANCE

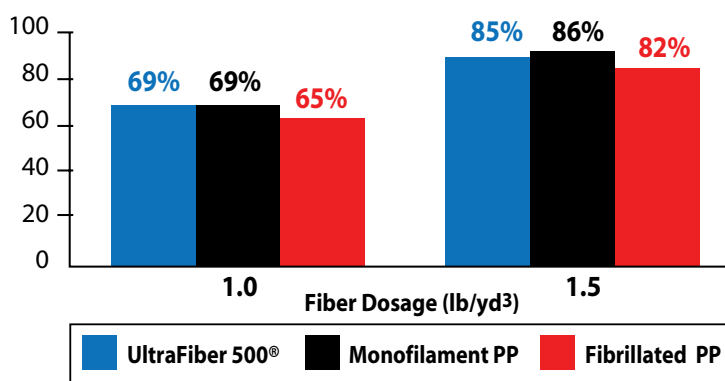
Crack Control

It is well documented that concrete commonly cracks due to intrinsic stresses that occur from shrinkage changes during curing. Temperature changes during the plastic state also contribute to early stage cracking. When fibers are introduced to the concrete they intersect micro-cracks, stop them from progressing, and disperse the energy. This substantially reduces the chance for development of visible macro-cracks. By controlling early age cracking, fibers contribute to the long-term durability of concrete.

The International Code Council (ICC) has established Acceptance Criteria (AC) for fibers used in the evaluation of concrete. ICC AC-32 was developed for evaluation of synthetic fibers and ICC AC-217 was developed for virgin cellulose fibers. Each criterion uses the same identical plastic shrinkage crack test method (Annex A in each criterion) to assess synthetic and cellulose fibers.

Figure E shows plastic shrinkage crack data from an ICC-ES certified test lab using the ICC standard plastic shrinkage crack method. In this finely controlled lab test, the concrete containing UltraFiber 500® performed essentially identical compared to the polypropylene fiber concrete samples. Also note that the fibers in each batch were dosed based on fiber weight per unit volume of concrete. This dosing methodology is standard in the concrete industry.

FIGURE E: ICC Certified Plastic Shrinkage Crack Testing



On a practical level, UltraFiber 500® has differentiated itself for crack control in the field. It is well known in the industry that the addition of PP fibers (monofilament or fibrillated) can substantially reduce the concrete slump. This creates the desire for additional water to be mixed in at the jobsite which lowers strength properties and increases the potential for cracking. The use of

UltraFiber 500® has a zero to negligible change on concrete slump and, therefore, the desire to add water at the jobsite is substantially reduced. This represents a significant advantage for UltraFiber 500® to control cracking in the field.

Alkali Resistance

Concrete is alkaline in nature due to the generation of predominantly calcium hydroxide and sodium hydroxide; therefore, it is important that fibers used in concrete are resistant to degradation in an alkaline environment. If the fibers were to degrade, it would increase the volume of voids and open channels within the concrete and could be detrimental to the long term durability of the concrete and to other performance benefits from FRC. There are some types of synthetic fibers that will degrade in an alkaline environment and there are other types that will not. The same is true for fibers derived from wood and plant raw materials. The source of cellulose, the type of processing, the degree of purity, etc., will all impact whether that particular type of cellulose fiber will deteriorate in an alkaline environment.

ICC requires that concrete reinforcing fibers demonstrate resistance to alkaline degradation. Acceptance Criteria 32 for synthetic fibers requires that cylinders be cast and then re-examined in 2 years to confirm that the fibers have not deteriorated. ICC also specifies an interim test for synthetic fibers where the fibers are soaked in calcium hydroxide for a set period of time and then tested for tensile strength before and after exposure to alkali (the procedure is provided in AC-32, Annex B). ICC requires that 90% of the synthetic fiber tensile strength be retained following alkaline exposure.

ICC Acceptance Criteria 217 specifies that cellulose fibers must be tested in accordance to ASTM D6942, "Standard Test Method for Stability of Cellulose Fibers in Alkaline Environments." The fibers must be soaked in saturated calcium hydroxide and 1.0 Normal sodium hydroxide for a set time period. Following alkali exposure, the fibers are tested for tensile strength and they must retain a minimum of 90% of their original strength. It should be mentioned that 1.0 Normal sodium hydroxide is significantly stronger than saturated calcium hydroxide and represents a severe condition not typical of concrete. UltraFiber 500® has been successfully tested for ASTM D6942 and it exceeded ICC's performance criteria. In saturated calcium hydroxide, UltraFiber 500 retained 100% fiber tensile strength and in 1.0 Normal sodium hydroxide it retained 96% fiber tensile strength. The following micrographs (FIGURES F and G) were taken from a driveway slab containing

UF-500 that was poured in the summer of 2002. Notice the presence of healthy, non-deteriorated UltraFiber 500® cellulose fibers.

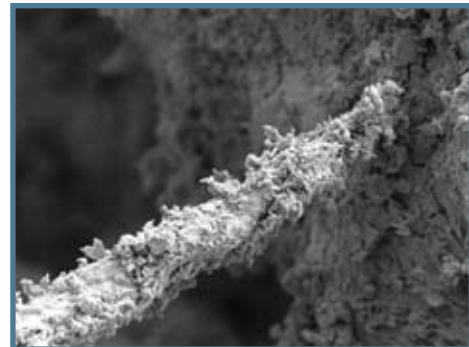


FIGURE F: UltraFiber 500® in concrete after 4.5 years

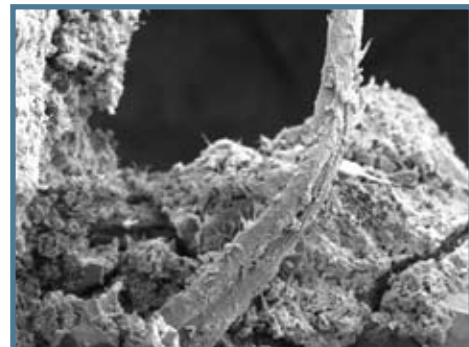
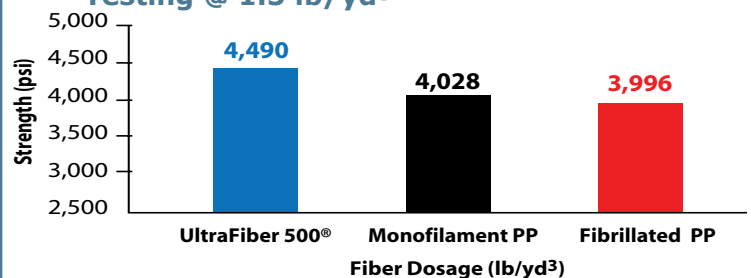


FIGURE G: UltraFiber 500® in concrete after 4.5 years

Compressive Strength

The hydrophilic nature of cellulose fibers provides an added benefit that hydrophobic synthetic fibers cannot provide. The moisture initially held by the fibers during mixing and initial placement is given up to enhance the hydration level in regions in and around the fiber. This phenomenon is commonly referred to as internal curing. This enhanced hydration can have a positive impact on strength properties. Identical mixes were tested for compressive strength; each mix contained 1.5 lbs/yd³ of fiber (see Figure H).

FIGURE H: Compressive Strength Testing @ 1.5 lb/yd³



The compressive strength of the concrete containing UltraFiber 500® exceeded the concrete containing synthetic polypropylene fibers.

Three residential grade slabs (6 yards each) were poured and placed side-by-side with identical mix designs on the same day, supplied by the same ready mix producer, and finished by the same contractor. Each slab contained 1.5 lbs/yd³ of one fiber type (UltraFiber 500®, monofilament PP, and fibrillated PP). After approximately 8 months of curing in the field, the slabs were tested for strength using a rebound probe and a Windsor probe. The data are summarized in Figures I and J.

FIGURE I: In-Field Slab Testing with Rebound Probe @ 1.5 lb/yd³

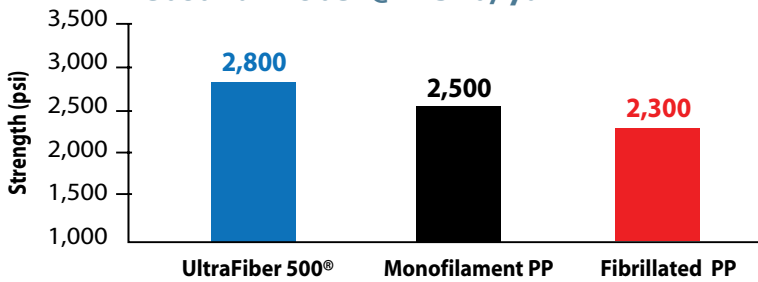
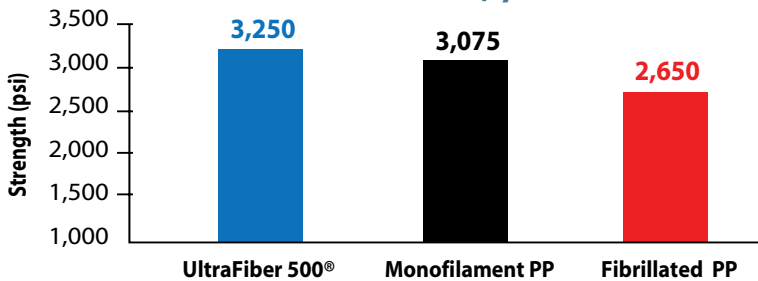


FIGURE J: In-Field Slab Testing with Windsor Probe @ 1.5 lb/yd³



In both test methodologies, the slabs containing UltraFiber 500® achieved higher in-place strength values.

Concrete Absorbency

The long term durability of concrete can be negatively impacted by high levels of water absorbency. During curing, the hydrophilic nature of cellulose fibers allows the cement paste to adhere and bond tightly to the fiber so that voids and openings are not introduced within the paste. Hydrophobic PP fibers repel the paste and create micro voids around the fibers within the paste. ASTM C1585, "Measurement of Rate of Absorption of Water by Hydraulic-Cement Concrete," was conducted on identical FRC mixes (see Figures K and L).

At equal void volume, the concrete containing UltraFiber 500® had a slower rate of water absorption and a lower amount of water was absorbed

FIGURE K: Rate of Absorption Results

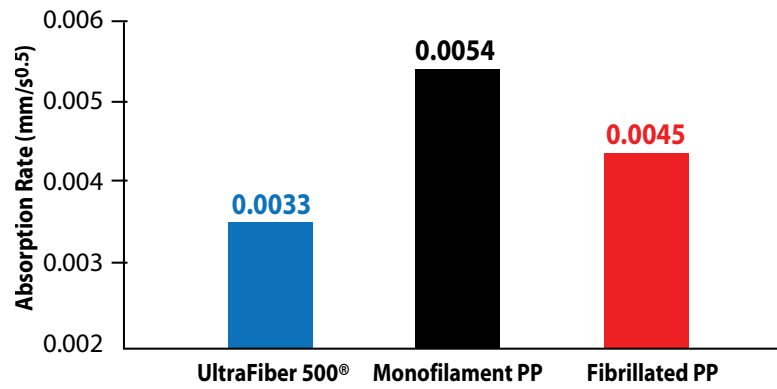
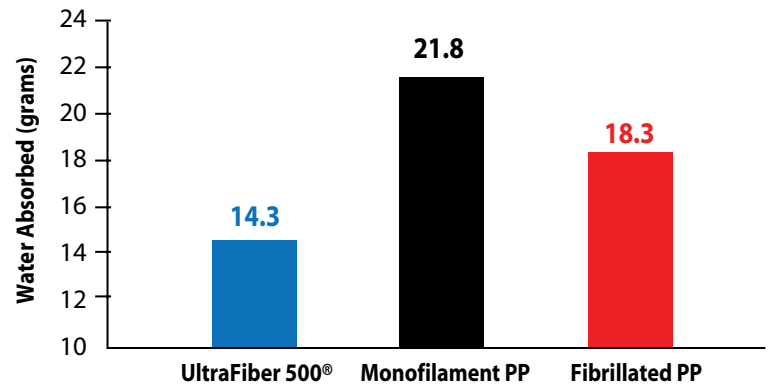


FIGURE L: Total Absorption Results

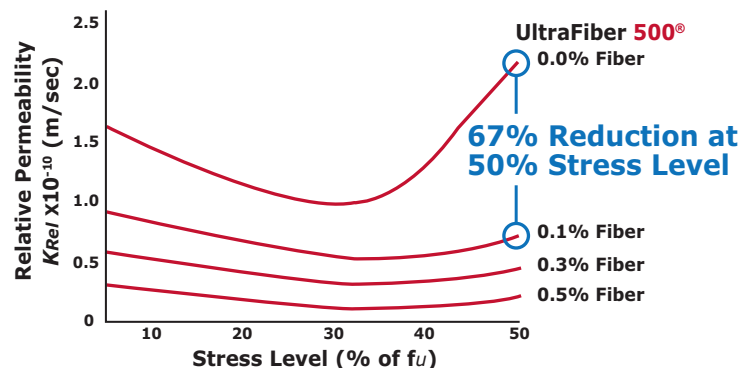


compared to the concrete containing PP fiber. According to Lucas-Washburne theory (Chatterjee, P. K., "Absorbency", Elsevier, NY, 1985, pp 36-40), these results indicate that the voids in cellulose FRC are more uniform, giving a lower effective capillary radius. The finer porosity also leads to a smaller amount of water being absorbed by capillary pressure.

Concrete Permeability

Recent novel research by Banthia (Banthia, N., "Do Fibers Reduce the Permeability of Stressed Concrete?", European Symposium on Service Life and Serviceability of Concrete Structures, June 2006) has shown that FRC containing UltraFiber 500® reduces the water permeability of unstressed and stressed concrete (see Figure M). The presence

FIGURE M: Water Permeability Results



of cellulose fibers in the concrete substantially reduces the increased water permeability that occurs from cracking under load. This behavior should have a substantial benefit for corrosion reduction in structural elements containing embedded rebar.

Freeze/Thaw Performance

The reduced concrete absorption and reduced concrete permeability benefits documented from the use of UltraFiber 500® have a favorable impact to freeze/thaw durability performance. The presence of UF-500 can improve the F/T resistance of concrete that would otherwise have poor performance. The data in Figures M and N show two different freeze/thaw test results using ASTM 666 and French Standard P 18-425 respectively. UltraFiber 500® was dosed at 1.5 lbs/yd³ for both tests. More testing is underway.

breaks apart and separates into individual pieces. Concrete containing fibers can increase the number of blows before the concrete breaks apart since the fibers can absorb some of the impact energy and disperse it throughout the concrete. UltraFiber 500® meets ICC acceptance criteria for impact resistance as do PP fibers.

Residual Strength/Toughness Testing

After the initial introduction of fibrillated PP fibers for concrete, monofilament PP fibers soon followed. In an effort to differentiate between these fibers, tests such as the average residual strength (ARS) test and toughness test have evolved. These tests have extremely high variability and are still being debated and modified in their respective ASTM committees. Problems in interpreting ARS and toughness of FRC are discussed by Banthia and Mindess (see ASTM Journal of Testing and Evaluation, March 2004, Vol. 32 (#2), pp 1-5). Synthetic PP fiber producers claim that these tests indicate the “crack holding power” of fibers. None of these tests are required by ICC in their evaluation criteria for the use of fibers (synthetic or cellulose) in concrete for secondary reinforcement. These values are used mostly as a marketing tool by PP fiber producers.

The mechanism of cracking in the field is different from what these tests measure. Cracks in concrete slabs are subject to movement due to shrinkage in the horizontal plane. The crack holding capacity of fibers during concrete shrinkage is directly proportional to the tensile capacity of the fibers. UltraFiber 500® obtains similar results in these test compared to monofilament synthetic fibers. But, more importantly, UltraFiber 500® performs at the micro level to combat crack formation and increase the stress carrying capacity of the concrete prior to reaching the first crack level (i.e. flexural strength). Flexural strength testing is required by ICC in their evaluation criteria for fibers in concrete (synthetic and cellulose). Flexural strength testing has shown that UltraFiber 500® fibers are equal to or better than synthetic fibers used for secondary reinforcement (see Figure P).

FIGURE N: Freeze/Thaw Testing, ASTM C666

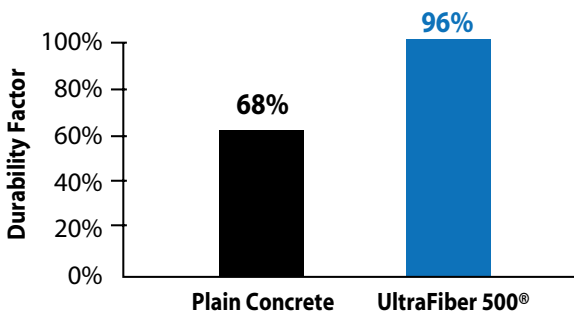
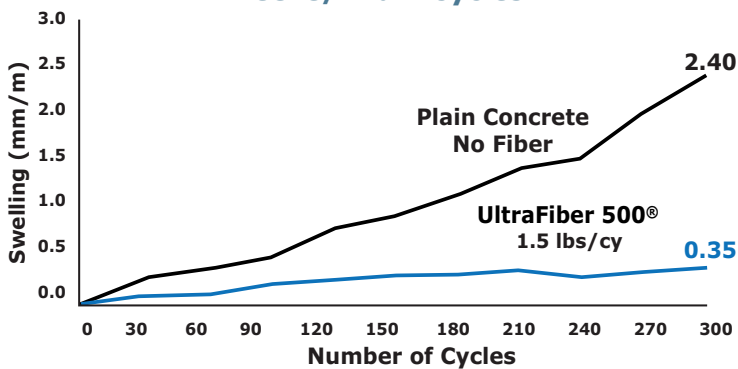


FIGURE O: Freeze/Thaw Testing, P 18-425

Swelling of Concrete Due to Repeated Freeze/Thaw Cycles

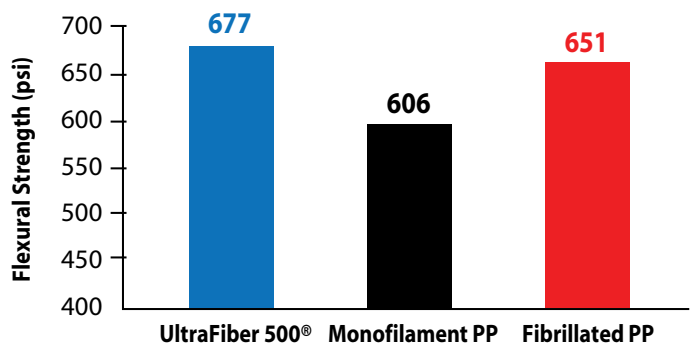


Compared to the poor results for the control in each of these tests, the presence of UltraFiber 500® had a substantial improvement on the freeze/thaw durability of the concrete.

Impact Resistance

ICC specifies that concrete containing fiber (synthetic and cellulose) show a performance benefit to impact resistance. This test requires a small concrete specimen be impacted multiple times with a drop hammer ball until such time the specimen

FIGURE P: Flexural Strength Testing @ 1.5 lb/yd³



Fire Testing

Cellulose fibers also provide a benefit to reduce explosive spalling due to fire. Figure Q below shows photographs of concrete specimens taken after fire exposure in accordance with EN 1363-1 using the ISO 834 fire curve. The cellulose reinforced concrete and the monofilament polypropylene reinforced concrete (both dosed at 3.0 lbs/yd³) stopped explosive spalling while the plain concrete specimen did not.

UltraFiber 500® fibers have also been tested by Underwriters Laboratories under ANSI/UL 263, thirteenth edition standards in a D900 series metal deck assembly. The fiber was used as an alternate for welded wire fabric for secondary reinforcement. The concrete containing UltraFiber 500® did not exceed the maximum temperature rise for over 2 hours. As a result, UltraFiber 500® has been successfully UL classified in D700, D800 & D900 series deck designs. More testing is underway at UL to expand this unique performance benefit for fire resistance.

Impacts to Finishing

Concrete has to be properly finished in order for it to provide maximum performance. It is well documented in the concrete industry that polypropylene fibers have a history of balling and finishing problems. As previously discussed, PP fibers do not always disperse well in the mixes. Their hydrophobic nature favors balling and clumping. Fibrillated PP fibers do not always open up into the "mesh" form that is required for proper performance. At the surface, PP fibers protrude out and are often observed in clumps or balls. Their presence at the surface makes it difficult to obtain a properly finished, densified surface. If the concrete is being used in a highly aesthetic decorative application, the finishing problems from synthetic fibers frequently eliminate the possibility for their use.

Hydrophilic cellulose fibers are able to uniformly disperse more easily in concrete so that performance can be maximized. Special finishing steps do not have to be taken – concrete containing cellulose fibers at normal dosages finishes very similar to plain concrete. Cellulose fibers do not clump or ball up at the surface allowing proper finishing techniques to obtain a properly sealed, smooth surface. The hydrophilic nature also helps to maintain more paste at the surface allowing excellent surface finishing ability. In decorative applications, cellulose fibers are invisible to the eye making them highly desirable in these applications where other fibers cannot be used.

FIGURE Q: Pictures From Explosive Fire Spalling Test

UltraFiber 500®



Plain Concrete



Monofilament PP



SUMMARY

- The International Code Council has developed acceptance criteria for the use of synthetic fibers (AC-32) and cellulose fibers (AC-217) in concrete for providing secondary reinforcement. The key test used to assess plastic shrinkage crack control is identical for both fibers.
- UltraFiber 500® cellulose fiber, monofilament polypropylene fiber, and fibrillated polypropylene fiber performed similarly in certified plastic shrinkage crack testing in accordance to ICC acceptance criteria.
- UltraFiber 500® cellulose fiber is alkaline resistant in concrete as proven through testing with ASTM D6942 using saturated calcium hydroxide and 1.0 Normal sodium hydroxide.
- UltraFiber 500® has a performance advantage in the field over synthetic fibers for crack control since it has zero to negligible impact on slump and synthetic fibers can substantially reduce the slump which creates the desire for water to be added at the jobsite.
- UltraFiber 500® cellulose fibers and synthetic fibers perform similarly in control of explosive spalling (ISO 834).
- UltraFiber 500® is UL Classified with a two-hour fire rating for all D700, D800 and D900 composite metal deck assemblies.

- UltraFiber 500® cellulose fiber provides the following advantages over synthetic fibers for FRC:
 - Higher surface area, higher fiber tensile strength, higher fiber count, and closer fiber spacing.
 - Cellulose fiber properties promote better fiber dispersion throughout the FRC.
 - Cellulose fibers assimilate and bond within the paste creating a tighter, denser paste.
 - Minimal to no negative impact to plastic properties of FRC
 - Provides enhanced curing by the gradual release of water to unhydrated cement.
 - FRC strength properties are improved from internal curing.
 - Reduced water absorbency and permeability
 - Improved freeze/thaw durability performance
 - Cellulose fibers do not create placement and finishing problems.
 - Processed cellulose fibers come from renewable resources.
- ARS and toughness tests are highly variable, frequently debated in technical circles, and not required by ICC to evaluate fibers in concrete.

In summary, it is clear that UltraFiber 500® cellulose fiber provides numerous and substantial advantages over synthetic polypropylene fiber for use as a secondary reinforcement for concrete.