PENN STATE **Concrete Clinic**

Jointly produced by
Department of Civil & Environmental Engineering and Instructional Systems

Polypropylene Fiber Reinforced Concrete

Much work has gone into researching the properties of synthetic fiber-reinforced concrete over the past decade, in particular polypropylene fiber reinforced concrete, as the addition of fibers can provide effective, inexpensive reinforcement for concrete. A synthetic fiber is defined as a manmade, flexible, homogenous body with a high aspect ratio (length/thickness). Fibers are manufactured from both synthetic polymers and naturally occurring macromolecules. Desirable fiber properties are attained through the creation of a highly oriented and crystalline molecular structure. This is achieved through mechanical drawing, when the filament is extended to several times its original length, immediately after extrusion. Drawing the fibers develops three-dimensional structural regularity and brings the molecules into the optimum stress bearing position. In order to actually increase the strength of concrete, fibers should have a modulus of elasticity greater than that of the concrete matrix. However, achieving a modulus of elasticity greater than that of the concrete matrix is difficult with most synthetic fibers. Research has indicated that even with low modulus fibers, improvements can be made in the strain capacity, toughness, impact resistance, and crack control of fiber-reinforced concrete. In most applications, enhancement of these properties is more important than increasing tensile strength.

Polypropylene is one of the most widely used types of fiber reinforcement in concrete. Polypropylene fibers are manufactured by drawing the polymer into thin film sheets, which are then slit and further processed to produce fine fibers. The fibers can be produced in a variety of configurations: as monofilaments, collated bundles, and continuous films. Monofilaments disperse evenly but are somewhat difficult to handle, while collated fiber bundles can be dispersed easily in concrete, and are convenient to handle. Continuous films are sheets (meshes or fabrics) which are used for high volume applications, and are placed in the concrete forms prior to placing the concrete. The photograph on the right shows polypropylene being manufactured at the Fibermesh plant.

Polypropylene fibers can be used as primary reinforcement (5 to 10% by volume) applied as a mesh or fabric, which provides continuous reinforcement. When used in low volumes (less than 0.3%) short polypropylene fibers provide effective secondary reinforcement against plastic shrinkage cracking. In low volumes, fibers have been shown not to contribute to the tensile strength of the concrete, but after the matrix has cracked, the fibers contribute by bridging the crack and providing residual strength. When fibers bridge cracks in the matrix they can provide resistance to further crack propagation and crack opening until the fibers are pulled out or stressed to rupture. Before pullout or rupture, the fibers act to distribute the microcracking that occurs, which increases the toughness of the specimen. It is only in large volumes (8% or more) that fibers may increase the tensile strength of concrete.


Courtesy of Fibermesh Inc.

Regardless of its geometry, polypropylene has several unique properties that make it especially suited for use in concrete. The fibers are chemically inert and stable in the alkaline environment of concrete, with a relatively high melting point, and low cost. Polypropylene fibers do not absorb water, due to a hydrophobic surface, which prevents any chemical adhesion with the concrete matrix. Fibers bond in the concrete matrix through interfacial adhesion and mechanical anchoring. The disadvantages of polypropylene fibers are that they are sensitive to fire, sunlight, and oxygen, they have a low modulus of elasticity, and they bond poorly with the concrete matrix. It has been found that using certain surface treatments, either chemical (detergents or mild acids), or mechanical (such as abrasion) can increase the cement to fiber bond. Despite the above disadvantages, polypropylene fibers can be used successfully, especially to control plastic shrinkage cracking.

It has been shown that adding polypropylene fiber to a concrete mixture gives an immediate reduction in workability and slump. To compensate for this a water-reducing admixture or superplasticizer can be used. It has been found that polypropylene fibers eliminated plastic shrinkage cracking in slabs subjected to high temperature and wind effects, but they had no noticeable effect on drying shrinkage. The addition of polypropylene fibers also increases flexural fatigue strength and endurance, as well as impact resistance and toughness. Toughness has been shown to increase uniformly with increasing fiber content. The load/deflection behavior of polypropylene fiber-reinforced concrete has been shown to be linear up to a peak load, which then falls off to a residual ‘holding load’ which is maintained for considerable deflection until the specimen fails due to fiber pullout or rupture.

Polypropylene fibers do not significantly increase compressive strength; in fact, compressive strength is generally reduced with the addition of fibers. Polypropylene fibers also increase creep in plain concrete by 20 to 40%. Permeability is also affected when polypropylene fibers are used. Even though the fibers reduce cracking, the poor bond between the fibers and the concrete matrix can allow passage for external substances. Despite potentially higher permeability, it has been demonstrated having polypropylene fibers in the concrete matrix retarded surface deterioration under adverse weathering conditions.

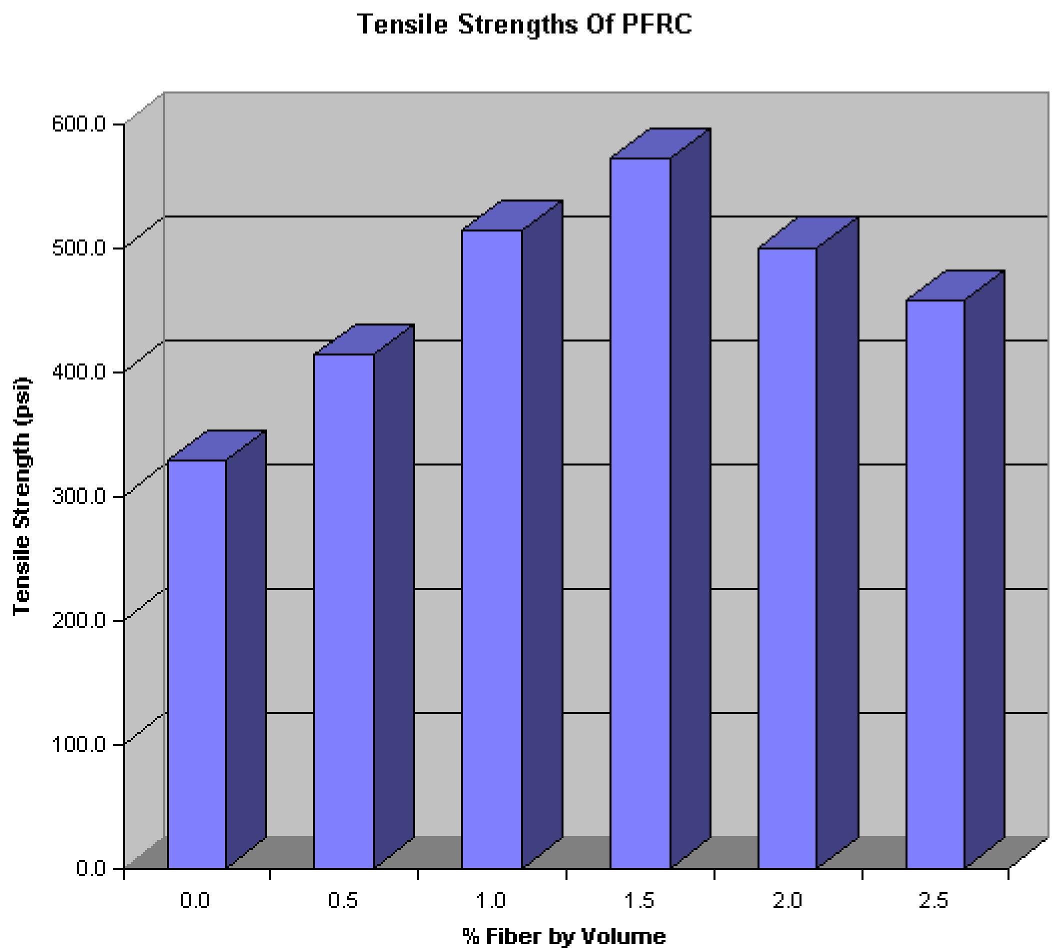
Tensile Performance

The tensile performance of plain concrete is quite poor. Concrete experiences sudden, brittle failure when its tensile strength is exceeded, usually by placing the concrete in flexure. The tensile strength of concrete is only about 10% of the compressive strength and is usually considered to be zero for the purposes of design. It has been shown that the proper addition of polypropylene fibers to a concrete mixture can be beneficial to the tensile properties of concrete.

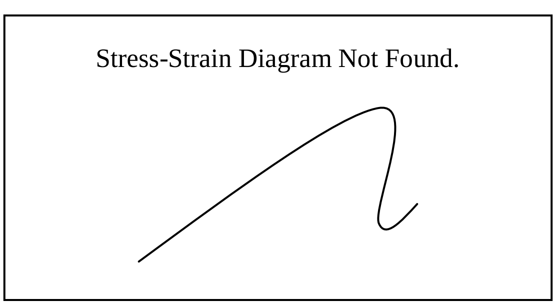
A study presented in ACI publication SP 105 demonstrated the beneficial effects of adding collated fibrillated polypropylene fibers added at 0.2 - 0.3% by volume. At these volumes, the fibers acted as crack arresters in the concrete matrix, prohibiting the propagation of cracks in the plastic state and the propagation of cracks in the hardened concrete. The fibers increased the flexural (tensile) strength of the concrete slightly, as well as the ductility and post-crack energy absorption capacity (toughness).

Another study, conducted by Tavakoli of the Sharif University of Technology, focused on studying the flexural properties of polypropylene fiber-reinforced concrete with percentage volumes ranging from 0 (control) to 2.5%. Tavakoli showed that the optimum percentage by volume for increasing tensile performance is 1.5%. There is a nearly linear increase in tensile strength up until 1.5% by volume, after which point the tensile strength decreases with the addition of more fibers. At 1.5% by volume, the concrete experiences an 80% increase in tensile strength, and shows maximum ductility and failure strain. See the chart below for information on the tensile tests carried out by Tavakoli.

It is clearly seen from the chart how the tensile strength peaks at a fiber volume of 1.5% and decreases when a higher percentage of fiber is used.



Shah (1991) carried out a study on the use of fibers in extremely high percentages (12-13%). He determined that at these volumes, the fibers serve to hinder the growth of microcracks, and well as increasing the tensile fracture strength, and the strain capacity of the concrete. In a separate study, researchers at the University of Michigan, Li and Wu showed that high volumes of polypropylene fibers increase the first crack strength and first crack strain (by 200-500%) due to the arresting of microcracks in the concrete matrix. They also showed how samples with a high percentage of fibers exhibited pseudo strain-hardening behavior. This behavior can be seen in the stress-strain diagram below.



It can be derived from the above figure that the concrete behaves normally in the portion of the diagram labeled A (up to the point of initial cracking). The behavior exhibited after the point of initial cracking (labeled B) is extremely similar to the strain-hardening portion of a steel stress-strain diagram. The sections labeled C of the stress-strain curve represent the ultimate stress that is carried by the concrete, as well as the failure of the specimen. Portions B and C of the diagram account for the increase in ductility and toughness that is reported for polypropylene fiber-reinforced concrete.

Many researchers have shown that the addition of polypropylene fibers is beneficial to the tensile strength, toughness, and ductility of concrete, and the key to success seems to lie with two points; first, the fibers must be uniformly distributed in the concrete matrix (no clumping or 'balling'), and secondly the fiber proportion must be selected properly. As noted above, 1.5% by volume seems to be a optimal value for increased flexural strength, and higher percentages of fiber greatly increase the toughness and durability of the concrete.

Percentages below 1.5% by volume do not seem to have any significant effect upon flexural strength, toughness, or ductility.

Toughness

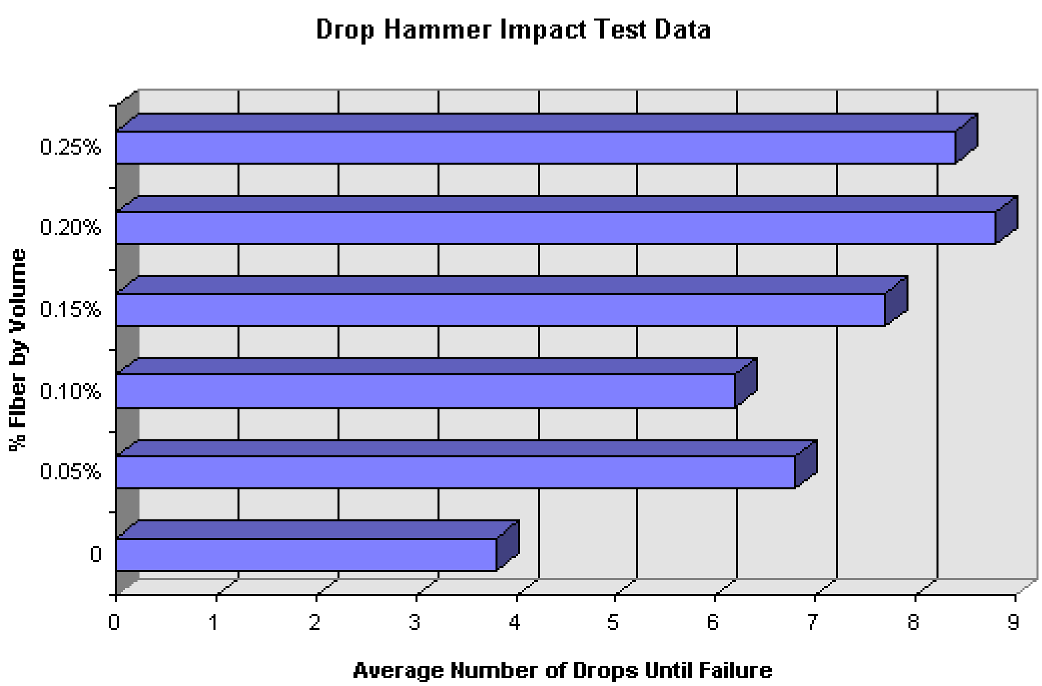
The toughness of a material is defined as a measure of the amount of energy that can be absorbed by the material before failure, (the area under the stress-strain curve). Since concrete is a brittle material, it cracks easily and has a low toughness index. The use of polypropylene fibers can greatly improve the toughness of concrete. This improvement in toughness is due to increased ductility of the concrete specimen. Increased ductility results in an increase in the area under the stress-strain curve, and increased toughness. The statistical improvement in toughness is illustrated directly by the studies conducted on the improvement of impact resistance.

Impact Resistance

Polypropylene fiber-reinforcement has been shown to markedly improve the impact resistance of concrete. This impact resistance is helpful in such applications as crash barriers, concrete piles, and slabs subjected to impact loading. Several studies have shown that the addition of polypropylene fibers by 0.2% by volume increases impact resistance by 250%, with one study demonstrating an increase in impact resistance of 900% when 0.3% fibers by volume are used. These dramatic results certainly are not typical of polypropylene fiber reinforced concrete, but are mentioned to give an idea of the material's potential. The chart below summarizes data from a study published in ACI SP-142, using a fiber length of 19mm (0.75 inches) (Berke, 1994). These results are what normally can be expected from PFRC concrete.

A study by Soroushian and Mirza at Michigan State University showed that an addition of 0.1% fiber by volume increased the impact resistance of pozzolan concrete by 100%, and of regular concrete by 50%. Another study by Mindess and Yan at the University of British Columbia demonstrated the effectiveness of increasing the bond strength (between concrete and steel rebar) and the impact resistance of concrete reinforced with traditional steel reinforcement. The fibers (at 0.5% by volume) increased the ductility of the sample, and enabled the stress of an impact to be transferred across a crack, slowing crack propagation and allowing the concrete matrix to accommodate increased deformations. This ability of the concrete to tolerate increased deformations allows the rebar to provide even more strength to the concrete. It was found that under impact loading, the rebar attained a higher average bond strength, and the overall impact resistance of the sample was increased.

The use of polypropylene fiber reinforcement greatly increases the impact resistance of concrete, and can be useful under impact loading conditions. Also, it is



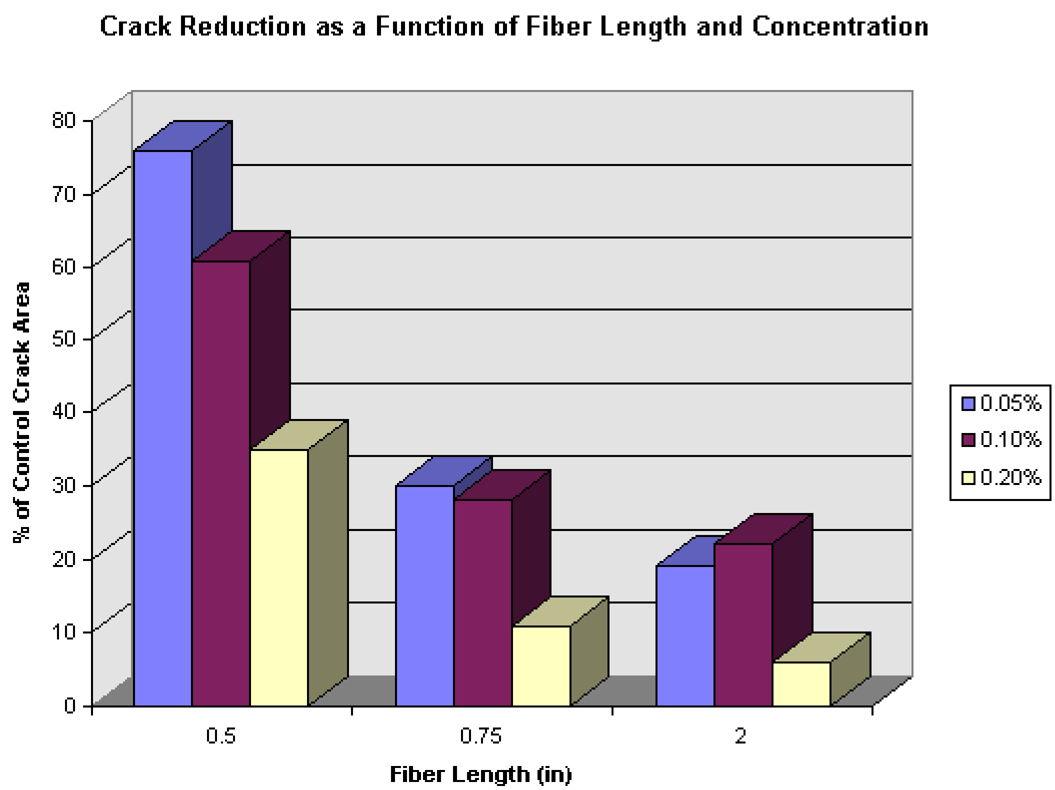
worthy to note that in pozzolanic concrete, the normally low impact resistance of this material can be greatly enhanced (doubled) by the addition of fibers.

Cracking

Cracking is the most common of concrete problems. Cracking occurs when stresses in the concrete exceed the concrete strength. There are two main types of cracking that occur due to the hardening (drying) of the concrete, and not from externally applied loads. These are plastic shrinkage cracking and drying cracking. Plastic shrinkage cracking occurs during the first few hours of curing and is caused by moisture quickly leaving the outer layer of the concrete. Since there is still the original amount of water in the concrete below the outer layer, stresses develop and cracking occurs. Drying shrinkage cracking is due to the localized buildup of stresses in the concrete, as concrete shrinks slightly as it ages. The most common way to avoid a large amount of drying shrinkage cracks is to use joints at proper intervals within slabs.

It is important to limit the amount of cracking in concrete to maintain low permeability and limit weak areas that are susceptible to early spalling or delamination. A crack is an easy way for water, chlorides, and oxygen to invade the concrete and cause freeze-thaw damage, attack steel reinforcement, and oxidize the matrix. Cracks from plastic and drying shrinkage cracking are also weak areas in the matrix that can lead to faster physical deterioration of the concrete.

Polypropylene fibers have been studied as a way to reduce plastic shrinkage cracking. In a study by Kovler et al. (1992), it was demonstrated that using 0.3% fibers by volume reduced plastic shrinkage cracking to such an extent that no cracks could be observed, and lower volumes of fibers (0.05 to 0.2% by volume) visibly restrained crack width compared to samples that were not fiber reinforced. The above mentioned study also found that there was no noticeable effect on free-shrinkage (drying) cracking, which occurred independent of fiber volume. Many other studies also showed that fiber addition rates of between 0.05 to 0.2% by volume significantly reduced plastic shrinkage cracking in the samples (by 40 to 80%). In conjunction with one of these studies, Berke and Dallaire (1994) reported that the addition of fibers at these small dosage rates did not adversely affect the freeze-thaw durability of the concrete. The graphic above is reproduced from Berke and Dallaires' 1994 study published in ACI SP-142, and shows the relationship between fiber lengths and dosage rates on the number of cracks observed.



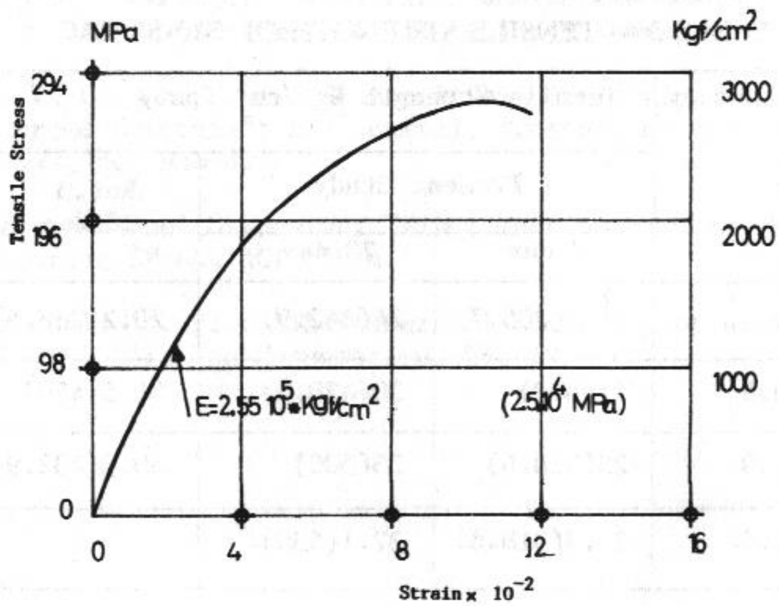


Fig. 1—Polypropylene fiber stress-strain curve

The addition of polypropylene fibers at low dosage rates (0.1 to .03% by volume) can be extremely effective in reducing plastic shrinkage cracking, with volumes of 0.2 to 0.3% being the most effective. Results are inconclusive on the effect of fibers on drying shrinkage cracking with some studies reporting moderate benefits, and others no benefits whatsoever. Proper concrete placement and joint spacing still seems to be the most effective control measure for drying shrinkage cracking. Industry advertising claims imply that polypropylene fibers can replace welded wire fabric in many slabs on grade. These claims are probably not entirely accurate since the scientific evidence seems to indicate that polypropylene fibers are only effective when used to reduce plastic shrinkage cracking, and welded wire fabric is used mainly to stop drying shrinkage and temperature cracking.

Continuous Reinforcement

Polypropylene can be applied as continuous reinforcement in a concrete matrix, as opposed to randomly dispersed fibers. The main forms of continuous polypropylene reinforcement are thin sheet and mesh reinforcement. Both of these forms allow the engineer to easily vary the volume of reinforcement in the concrete, and to place the reinforcement exactly where it is needed. Most applications of continuous reinforcement are in thin concrete members (e.g. concrete paneling) and this continuous reinforcement provides (at 8 to 12% by volume) increased flexural strength, ductility, and toughness.

Basic properties of polypropylene:

Polypropylene has several unique properties that make it especially suited for use in concrete. Polypropylene is chemically inert and stable in the alkaline environment of concrete, with a relatively high melting point, and low cost. Polypropylene does not absorb water, due to a hydrophobic surface, which prevents any chemical adhesion with the concrete matrix. Fibers made from polypropylene bond in the concrete matrix through interfacial adhesion and mechanical anchoring. The disadvantages of polypropylene are that it is sensitive to fire, sunlight, and oxygen, it has a low modulus of elasticity, and it bonds poorly with the concrete matrix. It has been found that using certain surface treatments, either chemical (detergents or mild acids), or mechanical, can increase the bond between polypropylene and concrete. Below are some typical polypropylene properties and their values.

Specific Gravity	0.90-0.91
Modulus of Elasticity	1240 - 1517 MPa (180-220 Ksi)
Melt Point	160° C - 170° C (320° F - 340° F)

Ignition Poin	590° C (11OO° F)
Absorption	Nil
Thermal Conductivity	Low
Electrical Conductivity	Low
Acid and Salt Resistance	High

Source: Eastman Chemical

The chart above shows a typical stress-strain curve for polypropylene.

Rheological Properties

When pouring concrete, one of the main concerns of a contractor is the workability of the material. The addition of pozzolans or fibers to a concrete mixture has a definite impact on slump, workability, and finishability. The effect of polypropylene fibers on workability has been extensively documented. Even small volumes of fibers drastically reduce the slump and workability of the concrete. It has been the author's own experience that fiber concentration around 0.5% by volume leads to zero slump, but workability and finishability can be maintained by the use of a superplasticizer. The addition of fibers increases the stability, cohesion, and internal resistance of the fresh concrete, which makes pumping more difficult, but results in better concrete since pumping problems, such as segregation are lessened. The picture below shows polypropylene fiber reinforced concrete being pumped into formwork.

Another advantage of increased stability and cohesion of the fresh concrete is that the time required to develop stiffness is greatly reduced. Faster times for developing stiffness means that formwork for slabs could be removed sooner than usual since the concrete will be stiff enough to resist its own lateral pressure. This faster time to develop stiffness means that slipform construction can proceed faster as well, as shown in the picture of Jersey barrier construction below.

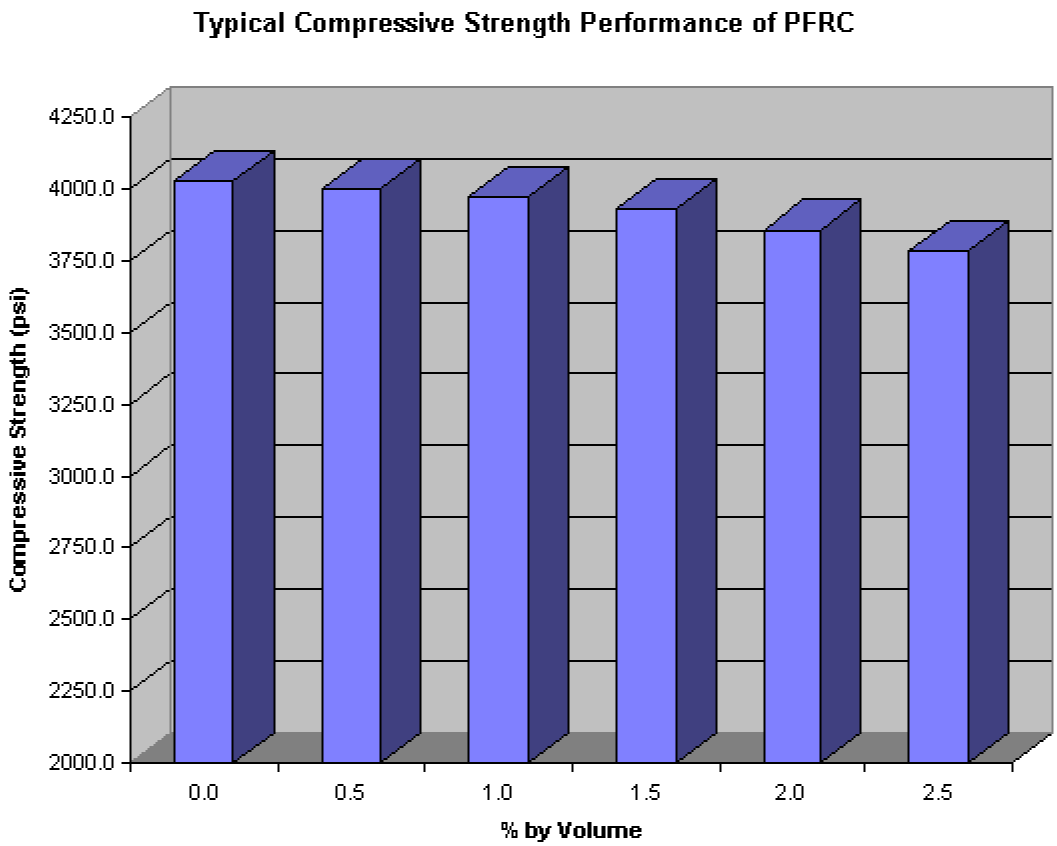
Despite a reduction in workability, the fibers do reduce the amount of bleeding in fresh concrete. This is beneficial because it means that there is less segregation of the concrete, and the water is more evenly distributed to ensure complete hydration of the hardening concrete. Finishing is also not significantly more difficult than with plain concrete. Workers report that polypropylene fiber reinforced concrete take all types of finishes well, but it generally has to be finished sooner than usual due to the rapid gain of stiffness.

In conclusion, the addition of any amount of fibers greatly effects the rheological properties of fresh concrete. Slump and workability are reduced, time to gain stiffness and the amount of bleeding decreases, and the finish must be applied more rapidly than usual. Some of these effects can be counteracted by the use of a superplasticizer or water-reducing admixture.

Compressive Strength

The compressive strength of any type of concrete is a vital parameter when designing concrete structures. If an additive such as polypropylene fibers significantly increases or decreases the compressive strength of concrete, this effect on strength must be considered for proper design with the material.

The effect of fibers on compressive strength when used in low volumes (.05 to 0.25%) is minimal. In terms of absolute values, the



compressive strength decreases slightly, but the difference is not statistically significant.

One study by Ramakrishnan, et al. (1987), showed that the addition of polypropylene fibers at 0.1, 0.2, and 0.3% actually increased the 28 day compressive strength by 10% for the 0.1 and 0.3% mixes, and by 20% for the 0.2% mix. In a study conducted by the author in the spring of 1998, it was found that the addition of polypropylene fibers at 0.45% by volume decreased the 28 day compressive strength by 47% under dry curing conditions. These results seem to indicate that there may be an effective volume threshold for adversely effecting the compressive strength of the concrete that is exceeded at 0.45% fiber by volume.

All things considered, it appears that at low dosage rates (0.05 to 0.3%), the addition of polypropylene fibers does not significantly detract from, and may even improve the compressive strength of concrete. Higher dosage rates may, however, decrease the strength of the concrete matrix due to higher volume of fibers interfering with the cohesiveness of the concrete matrix.

Creep

Creep is defined as a time dependent deformation under sustained loading. Knowing the creep of concrete is valuable for ensuring that members (e.g. columns) will be a sufficient length after being loaded for several months or years, in order to avoid unwanted effects such as doors not closing properly, or drywall cracking due to the column shortening.

A limited amount of research has been conducted on the effect of polypropylene fibers on creep. One study, conducted by Houde, et al. (1987), studied the effect on creep of concrete containing 0.1, 0.3, 0.5, and 1.0% fiber by volume. It was found that creep increased by 20-40% with these volumes of fiber.

From basic engineering principles, it can be assumed that the addition of a low strength, low modulus material to the concrete matrix will increase creep in the member. However, addition of materials which make the concrete denser, such as silica fume or fly ash could offset the effect of the fibers.

Permeability

When evaluating the quality of concrete, permeability is an important parameter. The less permeable a concrete sample is, the less susceptible it will be to water, chlorides and other damaging agents. Therefore, in order to determine the quality of polypropylene fiber reinforced concrete, the permeability must be evaluated.

A study by Soroushian and Mirza at Michigan State University showed no statistically significant change in permeability with 0.1% fiber by volume. The author suggested that at slightly higher dosage rates, permeability may be decreased due to the reduction of plastic shrinkage cracks. This suggestion is verified by the following case study. A study conducted by Sanjuan, Moragues, etal. (1991), found that the air permeability of concrete reinforced with polypropylene fibers at volumes ranging from 0.1 to 0.3% was actually reduced. This reduction in air permeability indicates that the concrete could perform more effectively in the long term.

The effects of polypropylene on permeability seem to be slightly positive (or at worst, neutral). For dosage rates higher than 0.1% by volume, permeability can be reduced, and plastic shrinkage cracking can be reduced and/or eliminated (reducing permeability), depending upon the volume of fiber used.

Durability

It has been suggested that the addition of polypropylene fibers to a concrete mixture can increase the durability of concrete. Testing has yielded mixed results. Several studies have shown that polypropylene fiber reinforced concrete has no advantages in terms of abrasion resistance, while others have indicated that collated fibrillated polypropylene fibers increase abrasion resistance. Polypropylene fibers have been shown to increase the performance of repairs to concrete slabs. An overlay of US 322 near Hershey, Pennsylvania (shown in the above picture) using 0.1% fiber by volume in 1985 has performed extremely well. The adjacent sections of non-fiber-reinforced roadway (of the same age) show obvious signs of distress, such as cracking, delamination, and spalling. In contrast, the fiber-reinforced section appears to be almost totally unscathed by the years of traffic. Another study of polypropylene fiber-reinforced concrete used on busy city streets in India yielded similar results. It seems as if there is a disparity between the laboratory and the real world in regards to the abrasion resistance of polypropylene fiber-reinforced concrete.

Despite the apparent differences between laboratory tests and real world experience, it is widely agreed upon that even the smallest volume of fibers inhibits spalling, dusting, and delamination. Laboratory tests which better represent real world conditions need to be carried out in order to properly assess the abrasion resistance of polypropylene fiber-reinforced concrete.

In low volumes, polypropylene fibers have no effect on the freeze-thaw resistance of properly air-entrained concrete (Berke, 1994). The benefit of fibers is that concrete experiencing freeze-thaw damage is more cohesive, and experiences less spalling and delamination.

Polypropylene fibers seem to have no effect on the resistance to chemical attack of a concrete mixture, since permeability is not drastically reduced, and the polypropylene fibers are fairly inert.

Deicing scaling of concrete is reduced with the addition of polypropylene fibers to a concrete mixture.

It stands to reason that the qualities of the fibers that inhibit cracking, and increase toughness and impact resistance would also provide resistance to abrasion, deicing scaling, spalling, dusting, and delamination, thereby increasing the overall durability of a concrete mixture.

Acknowledgement:

Department of Civil and Environmental Engineering
The Concrete Clinic Library
Penn State University
http://www.engr.psu.edu/ce/concrete_clinic/