Ends of "self-fibrillating" monofilaments fray during mixing to increase bond

Innovative Synthetic Fibers

by Jean-Francois Trottier and Michael Mahoney

After four years of research and development on improving the bonding capabilities of synthetic fibers, we recently patented a high-tensile-strength synthetic fiber that partially fibrillates upon mixing and shooting, increasing its final surface area and bonding capabilities to the concrete.[1] The fibers are introduced into the concrete mixer as monofilament units of relatively low surface area (F4-a in Fig. 1), allowing up to 2% vol. (18.5 kg/m^3 [31.2 lb/yd^3]) fiber dosages. During the mixing process, each fiber transforms into a unit having several fibrils at its ends (F4-b in Fig. 1). The fibrils anchor each fiber so their bonding capabilities are superior to those of conventional smooth and deformed monofilament fibers. The high number of fine fibrils in the concrete reduces plastic shrinkage cracking. Most importantly, these fibers have demonstrated an improved ability to increase the toughness and energy absorption capability of the concrete.

ID	Fiber Geometry (mm)	Material
F1	25; 0.55; 0.35	polypropylene
F2	50; 0.96; 0.63	polypropylene
F3	50; 0.55; 1.2	polypropylene
F4-a	50; 0.37; 1.1	polypropylene / polyethylene
F4-b	50; Various 0.05 - 1.0	polypropylene / polyethylene
F5	50; 0.80; 2.55	steel

Fig. 1: Fiber characteristics

Self-fibrillating fiber characteristics

Bond is the weak link that governs most of the mechanical properties of fiber-reinforced concrete, in which performance depends largely on the bond's effectiveness at transferring forces between the fibers and the matrix. The main components of bond are physical and chemical adhesion, friction, mechanical anchorage, and fiber-to-fiber interlock.[2]

The work we conducted at Dalhousie University showed that the pull-out resistance of smooth, straight, polyolefin fibers is generated mostly through frictional forces. During fiber pull-out testing, these fibers start to slip from the concrete at stresses far below their tensile strength, indicating that their properties are not fully utilized. We knew that if the bonding capabilities could be improved, the performance of concrete containing fibers would also improve. Unfortunately, the low tensile strength (275 MPa [39,900 psi]) and modulus of elasticity (2.65 GPa [384,000 psi]) of the smooth polyolefin fibers put a significant limit on the performance improvements that could be achieved even if the bonding properties with the cement matrix could be improved.

Recognizing those limitations, we developed a monofilament synthetic fiber with a 500+ MPa (72,500+ psi) tensile strength. To improve the fiber's bonding capability, we optimized the lateral surface area contacting the cement matrix, increasing the fiber's frictional resistance. To achieve this, the fiber partially fibrillates during the mixing process.

After reviewing the various polymeric materials available on the market and studying the synthetic filament manufacturing processes, we identified a high-strength monofilament that fibrillated when manipulated. Known as Polysteel™ in the rope manufacturing industry, this monofilament is obtained by extruding precise proportions of polypropylene and polyethylene resins. The fiber's fibrillating ability is obtained by mixing the two polymers, which are incompatible. After extrusion, visual observation doesn't indicate that the fiber is really two different materials.

Manipulation of the filament reveals its tendency to fibrillate, the result of the two polymers separating. A preliminary evaluation of the monofilaments cut at specific lengths revealed that the fibers did fibrillate when mixed in concrete. This important asset, combined with their 500± MPa (72,500± psi) tensile strength, 4.3 GPa (620,000 psi) modulus of elasticity, high resistance to concrete's alkaline environment, and good resistance to UV rays, convinced us that this synthetic material had all the required properties.

Before it's added to concrete or shotcrete, the fiber is a monofilament. For packaging purposes, monofilament fibers occupy less space than fibrillated fibers, a significant asset when dealing with large shipments. Most importantly, monofilament fibers enable a uniform distribution of 0.5% volumes or higher throughout the concrete mixer. After a few minutes of agitation, the fibers start to fibrillate. They don't tend to ball, as they are already well-separated and dispersed.

For the next two years, we worked on optimizing the fiber's fibrillating ability, tensile strength, and modulus of elasticity. These properties are dictated by the type of resins used, their proportions, and the specific extruder settings used during the manufacturing process. The optimal cross section of the rectangular filament and its exact length were determined from pull-out tests conducted on mortar and concrete samples.

Figure 2 shows typical pull-out strengths obtained on two prototypes of the 50 mm (2 in.) self-fibrillating fiber, compared with the results obtained on a smooth 50 mm (2 in.) fiber (F2 in Fig. 2). Each curve shows the maximum pull-out resistance after 1, 3, 7, 14, 21, and 28 days of curing. Fiber pull-out was the failure mode for all of the fibers. Our fiber's ability to resist pull-out stresses was at least three times greater, at all ages, than that of the conventional monofilament polyolefin fiber. Because the dimensions and specific gravity of the polyolefin fiber and our fiber are very similar, our fiber will require a much lower dosage in concrete than the polyolefin fiber to meet a certain performance criteria.

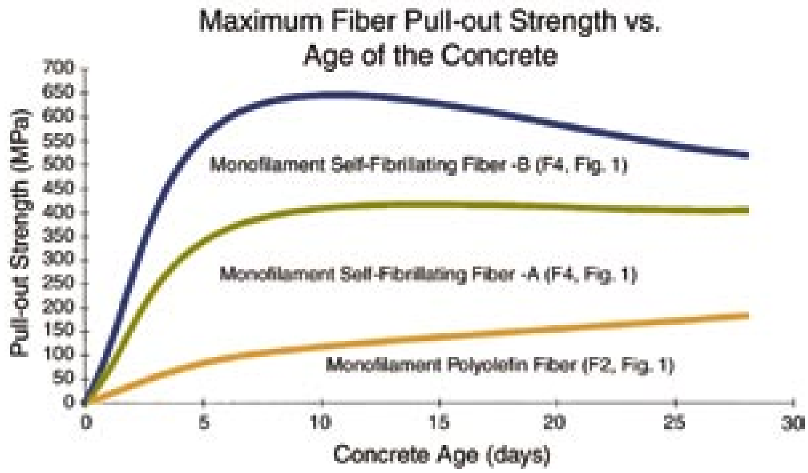

Fig. 2: Pull-out test

Comparative performance

Fiber addition through pumping

Even with the best of results from small-scale laboratory evaluations, a new fiber will only be suitable for use in day-to-day construction activities if it's easy to incorporate into the mixing unit; if its use doesn't significantly affect the production at the job site; and if it doesn't cause any significant balling, workability, or finishing problems.

We conducted full-scale, ready-mixed concrete trials first to evaluate if there would be any problems with dispensing and mixing the fibers with conventional construction equipment, and second, to produce test samples to compare against other types of reinforcement.

Method of fiber addition—For the trials, the fibers were packaged in nondissolvable 3.4 kg (7.5 lb) plastic bags. In the earlier stages of the fiber development project, the fibers had a tendency to clump together in the mixing unit because of their high aspect ratio. We changed the geometry of the fibers to obtain proper fiber distribution after mixing with no presence of fiber balls. We successfully added fibers at the beginning of the batching process into an empty truck, with the aggregates on the conveyor belt, and at the end of the batching process into the plastic concrete.

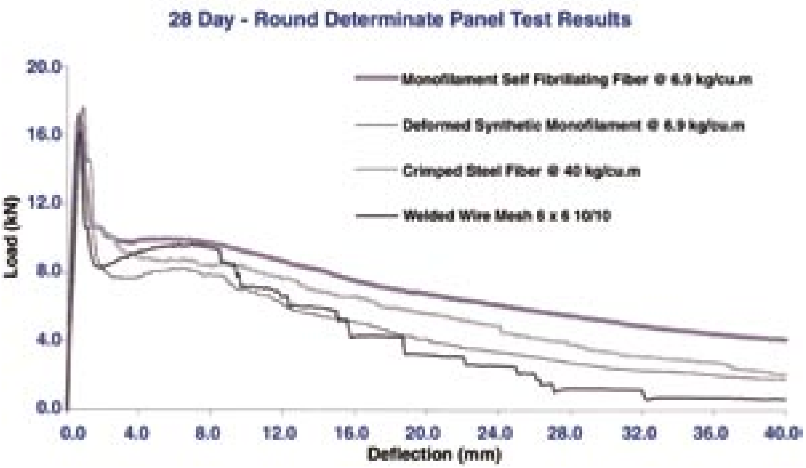

Fig. 3: Round determinate panel results

Mixing time—Adding all of the fibers required for a 5 m^3 (7 yd^3) concrete load at a 0.75% vol. fiber dosage (7 kg/m^3 [12 lb/yd^3]) took 60 to 90 sec. Depending on the workability of the concrete mixture, it took 2 to 5 min of mixing to obtain proper fiber dispersion and fibrillation. As anticipated, the fibers didn't affect the air content of the plastic concrete or the hardened concrete's specific surface area and air-void spacing.

Workability—As with other fiber types, our fibers caused a 50 to 100 mm (2 to 4 in.) slump reduction when used at fiber addition rates of 4.5 kg/m^3 (7.6 lb/yd^3) (0.5% vol.) to 9.0 kg/m^3 (15 lb/yd^3) (1.0% vol.). At such fiber addition rates, fiber-reinforced concrete mixtures typically require water-reducing admixtures and higher cement and fine aggregate content to maintain proper workability.[3]

Finishability—The finishing crew used screeds, roller bugs (in some cases), bullfloats, and power trowels to finish the test concrete. They commented that because the monofilament self-fibrillating fiber is very flexible, concrete containing it was easier to place and finish than concrete containing conventional steel fibers. Overall, the hardened concrete had an excellent finish and revealed very few visible fibers.

A large number of similar trials were performed at various locations with different crews. Their general consent was that the new fibers were user friendly and easier on the construction equipment than steel fibers.

Pumping—When being pumped, ready-mixed concrete and wet-mix shotcrete incorporating our fibers had very little pump-pressure difference than plain concrete. In an independent wet-shotcrete evaluation program, it was possible to pump and shoot as much as 1.5% vol. (13.5 kg/m^3 [22.7 lb/yd^3]) of the 50 mm (2 in.) fibers through a reduced 38 mm (1.5 in.) hose section without any problems.[4] In contrast, in the same evaluation program, the maximum fiber content at which a conventional fibrillated polypropylene fiber could be reasonably pumped and shot through a larger 50 mm (2 in.) diameter hose was only 0.55% vol. (5 kg/m^3 [8 lb/yd^3]). Their high surface area created workability problems at fiber contents higher than 0.55%. In the same program, shorter conventional 30 to 35 mm (1.2 to 1.4 in.) shotcrete steel fibers were used to allow pumping through the small 38 mm (1.5 in.) diameter hoses.

The various shotcrete trials revealed that our 50 mm (2 in.) long fiber can be easily batched, pumped, and shot with standard shotcreting equipment.

Flexural toughness in concrete

We conducted tests on cast-in-place concrete to evaluate the reinforcing ability of the self-fibrillating monofilament fiber compared with other types of reinforcement. To compare the fibers with welded wire fabric, we used the Round Determinate Panel test for toughness developed by Bernard and currently under ASTM review.[5] The test more reliably measures post-crack energy absorption than the ASTM beam test.[6] A central point load is imposed on a round, 800 mm (31 in.) diameter x 80 mm (3.1 in.) thick specimen supported on three radial points. The slender geometry of the specimen results in a failure mode dominated by flexure and membrane tension, reflecting in-place behavior closely.

Performance is measured by peak load capacity and energy absorption up to a 40 mm (1.6 in.) central deflection. The peak load capacity is taken to reflect the strength of the concrete matrix. The energy absorption—a direct reflection of the post-crack performance of the fibers or the mesh—is found by integrating the load-deflection curve up to the 40 mm (1.6 in.) deflection point. Because it is possible to accurately position the mesh layer in the mold when preparing the test panels, keep in mind that the values obtained for the mesh represent an ideal case scenario where the mesh layer has been positioned exactly at its intended plocation in the structure.

Figure 3 shows the average results of load deflection tests at 28 days for Round Determinate Panels reinforced with a 152 x 152 – MW9 x MW9 (6 x 6 – W1.4 x W1.4) welded wire mesh, 40 kg/m^3 (67 lb/yd^3) of steel-crimped fibers (F5 in Fig. 1), 6.9 kg/m^3 (12 lb/yd^3) of deformed monofilament synthetic fibers (F3 in Fig. 1), and 6.9 kg/m^3 (12 lb/yd^3) of the new monofilament self-fibrillating fiber. Two panels were tested for each type of reinforcement. All specimens were prepared under the same conditions using full-scale, ready-mixed concrete equipment and an identical 28 MPa (4000 psi) concrete mixture.

This method produced very consistent results with little variation between similar test specimens. All the panels broke at approximately the same load. This was expected because we used similar concrete for all specimens tested, and neither fibers at the low dosages evaluated nor welded wire mesh will increase the flexural strength of concrete. The differences in performance can be seen in the post-cracking zone of the load-deflection curves.

While some applications may require reinforcement that will provide the greatest cracking resistance at very small crack openings (small deflection), others, in which the formation of medium to large size cracks is anticipated, may require reinforcement performing well at mid to large deflection values. We measured approximate values of the maximum crack width during testing of the round panels. The maximum crack width at the bottom of the panel was 0.25 mm (0.010 in.) wide at a 3 mm (0.1 in.) panel deflection, between 0.25 and 2 mm (0.010 and 0.08 in.) wide for 3 to 12 mm (0.1 to 0.5 in.) deflections, and between 2 and 12 mm (0.08 and 0.5 in.) wide for 12 to 40 mm (0.5 to 1.6 in.) deflections. These values are listed here to provide a sense of the magnitude of the crack widths corresponding to the deflections shown in Fig. 3.

When looking at the behavior of the various samples at 0 to 3 mm (0 to 0.1 in.) deflections, the load of the mesh-reinforced panel suffers a significant drop immediately after matrix cracking. Because the mesh is only located at the mid-plane of the panel, and because the crack forms at the bottom of the panel, a greater deflection of the panel is required before the mesh actually becomes involved. In a fiber-reinforced panel, fibers bridge cracks forming at the bottom of the panel, resisting further opening.

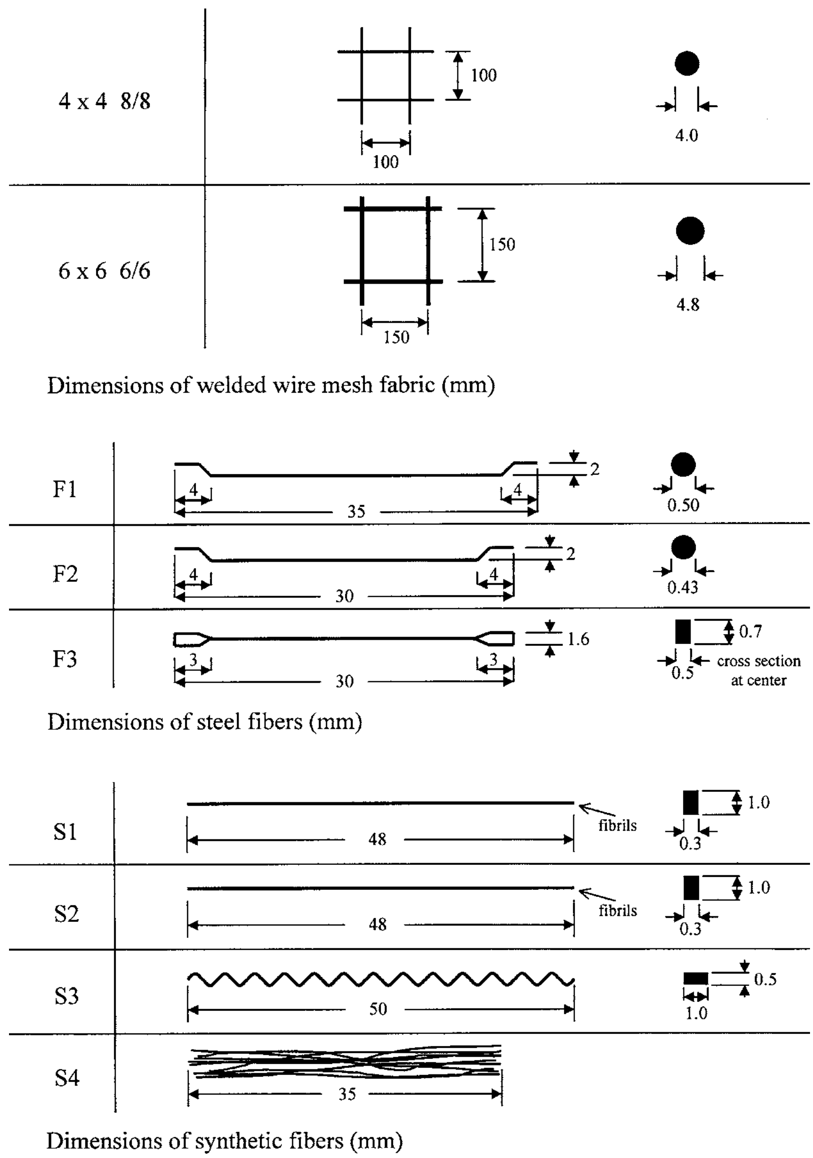

Fig. 4: Description of meshes, steel fibers, and synthetic fibers used in study

The curve in Fig. 3 shows that the mesh-reinforced panel actually reaches its maximum load-carrying capacity at a 7 mm (0.3 in.) deflection, after which several consecutive sudden drops in load correspond to progressive failure of the mesh. The panels reinforced with the deformed synthetic monofilament fibers (F3 in Fig. 1) exhibited the greatest drop in load after matrix cracking, indicating that they are not as effective as the mesh in picking up the sudden transfer of stresses. This poor performance at small deflections may be due to a combination of the low modulus of elasticity of the fibers and an insufficient ability to bond with the concrete. The behavior of panels reinforced with the steel

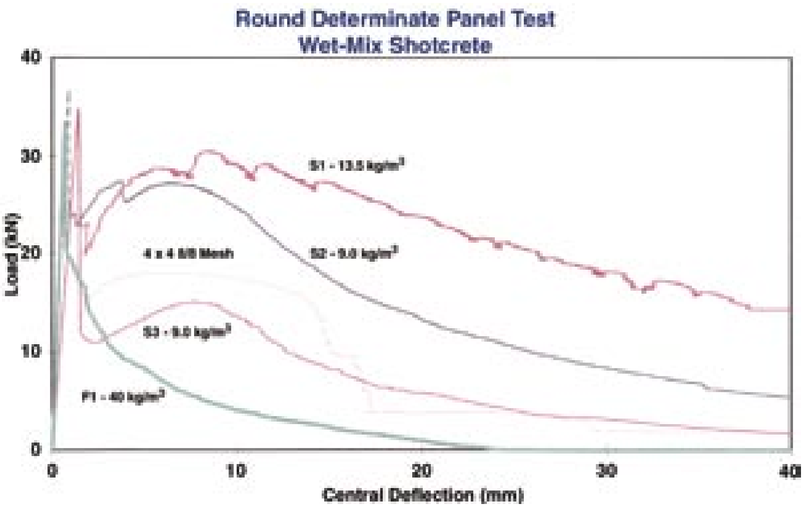

Fig. 5: Round determinate panel results

fiber (F5 in Fig. 1) and that of the self-fibrillating fiber was identical up to a deflection of 2.5 mm (0.10 in.), after which the synthetic fiber-reinforced panels exhibited a greater load-carrying capability.

With respect to energy absorption provided by each reinforcing alternative up to 40 mm (1.6 in.) deflection, the mesh option was the lowest at 174.4 joules (128.6 ft-lbf), closely followed by the deformed synthetic fiber (F3) at 184.9 joules (136.4 ft-lbf), followed by the steel fiber (F5) at 232.4 joules (171.4 ft-lbf). The greatest overall performance at both small and large crack openings was obtained with the self-fibrillating fiber, which recorded 284.8 joules (210.0 ft-lbf), a 63% increase over mesh, a 54% increase over the other synthetic fiber, and a 23% increase over steel fiber.

Similar trends were obtained when conducting ASTM C 1018 tests on beam specimens with the same fiber types and dosages, excluding the mesh.

Performance in shotcrete

The most comprehensive study completed to date on the performance of the new monofilament self-fibrillating fiber in shotcrete was conducted by Morgan et al.[4,7] Several distributors of steel and synthetic fibers and welded wire mesh were invited to evaluate the performance of their product in wet- and dry-mix shotcrete. One of the goals was to assess the performance of each technology, as measured using ASTM C 1018 flexural toughness beams, the Round Determinate Panel test, and the South African water bed toughness test.[8]

Figure 4 provides a description of the synthetic fibers, steel fibers, and welded wire mesh evaluated in the testing program. Figure 5 shows the results of the Round Determinate Panel tests for some of the alternatives listed in Fig. 4. The results clearly show that the new fiber (S1 and S2 in Fig. 5) outperformed the other reinforcing alternatives in terms of overall resistance to crack openings.

The round panels reinforced with 1% vol. (S2 at 9.0 kg/m^3 [15 lb/m^3]) of the new fibers resisted crack opening with 254 joules (187 ft-lbf) of energy in the 0 to 10 mm (0 to 0.4 in.) deflection range. This value represents a 47% increase over panels reinforced with a 102 x 102 – MW14 x MW14 (4 x 4 – W2.1 x W2.1) mesh, a 49% increase over the best steel fiber entry (F3) at 40 kg/m^3 (67 lb/yd^3), and an 80% increase over the deformed monofilament synthetic fiber (S3) at a similar fiber dosage.

At greater deflections, the advantages of using the monofilament self-fibrillating fiber become even more obvious. In the 0 to 40 mm (0 to 1.6 in.) range, panels reinforced with 9.0 kg/m^3 (15 lb/yd^3) of the new fiber recorded 608 joules (448 ft-lbf) of energy, an 80% increase over panels reinforced with a 102 x 102 – MW14 x MW14 (4 x 4 – W2.1 x W2.1) mesh, a 132% increase over the best steel fiber entry (F3) at 40 kg/m^3 (67 lb/yd^3), and a 106% increase over the deformed monofilament synthetic fiber (S3) at a similar fiber dosage. The same trends were also recorded under ASTM C 1018 beam tests and the South African panel tests. As seen in Fig. 5, a greater dosage of the monofilament self-fibrillating fiber (S1 at 13.5 kg/m^3 [23 lb/yd^3]) resulted in an even greater overall performance.

It was concluded by Morgan that shotcretes reinforced with the new fibers are well-suited for use in final linings in tunnels or other structures where only small deformations can be tolerated, and as primary linings in tunnels or mines in ground conditions where substantial movement is expected.[7]

A shotcrete build-up thickness and material rebound evaluation of the new monofilament self-fibrillating fiber was recently conducted by the Laboratoire d'expertise en Materiaux (SEM) in Quebec City, Canada.[9] Wet-mix shotcretes incorporating 9.2 kg/m^3 (15 lb/yd^3) of the new fibers recorded an 8% value for vertical rebound (overall material rebound), compared with 15% for shotcretes incorporating

40 kg/m³ (67 lb/yd³) of end-hooked steel fibers. Values recorded for the horizontal rebound were 16% for the new fiber, compared with 25% for the steel fiber. The overhead build-up thickness was improved by 40% when using the synthetic fiber in lieu of the steel fiber. Such reductions in rebound and improvements in build-up thickness could lead to production and materials savings in medium and large scale projects.

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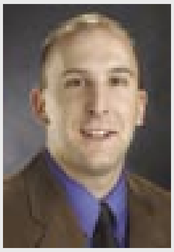

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