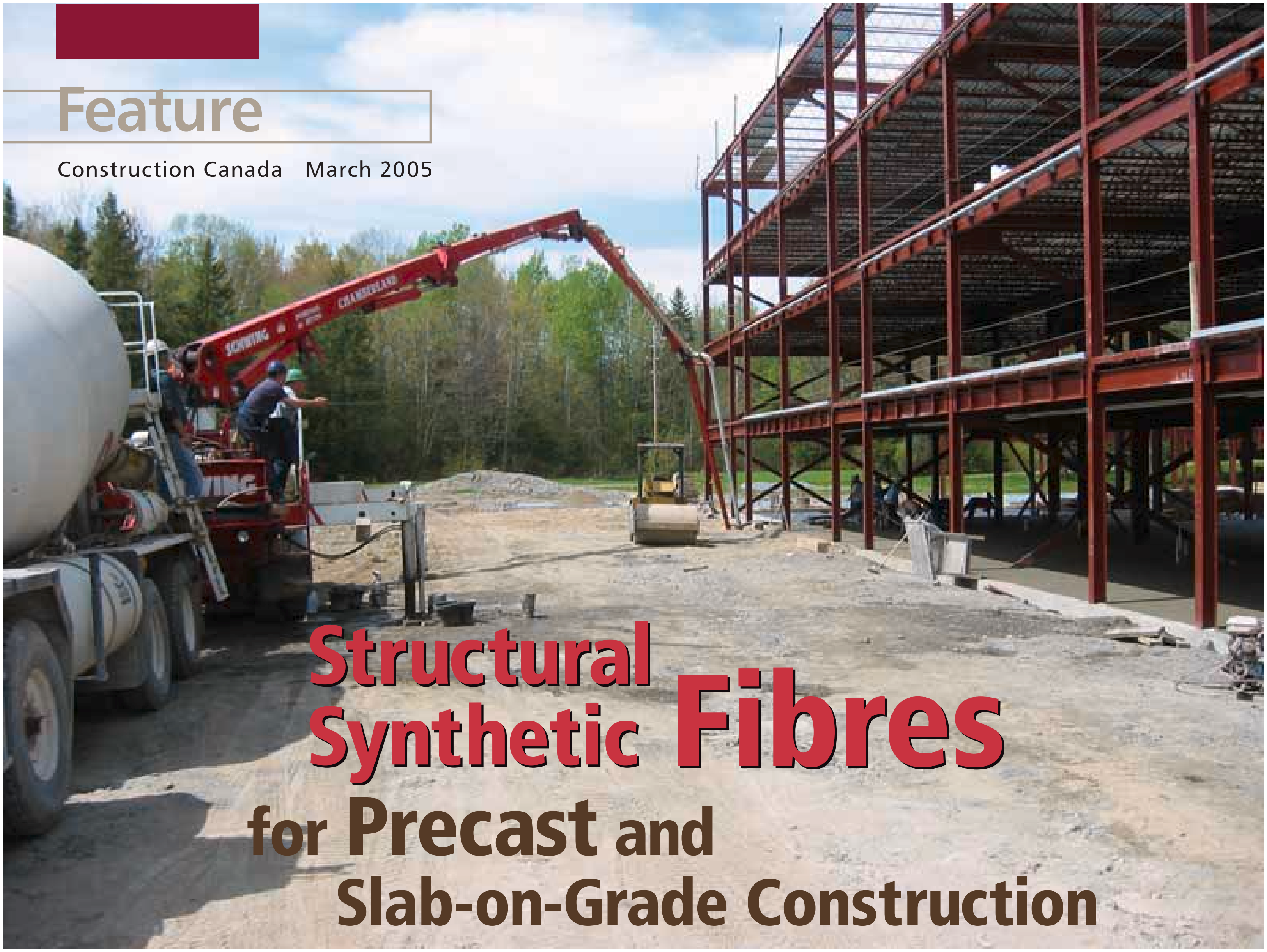
Feature

Construction Canada March 2005



# Structural Synthetic Fibres for Precast and Slab-on-Grade Construction

By Michael Mahoney

*Pumping macro-synthetic fibre-reinforced concrete at Bishop's University in Lennoxville, Que.*

As the use of synthetic fibres in concrete applications has grown, so has the range of available products, varying from large macro-fibres to aid in load-carrying capacity to monofilament and fibrillated micro-fibres for plastic shrinkage protection. The fibres themselves have varied compositions, including polypropylene, polyethylene, polyester, nylon and combinations thereof.

Some fibre manufacturers claim low-denier synthetic fibres (the traditional market) can replace welded wire fabric (WWF) for slab-on-grade and precast concrete applications, but this is only valid provided the WWF and fibres are being used solely for preventing plastic shrinkage cracking.[1] When resistance to crack openings and load-carrying capacity is also required, WWF shows itself as the superior alternative to micro-fibres. Due to their geometry and physical characteristics, these micro-synthetic fibres can only be added at dosage rates up to a maximum of 1.2 $kg/in^3$ (2 lb/cy).

Over the past decade, advancements in extrusion properties and polymer production have resulted in synthetic fibre materials capable of providing similar performance (under standardized testing) to steel fibres and selected reinforcing percentages, corresponding to WWF and light-gauge reinforcing bars. These fibres, generally larger and coarser than their predecessors, can be added at higher reinforcing levels, providing enhanced toughness.

A limited number of these products have also been

*Advancements in extrusion properties and polymer production have yielded synthetic materials providing similar performance to steel fibres. They can be added at higher reinforcing levels to offer enhanced toughness. The above photos show the placing and finishing of this fibre-reinforced concrete (FRC).*

shown to reduce plastic shrinkage potential while providing load-carrying capacity similar to WWF and bar reinforcing. These new materials are being branded with the marketing term 'structural fibres,' which can be misleading because the performance of a fibre type at a given reinforcing level ultimately determines whether any of the composite material's structural properties are present.

The more technically accepted name for these new fibres is 'macro-synthetic fibres'—this incorporates all materials capable of providing toughness similar to steel fibres and light conventional reinforcing. As such, it is important to provide test data and an appropriate analysis of the selected concrete product to determine whether these new materials provide the same structural capacity as their conventionally reinforced counterparts.

Through simple engineering principles for reinforced concrete design and current testing standards for fibre-reinforced concrete (FRC), one can compare the use of fibres versus conventional welded-wire fabric and light-gauge reinforcing bars for precast and slab-on-grade concrete.[2]

## Precast concrete

Unsupported concrete elements of uniform thickness subjected to an applied load can be considered as wide shallow beams for the purpose of design and analysis.[3] In such bending members, reinforcing bars are generally spaced uniformly over the whole cross-section, allowing analysis over a unit width section. As such, a section's maximum sustainable applied moment can be calculated given the concrete's compressive strength, thickness and depth to reinforcement. Manufactured concrete products falling under this category include septic tanks, manhole risers, tilt-up wall panels and burial vaults.

Once the bending capacity of the steel reinforced section is established, it is possible to equate a fibre-reinforced concrete solution providing the same strength capacity. The applied loads and induced stresses are usually unknown when determining the required dosage of a macro-synthetic fibre for replacing a specified steel reinforcement configuration (WWF or rebar), but they can be calculated. However, when the original reinforcement design is adequate, the alternative fibre dosage need only show equivalent performance in bending to be considered an acceptable replacement.

For most precast units, the typical reinforcing requirements are to safeguard against temperature and shrinkage cracks. Although micro-synthetic fibres can defend against the formation of plastic shrinkage cracks, they cannot supply the same tensile strength across a macro or visible crack. The use of a macro-synthetic fibre with equivalent bending capacity can be warranted, provided the testing information and field references are made available to the engineer and producer.

The typical mode of failure for precast concrete is bending, so comparing the bending performance of steel reinforcing to the bending resistance of a fibre dosage for a macro-synthetic fibre is necessary. Since

*Power troweling a freshly placed macro-synthetic fibre-reinforced slab at Bishop's University in Lennoxville, Que.*

*Placing macro-synthetic fibre-reinforced concrete.*

not all fibres provide the same performance at the same dosage rate, separate analyses are required for each fibre type.

To accomplish this, one must devise an analytical solution for the FRC alternative. One method of analysis is derived from the results of testing performed according to ASTM International C 1399, *Test Method for Obtaining Average Residual-strength of Fiber-reinforced Concrete*, which determines the post-crack carrying capacity of a fibre-reinforced concrete and converts it to a bending stress. To establish the required bending capacity of the conventionally reinforced section, the cracked bending moment capacity can be determined using engineering equations accounting for the concrete's strength, and the steel grade, spacing and thickness (per unit width), along with its location within the element.

Both analyses (reinforced moment capacity and ASTM C 1399) present the same type of information, but the relevant data contained within is the most important. Specifically, the post-crack response is critical for calculating the dosage of macro-synthetic fibre required to replace steel reinforcing. To compare the calculated moment capacity of the steel reinforced section to an FRC alternative, the calculated moment requirement must be converted to a stress using the sectional properties of the concrete section. Once determined, the fibre dosage matching this stress, as measured from ASTM C 1399, can be used as an equivalent reinforcing material.

The specification of an FRC alternative should also follow the same design philosophy as described in limit states design—the factored applied load shall be resisted by the factored member resistance. The test results should also have statistical validity where a repeated number of trials have been performed—in varying concrete mixtures—to ensure confidence in expected performance. The following is an example of a precast calculation:

Required factored stress from cracked steel-reinforced section: 2.5 MPa (360 psi).

Factored ASTM C 1399 test results: @ 4.5 kg/m$^3$ (7.75 lb/cy) – 2.3 MPa (334 psi), @ 6.9 kg/m$^3$ (11.5 lb/cy) – 3.5 MPa (508 psi).

Solution: Required fibre dosage must equal 2.5 MPa (360 psi). Therefore, 5 kg/m$^3$ (8.4 lb/yd3).

*A concrete bridge repair project in Howard, Wis., used synthetic fibres to gain resistance to repeated freeze-thaw cycling.*

This solution should then be verified through independent or third-party testing, with the fibre evaluated for proper distribution throughout the concrete matrix, compatibility with other admixtures and ease of placement within the precast form.

## Slab-on-grade concrete

The design of slabs-on-grade involves many factors, which cannot be summarized in short form. However, when the design has been carried out by other parties who have determined a certain concrete thickness is adequate for resisting all loading conditions applied to a slab-on-grade system, it is possible to calculate a fibre dosage directly from the specified temperature and shrinkage steel reinforcement. (This is only the case when the FRC has equal or better performance under the same loading conditions.)

A single layer of WWF in concrete slabs-on-grade is usually limited to controlling shrinkage- and temperature-related cracking. WWF is normally placed at a depth one-third the slab's thickness, or 50 mm (2 in.) from the top of the slab (whichever is lesser). Since the reinforcing's sole purpose is to counteract the tensile forces induced by shrinkage and temperature variations, this loading criterion can be used to evaluate an equivalent FRC dosage. (The absolute minimum ratio of steel reinforcement in any direction to the gross concrete area is typically 0.001 [0.1 per cent] for deformed bars or WWF.)

Shrinkage cracking occurs where the induced tensile forces are greater than the tensile capacity of the concrete in the slab system. In large slabs, this can occur in many surface locations. When determining the required fibre dosage to replace a specified conventional reinforcing configuration (where the applied loads and induced drag forces are unknown), it is first assumed the specified WWF or light-gauge reinforcing bar design was performed correctly with respect to shrinkage stresses and induced subgrade drag stresses. The fibre type and dosage, with an equivalent post-crack tensile strength to the conventional reinforcing, can then be specified.

WWF or light-gauge reinforcing bars are commonly referred to as 'distributed steel' in slabs-on-grade. When relatively small amounts of steel area are specified in a slab-on-grade, they are intended to hold together fracture faces when random cracking forms. Distributed steel does not prevent cracking, compensate for poor subgrade preparation or significantly increase the slab system's load-carrying capacity. (The traditional subgrade-drag formulation is used to determine the amount of distributed steel needed to prevent large crack widths.[4] The cross-sectional area of steel required can then be determined, and the direct tensile capacity of the steel calculated.)

Although there are no methods for evaluating the post-crack strength of FRC in direct tension, it can be inferred from existing standardized flexural testing. In this analysis, it is assumed the percentage of the post-crack load-carrying capacity to the flexural modulus

*On the left, a close-up illustrates the smooth final finish of a macro-synthetic fibre-reinforced concrete slab. The photo on the right depicts the application of surface sealer on a newly placed slab.*

of rupture of concrete from flexural testing (according to ASTM C 1018, *Standard Test Method for Flexural Toughness and First-crack Strength of Fiber-Reinforced Concrete [Using Beam with Third-point Loading]*) represents the FRC's post-crack direct tensile strength at a given dosage. By equating the two reinforcing methods, one can determine a direct relationship between FRC and conventionally reinforced slabs.

Again, as was illustrated for the precast concrete analysis, the specification of an FRC alternative should also follow the same design philosophy as described in limit states design. That is, the factored applied load must be resisted by the factored member resistance. Test results should also have statistical validity, where a repeated number of tests have been performed (in varying concrete mixtures) to ensure accuracy. For example:

Slab-on-grade specification: WWF 102 x 102mm (4 x 4 in.) 4/4,414 MPa (60,000 psi), in slab 152-mm (6-in.) thick, FR = 4MPa (580 psi).

Direct tensile strength provided by WWM [welded wire mesh] reinforcing (factored) = 0.6 MPa (87 psi). Set this value equal to the required fibre performance.

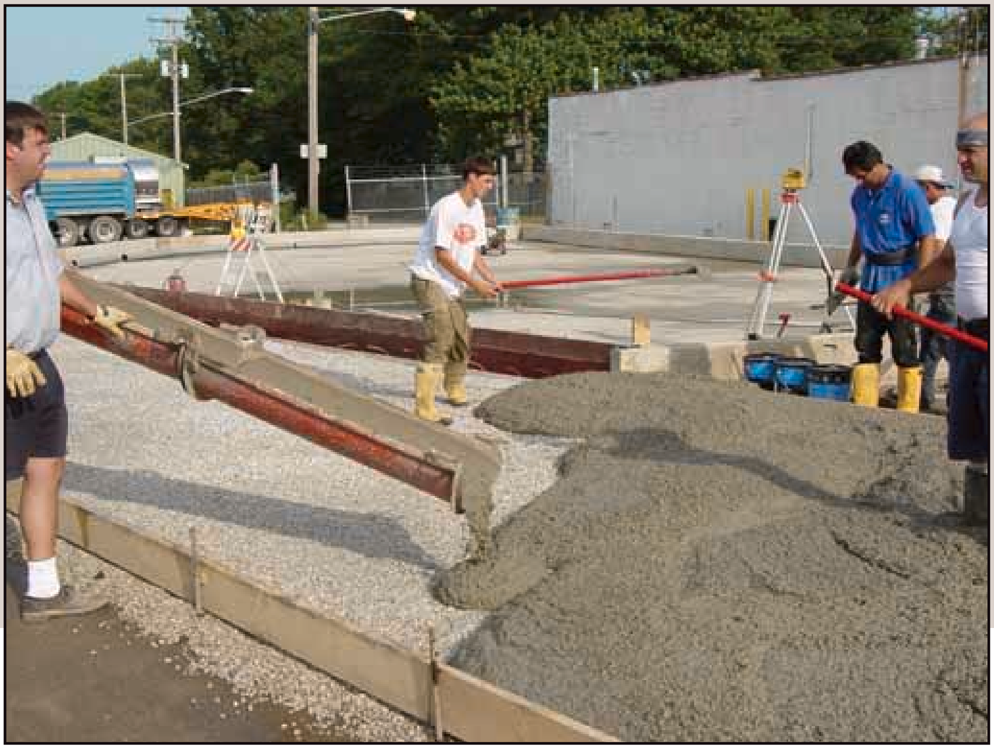
Factored ASTM C 1018 test results:
0.59 MPa (85 psi) = 3 kg/m$^3$ (5.0 Ib/cy),
0.79 MPa (115 psi) = 4 kg/m$^3$ (6.7 Ib/cy)
Therefore, use 3.1 kg/m$^3$ (5.2 Ib/cy).

Where the reinforcing has been engineered to provide more than just shrinkage and temperature crack control, slabs incorporating fibres must account for the required additional flexural capacity. Localized loading conditions (*e.g.* wheel, rack, post and other dynamic loads) from edge, corner and/or shrinkage stresses must be incorporated. This information, including subgrade conditions, must be available prior to the design analysis. Several methods are available for providing this advanced type of fibre-reinforced design, such as the equations and formulations provided by the Concrete Society's Technical Report (TR) 34, *Concrete Industrial Ground Floors*.[5]

## Conclusions

The most significant barrier in the promotion and acceptance of 'structural' synthetic (or macro-synthetic) fibres for precast and slab-on-grade applications is the lack of design guidelines and available references. Additionally, the general assumption these synthetic fibres are another kind of product for preventing plastic shrinkage must be addressed. Through both field trials and applied engineering research, this new class of material has proven itself capable of providing the same form of toughness and load-carrying capacity as steel fibre and specified welded wire fabric.

As previously mentioned, the examples used above are very generic and should not replace a specific engineered design procedure. Certified test results



*The reinforced concrete being poured in this photo contains macro-synthetic material capable of producing similar toughness to steel fibres and light-gauge rebar. As an increasing number of manufacturers and distributors are marketing these products, the various technical organizations are trying to develop approvals, practices and guide specifications.*

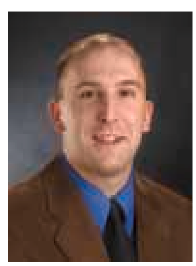
with statistical data are required when comparing fibre types, and field trials should be performed to verify compliance.

Several manufacturers and distributors currently market these new reinforcing materials, as well as the concrete producers using them. As a result, ASTM, the American Concrete Institute (ACI), the Canadian Standards Association (CSA) and other technical organizations are quickly trying to provide guidance on the use of these materials through approved product listings, guide specifications and approved practices.

As university research and industry practice become more entangled, the production and use of these durable and innovative construction materials will continue to improve our infrastructure needs. ■

## Notes

1. Trottier, J.F., M.A. Mahoney and D.P. Forgeron. "Can Synthetic Fibres Replace Welded Wire Fabric in Slabs-on-Ground?" *Concrete International* (November 2002). p. 59 to 68.
2. The explanations make several assumptions and do not cover the full analysis of precast concrete or slabs-on-grade. The information presented is meant to be used solely as an estimating tool and should not replace a complete analysis. A complete analysis of concrete structural design includes many factors not evaluated here, including all applied loads, subgrade properties (i.e. strength and friction coefficient) and factors describing actual site conditions (*i.e.* interior, exterior, humidity, temperature, joint spacing, etc.).
3. Pillai, S.U. and D.W. Kirk. *Reinforced Concrete Design 2nd Ed.* (McGraw-Hill, 1988).
4. Farny, J. *Concrete Floors on Ground* (Portland Cement Association [PCA], 2001).
5. For more information, visit www.concrete.org.uk.



*Michael Mahoney is the structural fibre technology manager for The Euclid Chemical Company (Cleveland, Ohio). He obtained his master's degree in civil engineering from the Technical University of Nova Scotia (Halifax), where he helped develop and patent a synthetic fibre for concrete reinforcement. He has also been involved with structural health monitoring of bridges using non-destructive testing methods. At Intelligent Sensing for Innovative Structures (ISIS) Canada, Mahoney worked on several key projects, including a steel-free bridge deck incorporating fibre-optic monitoring equipment within a fibre-reinforced concrete deck. Mahoney has co-authored several papers on the subjects of fibre-reinforced concrete, shotcrete and bridge systems, and is a member of the American Concrete Institute (ACI). He can be contacted at (800) 321-7628.*