SYNTHETIC STRUCTURE FIBERS FOR TOUGHNESS AND CRACK CONTROL OF CONCRETE

Jiang Jiabiao*, W R Grace (Singapore) Pte Ltd, Singapore
Steven Loh, W R Grace (Singapore) Pte Ltd, Singapore
Toh Gasho, Grace Japan K.K., Japan

29th Conference on OUR WORLD IN CONCRETE & STRUCTURES: 25 - 26 August 2004, Singapore

Article Online Id: 100029039

The online version of this article can be found at:

http://cipremier.com/100029039

This article is brought to you with the support of

Singapore Concrete Institute

www.scinst.org.sg

All Rights reserved for CI-Premier PTE LTD

You are not Allowed to re-distribute or re-sale the article in any format without written approval of CI-Premier PTE LTD

Visit Our Website for more information

www.cipremier.com
SYNTHETIC STRUCTURE FIBERS FOR TOUGHNESS 
AND CRACK CONTROL OF CONCRETE

Jiang Jiabiao*, W R Grace (Singapore) Pte Ltd, Singapore 
Steven Loh, W R Grace (Singapore) Pte Ltd, Singapore 
Toh Gasho, Grace Japan K.K., Japan

Abstract

Traditionally, the predominant means of controlling cracking in hardened concrete has been the use of light reinforcing bars or installation of welded-wire fabric, which are placed on construction site. Synthetic micro fibres have been added in concrete to control plastic shrinkage cracking. In recent years a new type of reinforced concrete technology - synthetic structural fibres has been introduced. In this paper, the features and benefit of structural synthetic fibres are discussed. It has been shown that the addition of these new highly engineered structural synthetic fibres improve concrete properties, including ductility, fracture toughness and crack control. A case of synthetic structural fibre application in tunnel lining is also presented.

Key word: Synthetic structural fibre, toughness, crack control, concrete

1 Introduction

It is well recognized that the presence of WWF (welded-wire fabric) or light reinforcing steel will not prevent concrete from cracking in elements such slab on ground, but will hold the cracks tight, maintain aggregate interlock, and prevent faulting of the slab [1]. Synthetic micro-fibre at low dosage is known being far more effective in controlling plastic shrinkage cracks than conventional WWF, but is unable to control cracks of any origin from opening up over time [2]. In terms of industrial requirements, it is desired that slabs crack as little as possible and if cracking occurs, these cracks should remain as tight as possible. In recent years, a new type of reinforced concrete technology has been introduced – synthetic structural fibers – that delivers many of the same benefits traditionally associated with WWF or light rebar but with the added advantage of plastic shrinkage crack control. One of the key objectives for the development of synthetic structural fibers is to deliver the flexural toughness of light reinforcement while eliminating some the issues associated with steel, such as costly placement, proper positioning, handling, corrosion and safety.

The purpose of this paper is to present the features of synthetic structural fibers in improving toughness of concrete and crack control, and other additional benefits, and to present a case study of synthetic structural fiber in tunnel second lining application.
2 Two types of synthetic fibers: macro versus micro fibers

It is important to understand that there are two classes of synthetic fibers – micro-fiber and macro fibers, which have distinct properties and capabilities. Micro-fibers were introduced about 25 years ago to reduce plastic shrinkage cracking in concrete, and are widely used now. A more recent development of synthetic structural fibers (macro-fiber), which are designed to control cracks in hardened concrete, debuted about 5 years ago.

Micro-fibers are usually with diameter less than 0.1 mm, and used at low addition rate, usually below 0.1% by volume of concrete. The common one is made of polypropylene. These fibers provide plastic shrinkage cracks control before concrete hardens. Micro-fibers may only be used at low addition rates since the concrete will have significant workability issue if they are used at higher dosage rates. For this reason, its affects on properties of hardened concrete, i.e., strength, flexural toughness, etc, are insignificant.

Synthetic structural fibers, on the other hand, are used at high addition rates up to 1% by volume of concrete, which provide increased flexural toughness, impact resistance and fatigue resistance to hardened concrete, as historical deformed steel fiber. Figure 1 shows two examples of latest synthetic structural fibers of blended polypropylene and polyethylene with different length and aspect ratio, the compositions and configuration of which are designed to achieve optimal performance for flooring and tunnel lining applications respectively. The properties of synthetic structural fibers enable them to deliver at least equivalent performance in flexural toughness and crack control of concrete to conventional WWF and light reinforcements in slab-on-grade floors or tunnels with additional benefits.

![Figure 1 Configuration of synthetic structural fibre Strux 90/40 and Strux 85/50](image)

3 Issues associated with WWF or steel fiber

WWF (welded-wire fabric) or steel fibers are commonly used in concrete structures, such as slab on ground, tunnel lining for flexural toughness and cracking control. Once concrete cracks, such steel reinforcement will hold the cracks tight and prevent faulting of the structures. However, lot of issues associated with using WWF (welded-wire fabric) or steel fibers are also well known in engineering community.

First of all, WWF (welded-wire fabric) or light steel reinforcing bars require precise positioning within the concrete, which is difficult, time-consuming process. When light reinforcement is properly placed, it increases durability and provides mixed results relatives to crack control in concrete structures. In fact, welded-wire fabric and light reinforcing bars provide only two dimensional reinforcement within concrete because they are placed in specific locations and not
dispersed throughout the concrete matrix, and hence it is less effective in controlling cracks with increasing thickness of slab. In addition, proper positioning of wire mesh has been a serious challenge. As a result, traditional steel reinforcements often do not perform as expected. In floors, for example, the wire mesh or rebar is frequently sitting on the bottom of the floor, or in the middle, because of difficulties during the placement process. This compromises the effectiveness of the reinforcement in the concrete and can lead to deleterious cracking and diminish the usable life of the structure. Secondly, hauling, stocking of WWF occupy space on construction site. Placing the reinforcement is additional step, and is not always easy (not safe) and can be expensive. Thirdly, corrosion of WWF or steel reinforcement is an issue, which will affect the aesthetics and durability of concrete slab, and it is tough to pour and consolidate concrete with WWF installed. Finally, WWF or steel reinforcement is not effective for control of plastic shrinkage cracking of concrete.

All these issues associated with WWF would be eliminated with the use of synthetic structural fibers. In fact, synthetic structural fibers disperse thoroughly and evenly throughout the concrete. The spatial distribution throughout the matrix provides three dimensional reinforcement, and better way in cracking control than WWF because fibers interfere with the cracking phenomenon as its inception, arrest micro-cracks and prevent them from becoming macro-cracks. Concrete with synthetic fibers is easier and safer to handle, and eliminates the step of installation of WWF or placing steel reinforcement. Even compared to steel fibers, synthetic structural fibers make concrete easier to mix, pump, eliminate unsafe pop out of steel fibers to workers during finish operation of flooring, or hazard rebound of steel fiber during spray of tunnel lining. In addition, the latest synthetic structural fiber is also able to provide additional advantage in plastic shrinkage cracking control. Generally, a greater number of individual fibers will be used with synthetic structural fibers compared to steel fibers. For example, at equal volumes STRUX 90/40 in the concrete represents 15 times more fibers compared to typical 60 mm flat steel fibers. Therefore there is 15:1 ratio of STRUX 90/40 available compared to steel fibers to intercept a micro-crack. Figure 2 shows plastic shrinkage cracking test results of concrete containing 1.8 kg/m3 synthetic structural fiber Strux 90/40. In this test, concrete panel was exposed to wind blow at a velocity of 20 m/hr for 24 hours in a wind tunnel with RH 27 ~ 35% and temperature of 40 ~ 46°C immediately after casting, and then measure the length and average width of cracks to calculate the total area of cracks. The total area of cracks in plain concrete is set as 100%. It is seen that inclusion of 1.8 kg/m3 STRUX 90/40 is able to reduce plastic shrinkage cracking by 75%. Even though synthetic structural fiber is not as effective as micro-fiber in the reduction of plastic shrinkage cracks up to more than 90%, its effect is much superior to steel fiber, as shown in Figure 2.
The question people would ask is if synthetic structural fibers can provide the same level of performance in flexural toughness that WWF or steel fibers can offer.

4 Flexural toughness

Toughness is the key property in understanding the benefits of inclusion of macro-fiber in concrete. Essentially, toughness is the ability of concrete to retain structural integrity after it has nominally failed by being exposed to a load which exceeds its flexural strength. Plain, unreinforced concrete, when subjected to a bending load, will withstand that load with very little movement until the load exceeds its flexural strength. At this point, the concrete will fail suddenly and catastrophically and fall to pieces. This is the classic behavior of a brittle material possessing no toughness. That is, it has no residual strength or post-crack strength after a sudden brittle failure.

But in the presence of macro-fibers, the differences become apparent immediately after failure. At failure, the concrete cracks, but the crack width is initially so small that it cannot be seen. The load has been transferred to the fibers. If the concrete unit continues to be loaded, then the fibers start to pull out, and the crack starts to widen. At this stage, the unit is broken, but is still able to withstand a large proportion of its maximum load. This ability to carry load after failure and to provide resistance of additional opening of the cracks in the hardened concrete is called toughness.

Figure 3 shows the improvement in the post-cracking behavior of concrete containing synthetic structural fiber Strux 90/40 tested in accordance with ASTM C1018 [3]. It is clearly seen that the concrete with Strux 90/40 is able to carry a proportion of max load after the occurrence of first crack, and this ability of concrete increases with increasing addition rates of synthetic structural fiber.

The current Standards for determining the post-cracking strength or residual strength of fiber reinforced concrete such as ASTM 1018, JSCE-SF 4, assume a linear elastic behavior to calculate the post cracking strength. This implies that the post cracking strength of fiber reinforced concrete can be easily calculated using the equivalent flexural strength determined from bending test specified in the standard test. The equivalent flexural strength ($F_{eq}$) is determined from load-deflection curve obtained in bending of beams in
accordance with ASTM C1018, and calculated to have the same area as the area obtained under load deflection curve from bending test, as shown in Figure 4. The $F_{\text{e}3}$ value must be determined on a beam with a 150 x 150 mm cross-section and a length of at least 500 mm tested according to ASTM C 1018 up to a beam deflection of 3 mm. This equivalent flexural strength is a strength parameter that characterizes the post-cracking resistance and can be used for design and stress analysis of fiber reinforced concrete structures.

In addition to dosage rate, the type of fibers, elastic modulus, fiber length, aspect ratio, etc., all these factors of fibers would affect the toughness of fiber reinforced concrete. Figure 5 shows equivalent flexural strength values of concrete with different types of structural fibers. It can be seen that synthetic fiber Strux 90/40 could give equivalent concrete toughness to middle grade steel fiber, depending on the fiber volume added.

Recent study has indicated that the toughness of fiber reinforced concrete would also be affected by the strength of concrete [4]. Figure 6 shows the equivalent flexural strength of concrete of different grades containing the synthetic structural fiber Strux 90/40. It is clearly seen that the $F_{\text{e}3}$ values increases almost linearly with increasing concrete strength.

As only a small portion of WWF can be inserted into a test beam with dimension 150 x 150 x 500 mm, ASTM C1018 beam bending test is considered not appropriate for evaluation of WWF performance. With this regard, large slab testing program was deployed to compare performance WWF and synthetic structural fibers in cracking control of concrete. Figure 7 shows load-deflection comparison of synthetic structural fiber with WWF in slab-on-ground. In this test program, a concrete mix with 35 ~ 40 Mpa, the dimension of testing slab of 2200 x 2200 x 150 mm. Slab was placed on a 203 mm thick subgrade of well compacted clay. Typical WWF of W2.9 was used in comparison with synthetic structural fiber Strux 90/40. Central load applied with hydraulic actuator until puncture failure. It is shown in Figure 7 that the performance of synthetic structural fiber Strux 90/40 at 0.48% vol. (4.4 kg/m3) is clearly superior to that of WWF of W2.9. The width of crack after failure in WWF slab is much larger than that in slab with synthetic structural fiber, as shown in Figure 8. It should be noted that WWM in this test is
place properly in the middle of slab, but this is not always the case in real world. Therefore, the test results of WWM is the best case which may not be always true in fields.

As discussed above, the inclusion of synthetic structural fibers improves significantly the flexural toughness with additional benefits in terms of handling and safety. The concept of equivalent flexural strength is a measure of performance which takes into account the toughness obtained from experiment, by measuring the area under the load deflection to a deflection of 3 mm (L/150), commonly referred to as the \( F_{e,3} \) value. The cognition of the post-cracking behavior at the design level is essential to transfer the technology of synthetic structural fibers to the industry. The biggest commercial opportunity for the use of synthetic structural fibers in the infrastructure lies in concrete flooring and paving, where their usage can be justified by the design of thinner and more economic concrete slab. A recently example for use of synthetic structural fiber Strux 90/40 in an industrial floor in UK has reduced the thickness of slab from original 200 mm with A6 wire mesh to 175 mm with 3.4 kg/m Strux 90/40. The new approach has given the contractor a net saving of US23,000 for the floor with a total area of 14,300m2. The other type of synthetic structural fiber application is in underground tunnel lining, where
flexural toughness of lining and safety of concrete spraying are concerned. The next section will present a case study of synthetic structural fiber application in tunnel lining project.

5 Application case of synthetic structure fiber in tunnel lining

In the Mitoyo tunnel project located at the side of Hokkaido Toya Lake in Japan, fiber reinforced concrete has been used for the tunnel second lining in order to prevent exfoliation of lining concrete in case of volcanic eruption (Mt.Usuzan -- volcanic) and an earthquake calamity. Synthetic structural fiber has been accepted by the tunnel construction management of Japan Highway Corp. (JH) due to its additional advantages over steel fiber in free rust, safety in shotcreting, light weight for easy handling.

In the Japan Highway Corporation specifications for the tunnel lining, the fiber reinforced concrete has to meet the following requirements in fiber uniformity in concrete and equivalent flexural toughness:

1) Equivalent flexural toughness obtained from bending testing on each of 4 beams of 150 x 150 x 530 mm in accordance with JSCE CF4 shall be not less than 1.4 Mpa (corresponding average load of 10.3 kN at load-deflection curve up to 3 mm deflection), and the loads in the load deflection curve up to 3 mm deflection shall be above 4.1KN for all 4 beams during the bending test in accordance with JSCE CF4.

2) The fiber shall be able to disperse in concrete uniformly. The average fiber content in concrete should be not less than 95% of designed fiber content, and the variation in fiber content from the designed number in each dispersivity test of fiber reinforced concrete should not be more than 20%.

The preliminary trials were conducted on a synthetic structure fiber Strux 85/50 to determine the addition rate, and to verify the dispersibility of fiber in ready-mix truck. Strux 85/50 is made of blended polypropylene and polyethylene with a length of 50 mm and a aspect ratio of 85. Figure 9 shows the load deflection curves of beam test with different dosage rates of Strux 85/50. It is seen that an addition rate of 0.3% by volume of Strux 85/50 in concrete with 35Mpa 28 days compressive strength is able to achieve the target of equivalent flexural strength specified. Fiber dispersivity tests were carried out in concrete with Strux 85/50 at 0.3% by volume. The samples of fresh concrete with fibers were taken from the front, middle and rear side in truck agitator to check the uniformity of fiber in concrete. The variations of fiber content in all samples were found below 3% from the designed fiber volume. Figure 10 and 11 show the field
results of Strux 85/50 in construction of second lining in terms of dispersivity and flexural toughness respectively. The successful application of Strux 85/50 in the Mitoyo tunnel project indicates that synthetic structural fiber is able to deliver the required flexural toughness that conventional steel fibers offer while reducing/eliminating the problems of steel fibers in corrosion and safety.

![Figure 11 Field results of equivalent flexural toughness](image)

### 6 Concluding remarks

Synthetic structural fibers are able to deliver the performance of flexural toughness at the same level as WWF or steel fiber can offer. It is also important to determine what volume of fibers are required to yield the desired toughness and crack control, this will make synthetic structural fibers the more cost-effective way to achieve expected results. With synthetic structural fibers, the issues associated with WWF or steel fibers in handling and safety would be reduced or eliminated. The latest synthetic structural fibers can also provide additional advantage in plastic shrinkage cracking control.

However, it should be noted that synthetic structural fibers are not appropriate for all types of concrete applications. While they can deliver flexural toughness and plastic shrinkage crack control in some applications, such slabs-on-grade flooring or tunnel lining, they are not intended to replace primary steel reinforcement which is designed to transfer high loads over significant distances. The determination is the domain of structural engineers.

### 7 References


