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Twisted Steel Micro-Reinforcement: Proactive Micro-Composite Concrete Reinforcement

Luke Pinkerton[1], Kevin Fuller[2], Jeff Novak[3]

[1]Chief Technology Officer, Helix Steel
[2]Chief Executive, Helix Steel Australasia
[3]Vice President of Engineering, Helix Steel

Abstract: Reinforced concrete is a two-part system that at best can be described as a “macroscopic” composite made of reinforcement bar and a concrete matrix. The bar is designed to carry load only after the concrete fails – reactive reinforcement. Adding Twisted Steel Micro-Reinforcement (TSMR) at a specified dose to an ordinary concrete matrix creates a “microscopic” composite. The unique design of the TSMR allows for efficient load re-distribution prior to failure of the concrete. The result is a significant increase in the concrete’s strain capacity. TSMR provides proactive reinforcement as, unlike conventional reinforcement and other forms of reinforcement, it engages the material before it actually fails. Similar to conventional methods of reinforcement, TSMR also provides reactive reinforcement as it continues to provide stable tensile resistance after the concrete’s strain capacity is exceeded. With existing design methods, structural engineers are not able to calculate the required dosage of TSMR. The authors present a simple design method to determine the necessary TSMR dosage to resist the tensile forces in an area of concrete equal to or greater than the conventional reinforcement. The TSMR design models specifically for TSMR reinforcement have been developed and have been validated through third party testing at an IAS/NATA certified laboratory, full scale field-testing, calibration, and peer review by structural engineers in multiple countries.

Keywords: concrete, elastic, fibre, testing, design

1. Introduction

Reinforced concrete, by definition, gives the concrete its required tensile strength after the formation of a dominant crack in the concrete. While there are many interesting academic pursuits in Ultra High Performance Concrete that promise true composite behavior under high loads and deflections, the cost is prohibitive due to the quantity of fibre required and the need for expensive component materials. On the other hand, the fibre industry has promoted use of deflection controlled bending tests of deflection softening mixtures to derive tensile resistance of fibre concrete. In these tests, the machine is programmed to very carefully remove load from the specimen (so it does not fail suddenly) as deflection increases (1). Over the last several years the deflection limit at which the performance is measured using such tests has continued to increase. There are testing standards that actually compute strength based on crack widths near 20 mm, which are 50 times the code limit and twice the limit for a structure to be deemed stable for occupational health and safety (2). The industry has missed the fact that in practice a load would certainly not be so carefully applied and therefore security/safety that is being promoted with such standards is misleading. Also, there is no direct relationship between flexural strength and tensile strength once a crack has formed in the concrete and therefore several assumptions must be made to estimate the tensile strength (3). Finally, while testing has shown an alarming degree of creep in certain types of low modulus, non-metallic reinforcements, the industry has largely ignored the issue (4).

Twisted Steel Micro-Reinforcement (TSMR) offers a solution to these problems both in the product’s performance and in its design methodology. TSMR increases the flexural tensile strength of the concrete (Modulus of Rupture, MOR) and decreases the coefficient of variation of the MOR. TSMR increases the ductility of concrete in tension prior to the formation of a crack (more deflection at the point of crack). While it does exhibit strain-softening behavior at certain dosages after a crack forms, TSMR provides stable tensile resistance in the range of maximum allowable code crack widths. Its design method (Uniform Evaluation Service (UES), Evaluation Report (ER) # 279) fully recognizes its limits and gives the designer a safe, reliable, peer-reviewed design and field QA guidance. TSMR is made of high tensile, high modulus steel, which has been shown to perform well over time (5). Testing measures the real pre-crack properties (MOR, Splitting Tensile) of the TSMR concrete using methods that apply a constantly increasing load to failure just as would occur in real life (i.e. when an overloaded fork truck drives on a floor). Post crack design of TSMR is permitted when restrictions aimed at controlling maximum crack width to sizes consistent with codes are in place.

2. Testing and Design Approaches

2.1 Test Methods

Unlike traditional reinforcement, the performance characterization and design of steel fibre concrete is not uniform throughout the industry. There are many competing test standards (Table 1) and design procedures (Table 2). While direct tensile resistance is the performance measurement needed for design, most test standards involve flexural tests. Tensile resistance is derived by assuming a relationship between flexural stress (which only exists in linear elastic materials and is invalid after a crack forms) and direct tensile stress (6). A multiplier of 0.37 is typically used to relate the flexural stress in beams with large cracks (3.5 mm) to direct tensile strength (3). Beam testing is also plagued with so called "size effect," the non-scalability of results to larger or smaller sections and/or cross correlation of crack size, fibre length and specimen size on results (7).

Table 1. Common Test Methods.

Test Standard	**Type**	**Control**	**Measurement**	**Single Operator COV**
ASTM C78 AS 1012.11-2000	Flexural Beam	Load	Peak only Post crack*	5.7%
ASTM C1609	Flexural Beam	Deflection	Peak Post crack	Peak: 8.2% Post: 17%
ASTM C1399	Flexural Beam	Load	Post Peak only	13%
ASTM C1550 RDP	Flexural Round Panel	Deflection	Peak Post crack	Peak 6.2% Post 10%
EFNARC	Flexural Square Panel	Deflection	Peak Post crack	Not Reported
EN 14651	Flexural Notched Beam	Crack Width	Post crack only	Not Reported
EN 12390-5	Flexural Beam	Load	Peak only Post crack*	Not Reported
RILEM TC 162-TDF	Flexural Notched Beam	Deflection	Post crack only	Not Reported
ASTM C496 EN 12390-6 AS 1012.10-2000	Splitting Tensile	Load	Peak Post crack*	5%
UES EC 015	**Direct Tension**	**Deflection**	**Peak crack Post crack**	**Peak 6.3% Post 11%**

2.2 Design Methods

While the fib Model Code 2010 (8) aims to become the general standard for fibre design in Europe, recently a new fibre design method was approved in Australia that is similar to the Model Code approach but contemplates an option to use direct tension design (9). There are still several competing design approaches and methods (Table 2). The design crack widths are different for different design methods. Some of the more robust approaches, like RILEM TC 162 TF (3), include some statistical considerations for variations in test results. UES EC 015 (10), is the only method evaluated that employs the Load and Resistance Factor Design (LRFD) method for deriving resistance factors employed by the world's major design codes (11,12,13).

The Papworth 2002 method of design for shotcrete is the only empirical approach evaluated. It uses the relationship between energy (too large deflection) in the round or square panel testing to rock type presented in a prescriptive table instead of a physics-based tensile strength approach. This method favors fibres that behave well at large deflections in the round panel tests.

Table 2. Fibre Design Methods.

Design Approach	Application and Criteria	Design Assumption	Test	Test vs design Stress Model
ACI-360	Slabs only cracked stress	4 mm crack Yield Line	ASTM C1609	Linear, Re3
RILEM TC 162-TDF (3)	General, cracked stress & strain	1.5 mm 3.5 mm crack	EN 14651	Bi-Linear $f_{R,1}$ x 0.45;$f_{R,4}$ x 0.37
Concrete Society TR-34	Slabs only cracked stress	3.5 mm crack Yield Line	EN 14651	Bi-Linear $f_{R,4}$ x 0.37
Fib Model Code 2010 (8)	General, cracked stress	0.5 mm or 2.5 mm crack	EN 14651	Bi-Linear $f_{R,1}$ x0.45; $f_{R,3}$ /3
Papworth 2002 (14)	Shotcrete Energy	Energy to 40 or 80 mm deflection	ASTM C1550, RDP	Empirical Table of Energy
DR AS 5100.5 -16 (15)	Bridges	1.5 mm crack	Direct Tension or EN 14651	Director or Bi-Linear $f_{R,4}$ x0.4 ; $f_{R,2}$ x0.7
UES EC015/ ER 279 (5,10)	**Stress & Strain**	**Peak or 1 mm crack**	**EC 015**	**Not Required**

The properties of TSMR reinforced concrete with higher tensile strength could provide benefit to designs using provisions for elastic design (Table 3) and plain concrete design. Unlike with conventional non-linear reinforced concrete design, these approaches consider concrete tensile strength. Testing of MOR of TSMR reinforced concrete may be used along with the "deemed to comply" provisions of these codes to allow the use of the enhanced MOR.

Table 3. Elastic Design Provisions

Design Approach	Application and Criteria	Design Assumption	Test	Test vs design Stress Model
EN 1992	General Section 5.4	Elastic Design	EN 12390-6	Elastic
AS 3600	General Section 3.1.1.3	Elastic Design	AS 1012.11-2000	Elastic
ACI 318	General Chapter 22	Elastic Design	ASTM C78 ASTM C496	Elastic
CSA 23.3	General Section 22.6.5	Elastic Design	ASTM C78 ASTM C496	Elastic

3. Twisted Steel Micro Reinforcement (TSMR)

TSMR is made from high carbon, cold-drawn, deformed steel wire complying with ASTM A 820, Type I. The steel wire has a tensile strength of 1850 MPa. TSMR comes in two sizes: TSMR 5-25 (0.5 mm x 25 mm length) and TSMR 8-50 (0.8 mm x 50 mm length). TSMR 5-25 has been proven to enhance MOR, splitting tensile and provides stable post crack performance. It has been employed successfully to replace conventional reinforcement and wire mesh for over a decade. TSMR 5-25 design and code approval is provided with an ISO Guide 65 Accredited Evaluation Report (10). TSMR 8-50 uses the same TSMR technology and advantages as 5-25, but its performance is optimized for standard post crack beam test performance (EN 14651) while still offering enhanced MOR and splitting tensile strength.

3.1 Functional Mechanism

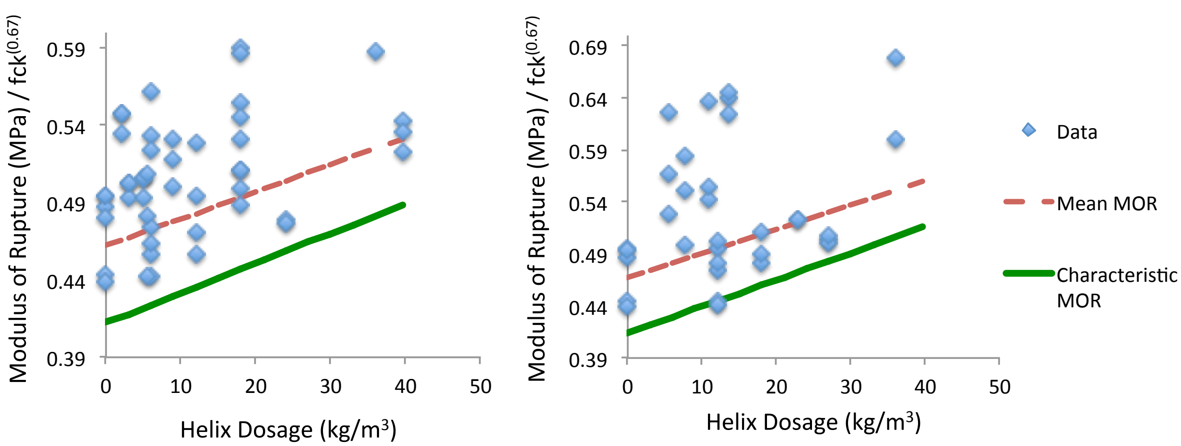
Twisted Steel Micro-Reinforcement (TSMR) is produced with a unique twisted profile (Figure 1) that allows each piece to bond to the matrix over its full length. In addition, the reinforcement must untwist as it pulls out of the concrete. This makes the product significantly different from traditional steel fibres because pullout is governed by untwisting resistance rather than friction. TSMR is active in both the "Proactive Phase" (pre-crack), increasing peak tensile strength, and during the "Reactive Phase" (post-crack) providing ductility and stable tensile resistance to large crack widths.

Figure 1: Twisted Steel Micro Reinforcement

4. TSMR Advantages

4.1 Flexural Tensile Strength (Modulus of Rupture)

Testing at independent laboratories has established a statically significant increase in the modulus of rupture (MOR) of concrete reinforced with TSMR. This is a unique feature of TSMR (as shown in Figure 2) as most codes and design guidance documents state that fibres do not increase the modulus of rupture (MOR) of concrete. The values are computed in accordance with RILEM TC 162 TDF Equations 5 and 6 (3). These equations take into account the mean and coefficient of variation of each of the source data sets. A mean and characteristic value is computed at each dosage tested. Linear regression is used to fit these points to establish the mean and characteristic curves.

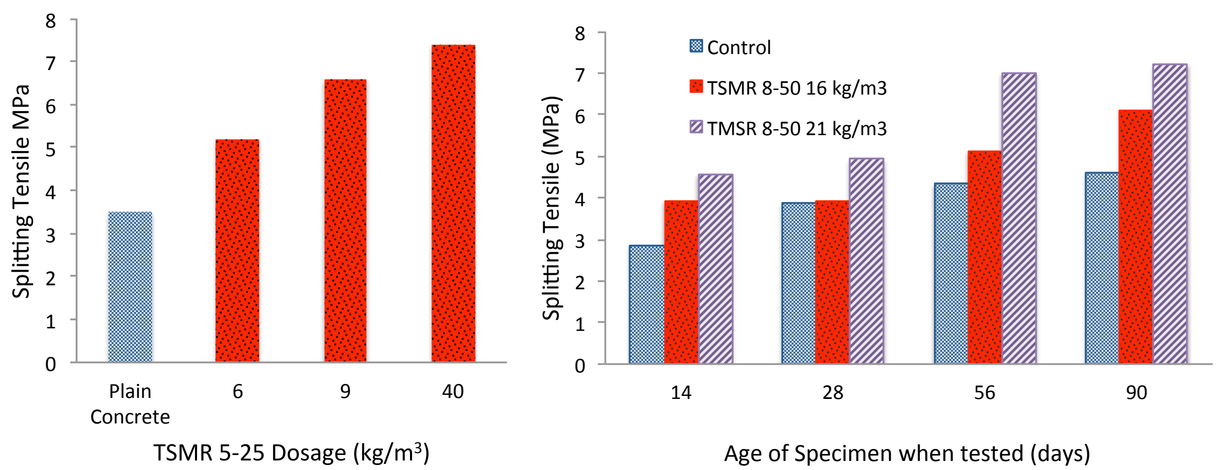


(a) TSMR 5-25 (16) (b) TSMR 8-50 (17)

Figure 2. Flexural Tensile Strength

4.2 Splitting Tensile Strength

Testing at multiple independent laboratories has shown significant increase versus the control (plain concrete) in splitting tensile with TSMR reinforced concrete as the dosage increases and as the age increases. The tests show that TSMR does not suffer from the age embrittlement (shift of failure mechanism from pullout to fibre fracture over time) that traditional steel fibres have exhibited in testing (18). Instead, the testing shows the strength of TSMR reinforced concrete increases as age increases. The increase in splitting tensile strength has particular advantages in tunnel construction where a tunnel boring machine's ram forces are high during segment installation. As a result, larger concrete segment designs may be viable with TSMR than previously thought possible.



(a) TSMR 5-25 Splitting Tensile Vs Dosage (19) (b) TSMR 8-50 Splitting Tensile Vs Curing Time (20)

Figure 3. Splitting Tensile Strength

4.3 Modulus of Elasticity

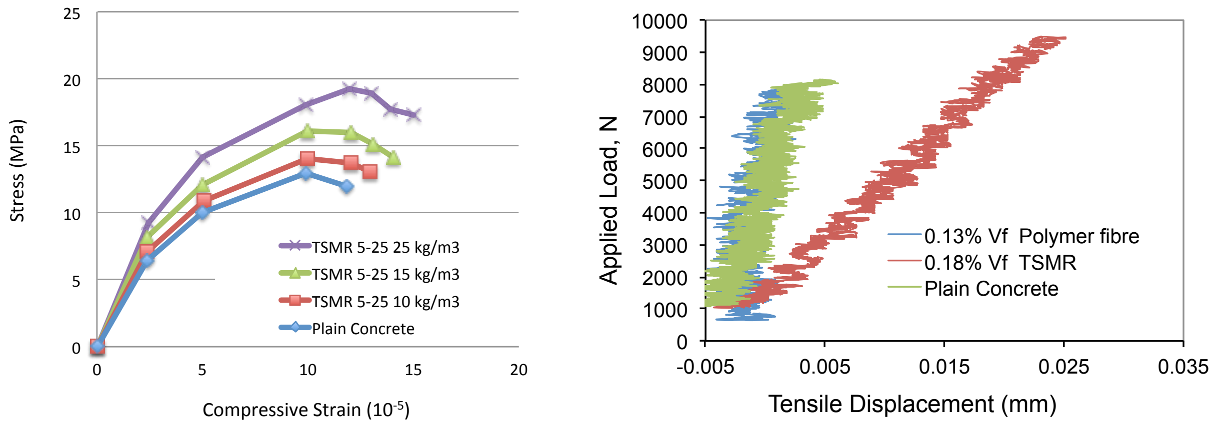
4.3.1 Modulus of Elasticity of TSMR Vs Plain Concrete

The stiffness of TSMR is equal to that of structural steel (200 GPa), 8 times stiffer than 25 MPa concrete (25 GPa) and 24 times stiffer than polymer fibres (8 GPa). Given polymer fibres have stiffness significantly less than concrete, it is physically impossible for them to carry any load until the concrete has cracked and become effectively softer than the polymer from which they are made. This helps explain why some testing and design methods that currently exist are based on large crack widths and do not conform with current concrete standards for allowable crack widths. While it is tempting to claim that a polymer fibres can provide the same structural integrity as steel, it's impossible to do so without allowing large cracks to form allowing the fibres to stretch enough to carry load (as Hooke's law requires).

4.3.2 Modulus of Elasticity of TSMR vs Reinforced Concrete

TSMR significantly increase the compressive modulus of elasticity (initial tangent modulus) of concrete. Tests have shown an increase of up to 38% (at 25kg/m3 dosages). The strain at failure in compression, however, increases to 40% over the control as the dosage increases to 25 kg/m^3 (21). This is a clear indication of increased plasticity prior to failure and increased ductility (Figure 4a).

TSMR also increases the strain at failure in tension (Figure 4b). Testing of TSMR confirmed the increase in strain at first crack with TSMR versus the control with 99% and 98% confidence respectively. TSMR technology is the only fibre type studied – steel or polymer – that exhibits this behavior (22). The strain at which force is transferred through shear into TSMR is very low due to the efficient bond the twist provides. TSMR can carry load almost immediately after strain is applied due to the high stiffness of the material. This condition provides alternative load paths that allow micro-cracking to initiate and higher strains than plain concrete at the development of the first visible crack. While this affect can appear as an increase in deflection at peak measurement in flexural testing, this value is typically ignored in favour of looking at the residual load after the formation of a crack up to 20 mm wide, well after the concrete would have catastrophically failed.



(a) Compressive Stress Vs Strain (21)

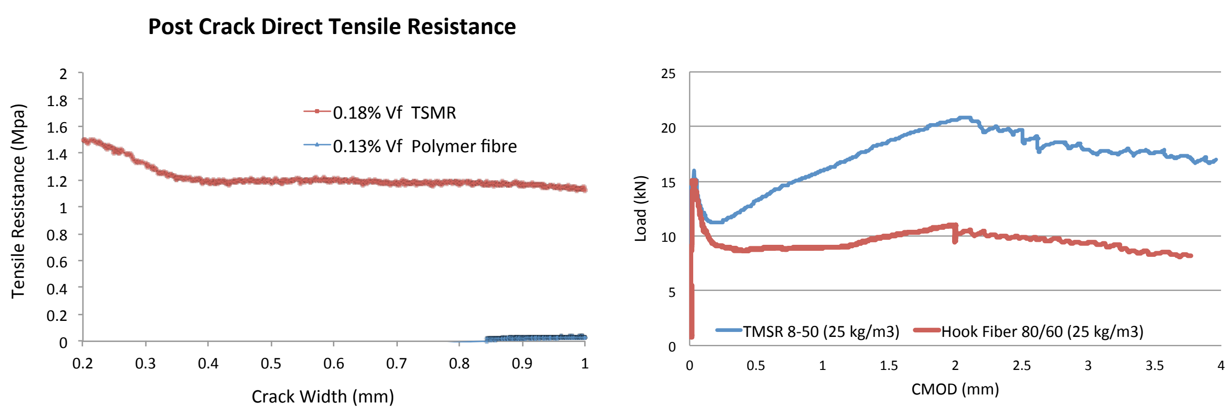
(b) Tensile Load Vs Displacement (22)

Figure 4. Modulus of Elasticity

4.4 Post Crack Behavior

Direct tension testing of TSMR (Figure 5a) shows stable load carrying capacity at code maximum crack widths (EN 1992 states that the maximum crack width in a low environmental exposure area is 0.4 mm).

Flexural testing of notched beams (for the EN 14651) indicates TSMR 8-50 performed 40% better than hook ended steel fibre at 3.5 mm crack width with more consistent results (Figure 5b). Post crack performance of 8-50, as measured in ASTM C1609, exceeds levels required in recent underground construction specifications at dosages lower than ever possible before with traditional steel fibres (23).



(a) TSMR 5-25 Direct Tension Vs Polymer (24)

(b) TSMR 8-50 Vs Steel Fibre EN 14651 (25)

Figure 5. Post Crack Testing

Round Determinate Panels (RDP) Testing of TSMR confirms the deflection at peak post-crack stability in the design crack width range exceeds hook ended steel fibres (Figure 6). TSMR holds a constant 15 kN load up to nearly 5 mm central panel deflection. While at very large cracks (40 mm central panel deflection) the product provides similar performance to hook fibres and polymer fibres, the behavior at these deflections is irrelevant due to the instability of the structure with cracks this large as determined by NIOSH, one of the worlds largest occupational health and safety organizations (2). In contrast, it should be noted that polymer fibres exhibit a sharp drop off in load carrying capacity to levels well below TSMR immediately after the crack. But, due the elasticity of the material, the polymer fibres provide a constant or increasing resistance as the crack is allowed to grow beyond the NIOSH limit of stability by the careful loading of the test machine (2).

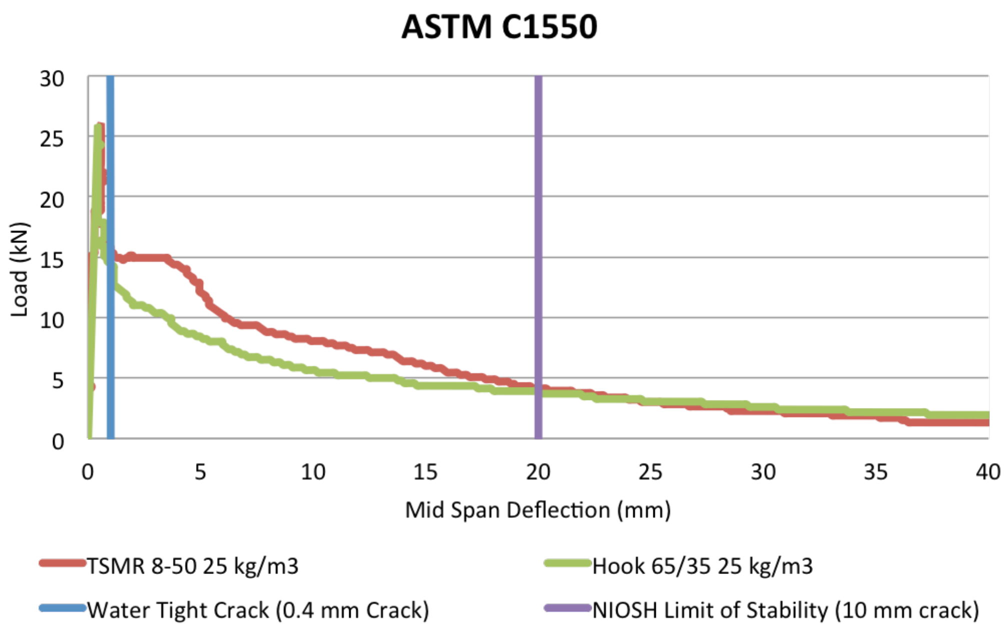


Figure 6. Post Crack Testing (26)

4.5 Fire and Blast Resistance

TSMR reinforcement does not adversely affect the fire resistance ratings when compared to conventionally reinforced concrete designs (5). Testing of steel fibres in general has shown enhancement of properties in precast tunnel segments (27). Blast resistance testing of TSMR shows efficacy of its use in conjunction with a reduced amount of conventional reinforcement to enhance the resistance of concrete to breach when exposed to explosives at close range, similar to a wearable improvised explosive device.

Figure 7 shows two 150 mm thick panels of equal cost after being exposed to 10 lb C4 at 380 mm standoff. Figure 7(a) is a concrete panel with two layers of 10 mm diameter bars at 100 mm spacing each way and Figure 7(b) is a concrete panel with 33% less conventional reinforcement than Panel 1 (two layers 10 mm bar at 150 mm) and 18 kg/m3 TSMR.

(a) Control 2 Layers of 10 mm Bar at 100 mm

(b) TSMR 5-25 at 18 kg/m3 with 10 mm Bar at 150 mm

Figure 7. TSMR Blast Testing (28)

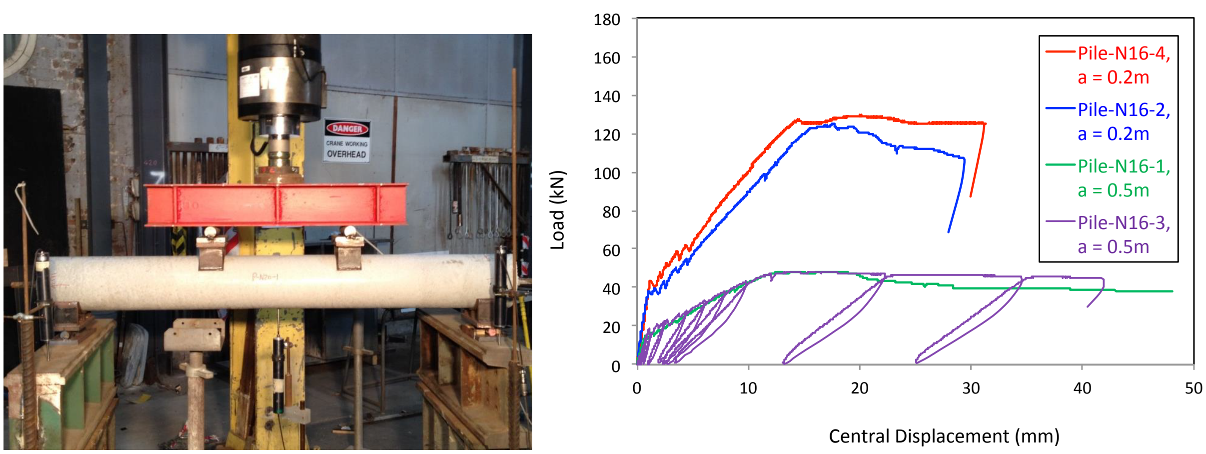
5. Design of TSMR Reinforced Concrete

Extensive research and testing has been carried out to develop a suitable design methodology and provide practical and safe applications of TSMR. TSMR design methodology has been independently evaluated (ISO Guide 65 Evaluation Report 279). TSMR 5-25 reinforced concrete using this method of design has been used successfully in Australia in hundreds of projects. Based on this approach to design, Elastic Design of TSMR 5-25 has also been used successfully in slabs-on-grade in hundreds of projects globally for 10 years. Furthermore, TSMR 8-50 provides the benefits of TSMR technology (increased MOR, Splitting Tensile, Pre-crack Ductility) along with improved post crack strengths at large crack widths. This improved large crack width performance allows TSMR 8-50 to conform to existing design methods listed in Table 2.

5.2 Evaluation Report 279 of TSMR 5-25

A unique method of design based on rigorous peer reviewed direct tension testing is available for TSMR 5-25. The ISO Guide 65 Evaluation Report (UES ER 297) described in other works (**5**, 10, 29), has been validated against hundreds of laboratory and field tests over a period of 10 years in nearly 30 countries. Furthermore, the ISO report is recognized in nearly 100 countries via mutual recognition treaties. The report includes a design guideline structured in a way that is familiar to engineers who are used to designing with conventional bar reinforcement. The report provides the required restrictions on its use and field QA procedures. This report is available for download at www.iapmoes.org/Documents/ER_0279.pdf. This document provides a building official with a third party review of all the performance testing required to meet the performance based "deemed to comply" provisions in the BCA for alternative building materials.

Testing conducted at the University of New South Wales illustrates the accuracy of of ER 279 design when using a combination of TSMR and conventional reinforcement as well as the ductility TSMR provides in both static and cyclic loading. Four 200 mm diameter by 1.5 meter span circular beam with one N16 in the center and 25 kg/m^3 Helix were tested, three statically and one cyclically. Two different shear spans, (minimum distance between support and load point) were evaluated, 0.5 and 0.2 m). A maximum bending moment of 11.5 kN-m was computed. The tests results ranged from 12-13 kN-m (4 beams). All of them, even the specimen tested under cyclic loading, exceeded the ER 279 prediction. The beams exhibited ductility that exceeded what was expected with ordinary plain concrete producing a stable response even when 15 mm cracks were present (30). A similar test confirmed that shear was also accurately predicted by ER 279.



(a) Circular Pile Test Setup a = 0.5 (b) Load - Deflection Results a=0.5, 0.2

Figure 8. UNSW TSMR Hybrid Beam Testing (30)

5.2 Elastic Design

Until now, the usefulness of the elastic (plain concrete) provisions of the building codes (Table 3) was limited due to the requirement for very thick and/or high strength concrete needed to develop the same resistance of thinner reinforced concrete sections. Both TSMR 5-25 and 8-50 exhibit increased modulus of rupture with low coefficient of variation with increasing dosage as reported in section 4.1. The curves in Figure 2 may be used in place of the standard values used to compute flexural tensile strength in the code. Many codes require a resistance factor or factor of safety be applied to this value. When the dosage is low, below 15 kg/m3, the standard plain concrete resistance factor should be used. At higher dosages, an increased resistance factor of 0.9 is recommended for both the mean and characteristic curves (16**,** 17) The factor is computed in accordance with the Load and Resistance Factor Design (LRFD method assuming reliability levels (β= 4) appropriate for plain concrete design (31).

In the case of AS 3600 section 3.1.1.3, one would use the Characteristic MOR value in Figure 2 to compute the flexural tensile strength, f_{ctf} and use 0.9 in place of the standard value of φ for plain concrete as stated in table 2.2.2. When designing structural concrete, the standard plain concrete resistance factor should be used when the TSMR dosage is below 15 kg/m^3 because testing indicated that while there is an increase in MOR, there is still high variation at low dosage (Table 4). The mean value rather than the characteristic value is allowed for slab design in many slab design approaches (ACI 360). All other restrictions of the code for structural plain concrete/elastic design or slab design must be followed when using the enhanced design with TSMR. Since this method relies on enhanced modulus of rupture versus code values, engineers need to obtain approval through the "deemed to comply" provision of the code BCA. The reference documents (16,17) provided the test data needed to satisfy these provisions.

6. Conclusions

After 10 years of successful implementation worldwide, the success of TSMR reinforced concrete is undeniable. This very fact, in addition to the significant increases in modulus of rupture and splitting tensile strength TSMR provides, calls into question common fibre testing and design guidelines that assume the concrete has failed prior to any contribution. A fundamental question must be addressed, is it really OK to design fibre concrete assuming large cracks have formed? And why do we give up on the concrete so easily?

- TSMR has successfully achieved what the fibre industry has been in search of for decades – a fibre reinforcement that engages the concrete before it fails, i.e. TSMR increases the modulus of rupture of concrete. This increase starts at very low dosage and increases further as dosage increases. The variability (COV) is also lower on average, than the control. All existing design procedures examined in this report completely ignore the pre-crack phase.
- The existing design procedures in table 2, examined in this report use post crack performance measurements for design, ignoring the pre-crack phase.
- Current test and design methods fail to provide adequate tools to the engineering community to design safe, reliable, structural concrete with fibres as they place too much emphasis on capacity at large crack width (after the structure would have far exceeded its ultimate limit state in real life).
- Steel and Polymer fibres are designed for optimum performance in these tests but most do not perform well until cracks larger than code limits (about 0.4 mm) have formed.
- TSMR increases splitting tensile strength of concrete. The increase becomes even larger as the concrete ages and as dosage increases. This addresses concern with age embrittlement of TSMR concrete and may allow design of larger tunnel segments than ever before possible with other fibres.
- The modulus of elasticity of TSMR is 24 times that of polymer fibres and 8 times that of plain concrete. The high modulus of elasticity, in addition to the efficient bond provided by the twist provides enhanced ductility in both tension and compression.
- Both TSMR 8-50 and 5-25 exhibit deflection softening but stable post crack behavior at typical dosages (below 30 kg/m^3) beyond code allowable crack widths (0.4-1 mm) in standard beam and panel tests. TSMR 8-50 outperforms leading hook ended fibres even at large crack widths (R4 value at 3.5 mm crack width).
- The enhanced ductility of TSMR is dramatically demonstrated in blast testing where spalling was almost completely eliminated by partially substituting traditional reinforcement with TSMR.
- Design of TSMR 5-25 may be accomplished using an ISO Guide 65 Evaluation report that demonstrates compliance with the "deemed to comply" provisions of various building codes including the BCA.
- Design may alternatively be accomplished using the elastic design provisions of the code along with the enhanced MOR values provided by TSMR reinforcement at respective dosages.

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The proceedings contain 171 papers across 14 themes. All the papers included in the proceedings have been selected on the basis of at least two peer reviews which were provided by independent reviewers (referees) who were experts in the subject field of the paper.

The theme of the conference is Research into Practice. The Concrete Institute of Australia is an industry led association whose primary charter is to promote good practice in concrete construction. The theme is in line with this charter and is relevant in the current climate where the Australian industry is being asked for greater participation in R&D while the researchers are being asked to show greater impact and practical outcomes of their research. The proceedings contain papers from 20 different countries. Nearly half of them are from Industry and half from Researchers.

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