
TWISTED STEEL MICRO REINFORCEMENT (TSMR) FOR SHOTCRETE

VERDRILLTE STAHLFASERN ALS MICROBEWEHRUNG (TSMR) FÜR SPRITZBETON

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Steel fibers have been used to reinforce shotcrete, replacing traditional steel wire mesh, for over twenty years. They are added to shotcrete to improve energy absorption, crack resistance and provide ductility. All three properties are very important for support systems designed for tunnel and mine conditions. TSMR (Twisted Steel Micro Reinforcement), takes shotcrete reinforcement one step further.

The twisted anchorage and yielding properties of these new fibers provide all these benefits and more at much lower dosages than had previously thought possible – 50 % lower than hooked type fibers. Significant improvements in compressive, splitting tensile and flexural strengths have been documented.

Stahlfasern als Ersatz für die traditionelle Mattenbewehrung werden bereits seit 20 Jahren für Spritzbeton eingesetzt. Sie werden dem Spritzbeton zugesetzt, um das Energieabsorptionsvermögen und den Widerstand gegen Rissbildung zu verbessern und dem Beton duktilere Eigenschaften zu geben. Alle drei Eigenschaften sind für die Sicherung von Tunnels und Bergwerken von großer Bedeutung. TSMR (Verdrillte Stahl Mikro Bewehrung) bringt die Spritzbetonbewehrung einen Schritt weiter.

Die Verdrillung der Verankerung und die Fließigenschaften dieser neuen Faser ermöglichen diese Vorteile bei deutlich reduzierter Dosierung. 50 % Reduzierung gegenüber Fasern mit Endhaken waren früher nicht vorstellbar. Erhebliche Verbesserungen bezüglich Druckfestigkeit, Spaltzugfestigkeit und Biegezugfestigkeit werden belegt.

1. Introduction

Steel fibers have been used to reinforce shotcrete, replacing traditional steel wire mesh, for over twenty years. They are added to shotcrete to improve energy absorption, crack resistance and to provide ductility. But do these fibers really perform this function? Or are these improvements simply elaborate marketing tools developed by fiber manufacturers to convince engineers to specify their products?

Testing and design approaches for fiber reinforced concrete have evolved over time with heavy influence of material manufacturers [1]. The industry is now focused on deflection controlled round panel tests (ASTM C1550/RDP). This configuration measures bi-axial energy absorption (area under load deflection curve) to large deflections / crack widths using closed loop deflection control. Shotcrete design is moving towards an empirical energy based approach that uses results from this type of test [2]. The method favors polymer fibers

which exert force on the concrete only AFTER large cracks are formed, since their moduli of elasticity are lower than concrete (they stretch like rubber bands). Further, the test machines use sophisticated controllers programmed to immediately remove the load when the concrete cracks. This provides a false sense that low modulus fibers provide strength immediately after crack formation.

There are three problems with current test and design methods:

- 1) Current test methods fail to measure properties needed for design directly (tensile resistance) and rely on empirically based assumptions to convert equivalent bending stress (from beam tests) to tensile stress.
- 2) Current design methods allow (and in many cases encourage) design assuming very large deflections and large crack widths (up to 40 mm deflection and 15 mm cracks) in flexural tests. The cracks are nearly 38 times the maximum code allowed crack width (EN 1992, 0.4 mm) and 72 times the width allowed when water-tightness is required (0.2 mm) [3]. By arguing that large crack widths are acceptable and even desirable, the polymer fiber industry has quietly convinced the industry that it is acceptable to have large cracks in concrete [4, 5].
- 3) Studies have shown strength variations of as much as 200 % in flexural testing associated with specimen size, preparation, and/or support conditions [6]. This calls in to question the idea of using data from such tests for design purposes.

Twisted Steel Micro Reinforcement (TSMR) Technology is both a product and a design method. The product has a statistically significant effect on the tensile strain capacity and modulus of elasticity of the concrete and it provides stable post crack resistance [7]. Unlike polymer fibers, TSMR provides tensile resistance prior to the development of code maximum cracks allowing for watertight design. This is accomplished via its twisted geometry which provides better anchorage/bond prior to crack formation and because it must actually untwist (provides constant resistance) to pull out of concrete (Figure 4). Unlike polymer fibers, TSMR increases the tensile strength and ductility of concrete prior to cracking and provides significant tensile resistance starting at 0.005 mm crack width.

The design approach is unique because it solves the problem of specimen size and geometry by isolating the two primary variables and testing them separately: Force per TSMR and distribution of TSMR. Separating the distribution part of the limit state function allows for less expensive testing with smaller specimens without compromising design. The design approach is based on tensile stress capacity but is restricted by tensile strain (crack width). With cracks held smaller than 0.20 mm, structures remain water-tight and corrosion of steel does not come into play. The strain check also has the benefit of adequately addressing size effect, an issue that plagues standardized fiber testing and design approaches today.

2. Testing and Design Approaches

Unlike traditional reinforcement, the performance characterization and design of steel fiber 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 the flexural stress (which only exists in linear elastic materials and is invalid after a crack forms) and direct tensile stress [8]. A multiplier of 0.37, (which assumes linearly decreasing load as crack width increases) is typically used to relate the flexural stress in beams with large cracks (3.5 mm) to direct

tensile strength [5]. 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, fiber length and specimen size on results. [6]

Table 1: Fiber Test Methods

Test Standard	Type	Control	Measurement	Single Operator COV
ASTM C78	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	Direct Tension Notched	Deflection	Post crack only	Not reported
ASTM C496 EN 12390-6	Splitting Tensile	Load	Peak Post crack*	5 %
UES EC 015	Direct Tension	Deflection	Peak crack Post crack	Peak 6.3 % Post 11 %

*Note: measurable only when post crack strength is higher than first crack strength

While the fib Model Code 2010 aims to become the general standard for fiber design in Europe, 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, include some statistical considerations for variations in test results. UES EC 015, 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. [9, 10]

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 [2]. This method favors fibers that behave well at large deflections in the round panel tests.

The properties of TSMR reinforced concrete with higher tensile strength could provide benefit to designs using provisions of EN 1992 and ACI 318 for elastic design and plain concrete design. Unlike with conventional non-linear reinforced concrete design, these approaches consider concrete tensile strength in their design.

Table 2: Steel Fiber 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
ACI 506.1R-9	Shotcrete cracked stress	0.5 mm crack	ASTM C1609	Linear, stress at 0.5 mm
RILEM TC 152-TDF	General, cracked stress & strain	1.5 mm 3.5 mm crack	EN 14651	Bi-Linear f1x0.45; f4x0.37
Concrete Society TR-34	Slabs only cracked stress	3.5 mm crack Yield Line	EN 14651	Bi-Linear f4x0.37
Fib Model Code 2010	General, cracked stress	0.5 mm or 2.5 mm crack	EN 14651	Bi-Linear f1x0.45 f3/3
Papworth 2002 [2]	Shotcrete Energy	Energy to 40 or 80 mm	ASTM C1550, RDP	Empirical Table of Energy
EN 1992	General Section 5.4	Elastic Design	EN 12390-6	Elastic, MOE, Tensile Strength
UES EC015/ ER 279	Stress & Strain	Peak or 1 mm crack	EC 015	Not Required

3. Advantages and Disadvantages of Steel vs. Polymer Fibers in Shotcrete

While polymers can be engineered to have tensile strengths equal to or greater than mild steel, the primary difference between steel and polymer fibers is modulus of elasticity (stiffness). Figure 1 illustrates the profound difference in modulus of elasticity between concrete, steel and several polymer types commonly used in concrete fibers. Steel is 800 % stiffer than concrete and the best polymer has only 38 % the stiffness of concrete. [11]

Even with a very efficient concrete fiber bond, the polymer fibers do not provide tensile resistance prior to the development of cracks and they are stretched enough to provide resistance (they act like a rubber band in relation to the concrete). Direct tension comparing plain, polymer fiber, and TSMR concrete suggest pre-crack tensile is not affected by polymer fibers. This intuitively makes sense given the polymer fibers are nearly inactive until stretched (Figure 2) [12] due to their low elastic modulus.

Steel, on the other hand, can provide resistance to concrete prior to crack due to its high elastic modulus and tensile strength relative to plain concrete. Provided these conditions are met and the bond between concrete and steel is adequate, the steel will increase the ductility of the concrete prior by providing alternative load paths of micro-cracking initiates. The testing confirmed the increase in strain at first crack with TSMR versus control is with 99.92 % confidence. TSMR technology is the only fiber type studied – steel or polymer – that exhibits this behavior.

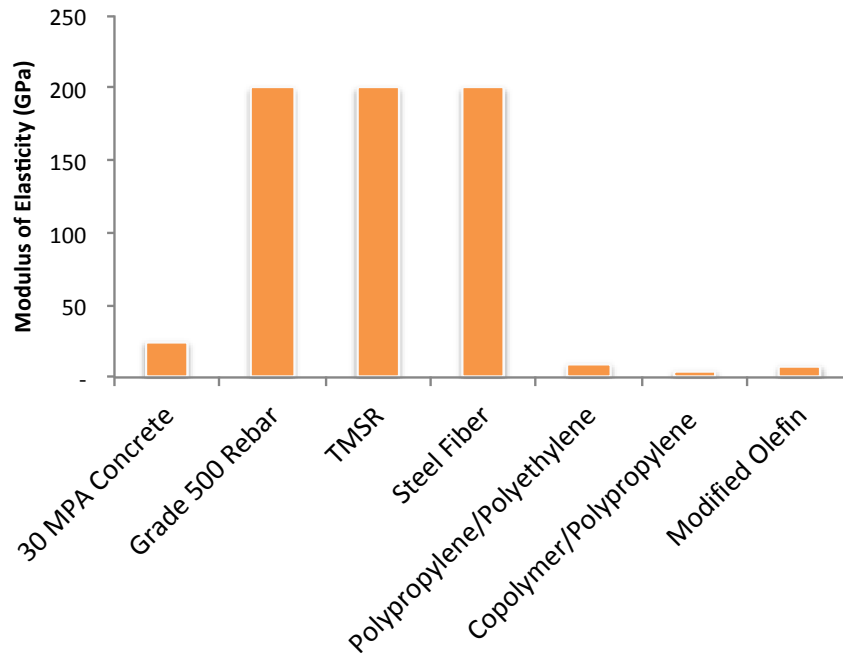


Figure 1: Concrete and Fiber Material Modulus of Elasticity [11]

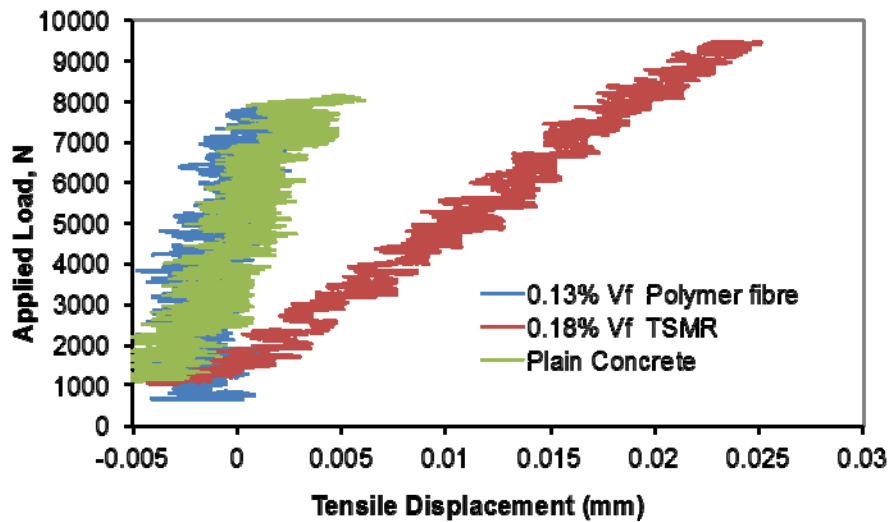


Figure 2: Pre Crack Direct Tensile Load Vs Displacement [12]

Polymer fibers do not begin exerting significant tensile force until after a crack of 0.85 mm wide forms (Figure 3). Once the concrete has developed a dominant crack of this size, the fiber can provide some tensile resistance as the crack increases in size to 3.5 mm and it stretches. Its best performance occurs at 3.5 mm, not coincidentally, the same crack width most of the design methods employ (remember EN 1992 states that the maximum crack width in a low environmental exposure area is 0.4 mm) [3]. The lower stiffness of the TSMR concrete is due to the efficient bond and screw shape of the TSMR product. This unique shape and bond allows the concrete matrix develop micro-cracks but not allow those micro-cracks to localize as quickly when the TSMR is not present. The TSMR is acting similar to a torsion spring, which stretches before the bond is broken and untwisting begins. This response is noticeable in both flexural (ASTM C1609 & C78) and direct tension (UES E015) testing by an increase in the peak (MOR) and deflection/displacement at peak, not seen in steel or polymer fibers or rebar [12, 18, 20]. In fact,

it accepted that any reinforcement including rebar and wire mesh increase the frequency of cracking thus weakening plain concrete (i.e. EN 1992, ACI 318, 224R-01).

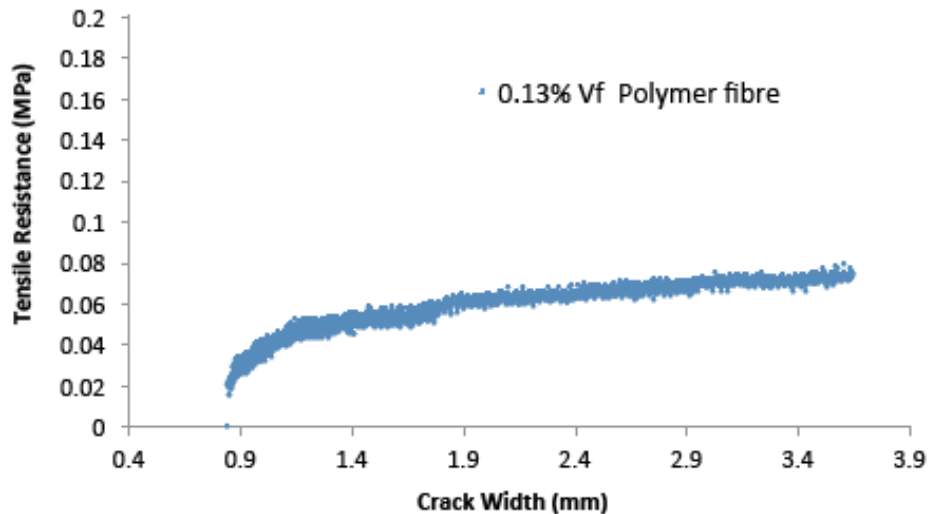


Figure 3: Polymer Fiber Concrete Post Crack Direct Tensile Load Vs. Displacement [12]

4. Geometry, Material and Physical Properties of TMSR

TMSR 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 and can be zinc coated for corrosion protection (also sold without coating). The length is 25 mm and its equivalent diameter is 0.5 mm. Each TMSR has a minimum of one 360-degree twist [13]. The TMSR can be customized in all areas (tensile, length, diameter, twists) for specific structures, designs, test standards or performance requirements.

Twisted Steel Micro Reinforcement (TMSR) is produced with a unique twisted profile (Figure 4) 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 this product significantly different from traditional steel fibers because pullout is governed by untwisting resistance rather than friction. TMSR 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 4: Twisted Steel Micro Reinforcement

5. Performance Characterizations and Design of TSMR

5.1 Testing Per UES EC 015

TSMR tension resistance is measured using direct tension testing [14, 15]. The test uses a 150 mm diameter “dogbone” shaped coupon fitted with an adhesive anchor on the top and bottom and three strain measuring devices (Figure 5). These specimens are typically cast, methods of specimen preparation with shotcrete using a nozzle attachment are under development. The machine measures the direct tensile behavior using the procedures outlined in ASTM E111 both before and after a crack forms. The specimen geometry was designed using finite element analysis to assure there are no stress concentrations in the gage length.



Figure 5: Direct Tensile Test Setup

The test method and data analysis method is detailed in Uniform Evaluation Criteria #015. These criteria are an ISO Guide 65 compliant peer reviewed code document, recognized in 99 countries through International Standards Organization Mutual Recognition Agreements.

5.1.1 Test Results – Direct Tensile

Before a dominant (localized visible) crack forms, the bond provided by the twisted shape of TSMR in addition to the high modulus allows for force re-distribution into the TSMR. The TSMR concrete has a lower modulus (thus it is more flexible) and requires more energy (area under load deflection curve) to crack (Figure 2). This occurs as result of a small amount of elastic stretching and untwisting that occurs as load is re-distributed into TSMR; the concrete micro-cracks prior to the formation of a dominant crack. The polymer fiber concrete sample cracked at 1/10th the displacement of the TSMR sample, similar to the control.

After a crack forms, TSMR maintains stable tensile resistance up to a 1 mm crack width at low dosages as it stretches and begins to untwist (Figure 6). The TSMR resistance will decrease as the crack width increases beyond this as the TSMR's ends begin to move and pull out. The force carried at equal volume fraction compared to polymer fibers is twelve times at 1 mm crack and four times at 3.5 mm crack (Figure 6). Higher dosages of TSMR (>0.5% Vf) are capable of deflection hardening behavior in bending (Figure 8) [18].

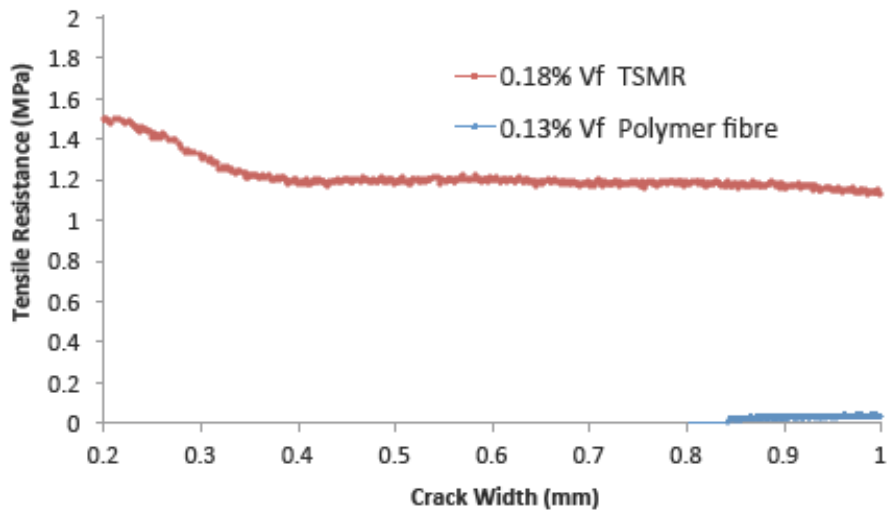


Figure 6: TSMR vs Polymer Fiber: Post Crack Direct Tension [12]

5.1.2 Test Results – Spitting Tensile

Splitting tensile strengths with TSMR dosage (Figure 7), further demonstrating its ability to improve the pre-crack properties of the concrete. Similar increases in first crack strength (Modulus of Rupture) occur in beam testing and direct tension testing (Figure 8).

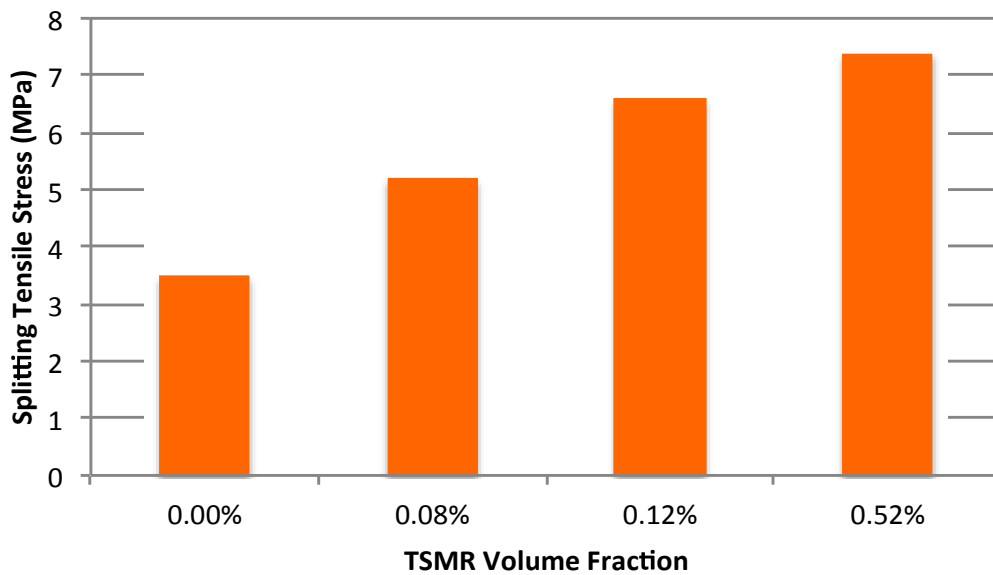


Figure 7: TSMR Splitting Tensile Strength [17]

5.1.3 Test Results – Beam Test (without notch)

Standard flexural beam testing conducted in accordance with ASTM C1609 (100 mm x 100 mm specimen size) shows that the same level of performance as with a 35 mm, 65 aspect ratio hook fiber can be achieved with 50 % the dosage of TSMR 5-25 (25 mm x 0.50 mm diameter). Further, the data shows that deflection hardening is possible with higher dosages of TSMR (Figure 8).

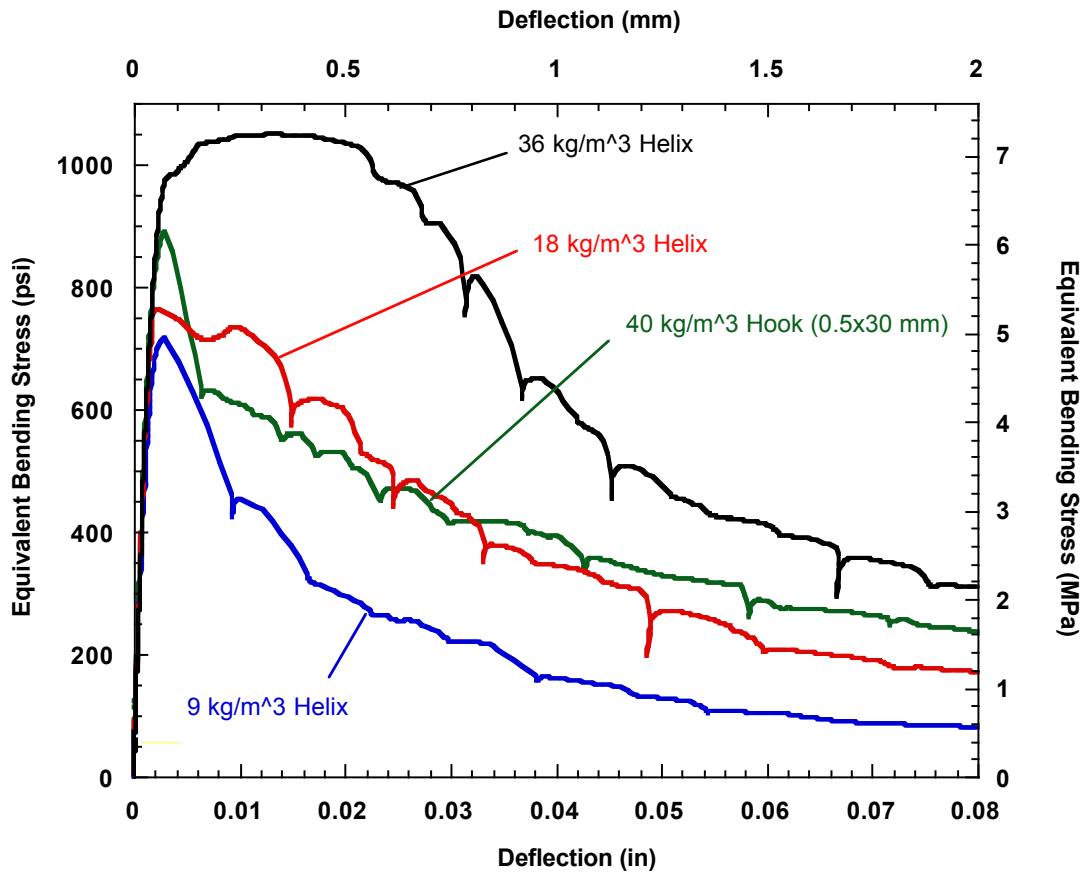


Figure 8: ASTM C1609 Beam [18]

While behavior of the 0.50 mm TSMR product is excellent in 100x100 mm beam tests, certain modifications of the base TSMR product have to be made to allow maximum performance in larger 150x150 mm specimens due to the size effect. A TSMR product (TSMR 8-50, 0.8 mm x 50 mm) has been developed specifically to allow BOTH design per UES EC 015 and design per existing standards that use the ASTM C1609 and EN 14651 (150x150x450 mm samples) test and indirect determination of tensile resistance as input to design. Testing in two different mixes shows the increases in the peak bending stress and deflection at peak expected with TSMR along with stable post crack behavior (Table 3 and Figure 9). The performance both pre and post crack exceeds levels required in recent underground construction specifications at dosages lower than ever before possible with a steel fiber [17]. The splitting tensile values with TSMR are significantly higher than those published in EN 1992.

Table 3: ASTM C1609 Test Results Helix TSMR 8-50 [19]

	f'_c MPa	Splitting Tensile, f_{ct} MPa	Peak Bending Stress MPa	Deflection at Peak mm	Stress at 0.75 mm, f_{600} MPa	Stress at 3 mm, f_{150} MPa	Average Stress to 3 mm, f_{e3} MPa	R_{e3}
TSMR 8-50 12 kg/m ³	37	3.15	4.69	0.072	1.66	1.21	1.70	40%
COV		4%	3%	4%	14%	17%	12%	15%
TSMR 8-50 18 kg/m ³	37	3.29	4.79	0.083	2.66	1.95	2.60	60%
COV		1%	4%	5%	13%	4%	8%	10%
TSMR 8-50 27 kg/m ³	63	5.37	7.10	0.100	5.20	3.30	4.77	71%
COV		6%	1%	6%	8%	16%	6%	4%

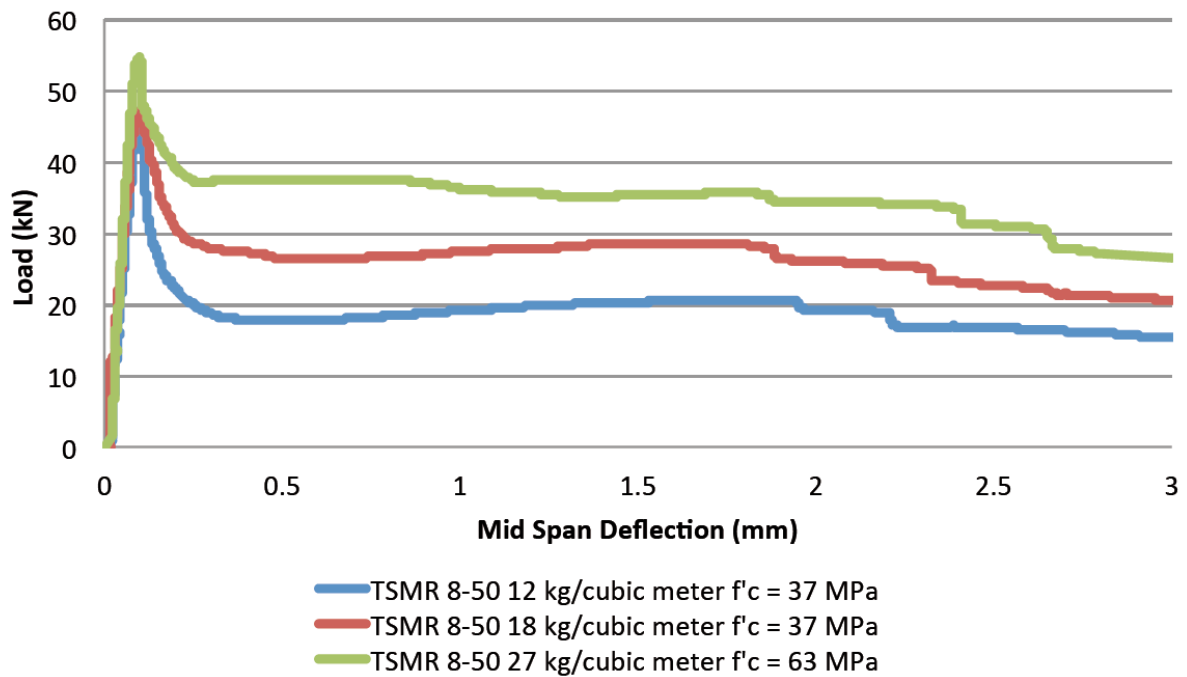


Figure 9: TSMR ASTM C1609 Test Results [19]

5.1.4 Test Results – Notched Beam Test

Testing indicates that TSMR developed for the EN 14651 test preformed 40 % better than 65-aspect ratio hook ended steel fiber at 3.5 mm crack width with more consistent results (Figure 10 and Table 4). While an evaluation report is pending for this product, testing at Element Labs (Report ESP013997P) against the criteria for TSMR outlined in UES EC 015 confirms an increase in tensile strain at first crack of 19 % over the control (plain concrete) with 98 % confidence ($p=0.017$) and post crack stable direct tensile behavior.

Table 4: EN 14651 Test Results Helix TSMR 8-50 Vs Hook Fiber 80/60 [20]

Product	Dosage kg/m ³	Aspect Ratio	$f_{ct,L}$ MPa	$f_{R,1}$ MPa	$f_{R,2}$ MPa	$f_{R,3}$ MPa	$f_{R,4}$ MPa
Helix 8-50	25	62	5.1	3.8	5.3	5.4	4.8
COV			3%	12%	9%	11%	10%
Hook 80/60	25	80	5.0	3.2	4.0	4.0	3.4
COV			6%	16%	14%	17%	16%
Increase vs Hook with TSMR			2%	20%	31%	37%	41%

5.2 Design Per UES EC 015

The TSMR design procedure uses tensile values developed from UES EC 015 direct tension testing. A regression analysis is performed to derive a function for tensile resistance measured with direct tension testing as a function of the number of TSMR spanning the broken cross section and concrete compressive strength (Figure 11).

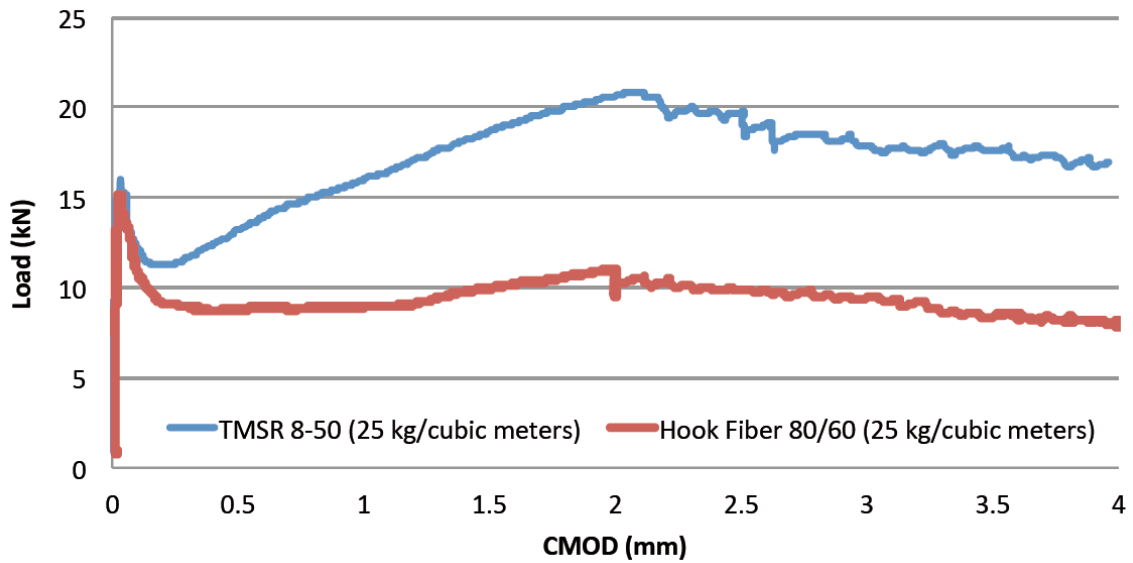


Figure 10: TSMR EN 14651 Test Results [21]

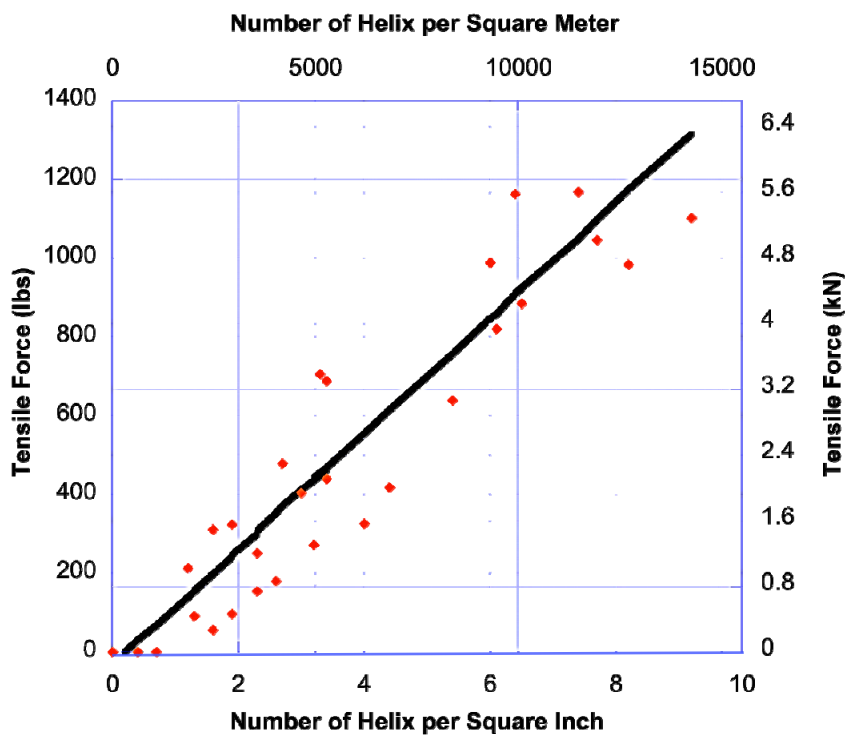


Figure 11: Direct Tensile Test Results [22]

Uniform Evaluation Criteria #015, also specifies a tensile “stress block” design method (Figure 12) similar to the method prescribed in RILEM TC 152-TDF and the fib 2010 Model code with a few exceptions:

- 1) The LRFD method is used to derive limit state equations and appropriate resistance factors used in design using the direct tension testing data that takes into account both the measurement itself and the variation in the measurement [23].

- 2) A rectangular, rather than a triangular, stress block is assumed since TSMR provides stable tensile resistance as it untwists.
- 3) The design method specifically requires the engineer to determine the expected tensile strain based on loading and support conditions. Strain based restrictions and limitations are imposed to ensure the TSMR remains in the pre-cracked region or the stable post crack region (where fibers are stretching, not pulling out). The strain limits adequately address the size effect that occurs as sections become deep and strains (and crack widths) increase because it requires the engineer to compute the strain and ensure TSMR is used only when strains at ultimate are kept below maximums.

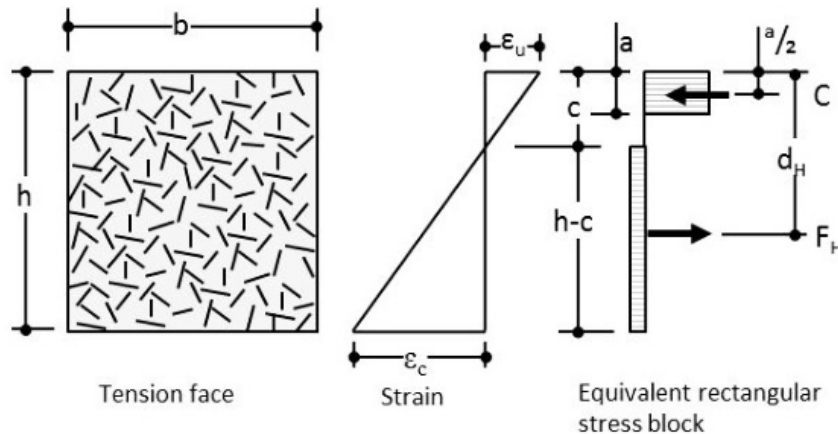


Figure 12: TSMR Stress Block Model [14]

Flexural and shear prediction obtained using the design approach were validated against independent test results from 36 different test programs of different size specimens (including both 100x100 mm and 150x150 mm specimens) in different concrete mixes conducted at different labs [24]. Details of the design procedure and validation are in Uniform Evaluation Report 0279 and Evaluation Criteria 015 [13, 14].

6. Conclusions. Suggested Modifications of Pertinent Clauses in Design Codes

- TSMR has successfully achieved what the fiber industry has been in search of for decades – a fiber that engages the concrete BEFORE it fails. Unfortunately, since other products are unable to engage the concrete prior to its failure due to poor bond and/or low modulus of elasticity, ALL existing design procedures examined in this report completely ignore the pre-crack phase. DON'T GIVE UP ON THE MATRIX!
- Direct tension testing eliminates the need for estimating tensile response from beam tests using relationships that may not be the same for all fibers. Since force is measured on a per fibre basis the test is independent of fiber distribution and therefore has lower variations.
- Direct tension evaluation of TSMR vs. macro polymer fibers confirms the hypothesis that these fibers, due to their low modulus of elasticity, do not become active until large cracks have already formed.
- Analysis of the pre-crack portion of the direct tension curves suggests that polymer fibers may make the concrete more brittle than plain concrete. More testing needs to be done to confirm this.
- TSMR increases splitting tensile strengths. This may be useful for elastic design.

- While TSMR can be “tailored” to perform well under standardized testing (by designing its length and diameter for the test specimen size), it is not necessary if the engineer uses the TSMR method (UES EC015/ER279). The tension-based design provides appropriate design limitations and resistance factors based on variations of force and distribution resulting in accurate predictions or capacity regardless of thickness/size.
- TSMR should be the product of choice whenever the engineer seeks to limit and control crack sizes to widths consistent with relevant concrete structural codes. Any structure where water infiltration, or visible cracks are a concern are ideal applications as TSMR adds tensile resistance prior to development of visible cracks.
- Engineers should be aware of the consequences of the use of polymer fibers – large cracks are expected prior to the fibers providing any benefit to the concrete.

7. References

- [1] Bernard, S.:
New Round-Panel Test Evaluates the Performance of Alternative Concrete Reinforcement Systems. ASTM Standardization News, November (2002).
- [2] Papworth, F.:
Design guidelines for the use of fiber reinforced shotcrete in ground support. 27th Conference on OUR WORLD IN CONCRETE & STRUCTURES, (2002), 29-30.
- [3] EN 1992-2004, Eurocode 2:
Design of Concrete Structures, European Committee for Standardization, (2004), Table 7.1N.
- [4] TR-34:
Concrete Industrial Ground Floors. The Concrete Society, 4th Addition (2013).
- [5] TDF 162:
Test and design methods for steel fiber reinforced concrete. Materials and Structures, RILEM, March (2004).
- [6] Wille, K., Parra-Montesinos, G.:
Effect of Beam Size, Casting Method and Support Conditions on Flexural Behavior of Ultra High Performance Fiber Reinforced Concrete. ACI Materials Journal, May/June (2012) 379-388.
- [7] Pinkerton, L., Stecher, J., Novak, J.:
Twisted Steel Micro Reinforcement. Concrete International, Vol 35, No. 10 (2013).
- [8] Megson, T.H.G.:
Structural and Stress Analysis. Second Edition, Elsevier Butterworth-Heinemann, Great Britain, 2005, 744 pp.
- [9] ACI 318-11:
Building Code Requirements for Structural Concrete. American Concrete Institute, (2011).
- [10] EN 1992-2004, Eurocode 2:
Design of Concrete Structures. European Committee for Standardization, (2004).
- [11] MOE Data Sources:
Concrete: ACI 318-11 Section 8.5, 10.2.5; Rebar ACI 318-11 Section 8.5; Helix: Uniform Evaluation Service (www.iapmoes.org) ER 279, Section 3.1; Steel Fiber: Bekaert Dramix 65/60 Data Sheet (www.bekaert.com), Polypropylene/Polyethylene: Euclid TufStrand Data Sheet (www.euclidchemical.com); Copolymer /Polypropylene: Forta Ferro Data Sheet (www.forta-ferro.com); Modified Olefin: Barchip Data Sheet (www.elastoplastic.com).
- [12] Report ESP017071P, Direct Tension Testing of Polypropylene / Polyethylene Fiber. Element St Paul (2014),
Report ESP011215P Direct Tension Testing of TSMR 5-25. Element St Paul (2014),
Report ESP010572P Direct Tension Testing of Plain Concrete. Element St Paul (2014).
- [13] ER-279, Uniform Evaluation Service Evaluation Report #279, Uniform Evaluation Service, 5001 E. Philadelphia St. Ontario, CA 91761 – USA (2014).
- [14] EC-015, Uniform Evaluation Service Evaluation Criteria #015, Uniform Evaluation Service, 5001 E. Philadelphia St. Ontario, CA 91761 – USA (2014).

- [15] Pinkerton, L., Novak, J.:
Twisted Steel Micro Reinforcement Advantages of Microscopic Composites. Concrete Society, June (2014) 36-37.
- [16] Novak, J.:
Metal Guru. Tunnels and Tunnelling, November (2013), 33-35.
- [17] Euclid Creek OH, USA, Blue Plains MD, USA, Bay Tunnel, Central Subway, NY, USA,
Construction Specifications for Fiber Concrete in Precast Tunnel Segments.
- [18] ASTM Bending Test of TMSR 5-25, University of Michigan, DRDA Contract # 04-2678 (2006).
- [19] Report 14-922, ASTM C1609 Testing of TSMR 8-50, TEC Services Lawrenceville, Georgia, USA (2014).
- [20] Report SER-22013-0268L F1404-05A(18-19), SIKA Services AG (2014).
- [21] Report SER-22013-0268L F1404-05A(18-19), SIKA Services AG (2014) 18 beam 2 and 19 beam 2.
- [22] Reports ESP010572P, ESP011215P, Direct Tension Testing of TSMR 5-25 Element Labs 3, Element St Paul (2013).
- [23] MacGregor, J.:
Safety and Limit States Design for Reinforced Concrete. Canadian Journal of Civil Engineering, V. 3, No. 4, Dec. (1976), pp. 484-513.
- [24] TMSR 5-25 Calibration Report, A&A Engineering, Toledo, OH (2013), available from Helix Steel (info@helixsteel.com).

Copies of reports of independent testing cited above, conducted at Element St Paul and TEC Services Lawrenceville, Georgia (both ISO/IEC 17025:2005 accredited laboratory) Sika Services AG and the University of Michigan are available from the authors.

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