Twisted Steel Micro Reinforcement Pavements with Unprecedented Thickness Reduction

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Abstract: Concrete pavements reinforced with Twisted Steel Micro Rebar (TSMR) perform in severe environments at half the thickness as plain concrete with the same design equivalent axle load requirements. TSMR is a micro reinforcement mixed into concrete rather than placed. Its twisted shape, high tensile strength and high modulus of rupture give its unique properties and advantages over other reinforcement. TSMR is the only reinforcement that increases the Modulus of Rupture, Splitting Tensile and Fatigue resistance of the concrete. The combination of these enhancements allows for unprecedented reductions in concrete thickness. Standard design models for pavements that use these parameters may be used to design pavements with TSMR. These models include AASHTO 1997, AirPave, PCA method and other fatigue based design approaches. Studies of the basic material properties including of TSMR reinforced concrete are presented along with implementation of these parameters in popular design models. Field results collected over nearly a decade are presented and used to validate the use of the standard models with TSMR parameters and thickness reductions.

1.0 INTRODUCTION

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. While there are two products available, TSMR 5-25 and 8-50, this paper will focus entirely on TSMR 5-25. The twist makes the product significantly different from traditional hooked end steel fibers because untwisting resistance rather than friction governs TSMR pullout. TSMR works in both the “Pro-active Phase” (pre-crack), increasing peak tensile strength, splitting tensile strength, and during the “Reactive Phase” (post-crack) providing ductility and stable tensile resistance to large crack widths in beam testing (1).

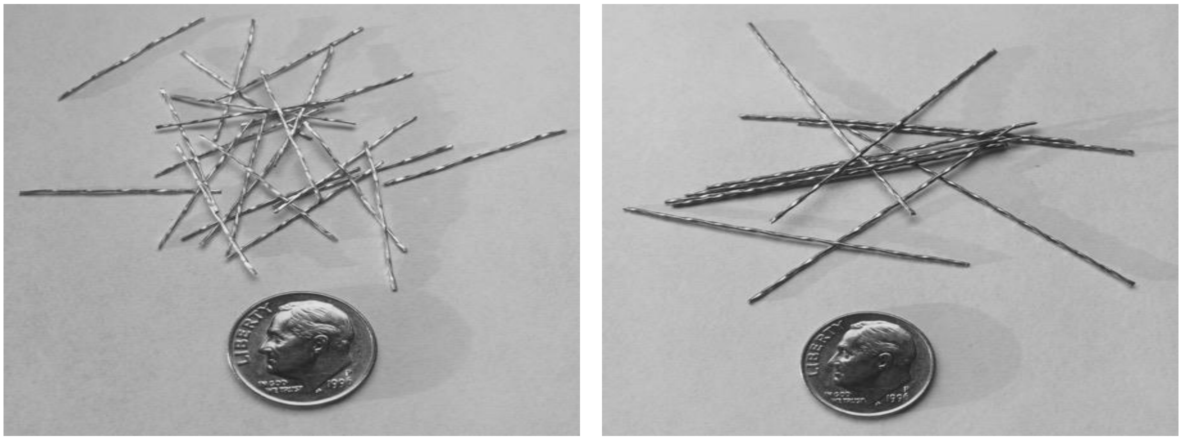


Figure 1. TSMR 5-25 and 8-50

TSMR has been used in millions of square meters of slabs and pavements that have now been installed for as long as 15 years many of which employed thickness reductions. The performance has been remarkable even with aggressive thickness reductions.

While the early projects were based on the Portland Cement Association (PCA) Design Method (Mechanistic, elastic design with static point loads), these projects can now be used to evaluate the efficacy of more sophisticated pavement design methods for designing with TSMR.

2.0 TSMR PROPERTIES

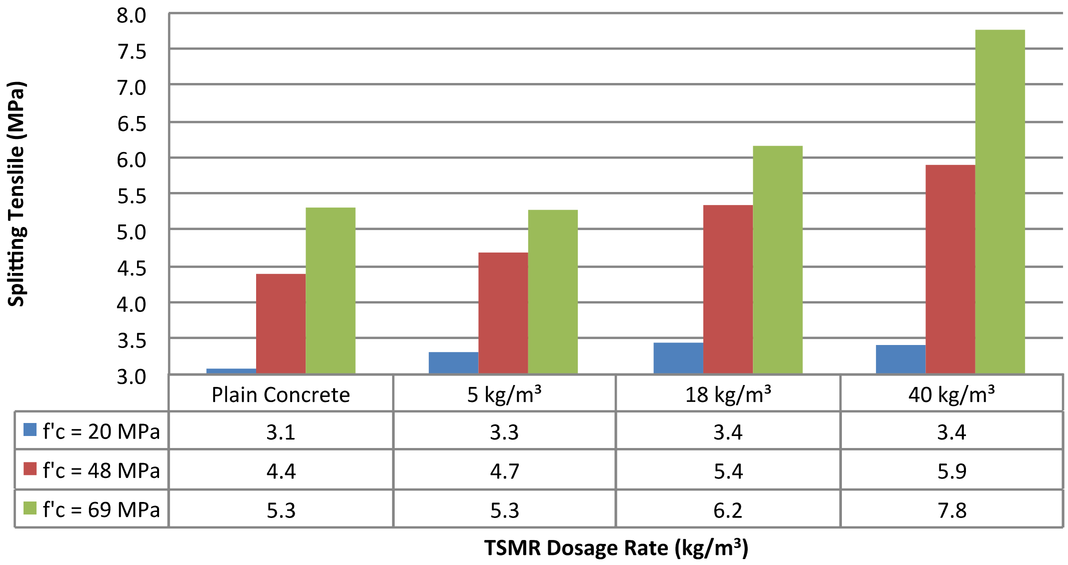
TSMR is unique in its ability to improve the pre-crack properties. Extensive testing shows a significant increase in Modulus of Rupture, Splitting Tensile, increase in tensile strain at crack, and a reduction in tensile pre-crack modulus of elasticity.

2.2 Modulus of Rupture (MOR)

The modulus of rupture (MOR) or flexural tensile strength is an indirect measure of tensile strength. The increase in modulus of rupture with TSMR has been reported in prior works (1). Increases in modulus of rupture are typically ignored in SFRC research in favour of post crack strength. Twisted Steel Micro Rebar has been shown to provide an increase in MOR over plain concrete. This increase has been validated both in the laboratory and in field as applied in over 5 million square meters of Slab on Grade designed using the enhanced modulus of rupture of twisted steel micro reinforcement (2). The average increase in MOR with TSMR 5-25 is 2% for every 3 kg/m^3 increase in dosage over average expected MOR for plain concrete (1).

2.3 Splitting Tensile

Splitting tensile is a measure of tensile strength of concrete that occasionally used in design of pavements and slabs. Testing of splitting tensile strength of TSMR 5-25 was evaluated in three different concrete mix designs were at dosages between 6 and 18 kg/m^3. The results are presented in Figure 2. The increases range from 10% to 47% depending on dosage and concrete strength.



	Plain Concrete	5 kg/m³	18 kg/m³	40 kg/m³
🟦 f'c = 20 MPa	3.1	3.3	3.4	3.4
🟥 f'c = 48 MPa	4.4	4.7	5.4	5.9
🟩 f'c = 69 MPa	5.3	5.3	6.2	7.8

Figure 2. TSMR 5-25 Splitting Tensile Vs TSMR Dosage (3)

While the increase in splitting tensile is significant, it may not accurately reflect the tensile cracking stress due to second order effects (the interaction of the support condition, etc.). The correlation between splitting tensile and MOR needs to be evaluated in a controlled study. It is therefore not used in design for this particular study.

2.4 Modulus of Elasticity (MOE)

Prior research has shown a decrease in the modulus of elasticity of concrete in tension as measured by direct tension testing (4) when TSMR 5-25 was present. On average this decrease measured was 20% (n=29 TSMR samples, 9 Plain Concrete Control Samples) for dosages between 3 and 60 kg/m^3. Figure 3 shows as typical load deflection curve in tension comparing TSMR reinforced concrete to plain concrete.

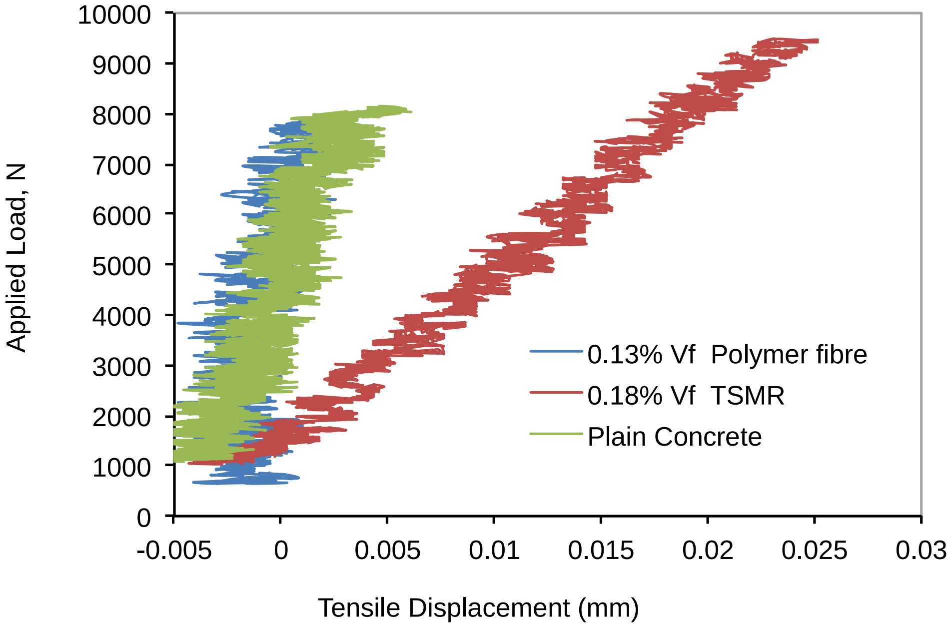


Figure 3. TSMR 5-25 Tensile Stress Strain (5)

2.5 Post Crack Strength

While TSMR post crack strength is typically measured using direct tension testing, it has been evaluated under the ASTM C1609 test standard by third party laboratories to evaluate its post crack resistance in a fully cracked/failed condition, specifically, the Re3 parameter. Table 5 shows the results of the testing. Unlike steel and polymer fibre products, TSMR is optimized for proactive/pre-crack properties and post crack direct tension up to a 1 mm crack width, not optimized for post crack residual flexural strength up to 3 mm crack width (Re3).

2.5 Fatigue Life

Additional economy may be possible by studying the fatigue life of the TSMR. It has been shown that steel fibres can increase the number of cycles to failure over plain concrete in fatigue testing (7). The effect of fatigue resistance is not considered in this study.

3.0 REVIEW OF PAVEMENT DESIGN METHODS

There are three basic methods of slab and pavement design approaches: Elastic design, Yield Line Design, and Empirical Design. Table 1 summarizes several common pavement design methods used in the US and Australia,

Design Method	**Type**	**Key Inputs**
PCA Method	Mechanistic	Loads, MOR, Subgrade Modulus
AIRPAVE12	Mechanistic /Empirical	Loads, MOR, MOE, Subgrade Modulus, Stress Ratio
STREETPAVE12	Mechanistic /Empirical	Loads, MOR, MOE, Subgrade Modulus, Traffic, Re3, Reliability factors
AASHTO 1993	Empirical	Loads, MOR, MOE, Subgrade Modulus, Traffic, Reliability factors

Table 1. Slab and Pavement Design Methods (8)

3.1 PCA Method

The Portland Cement Association Method (PCA) is the simplest, physics based (mechanistic), approach available. It simply considers the MOR of the concrete in an elastic analysis of the slab supported on elastic soil. The thickness of the slab is computed based on a linear stress analysis based on point loads or uniform loads applied with a factor of safety. Its simplicity is its advantage. The disadvantage to this approach is it is not able to analyze traffic and fatigue effects.

3.2 AirPave12

AirPave 12 employs a stress/fatigue based model developed by the American Concrete Paving Association (APCA). The AirPave software allows the user to input MOR, MOE, and Desired Stress Ratio. It uses point loads to compute stress ratio (9). If the stress ratio is below 0.5 then the pavement is considered not to have a fatigue limit state. While it was originally developed for runway pavement design it has load profiles that can be used to assess truck or point load traffic. The advantage of the approach is, like the PCA approach, its simple and it does add some features to allow assessment of fatigue life but is still primarily basing design of static loads, not traffic patterns.

3.3 StreetPave12

StreetPave12 employs a stress/fatigue based model developed by the American Concrete Paving Association (APCA) in 1966 (it is similar to the model employed by AirPave). StreetPave12 software, however, bases design on Traffic Patterns and includes a factor for macro fibre reinforced concrete (8). The main advantage of StreetPave 12 is that it includes advanced features for considering traffic patterns as well as the effect of fibres that provide resistance after the concrete has cracked (tradition steel and polymer fibres).

3.4 AASHTO 1993

The ASHTO 1993 is a purely empirical method developed based on 368 and 468 experimental pavement sections tested between 1958 and 1960 (8). Inputs include input MOR, MOE, reliability factors and traffic factors. This method will not be evaluated in this study given its highly empirical basis.

4.0 PARAMETIC STUDY – MAIN ARTERIAL ROAD (StreetPave 12)

A parametric study was undertaken to study the effect of key performance indicators that TSMR affects: MOR, MOE and Re3.

4.1 Study Parameters

The baseline pavement design criteria considered in the SteetPave12 parametric study are shown in table 2.

Parameter	**Baseline Input**
Design Mode	New Pavement Design
Traffic Spectrum	Major Arterial
Trucks Per Day	1000
Traffic Growth Rate	2%
Directional Distribution	50%
Design Lane Distribution	100%
Total Trucks	7,408,745
Terminal Serviceability	2
Reliability	85%
Convert CBR	28.4
Subgrade Modulus	27.15
Cracked	15%

Table 2. StreetPave12 Parametric Study Parameters

Pavement thickness versus TSMR dosage was computed using the relationship between dosage and MOR outlined in section 2.2 and shown in Table 5.

4.2 Results – Thickness Sensitivity Analysis

The results are presented in Figure 4 in graphical form. The baseline, Reduced MOE and Re3 15% curves show the effect of these parameters on pavement thickness as a function of TSMR dosage (which increases the MOR). The Optimized curve includes in addition to the increase in MOR due to dosage, the benefit of the decrease in MOE, fibre and Re3 effect. This curve represents the best case effect of adding TSMR to the mix. The sharp decrease in thickness at low dosage presents a significant opportunity to provide durable pavements with reduced thicknesses with minimal dosages of TSMR without negatively affecting pavement life.

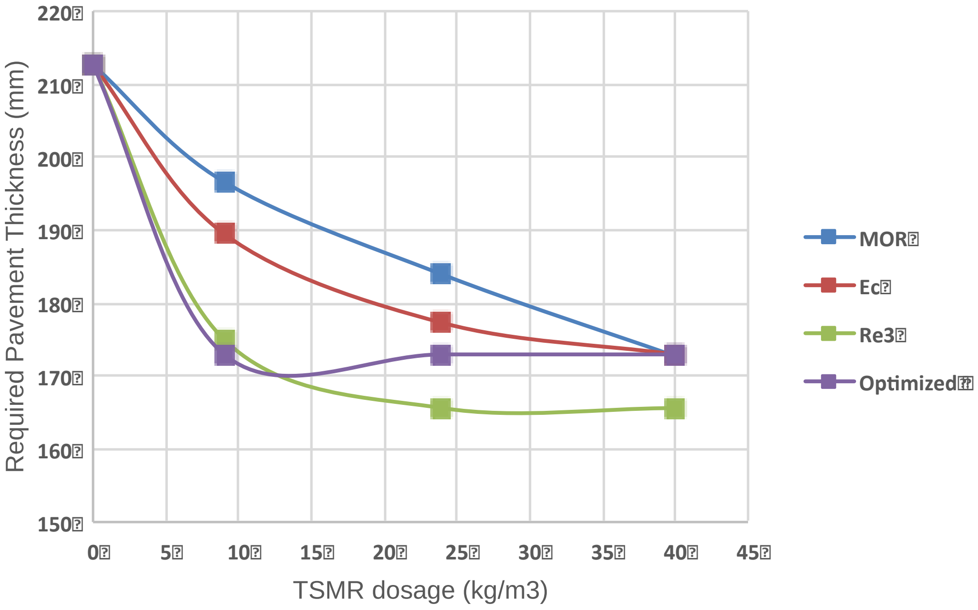


Figure 4. TSMR 5-25 Parametric Analysis

4.3 Results – Value

The value of the resulting solution can be broken into three components: 1) direct labour and material costs, 2) Environmental Impact (measured by CO_2 footprint reduction, using values from c02list.org) and 3) Time Savings (measured by the reduction in the number of 6.5 cubic meter trucks required to pour a 1 km x 10 meter wide road. The direct cost savings is not assessed given variability in local market conditions the savings from the reduction in concrete thickness helps to offset cost of the added TSMR. In addition to this there are positive environmental and efficiency gains of all options regardless of thickness reduction and dosage.

TSMR 5-25 Dosage	TSMR Thickness based on MOR	Concrete Reduced	TSMR Qty	Co_2 Reduction	Truck Reduction
kg/m^3	mm	m^3 / m^2	kg/m^2	kg/km	trucks/km
0	213	0.000	0.000	-	0
9	197	0.016	0.048	31,136	25
24	184	0.029	0.172	54,300	45
40	173	0.040	0.359	73,299	62

Table 3. Value Analysis of TSMR Pavement

5.0 CASE STUDY: MARTIN MARETTA AGGREGATE PAVEMENT (StreetPave 12)

While the parametric analysis above shows significant value and opportunity for thickness reduction, it is necessary to validate approach with field data. TSMR 5-25 was installed in a jointed pavement at the Cayce Martin Marietta Aggregate mine located in Columbia, South Carolina, USA in 2008.

5.1 Original Design

The original construction of this road was a 300 mm thick plain concrete jointed pavement. After two years the 300mm thick pavement was cracked and became in significant disrepair. The owner requested a solution that would last at least 5 years before repairs would be needed.

5.2 Pavement Traffic Requirements

The company estimated that the road receives an average of 165 passes per day of 5 Axle Hauling Trucks (each with an equivalent 3.9 ESAL's per truck) over the last 8 years (Figure 5).

Figure 5. Typical Aggregate Hauling Truck

5.3 TSMR Pavement Design

The design life specified by the owner was 5 years. Load analysis was performed using an elastic model based only on the truck axle load and the subgrade modulus. The resistance and dosage calculation was done using a design approach that used beam tests to assess tensile capacity. This method was ultimately updated to a pure direct tension based design approach with the release of IAPMO Evaluation Report 279 (www.iapmo.org) in 2013. A 150 mm thick pavement was designed using 4000 psi concrete [27.5 MPa] containing 18 kg/m^3 TSMR 5-25. The pavement was constructed on silty/sandy (near a river) soil with modulus of subgrade reaction of 13.5 MPa/m.

5.4 Condition of Pavement after 8 years

The site was surveyed in 2016, 8 years after the installation (Figure 6). There were areas of minor hairline cracking (less than 15% of slab) and no failure at joints. There was some abrasion of the surface in isolated areas (less than 5% of the area).

Figure 6. Pavement Condition after 8 Years

5.5 Analysis of PAVEMENT with StreetPave12

A StreetPave12 (available for download at www.apca.org) analysis was conducted on the pavement using the assumptions below (Table 4).

Parameter	**Baseline Input**
Design Mode	New Pavement Design
Traffic Spectrum	334 Single 50 kN Axles/1000 Trucks 666 Tandem 150 kN Axles/1000 Trucks
Trucks Per Day	175
Traffic Growth Rate	0%
Directional Distribution	100%
Design Lane Distribution	100%
Total Trucks	511,350
Terminal Serviceability	2
Reliability	85%
Convert CBR	28.4
Subgrade Modulus	13.5
Cracked	15%
Re3 (based on 9 kg test)	17%
F’c	28 MPa
MOR with TSMR	4.64 MPa
MOE with TSMR	25,033 MPa

Table 4. StreetPave12 Parameters Martin Marietta Pavement

The program computed a minimum design of thickness of 144.02 mm versus the installed 150 mm thickness of the actual slab. Further the program predicts the life of the pavement will be 10 years (the expectation will be that in 2019 after 10 years the slab will be more than 15% cracked).

By comparison a plain concrete pavement would have needed to be at least 192 mm thick, nearly 50 mm (33%) thicker to reach the same design life, 10 years. The program did not predict the failure that occurred in the 300 mm original pavement.

5.6 ANALYSIS OF PAVEMENT WITH AIRPAVE12

The same parameters used in StreetPave 12 (Table 4) were used along with a 10-ton dual wheel configuration (equal to one set of dual wheels on one axle of truck).

The Airpave results are less conservative, possibly because the analysis focuses only on one wheel pair. The required design thickness with TSMR is 128 mm. At 150 mm the stress ratio 0.36 indicating the 150 mm thick pavement will have unlimited life given the single wheel pair loading. Without TSMR the required pavement thickness is only slightly higher (150 mm).

6.0 RECOMMENDED DESIGN PARAMETERS

Based on prior research and data presented in this paper we recommend the following design parameters (Table 5).

TSMR 5-25 Dosage	Mean Modulus of Rupture (MPa)			Mean Modulus of Elasticity (MPa)			Re3
kg/m^3	f'c =20 MPa	f'c = 28 MPa	f'c = 35 MPa	f'c =20 MPa	f'c = 28 MPa	f'c = 35 MPa	
0	3.34	3.95	4.42	21,019	24,870	27,806	0%
3	3.66	4.23	4.73	21,019	24,870	27,806	0%
6	3.73	4.31	4.82	16,815	19,896	22,244	12%
9	3.8	4.39	4.91				17%
12	3.87	4.47	5				17%
15	3.94	4.55	5.09				17%
18	4.01	4.64	5.18				30%
21	4.09	4.72	5.27				30%
24	4.16	4.8	5.36				30%
27	4.23	4.88	5.46				30%
30	4.3	4.96	5.55				30%
33	4.37	5.04	5.64				30%
40	4.52	5.22	5.84				30%

Table 5. TSMR Properties for Pavements

7.0 CONCLUSIONS

TSMR has been shown in prior works to improve key parameters influencing pavement design. This study evaluated the efficacy of using these improved pre-crack and post-crack properties improved by TSMR in standard models for pavements.

- TSMR provides significant improvements in MOR, Re3 and Splitting Tensile Strength as well as a decrease in modulus of elasticity.
- A Parametric analysis showed pavement thickness, as designed with Street Pave12, significantly decreases with low dosages of TSMR due to the enhances in MOR, MOE and Re3. A maximum of 30% thickness reduction was achieved.
- Reduction in pavement thickness provides potential direct cost savings, carbon footprint reduction and reduction on time and number of trucks needed to complete a job.
- The evaluation showed analysis using StreetPave12 Model with modified TSMR properties (MOR, MOE and Re3) adequately predicted performance.
- The evaluation showed AirPave12 produced less conservative designs possibly because loading was essentially static and the pattern was simplified. While the same parameters (figure 5) may be used for AirPave12, more evaluation is needed

Additional thickness reduction opportunities could be achieved by characterizing the product in fatigue testing.

ACKNOWLEDGEMENT

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