Twisted Steel Micro Reinforcement in Durable Structures

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HELIX STEEL

FORTA
STRONGER LASTING™

ACI Spring Convention 2024

Summary and Learning Objectives

Twisted steel micro reinforcement has been successfully applied by Helix Steel in tens of thousands of structural elements over the last two decades. Design is accomplished with a simple elastic design approach based on a nearly forgotten chapter of ACI 318 for mild structural applications and is supported by ICC-ES criteria and report. We will review projects dating back to 2002 in applications subject to extreme conditions including impact, abrasion, heavy loading and severe weather.

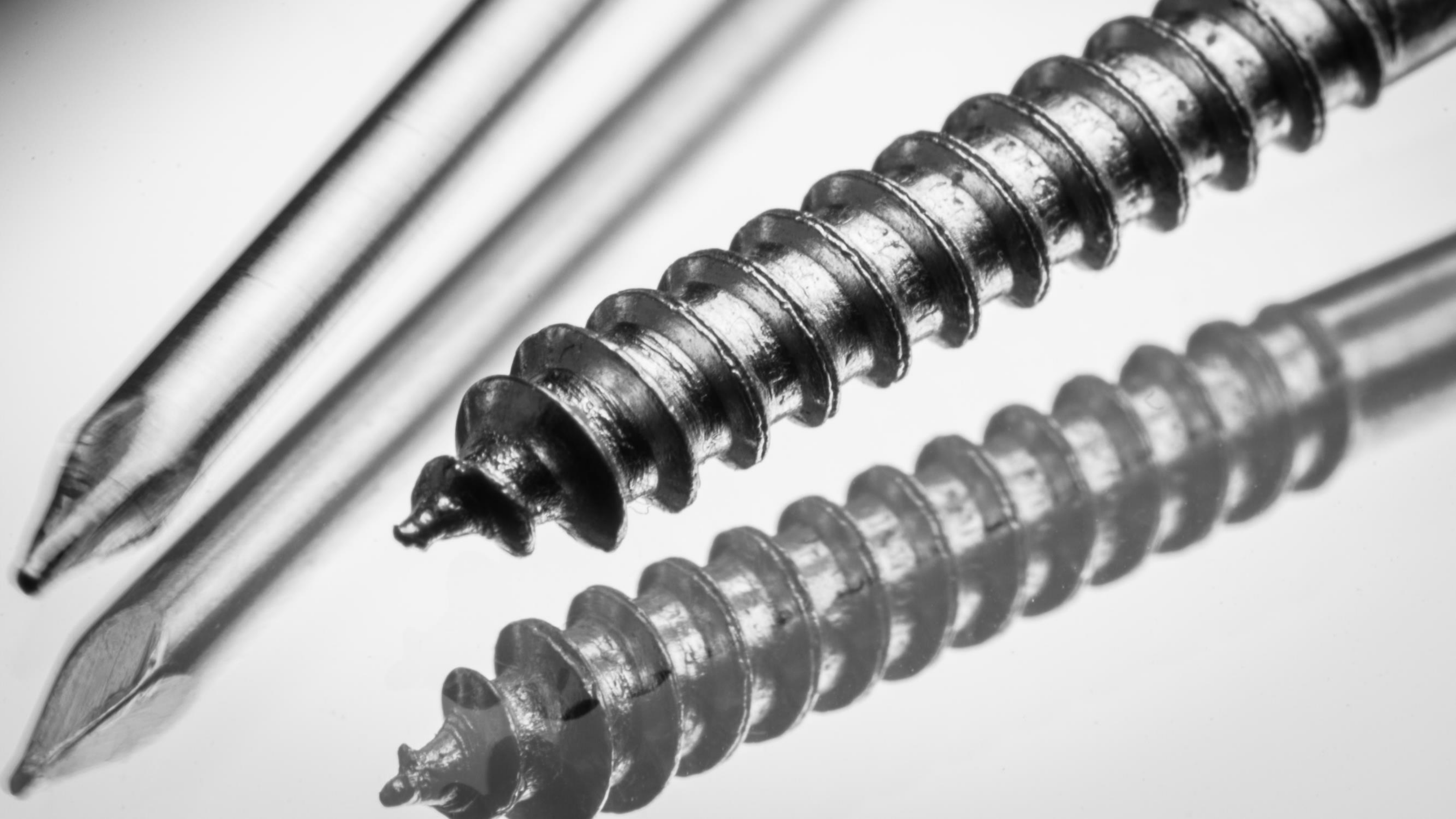
1. Understand the simplicity, utility and limitations of design with twisted steel micro reinforcement
2. Learn how to apply research reports to demonstrate code compliance through IBC/IRC 104.11 and ICC-ES
3. Understand challenges with durability in real word applications
4. Describe the long value in terms term durability in real word applications

Durability ACI CT-23

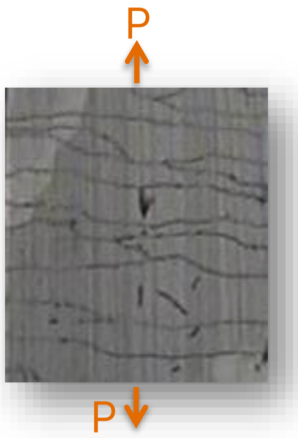
durability	—	the ability of a material to resist weathering action, chemical attack, abrasion, and other conditions of service.
durability factor	—	(1) a measure of the change in a material property over a period of time as a response to exposure to a treatment that can cause deterioration, usually expressed as percentage of the value of the property before exposure; (2) in ASTM C666/C666M, a measure of the effects of freezing-and-thawing action on concrete specimens.

Durable Structures

- Twisted Steel Micro Reinforcement Introduction
- Weathering Action –Jetty
- Chemical Attack & Freeze Thaw – Bridge Deck
- Abrasion – Warehouse Slab
- Other Conditions of Service
  - Impact – Exterior Pavements
  - Hurricane/Tornado – Residential Walls
  - Vehicle Loads – Roads
- Conclusion

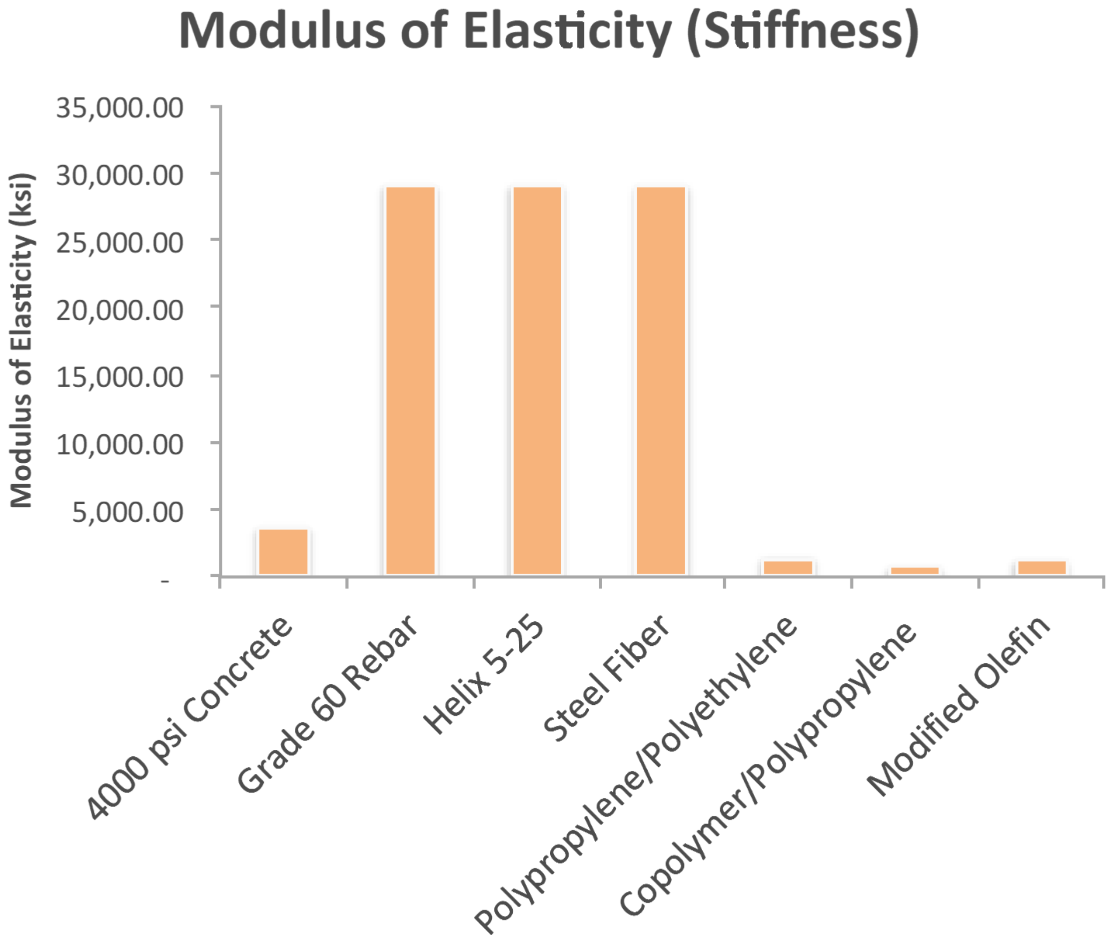


Stiff/Strong Bond
High Modulus



Load redistribution and micro cracking

Proactive



Weak Bond
Low Modulus

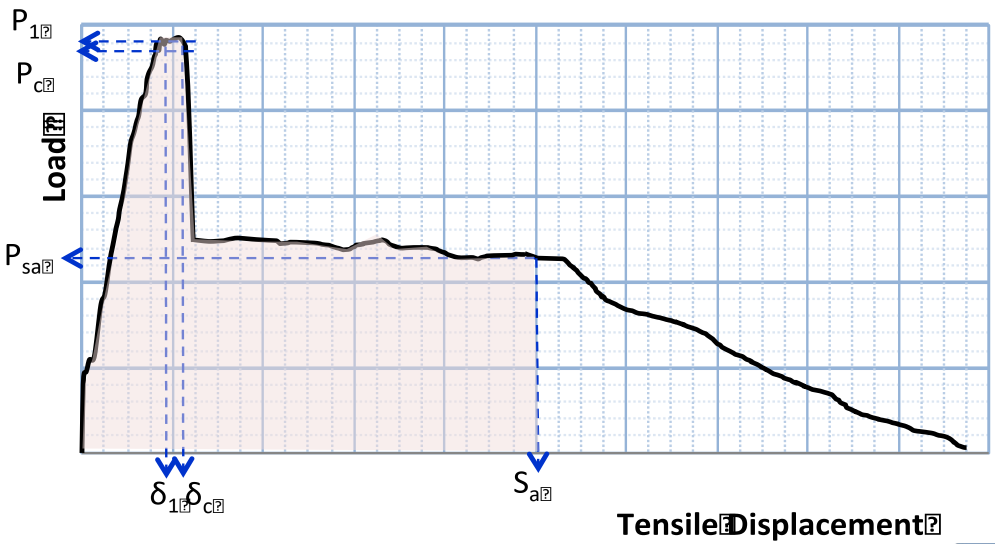
Dominant Crack and Localization

Reactive

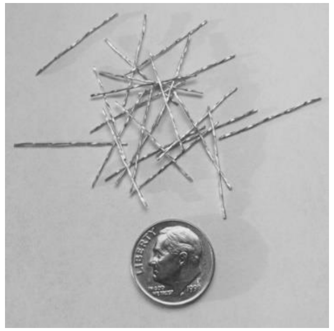
Helix Durability

<u>Helix Durability™</u>

Helix Micro Rebar provides resistance before and after crack formation, therefore it takes more energy for a visible crack to form. Essentially the amount of energy needed to form a 1 mm crack, Helix Durability™ is the area under the direct tension load displacement curve up to 0.04 in [1 mm]. For plain and reinforced concrete, this energy is limited by the point of fracture because concrete has no tensile capacity after crack formation and must crack before rebar begins working. Helix is taken from direct tension testing in accordance with IAPMO-ES EC-015

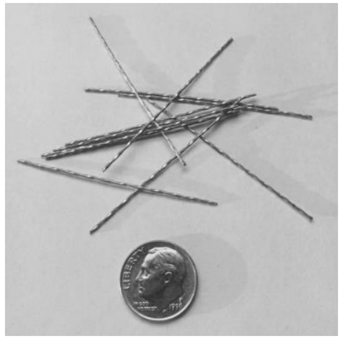


HELIX® 5-25 MICRO REBAR

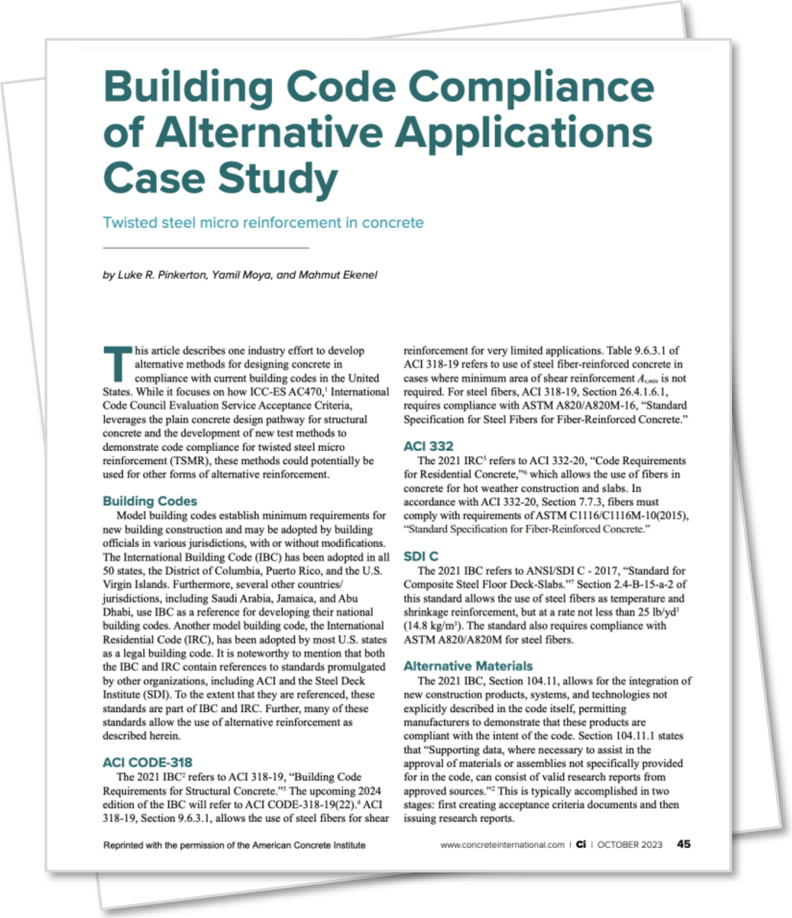


- Steel wire tensile strength: 270 ksi
- 1-inch long × 0.020-inch diameter
- 800 million square feet, 15+ years in structural concrete
- ICC-ES, IAPMO-ES and UL Listed

HELIX® 8-52 MICRO REBAR



- Steel wire tensile strength: 270 ksi
- 2-inch long × 0.030-inch diameter
- Optimized for maximum L/150 performance
- More than 2 miles tunneling NY MTA
- General Motors "GM-1" Spec



Building Code Compliance of Alternative Applications Case Study

Twisted steel micro reinforcement in concrete

by Luke R. Pinkerton, Yamil Moya, and Mahmut Ekenel

This article describes one industry effort to develop alternative methods for designing concrete in compliance with current building codes in the United States. While it focuses on how ICC-ES AC470,[1] International Code Council Evaluation Service Acceptance Criteria, leverages the plain concrete design pathway for structural concrete and the development of new test methods to demonstrate code compliance for twisted steel micro reinforcement (TSMR), these methods could potentially be used for other forms of alternative reinforcement.

Building Codes

Model building codes establish minimum requirements for new building construction and may be adopted by building officials in various jurisdictions, with or without modifications. The International Building Code (IBC) has been adopted in all 50 states, the District of Columbia, Puerto Rico, and the U.S. Virgin Islands. Furthermore, several other countries/jurisdictions, including Saudi Arabia, Jamaica, and Abu Dhabi, use IBC as a reference for developing their national building codes. Another model building code, the International Residential Code (IRC), has been adopted by most U.S. states as a legal building code. It is noteworthy to mention that both the IBC and IRC contain references to standards promulgated by other organizations, including ACI and the Steel Deck Institute (SDI). To the extent that they are referenced, these standards are part of IBC and IRC. Further, many of these standards allow the use of alternative reinforcement as described herein.

ACI CODE-318

The 2021 IBC[2] refers to ACI 318-19, "Building Code Requirements for Structural Concrete."[3] The upcoming 2024 edition of the IBC will refer to ACI CODE-318-19(22).[4] ACI 318-19, Section 9.6.3.1, allows the use of steel fibers for shear reinforcement for very limited applications. Table 9.6.3.1 of ACI 318-19 refers to use of steel fiber-reinforced concrete in cases where minimum area of shear reinforcement $A_{v,min}$ is not required. For steel fibers, ACI 318-19, Section 26.4.1.6.1, requires compliance with ASTM A820/A820M-16, "Standard Specification for Steel Fibers for Fiber-Reinforced Concrete."

ACI 332

The 2021 IRC[5] refers to ACI 332-20, "Code Requirements for Residential Concrete,"[6] which allows the use of fibers in concrete for hot weather construction and slabs. In accordance with ACI 332-20, Section 7.7.3, fibers must comply with requirements of ASTM C1116/C1116M-10(2015), "Standard Specification for Fiber-Reinforced Concrete."

SDI C

The 2021 IBC refers to ANSI/SDI C - 2017, "Standard for Composite Steel Floor Deck-Slabs."[7] Section 2.4-B-15-a-2 of this standard allows the use of steel fibers as temperature and shrinkage reinforcement, but at a rate not less than 25 lb/yd^3 (14.8 kg/m^3). The standard also requires compliance with ASTM A820/A820M for steel fibers.

Alternative Materials

The 2021 IBC, Section 104.11, allows for the integration of new construction products, systems, and technologies not explicitly described in the code itself, permitting manufacturers to demonstrate that these products are compliant with the intent of the code. Section 104.11.1 states that "Supporting data, where necessary to assist in the approval of materials or assemblies not specifically provided for in the code, can consist of valid research reports from approved sources."[2] This is typically accomplished in two stages: first creating acceptance criteria documents and then issuing research reports.

aci CONCRETE CONVENTION

Weathering

STATE OF MICHIGAN
DEPARTMENT OF TRANSPORTATION
LANSING

JENNIFER M. GRANHOLM
GOVERNOR

GLORIA J. JEFF
DIRECTOR

October 20, 2005

Michigan Department of Transportation
John Staton, P.E.
Manager of New Materials

Corrosion test results – Helix

A corrosion resistance evaluation was conducted to qualify the fiber's resist the aggressive attach from deicer salts. A representative sample of the fracture concrete specimens was subjected to continuous submersion in three percent sodium chloride solution for 90 days. The intent of this protocol is similar in concept to the qualitative evaluation by visual examination described in ASTM C 672, Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals, and AASTHO T259, Resistance of Concrete to Chloride Ion Penetration. The difference, however was that our visual examination focused on corrosion and section loss of the steel fibers, rather than the integrity of the concrete mortar matrix. At the conclusion to the evaluation period, it was observed that oxidation deposits were present on the exposed surfaces; however, there were no visual indication of section loss.

ACI 544.4R-88
(Reapproved 1999)

2.8-Abrasion/cavitation/erosion resistance

Both laboratory tests and full-scale field trials have shown that SFRC has high resistance to cavitation forces resulting from high-velocity water flow and the damage caused by the impact of large waterborne debris at high velocity (Schrader and Munch 1976a; Houghton et al. 1978; ICOLD 1982). Even greater cavitation resistance is reported for steel fiber concrete impregnated with a polymer (Houghton et al. 1978).


CAT

Chemical Attack & Freeze Thaw

Freeze-Thaw Durability - ASTM: C666, Method A
(Helix 5-25@ 9 lbs/yd^3, Restated from ESP010579.4)

Specimen Type:	Fiber	Fiber	Fiber
Mix Number:	3	3	3
Moist Cured, days:	27	27	27
Age of Specimen at Test Start, days:	28	28	28
Fundamental Transverse Frequency at 0 Cycles, kHz:	920	890	890
Fundamental Transverse Frequency After 300 Cycles, kHz:	830	860	810
Durability Factor:	81.4	93.4	82.8
Weight Loss:	1.5%	1.7%	1.2%

Freeze-Thaw Durability - ASTM:C666, Method A (Helix 5-25@ 60 lbs/yd^3)

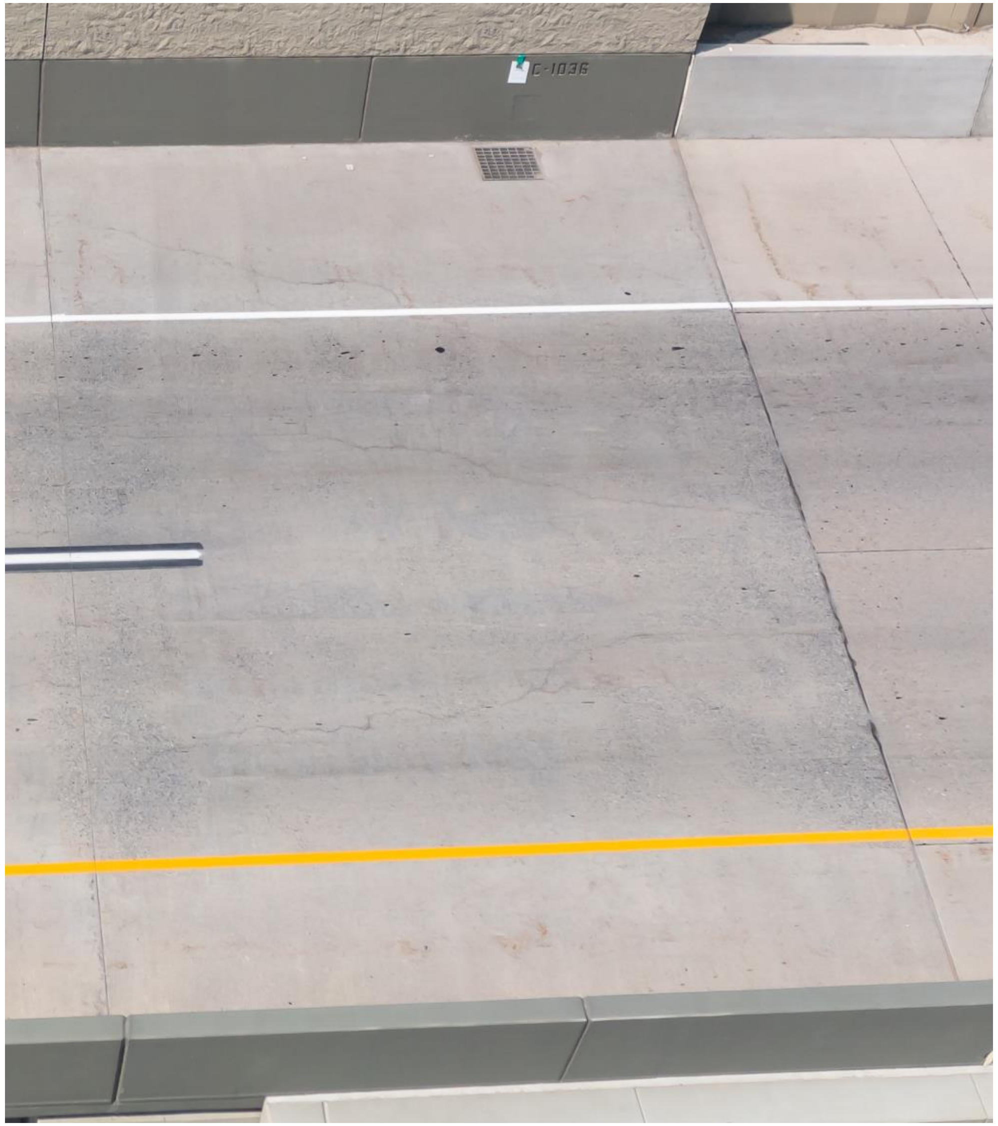
Specimen Type:	Fiber	Fiber	Fiber
Mix Number:	3	3	3
Age of Specimen at Test Start, days:	28	28	28
Fundamental Transverse Frequency at 0 Cycles, Hz:	1923	1965	1984
Fundamental Transverse Frequency After 300 Cycles, Hz:	1745	1867	1725
Durability Factor:	90.7	95.0	86.9
Weight Loss:	0.9%	0.8%	1.1%

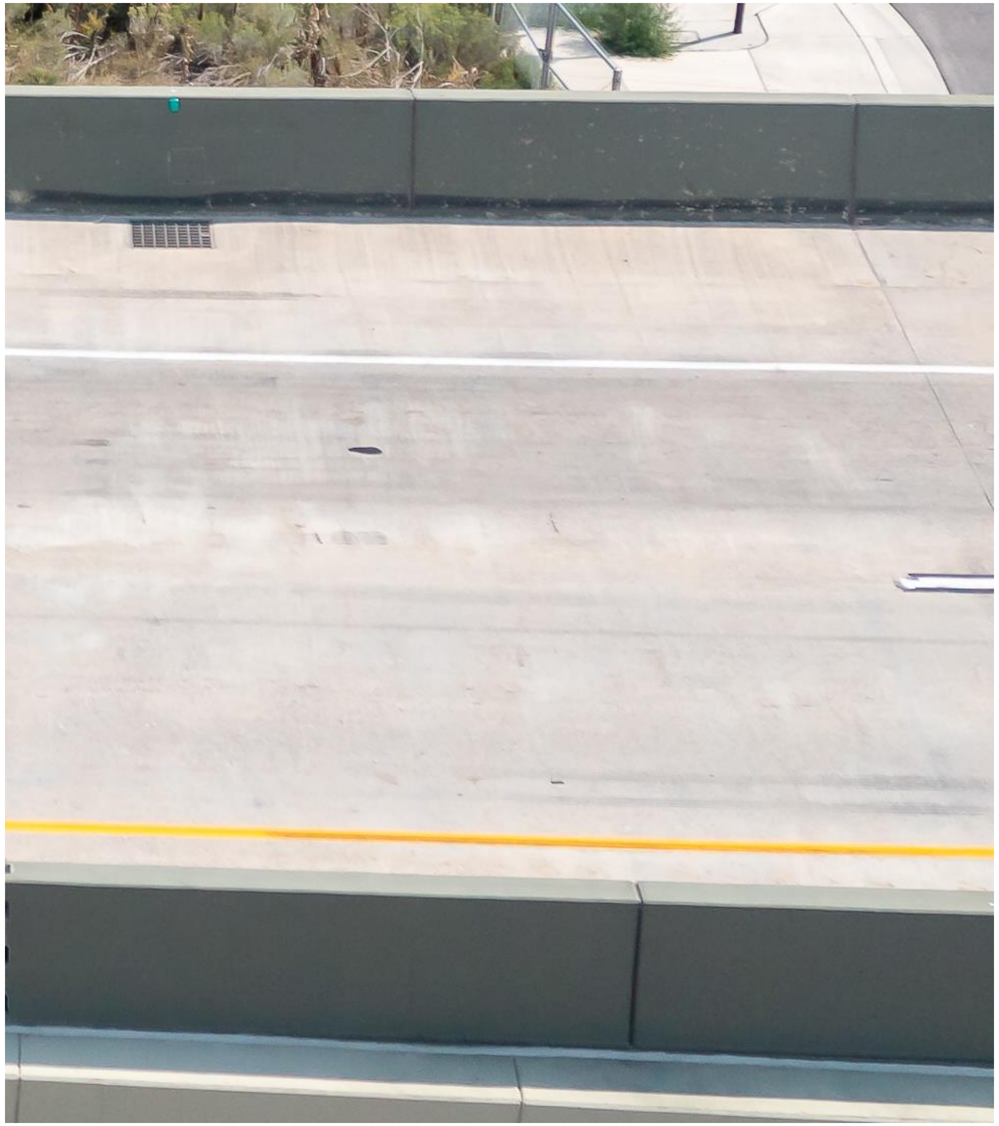
Helix 9 lb/yd
Average Durability Factor: 86

Helix 60 lb/yd
Average Durability Factor: 91

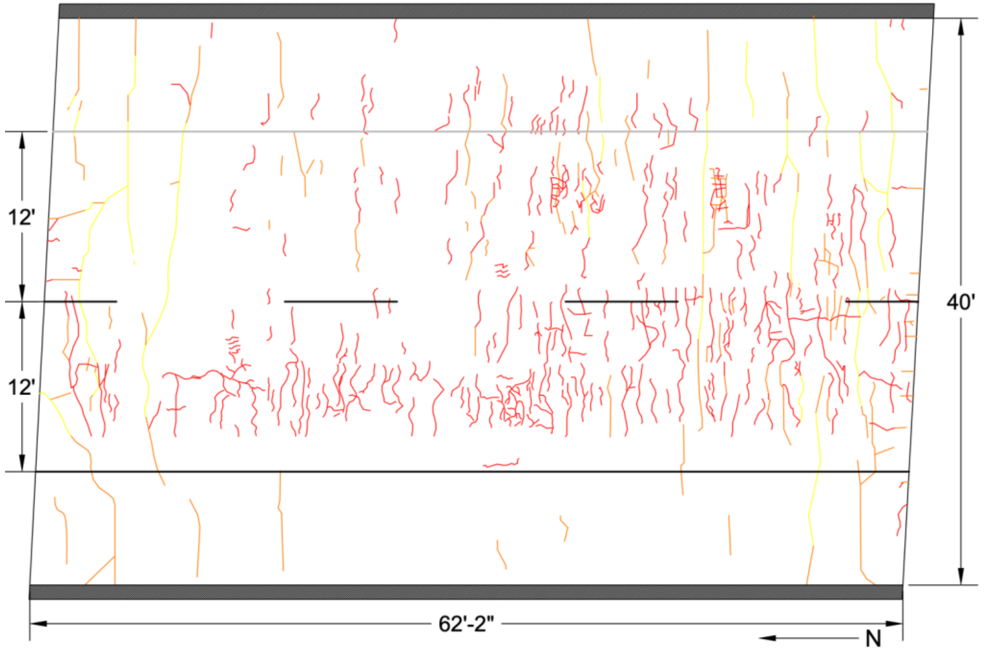
ICC AC 208 / AC 470 Criteria
Target: 80

Conventional vs Helix

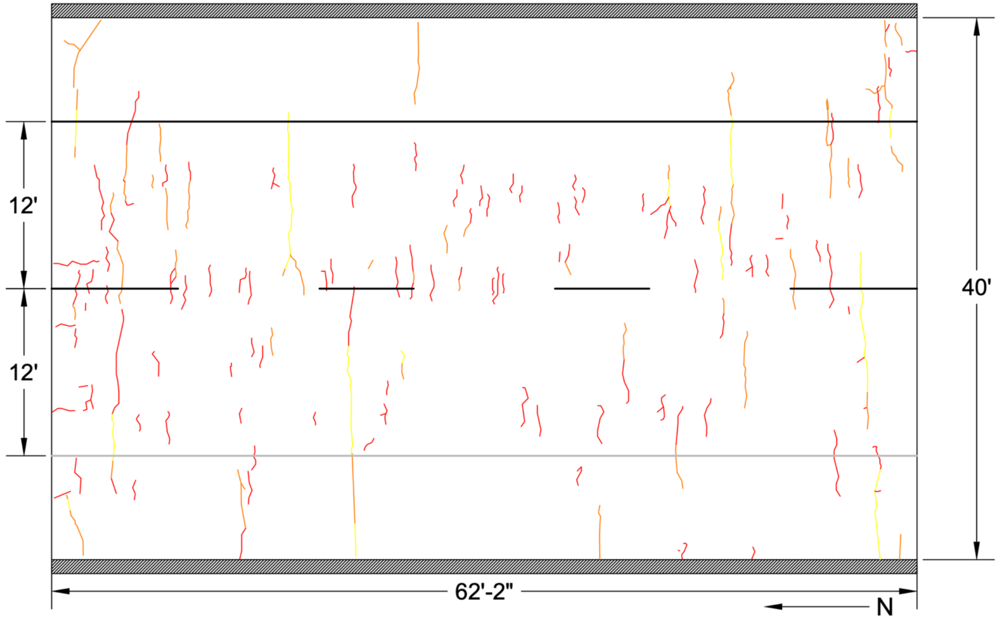




Conventional Design



40 lb/yd Helix



2020 Intermountain Engineering, Technology and Computing (IETC)

Mitigation of Cracking in Concrete Bridge Decks Using Twisted Steel Micro-Rebar

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***Abstract*— The objective of this research was to investigate the effects of twisted steel micro-rebar (TSMR) fibers on the early cracking behavior of concrete bridge decks. The methodology for this research involved the evaluation of four newly constructed bridge decks, two that were constructed using conventional concrete and two that were constructed using TSMR. At bridge deck ages of 3 months, 1 year, and 2 years, the extent and severity of any deck surface cracking was documented in terms of crack lengths and widths, respectively. The data were used to create crack maps, and crack density was calculated for each bridge deck. Bridge decks containing TSMR exhibited notably reduced cracking when compared to the conventional decks. The bridge decks containing TSMR also exhibited the ability to limit the expansion of existing cracks. The significant decrease in the amount of cracks and reduced crack widths indicate that the TSMR fibers were successful in mitigating bridge deck cracking.**

Keywords—concrete bridge deck, corrosion, cracking, steel fibers, twisted steel micro-rebar

I. Introduction and Background

Design of durable concrete has become an increasingly important engineering objective as the need for sustainable infrastructure has become more prominent [1]. More than 235,000 bridges in the United States are constructed with conventional reinforced concrete, and most of these were built with the intention of providing only a 50-year lifespan [2]. The majority of bridges, however, experience some degree of deterioration before the intended service life is complete. Such deterioration can be caused by a variety of mechanisms, such as concrete shrinkage and degradation, fluctuating temperatures, settlement, overloading, and creep [3, 4]. Corrosion of the reinforcing steel, however, is often cited as the leading cause of premature bridge deck deterioration [5]. Of the $90.9 billion that is needed to rehabilitate and repair structurally deficient bridges, as estimated by the United State Department of Transportation, approximately 40 percent of the backlog is directly attributable to corrosion of reinforcing steel in concrete bridge decks [6].

Corrosion products can be up to 10 times larger in volume than the original steel, thereby causing internal pressures that may exceed the tensile strength of the concrete [1, 4]. If the tensile strength is exceeded, more cracks are formed, and a repetitive cycle begins as the new cracks allow the penetration of more corrosive agents into the deck [7]. During this process, the reinforcing steel loses some of its cross-sectional area, further compromising the structural integrity of the bridge deck. Therefore, the service life of a bridge deck is largely associated with the time required for chlorides to penetrate the concrete to the depth of the reinforcing steel [8, 9, 10]. This process is accelerated as cracks form in the concrete, providing a direct path for chlorides to reach the reinforcing steel [4, 11]. Cracks can form very early after construction and often appear even before a bridge deck is open to normal trafficking [12]. With time, these cracks propagate and widen, creating a direct path for corrosive agents to penetrate the deck. Efforts to mitigate concrete cracking have been made as early as the 1960s, yet to date concrete cracking continues to reduce the service life of bridge decks [12].

Many methods to reduce concrete cracking have been implemented over the past 50 years, including the use of shrinkage-reducing admixtures, internal curing agents [13], selected aggregates, and fiber additives. While many types of fiber additives exist, the use of steel fibers in a concrete matrix has become a common solution to mitigate cracking. Steel fibers enhance the post-cracking behavior of a structure by bridging across a crack, thereby minimizing the expansion of an existing crack. The effectiveness of such fibers, however, depends on the ability of the fiber to bond with the surrounding concrete matrix [14, 15, 16]. Despite efforts to create a fiber with increased anchorage in the concrete, no such fiber has proven effective to mitigate cracking enough to significantly extend the service life of bridge decks.

Twisted steel micro-rebar (TSMR), shown in Fig. 1, is a recently introduced steel fiber admixture that has already been used in several applications worldwide. In theory, TSMR fibers, which are shaped with a minimum of a 360-degree twist, should provide the needed bond between the fiber and the concrete matrix to stop cracks even before they become visible [17]. The unique properties of TSMR could have substantial benefits for not only crack mitigation, but also for improvement of basic mechanical properties of bridge decks. While the use of TSMR in concrete bridge decks could significantly improve the behavior of the decks, thereby leading to an increased lifespan, physical data have not yet been published regarding these fibers in bridge decks.

The Utah Department of Transportation funded this research.

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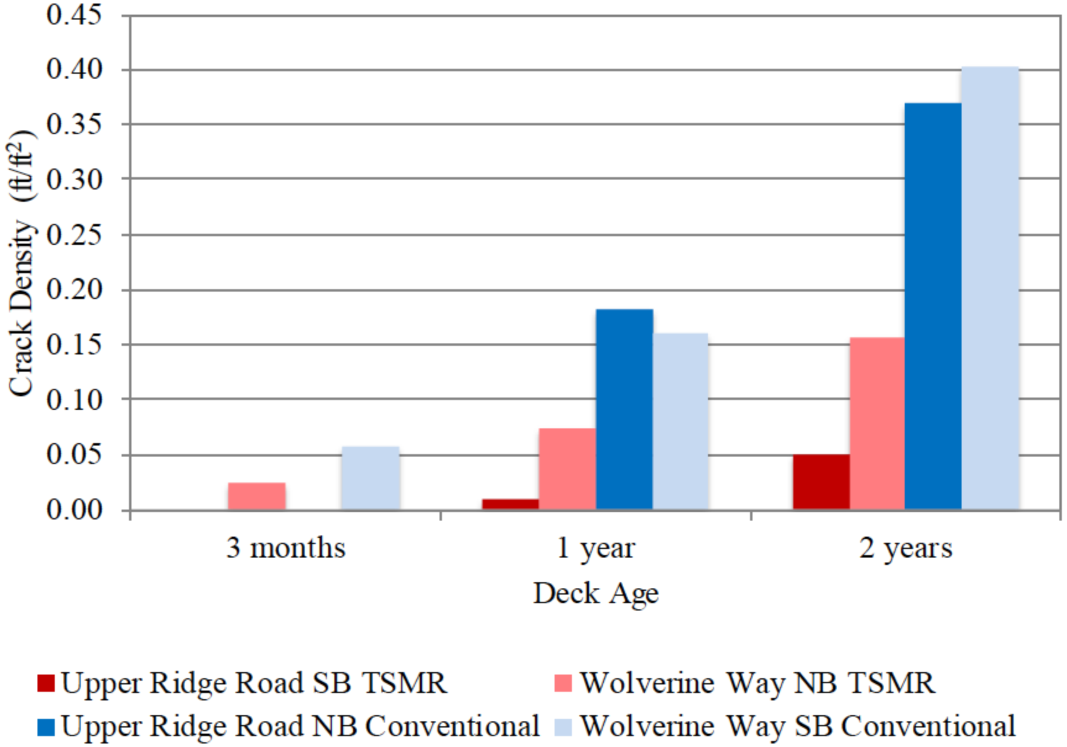


“the use of TSMR in concrete bridge decks is recommended to provide additional protection against cracking and reduce the occurrence of larger cracks”


SPEED LIMIT
5
CAT

Abrasion

Chaplin
Abrasion tester
BS8204

Chaplin Abrasion Wear Rating Chart				
Wear Class	**Degree of Wear Resistance**	**Maximum Wear Depth**	**Typical Use**	**Traffic**
Special	Extremely High	0.055 mm	Very Heavy Duty Factories	Heavily Loaded Steel Tires, Impact, Dragged Loads
AR1	Very High	0.100 mm	Heavy Duty Factories and Warehouses	Steel Tires, Impact
AR2	High	0.200 mm	Medium Duty Factories and Warehouses	Lightly Loaded Steel tires, and hard Plastic tires
AR#	Good	0.400 mm	Light Duty Factories and Warehouses	Rubber Tires

Impact and Fatigue

ACI 360R-10

Table 5.3—Stress ratio versus allowable load repetitions (Portland Cement Association 1984)*

Stress ratio	Allowable load repetitions	Stress ratio	Allowable load repetitions
<0.45	Unlimited	0.73	832
0.45	62,790,761	0.74	630
0.46	14,335,236	0.75	477
0.47	5,202,474	0.76	361
0.48	2,402,754	0.77	274
0.49	1,286,914	0.78	207
0.50	762,043	0.79	157
0.51	485,184	0.80	119
0.52	326,334	0.81	90
0.53	229,127	0.82	68
0.54	166,533	0.83	52
0.55	124,523	0.84	39
0.56	94,065	0.85	30
0.57	71,229	0.86	22
0.58	53,937	0.87	17
0.59	40,842	0.88	13
0.60	30,927	0.89	10
0.61	23,419	0.90	7
0.62	17,733	0.91	6
0.63	13,428	0.92	4
0.64	10,168	0.93	3
0.65	7700	0.94	2
0.66	5830	0.95	2
0.67	4415	0.96	1
0.68	3343	0.97	1
0.69	2532	0.98	1
0.70	1917	0.99	1
0.71	1452	1.00	0
0.72	1099	>1.00	0

<u>**Fracture Toughness**</u>

Fracture toughness describes the ability of a material containing a crack to resist fracture (ACI 446.1R-91) and is determined with Equation 2. Helix Micro Rebar typically increases Fracture Toughness as dosage increases Higher fracture toughness means that the material has better ability to contain or limit cracking thereby providing increased resistance to fracture.

$$2 \times f_r\sqrt{3G} \qquad \text{(Equation 2)}$$

Where

f_r is the modulus of rupture (flexural strength),

G is the average particle size assumed to be 1 inch (25 mm).

AHRENS COMPANIES

September 30, 2014

RE: Sun Recycling Centers

To Whom It Concerns:

We began working with Helix on our Sun Recycling projects in 2011. We have poured multiple projects for Sun Recycling using Helix reinforcement which is well over 500,000 sf of surface. The heavy-duty slabs are designed to handle very heavy repeat traffic and loads including HS-20 trucks and wheel loaders.

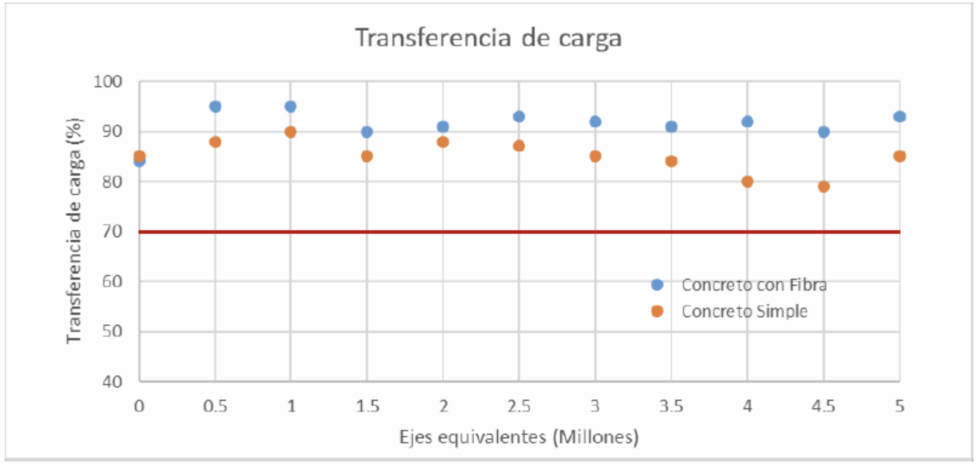
The project pours went well and all parties are happy with the results. The slabs have performed exactly as designed.

Please contact me by email if you would like any further information.
rahrens@ahrenscompanies.com

Sincerely
Ahrens Companies

Richard Ahrens
CEO

Repetitive Vehicle Loads



5 Millions ESALS
180mm W/ Helix vs
250mm


0100113


THERMO KING
ISUZU

Hurricane and Tornado Impact


ADELPHI AV

Conclusion

Application	Date	Challenge	Helix Durability	Study/Test
Jetty	2019	Weathering	131%	MDOT - Corrosion
Bridge Deck	2017	Chemical / Freeze Thaw	33%	UDOT - BYU
Low Water Crossing	2019	Chemical / Freeze Thaw	80%	ASTM C666
Warehouse Slab	2022	Abrasion	46%	BS 8204
Recycling Center	2011	Impact	46%	ASTM C78
Highway	2020	Vehicle Repetition	10%	IMT Study
Residential Walls	2007	Extreme Weather	17%	Texas Tech Study

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Backup Slides

amazon

HONDA

Coca-Cola

ABInBev

UNITED STATES ARMY CORPS OF ENGINEERS

gm

Exxon

Kiewit

DTE

ConocoPhillips

JOHN DEERE

RIVIAN

FedEx Ground

JMU JAMES MADISON UNIVERSITY

TVA TENNESSEE VALLEY AUTHORITY

Microsoft

3M

DETROIT

Panasonic

Habitat for Humanity

Martin Marietta

PELOTON

ABB

THE WORLD'S GATHERING PLACE FOR ADVANCING CONCRETE

aci CONCRETE CONVENTION

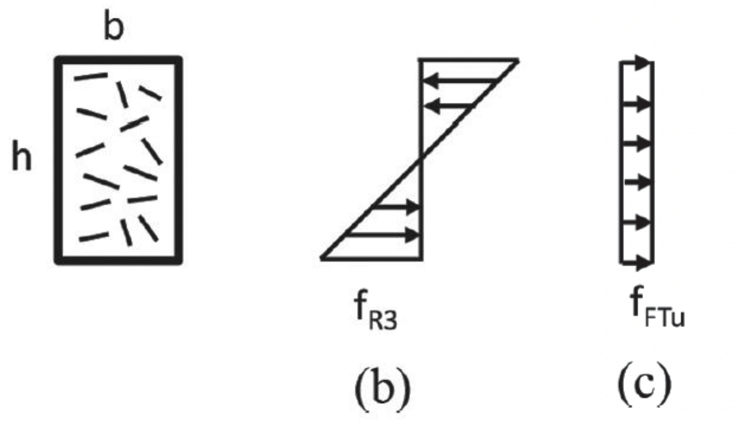
The Standard Approach (Rigid Plastic)

$$M_u = \phi f_{150} S_m$$

- ϕ — Resistance Factor
- f_{150} — Residual Strength Factor
- S_m — Section Modulus: $bh^2/6$

$$f_{150} < \frac{1}{2} R$$

ASTM C1609
Expensive & limited availably test



ACI 544.4R Fig 4.6

An Alternative Approach

Scale Effect Adjustment Factor

Modulus of Rupture

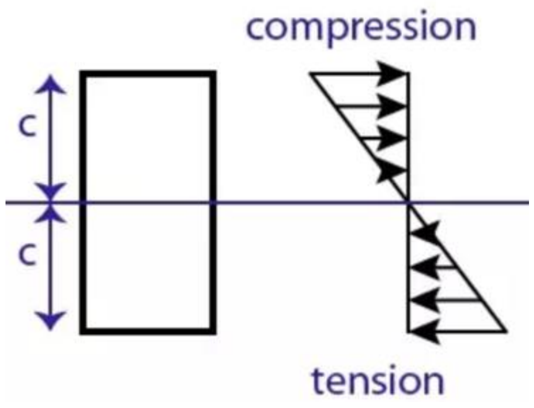
$$M_u = \lambda\ \phi R S_m$$

Resistance Factor

Section Modulus: $bh^2/6$

$$R > 2\ f_{150}$$

ASTM C78
Inexpensive & widely available test



ACI 318 Chapter 14

Research Report (ISO 17065)

<u>Third-Party Assessments</u>

- Modulus of Rupture
- Compressive Strength
- Minimum Residual Strength
- Freeze Thaw Resistance
- Composite Deck Shrinkage
- Factory Quality Control Audit

<u>Application</u>

- Residential
- Footings and Foundations
- Walls
- Slabs

ES ICC EVALUATION SERVICE®

ICC-ES Evaluation Report **ESR-3949**

Reissued September 2021

This report is subject to renewal September 2022.

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DIVISION: 03 00 00—CONCRETE
Section: 03 31 00—Structural Concrete

REPORT HOLDER:

HELIX® STEEL

EVALUATION SUBJECT:

HELIX® 5-25 MICRO REBAR™ & HELIX® 5-25U MICRO REBAR™ REINFORCEMENTS

1.0 EVALUATION SCOPE

Compliance with the following codes:

- 2018 *International Building Code®* (IBC)
- 2018 *International Residential Code®* (IRC)
- 2013 *Abu Dhabi International Building Code* (ADIBC)†

†The ADIBC is based on the 2009 *International Building Code*. 2018 IBC code sections referenced in this report may be considered as equivalent sections under in the ADIBC.

Properties evaluated:

- Durability
- Structural
- Crack control

2.0 USES

Helix® Micro Rebar™ reinforcements (Helix® 5-25 Micro Rebar™ and Helix® 5-25U Micro Rebar™) are used as alternatives to the shrinkage and temperature reinforcement specified in Section 24.4 of ACI 318 for plain concrete footings and for plain concrete slabs (as defined by ACI 360) supported directly on the ground.

Helix® Micro Rebar™ reinforcements are also used to increase the modulus of rupture for the design of structural plain concrete using linear elastic design in applications within the scope of ACI 318 Chapter 14, IBC Section 1906 and ACI 332 Section 8.2.1, IRC Sections R404.1.3 and R608.1, or Tables 8.2.1.3a and 8.2.1.3b of ACI 332.

Helix® Micro Rebar™ reinforcements are also used as an alternative to horizontal temperature and shrinkage reinforcement in structural plain concrete walls as described in IBC Section 1906, IRC Sections R404.1.3 and R608.1, and ACI 332 Sections 8.2.1 and 8.2.7.

Helix® Micro Rebar™ reinforcements also applies to slabs-on-ground applications that are designed in accordance with Chapter 7 or Chapter 11 of ACI 360.

Helix® Micro Rebar™ reinforcements also applies to plain concrete parking lot applications that are designed in accordance with Chapter 3 of ACI 330.

Under the IRC, an engineered design in accordance with IRC Section R301.1.3 must be submitted to the code official for approval, except in the following cases:

1. Below grade walls designed in accordance with the requirements of Table 3 of this report.
2. When Helix 5-25 is used at a dosage rate of 9 lb/yd³ (5.4 kg/m³) to replace temperature and shrinkage reinforcement in footings inSeismic Design Categories A, B and C meeting the requirements of IRC Section R403.1.1.

3.0 DESCRIPTION

Helix® Micro Rebar™ reinforcements are made from minimum 240 ksi (1650 MPa), 0.020 in +/-0.007 in (0.51 mm +/- 0.02 mm) cold drawn steel wire. Each Helix® Micro Rebar™ has a minimum of one 360-degree twist. Helix® Micro Rebar™ reinforcement is used in dosages between 9 lb/yd³ and 34.5 lbs/yd³ (5.4 kg/m³ and 21 kg/m³). Helix® 5-25 is electroplated with zinc; whereas, Helix® 5-25U is uncoated.

3.1 Structural Plain Concrete: Structural normal-weight plain concrete must comply with Section 1906 of the IBC. Concrete design must follow ACI 211.1 and ACI 318 Section 26.12.3.1 with specified compressive strength, f'_c, between 3000 psi and 5000 psi (21 MPa and 35 MPa) [minimum 24 MPa is required under ADIBC Appendix L, Section 5.1.1].

4.0 DESIGN & INSTALLATION

4.1 Type N (Temperature and Shrinkage): Helix® Micro Rebar™ reinforcements are used as an alternative to shrinkage and temperature reinforcement specified in Section 24.4 of ACI 318 for plain concrete footings and for plain concrete slabs (as defined by ACI 360) supported directly on the ground for dosage rates between 9 lb/yd³ and 34.5 lbs/yd³ (5.4 kg/m³ and 21 kg/m³).

4.2 Type S (Linear Elastic Design): Type S applications fall within the scope of ACI 318 Chapter 14, IBC Section 1906 and ACI 332 Section 8.2.1, IRC Sections R404.1.3 and R608.1, or Tables 8.2.1.3a and 8.2.1.3b of ACI 332. Design for flexure in accordance with Section 4 of this report must be limited in capacity by the values presented in Table 1 and Equations 1 or 2, and all designs must be verified to meet the criteria of ACI 318 Section 14.1.3 excluding slabs on grade (e.g. slabs designed per ACI 360 Chapter 7.2.1 PCA method where only flexural capacity is required).

ESR 3949

Plain Concrete

CT 23

Plain concrete is defined by the American Concrete Institute Concrete Terminology (CT-23) as follows:

> ***plain concrete*** — *structural concrete with no reinforcement or with less reinforcement than the minimum amount specified for reinforced concrete in the applicable building code.*

Flexural Strength

CT 23

The American Concrete Institute reports the definition of modulus of rupture in CT 23 as follows. Note that the point of rupture is determined at the maximum applied load.

- ***modulus of rupture*** *- the flexural stress in the extreme tension fiber of a plain concrete beam test specimen calculated from the maximum applied load measured in accordance with a standard test method. (See also flexural strength.)*
- ***flexural strength*** *- the measured maximum resistance of a concrete specimen to flexural loading and reported as modulus of rupture. (See also modulus of rupture.)*

Slag Cement (ACI 223R-17)

The American Concrete Institute Committee on Slag Cement reports that use of slag cement generally yields higher modulus of rupture at ages beyond 7 days. The report suggests the reason for this increase is increased density of the paste and improved bon strength at the aggregate-paste interface.

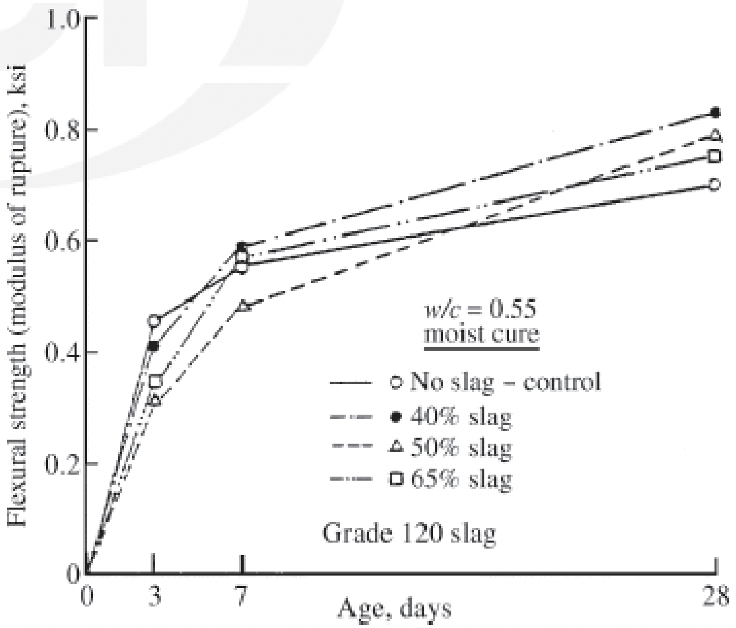

Fig. 7.2—Flexural strength (modulus of rupture) of concrete containing various blends of slag cement, compared with concrete using only portland cement as cementitious material (Hogan and Meusel 1981). (Note: 1 ksi = 6.89 MPa.)

Steel Fiber Reinforced Concrete (ACI 544.4R-88)

Reapproved in 2009 but superseded in 2018

The American Concrete Institute Committee on Fiber Reinforcement 544.4R-88 “ Design Considerations for Steel Fiber Reinforced Concrete” provided equations in section 3.2 for predicting ultimate composite flexural strength based on steel fiber volume fraction in equation 3.1

$$\sigma_{cf} = 0.97\, f_r V_m + 494\, V_f \frac{l}{d_f}$$

(Equation 1)

Where,

V_m =volume fraction of matrix

V_f = volume fraction of fibers

f_r = modulus of rupture of the plain concrete

l= length of fiber

d_f= diameter of fiber

High Strength Concrete (ACI 363R-10)

The American Concrete Institute Committee on High Strength Concrete reports equations using ratios of compressive strength to flexural strength higher than normal strength concrete with high strength concrete and steam cured concrete.   It further notes the the standard equation in ACI 318 tends to underestimate the modulus of rupture especially at the high end of compressive strength.

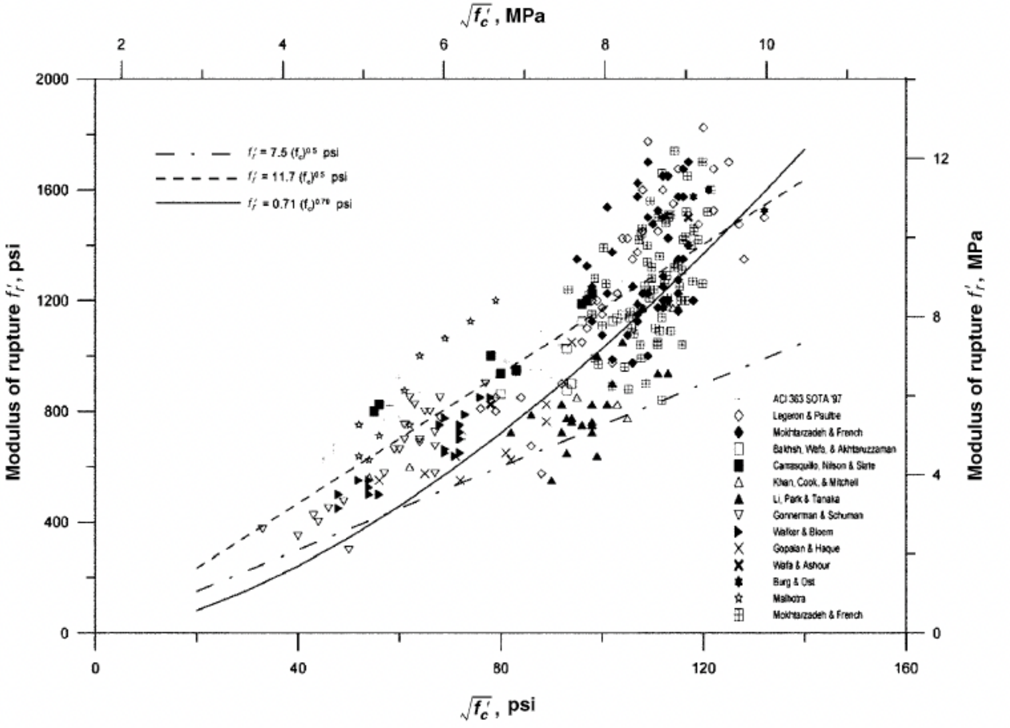

Fig. 6.6—Relationships between modulus of rupture and square root of compressive strength (adapted from Myers and Yang [2004]).

Twisted steel micro reinforcement

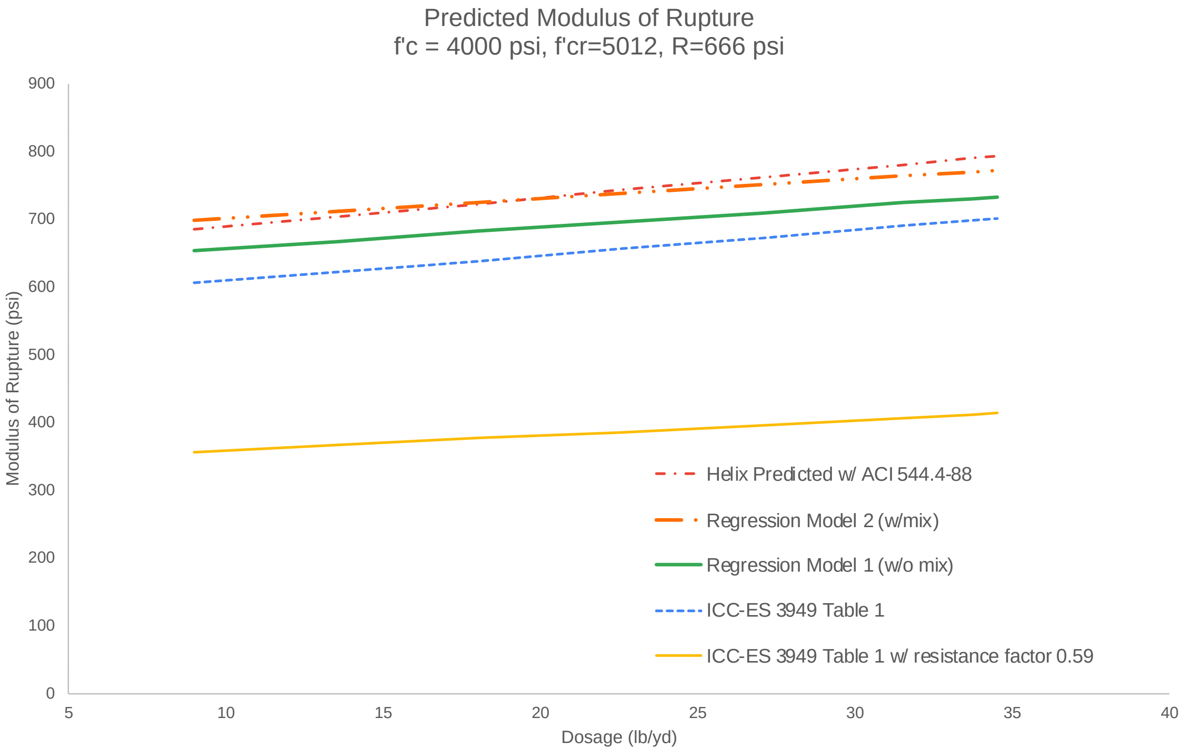

TABLE 1—CALCULATED L_f VALUES[1,2,3,4]

Dosage rate (lbs/yd^3)	Compressive strength (psi)				
	3000	3500	4000	4500	5000
	φ Strength Reduction Factor				
	0.56	0.58	0.59	0.6	0.6
9	8.93	9.25	9.58	9.90	9.90
13.5	9.01	9.43	9.84	10.25	10.25
18.0	9.10	9.60	10.10	10.61	10.61
22.5	9.19	9.78	10.37	10.96	10.96
27.0	9.28	9.96	10.63	11.31	11.31
31.5	9.37	10.13	10.90	11.66	11.66
33.8	9.41	10.22	11.03	11.84	11.84
34.5	9.43	10.25	11.08	11.90	11.90

For **SI**: 1 psi = 0.0069 Mpa. 1 lb/yd^3 = 0.59 kg/m^3.

[1]Interpolation between dosage rates and compressive strengths is permitted. Minimum of 24 Mpa compressive strength is required under ADIBC Appendix L, Section 5.1.1.

[2]Structures assigned to Seismic Design Category D, E or F must be in compliance with Section 14.1.4 of ACI 318, and combined flexure and axial compression must be considered in accordance with Section 14.5.4 of ACI 318.

[3]RDP must calculate project-specific scale-effect factor (Equation 3) and multiple it with Table 1 values.

[4] To convert L_f from psi to Mpa, reported values must be multiplied by 0.083, which is $\sqrt{0.0069}$.

Study involves the use of Historical Data from 21 test programs (272 specimens) conducted at third party laboratories.