# MATERIAL PROPERTIES AND DESIGN CONSIDERATIONS

## MMFX 2 (ASTM A1035/AASHTO MP 18)

### Concrete Reinforcement Steel and Pavement Dowel Bars

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# 1. Product Description

## A. MMFX 2 Concrete Reinforcing Steel

MMFX 2 steel bars are uncoated, corrosion-resistant, high-strength steel-reinforcing products that meet or exceed the mechanical properties of ASTM A615 Grades 75 and 80, ASTM A1035/A1035 M (4. C – Ref. 2), and AASHTO Standard Specification MP 18M/MP 18 (4. C. Ref 3). MMFX 2's material properties (corrosion-resistance and high-strength) result from both its chemical composition and manufacturing process.

Figure 1 - MMFX 2 Steel Plain and Deformed Bar

## B. Material Composition

Conventional carbon steels form a matrix of chemically dissimilar materials – carbide and ferrite. These carbides are strong, yet brittle – immovable at the grain boundaries. In a humid environment, a battery-like effect occurs between the carbides and the ferrites that destroy the steel from the inside out. This effect (a microgalvanic cell) is the primary corrosion initiator that drives the corrosion reaction. MMFX's patented proprietary steel technology forms a matrix that is almost carbide free.

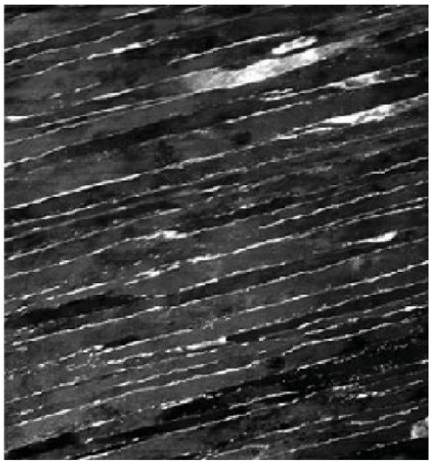

Figure 2. Transmission Electron Microscopy (TEM) photograph of MMFX's patented microstructure

MMFX 2 steel is a low-carbon, chromium alloy steel that is produced as part of a controlled-rolling production process (i.e. rolling steel within a well-defined temperature range and cooled at a specific rate). The combination of MMFX 2 steel's chemical composition and manufacturing production process produces a steel that has a completely different structure at the nano, or atomic, scale (a laminated lath microstructure resembling "plywood" – See Figure 2). Steel made using MMFX nanotechnology minimizes the formation of microgalvanic cells (the driving force behind corrosion). MMFX's "plywood" effect provides superior strength, ductility, toughness, and corrosion resistance.

Most steel exhibits strength at the cost of ductility (or brittleness). Steel that is made using MMFX's proprietary technology is not only stronger and tougher (not brittle), but is also significantly more corrosion-resistant than conventional steel. This technology and material composition has enabled the development of high-strength, cost-effective MMFX steels.

Since MMFX Steel's initial production in 2001, MMFX 2 steel's material composition has remained consistently the same as indicated in Table 1 from numerous commercial heats.

**Table 1 - MMFX 2 (ASTM A1035/AASTHO MP 18) Material Composition**

(Maximum weight percentage of chemical constituents, except where noted * **)

| | C% | Cr% | Mn% | Si% | S% | P% | Cu% | Ni% | Mo% | $N^2$ ppm |
|---|---|---|---|---|---|---|---|---|---|---|
| Average Heat Chemistry | 0.074 | 9.305 | 0.619 | 0.147 | 0.014 | 0.009 | 0.171 | 0.118 | 0.023 | 177.4 |
| ASTM A1035 Certification | 0.15 | 8 to 10.9 * | 1.5 | 0.50 | 0.045 | 0.035 | - | - | - | 500 |
| AASHTO MP 18 Certification | 0.15 | 9.2 ** | 1.5 | 0.50 | 0.030 | 0.045 | - | - | - | 200 |

* Range is given as per ASTM A1035

** Minimum weight is specified as per AASHTO MP 18

## C. Products

MMFX is currently in the North American and Middle East markets with the following concrete reinforcing steel products:

- #3 through #11 standard bar sizes (North American market)
- #14 bar size - special order (North American market)
- 12, 14, 16, 18, 20, 25, 32 mm standard bar sizes (Middle East market)
- 36 and 40mm bar sizes - special order (Middle East market)
- Custom-mill-cut lengths available by special order only in 25, or greater, ton increments
- Available in straight-length-bundle quantities from MMFX
  - ASTM A1035 – Grade 100
  - AASHTO MP 18 – Grade 100

- Available fabricated
  - ASTM A1035 – Grade 100
  - AASHTO MP 18 – Grade 100
- Smooth bar material (used for pavement dowels) available in 1-1/4 and 1-1/2 inch rounds

## 2. Material Properties

### A. Corrosion Resistant

MMFX 2 (ASTM A1035/AASHTO MP 18) rebar's corrosion resistance, in terms of its critical chloride threshold level (CCTL - the quantity of chloride in concrete that initiates corrosion), has been demonstrated to be more than triple the CCTL of ASTM A615 conventional carbon steel bar. Figure 3 is a schematic graphic illustration comparing MMFX steel's corrosion protection in relation to conventional black steel, where $T_i$ is time to corrosion initiation and $T_p$ is time for corrosion propagation to the structure's end of service life. MMFX steel's corrosion resistance means that it takes a significantly longer time for corrosion to start and progress to the extent that requires repair to a structure, than it does for conventional black steel.

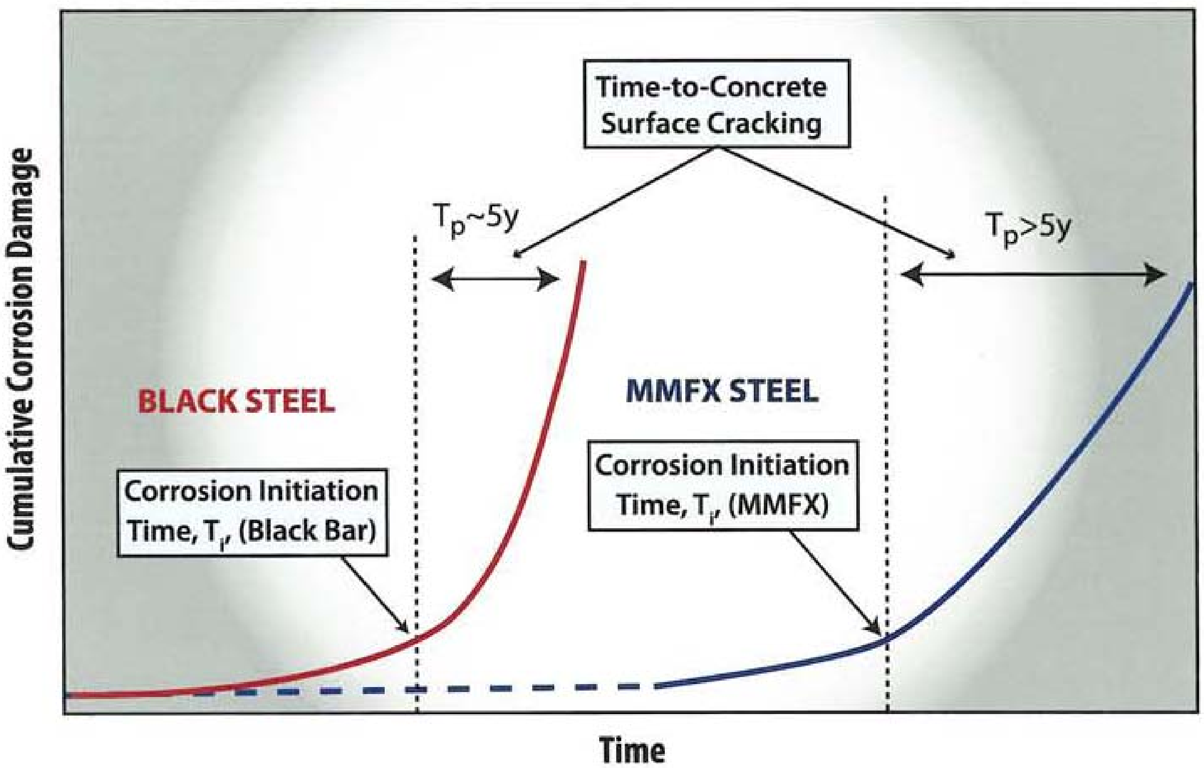


Figure 3 - MMFX 2 Comparative Corrosion Protection

MMFX 2 (ASTM A1035/AASHTO MP 18) steel's corrosion performance has been demonstrated by various test methods with a variety of reinforcing steel surface conditions, as illustrated in Table 2. MMFX 2's corrosion resistance is measured in each of Table 2's testing programs by comparing the test results in relationship to black steel as the basis for measurement. Each test program included both MMFX 2 and black steel, either with or without mill scale. A number of these corrosion performance test programs also incorporated different types of stainless steel bars, with and without mill scale. The table reflects each test result as a ratio of the test's measured corrosion performance value for black steel to the different reinforcing materials that were part of these test programs. For example, 4 A Ref. 15 the "WJE Report" reported a chloride threshold for ASTM A1035 (MMFX 2) of 12.7 lb/cy and black steel of 3.8 lb/cy for a test result ratio of 3.3:1 for MMFX 2 to black steel.

## Table 2 - Measured corrosion performance of MMFX 2 (ASTM A1035/AASHTO MP 18)

| Corrosion Program Test Ref (See "4.A.Corrosion Test Reports") | Basis for corrosion performance measurement as a ratio to ASTM A615 Black Steel base material | Test Time Length | Test Sample Surface Condition | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | "As Received" with mill scale | | | | | | without millscale {"polished"}-[pickled] | | | | | |
| | | | **ASTM A1035** | 3Cr12 SS | 2201 LDXSS | 2205 SS | 304 SS | 316 SS | **ASTM A1035** | 3Cr12 SS | 2201 LDXSS | 2205 SS | 304 SS | 316 SS |
| Ref 3 - ACI Materials Journal106-M22 - Mar/Apr 10 | Chloride Threshold ratio | 24 wks | **3.9** | | | | | | | | | | | [11.7] |
| Ref 5 – NRC Canada Report IRC RR-284 - Sep 09 | Chloride Threshold ratio | 24 mnths | | | | | | | **5 sand blasted** | | | | | [21] |
| Ref 8 - FHWA-HRT-09-020 - May 09 | Chloride Threshold ratio | 6 yrs | **4.8** | | | | | | | [4.4] | [3.6] | | [10.2] | [13.9] |
| Ref 14 - UCB test Report Mar 08 | Corrosion rate (μm/yr) ratio | 1 day | | | | | | | **{0.08}** | | | | | |
| Ref 15 - WJE Report No. 2003.0707.0 - Feb 08 | Chloride Threshold ratio | 232 wks | **3.0** | | | | | | **3.3 sand blasted** | | | | [>5.4] | |
| Ref 18 – Mich. DOT Report R-1499 - Sep 07 | Comparative Corrosion Performance reported (A) | 196 wks | **>A615** | | | | | | | | | | [>A615] | |
| Ref 19 - FHWA-HRT-07-039 - 0 - Jul 07 | Time to active corrosion ratio (B) | 66 wks | **3.3** | | 2.2 | NA | | | | | [2.9] | | | NA |
| Ref 20 - FHWA No. S/CA/RI-2006/27 - Jan 07 | Polarization Resistance (Rp) ratio (C) | 78 wks | | | | | | | **35 machined** | | | | | 73 [clad] |
| Ref 23 - CTRE Project 02-103 - May 06 | Time to corrosion initiation ratio (D) | 31 wks | **6.2** | | | | | | | | | | | |
| Ref 25 - FHWA/NC/2006-31 Dec 05 | Percent wt loss ratio --wet/dry test exposures | 26 wks | **0.24** | | | | | | | | | | | |
| Ref 26 - U of Kansas - SM Report No. 80 - Dec 05 | Southern Exposure Test -- Corrosion rate (μm/yr) ratio | 96 wks | **0.49** | | 1.35 | 0.07 | | | | | [0.53] | [<0.01 ] | | |
| Ref 29 - ACI Materials Journal102-M12 - Mar/Apr 05 | Chloride Threshold ratio to A615 with mill scale | 5 wks | **9.6** | | | | | | **{12.7}** | | | | [10.6] {13.0} | [22.6] {14.5} |
| Ref 32 - VTRC Report 04-R7 - Dec 03 | Time to corrosion ratio | 35 wks | **2.7** | | 1.6 | | | | | | | | [>11. 8] | [>11. 8] |

*Note (A) Program terminated after A615 activated without activation of A1035 samples*

*(B) A615 bar activated at 35 days per test criteria, 2205 SS and 316 SS sample did not activate during program*

*(C) ASTM A1035 machined to size to provide program's 1 ¼" dia. Samples*

*(D) A615 bar activated at 35 days per test criteria*

## Material Service Life

An assessment of MMFX 2 (ASTM A1035/AASHTO MP 18) rebar's corrosion resistance performance is made through the measure of its service life and/or critical chloride threshold level (CCTL), as noted in 4.A *"Corrosion Test Reports."*

- Williamson and Weyers (4.A. ref. 12) indicated that A1035, when used in conjunction with LCP (low-permeability concrete), provides greater than 200 year service life.
- Cui and Krause (4.A. ref 15) noted that A1035 would provide about 2 times the service life and had approximately 3 times the chloride threshold of carbon steel.
- Darwin and Browning (4.A. ref 17) said that corrosion initiation in uncracked bridge decks would take about 3.8 times longer than black steel; and 2.4 times longer than galvanized (zinc coated) rebar. This study replicated some of the findings of Pianca and Schell (4.A. ref 28) concerning galvanized (zinc coated) rebar.
- LaNier and Springston (4.A. ref 27) states that on the US Navy's modular pier project, A1035 saved about $2.8 million over the original proposed design, while providing a 75-yr service life.
- Clemeña and Virmani (4.A. ref 30) reports that A1035's chloride threshold is about 5 to 6 times that of black bar and 2 times that of 2101 LDX bars.

These studies consistently demonstrate MMFX 2's ability to provide long-term corrosion performance and added value to structures in corrosive environments.

## B. High-Strength

MMFX 2 (ASTM A1035) steel rebar is produced in two grades, which are certified as indicated in Table 3 for their tensile, yield and elongation properties.

**Table 3 - MMFX 2 (ASTM A1035/AASHTO MP 18[A])**
**Mechanical Tensile Test Properties**

| | Grade 100 [690][A] | | Grade 120 [830] | |
|---|---|---|---|---|
| Tensile strength, min, psi [MPa] | 150,000 | [1030] | 150,000 | [1030] |
| Yield strength (0.2% offset, min, psi [MPa] | 100,000 | [690] | 120,000 | [830] |
| Stress corresponding to an extension under load of 0.0035 in./in. (0.0035mm/mm), min. psi [MPa] | 80,000 | [550] | 90,000 | [620] |
| Elongation in 8 in. [200 mm], min.%;<br>Bar Designation No. 3 through 11 [10 through 36] | 7 | | 7 | |
| Bar Designation No. 14,18, [43, 57] | 6 | | -- | |

*[A]AASHTO MP 18 only has a single Grade 100*

MMFX 2 rebar is appropriate for use as concrete reinforcement in building, industrial, transportation and other reinforced concrete applications. MMFX 2 (ASTM A1035/ AASHTO MP 18) bars have been used in building (piles, foundations, slabs, beams, columns), bridge (decks, girders, columns, abutments), retaining walls, marine facilities (docks, piers, fenders, etc.), pavement (dowel bars and lane tie bars) and other related cast-in-place and precast reinforced concrete members.

MMFX 2 steel rebar meets or exceeds the requirements of ASTM A615 Grades 75 and 80, ASTM A1035, and AASHTO MP 18. Section 3 B "*High Strength Design Applications"* provides engineers with assistance in the safe and efficient use of MMFX 2 rebar's high strength properties.

# 3. Design Considerations

MMFX 2 (ASTM A1035/AASHTO MP 18) rebar's unique combination of mechanical and corrosion-resistant properties enables the engineers to design more durable, economical and safer structures. Use of MMFX 2 rebars mitigate many of the corrosion and rebar congestion problems facing the concrete construction industry. MMFX 2 products are intended for concrete-reinforcement use and are not recommended for applications outside of concrete.

## A. Corrosion Protection Applications

Corrosion-resistant MMFX 2 rebars are ideal for structural members and systems exposed to, or in direct contact with, corrosive environments, such as: marine environment, de-icing salts, foundation systems in high water tables, or corrosive soil conditions. MMFX rebars have been successfully used in the following applications for corrosion protection: bridge decks and beams, foundation piles and systems, pavement dowel and tie bars, diaphragm walls, marine structures and seawalls, industrial equipment foundations, and exposed balconies. Structural systems reinforced with MMFX 2 rebars have been shown to achieve design service lives in excess of 75 years.

## B. High Strength Design Applications

- **ACI Building Code Design Considerations**

The high-strength property of MMFX 2 rebars has been demonstrated to be cost-effective, improve constructability, and reduce construction schedules. The American Concrete Institute (ACI) has recently published the ITG-6R-10 document "*Design Guide for the Use of ASTM 1035/A1035M Grade 100 (690) Steel Bars for Structural Concrete"* (4.B ref. 4), which was prepared to provide engineers assistance in the safe and efficient use of MMFX 2's high strength properties. The ITG-6R-10 is largely based on the research and studies noted in Section 4.B Structural Reports and provides design recommendations for structural components including: beams, columns, slab systems, walls, footings and pile caps; and mat foundations. The recommendations address the current design limitations of ACI 318-08 "*Building Code Requirements for Structural Concrete*" in utilizing high-strength rebars.

**Flexural Design**

The ITG-6R-10 concludes that flexural design of concrete members reinforced with MMFX 2 rebar follows the same methodology as that of members reinforced with conventional steel bars. A simplified flexural design method for ASTM A1035 steel, together with an idealized elastic-plastic stress-strain relationship, form the basis for flexural design. Compression-controlled and tension-controlled strain limits for members designed with ASTM A1035 rebars at design strength of 100 ksi [690MPa] are modified to 0.004 and 0.009 respectively, to ensure comparable level of displacement and curvature ductility as members with conventional rebars. Due to strain compatibility with concrete, design strength for rebars in compression is limited to 80 ksi [550 MPa]. Development and splice lengths can be adequately determined using ACI 318-08 provisions for confined splices, and using the modified equation in ACI 408R-03 "*Bond and Development of Straight Reinforcing Bars in Tension"* for both confined and unconfined splices.

**Transverse Reinforcing**

Design requirements for transverse reinforcing steel have increased over time, particularly in concrete columns, shear walls and piles. Reinforcing steel required for these designs may either exceed the practical capacity of conventional steel bars, or result in significant steel congestion, as seen in Figure 4. As a result, reinforcing bar placement and concrete consolidation has become difficult in these reinforced concrete structures.

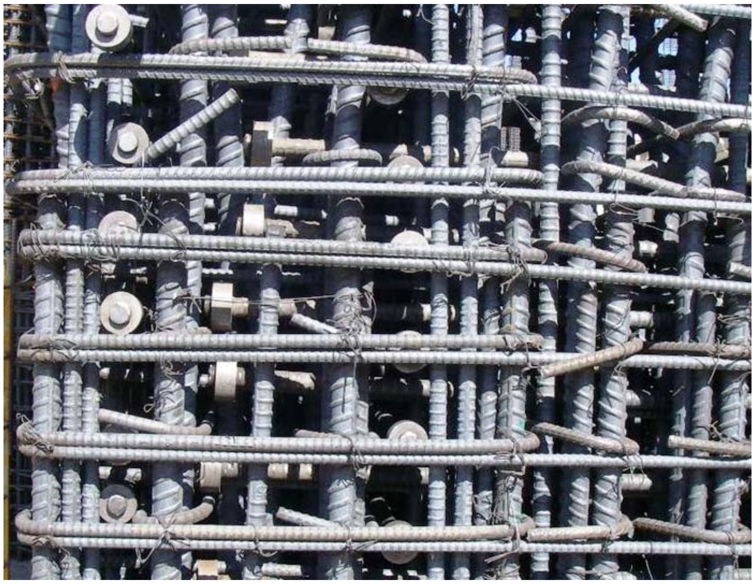

Figure 4 – Conventional Rebar Congestion

The ITG-6R-10 concludes that stirrups used as shear reinforcement may be designed at 80 ksi [550 MPa] when shear cracking is not critical. The ACI 318-05 building code already allows the use of 100 ksi [690 MPa] for design of transverse spiral reinforcement. In addition, the ACI 318-08 building code now permits the use of ASTM A1035 steel bars in transverse reinforcement ties for seismic confinement purposes, allowing a yield strength up to 100 ksi [690 MPa], for special moment frames and special structural walls.

- **AASHTO LFRD Design Considerations**

Beginning in 2007, research funded by the Transportation Research Board (TRB), was performed under National Cooperative Highway Research Program (NCHRP) Project 12-77 to provide an evaluation of existing *AASHTO LRFD Bridge Design Specifications* related to the use of high-strength reinforcing steel. At the conclusion of this comprehensive research and analytical program in 2011, NCHRP Report 679 (4.B. ref.2) was published. This report makes recommendations to *AASHTO LRFD Bridge Design Specifications,* Sections 3, 5 and 9 that permit use of high-strength reinforcing steel with yield strengths up to and including 100 ksi, such as ASTM A1035/AASHTO MP 18.

Research and analysis covered in NCHRP Report 679 confirmed that:

- 100 ksi yield strength design can be done without significant changes to the *AASHTO LFRD Bridge Design Specifications*
- High strength reinforced flexural beams showed behavior similar to beams with conventional reinforcement, while exceeding their design strength and ductility requirements
- Accepted values for the fatigue limit for conventional steel are also applicable to high strength bars

- Current procedures for calculating shear capacity are acceptable for values of shear reinforcement yield fy equal or less than 100 ksi
- Shear Friction fy needs to be limited to 60 ksi
- Current requirements for design in compression members for both longitudinal and transverse reinforcement are valid for fy equal or less than 100 ksi
- Current design requirements for high-strength bars used in development, splice, and anchorage regions should be provided with cover and confining reinforcement.
- Use of current serviceability provisions for service load levels deflections and crack widths were determined to be predictable and within accepted limits.

- **Bridge Seismic Design Considerations**

*Design Guide for Use of ASTM A1035 High-Strength Reinforcement in Concrete Bridge Elements with Consideration of Seismic Performance* (4.B. ref.1) has been published to supplement the findings of NCHRP Report 679. This study used both the NCHRP report and sponsored research projects to evaluate the maximum strength of reinforcement that may be used in the design of different bridge structural members in Seismic Zones 1, 3 and 4.

## C. Construction Specifications

MMFX Technologies has prepared a Product Guide Specification – "*Microcomposite (MMFX 2) Steel Uncoated, Plain and Deformed Bars for Concrete Reinforcement*" - (Ref 4.C.1.) This guideline construction specification for MMFX 2 (ASTM A1035/AASHTO MP18) concrete reinforcing bars include: reference codes and standards, material delivery, storage and handling measures, certified material requirements for chemical composition and mechanical properties; bar fabrication and field placement practices.

# 4. Reference Publications / Reports / Papers

The following reference documents provide a more detailed review of MMFX 2 (ASTM A1035/AASHTO MP 18) rebar's corrosion and structural characteristics.

## A. Corrosion Test Reports, Papers, and Analysis References

1. **A Critical Review of Corrosion Performance for Epoxy-Coated and Select Corrosion Resistant Reinforcements in Concrete Exposed to Chlorides – W. Hartt, Prof. Emeritus Florida Atlantic Univ. - March 2012** (**8 pages):** This paper reviews the corrosion performance of Corrosion Resistant Reinforcing (CRR) materials, including epoxy coated reinforcement (ECR), using numerous studies from 1987 thru 2010. It notes: *"A finding from a number of the above referenced studies was that ECR experiences corrosion at coating defects along with cathodic disbondment of the adjacent coating. Also noted was wet adhesion loss and underfilm corrosion*." The report states: "*A fundamental difficulty in projecting future ECR performance is that, first, long-term deterioration processes are, for the most part, not necessarily reflected by results from short-term exposures and, second, it is not possible to perform first-principles based modeling of the coating disbondment, embrittlement, and underfilm corrosion processes. Such modeling can be performed for uncoated bars,* …" The paper indicates that long term studies of uncoated bars including MMFX 2 (ASTM A1035) and UNS-S41003 (3Cr12) indicate these uncoated bars provide mean critical chloride threshold ($C_T$) values at 4 times that of black steel. In conclusion the paper states: *"In summary, long-term performance of ECR in chloride contaminated concrete is uncertain; and no first-principles based analytical tools are available for projecting this. On the other hand, sufficient data are available, along with a first-principles based methodology, for projecting long-term performance of uncoated BB and CRRs such as 3Cr12 and MMFX2™. Results from the latter analysis indicate that in the case of these CRRs a low maintenance service life of 75 and even 100 years can be expected.*"

2. **Corrosion Initiation Projection for Reinforced Concrete Exposed to Chlorides – Part II: Corrosion Resistant Bars – NACE Corrosion 11 – William Hartt, Professor Emeritus Florida Atlantic University - March 2011 (11 pages):** This paper presents the results of a study utilizing an equation from the literature to analyze the growth of reinforcement corrosion initiation (Ti) in concrete exposed to chlorides. The study's analytical method was comparatively applied to black bar (BB) and to corrosion resistance reinforcement (CRR) steels (ASTM A1035 and UNS-S41003 - 3Cr12 stainless steel), varying 1) the surface $Cl^-$ concentration ($C_s$), 2) the effective diffusion coefficient (D) in the equation. The analysis used previously published CRR steel's critical $Cl^-$ concentration threshold values ($C_T$), at four (4) times that of BB. The study's findings included:
   - Analyses projected the Ti for initial occurrence of CRR corrosion to be almost ten (10) times greater than for BB.
   - An analysis comparing the Ti trend of BB in high performance concrete (HPC) with the Ti trend of CRR in portland cement concrete (PCC), indicated that almost 50 percent less of the CRR/PCC system initiated active corrosion than the BB/HPC system after 100 years. If the analysis had considered the greater tendency of HPC compared to PCC to exhibit shrinkage cracking, then the difference between the two trends would have been greater.

3. **Critical Chloride Corrosion Threshold of Galvanized Reinforcing Bars - ACI Material Journal - Technical Paper M106-M22—March-April 2010 – D. Darwin, J. Browning et. al.( 8 pages)** This technical paper based on research as part of the International Lead Zinc Research Organization, Inc. under Project Code ZC-24-2 (See also A. 12.) indicated the following: "*The average critical corrosion threshold for galvanized reinforcement, 2.57 lb/yd$^3$ (1.5 kg/m$^3$), is higher than the observed critical corrosion threshold of conventional (A615) steel, 1.63 lb/yd$^3$ (0.97 kg/m$^3$), and lower than the value for A1035 steel, 6.34 lb/yd$^3$ (3.76 kg/m$^3$), and the lower-bound value for 316LN stainless steel, 19.14 lb/yd3 (11.36 kg/m$^3$). " "Based on chloride surveys of cracked bridge decks, galvanized steel can be expected to increase the average time to corrosion initiation at crack locations from 2.3 years for*

*conventional steel to 4.8 years for bars with 3 in. (76 mm) of concrete cover. Corrosion initiation would be expected to occur at an average age of 15 years for ASTM A1035 reinforcement and not to occur for bars consisting of 316LN stainless steel."*

4. **The Use of Corrosion Resistant Reinforcement as a Sustainable Technology for Bridge Deck Construction - TRB Annual Meeting 2010 Paper #10-2214 – January 2010 – A. Moruza, S. Sharp – (24 pages**): "*As part of the Innovative Bridge Research and Construction Program (IBRCP), this study used the full-scale construction project of the Route 123 Bridge over the Occoquan River in Northern Virginia to identify differences in the installation practices and comprehensive placement costs of epoxy-coated reinforcing steel (ECR) and corrosion-resistant reinforcing steel (CRR), specifically an ASTM A1035 steel. Internal VDOT construction records provided construction costs specifically associated with one of the two reinforcement materials. … For this project, the cost advantage of ECR at the time of contract award was not preserved after inclusion of unanticipated construction costs directly related to ECR. Specifically, adding the cost of deck sealing operations to the bid cost of ECR produced an in-place cost estimate of $.804/lb compared to $.780/lb for CRR. Inclusion of the indirect costs of the sealing operations, however, more than quadrupled the unit cost of ECR over bid, predominantly because of road user costs to the public. … CRR was ultimately cost-competitive with ECR in this project when costs of common VDOT practices related to ECR were included, but CRR potentially possesses superior longevity benefits as a sustainable choice for deck reinforcement, especially since significant traffic growth is expected on this new structure."*

5. **Laboratory Study of Corrosion Performance of Different Reinforcing Steels for Use in Concrete Structures - National Research Council of Canada - Research Report IRC-RR-284 - J. Zhang, S. Qian, B. Baldock - September 2009 (55 pages):** This report presents the results of a two-year program comparing the corrosion performance of ASTM A 615 (carbon steel), ASTM A 1035 "MMFX 2" ( referred to as "Cr steel" in the report); and stainless steels 316LN, 304LN and 2205 bars. The primary testing program was performed in electrochemical cells by using different electrochemical techniques (simulated concrete pore solutions), and concrete prisms using sand blasted bars. Comparing A615 to ASTM A1035 bars, the report states: ."*In the simulated concrete pore solution (pH=12.6), it was found that the average chloride threshold of carbon steel was about 1.0% by weight; the average chloride threshold of Cr steel was about 5.0%." … "Pitting corrosion was observed to initiate on Cr steel at a range of chloride concentrations from 0.18% to 0.3%. Pitting corrosion was initiated on carbon steel, at a much lower chloride concentration around 0.06%."* The following observations were made concerning concrete prism testing program: "*In concrete containing 1.5% of chlorides, Cr steel remained in passive state before undergoing active corrosion at ten months of age… As the chloride concentration increased from 1.5% to 3.0%, Cr steel showed lower corrosion rate than carbon steel". … "the corrosion rate of Cr steel did not increase significantly as the chloride concentration was increased from 3.0% to 6.0%."…"The corrosion rate was within a range of low to moderate at these concentrations."* The report also made the following observation concerning concrete prism testing of A1035 bars with mill scale: "*The corrosion rate of as-received Cr steel (non-sandblasted) was found to be much higher than that of sandblasted Cr steel, and the difference became greater with increasing chloride concentrations. The difference was about half an order of magnitude at 1.5% and 3.0% of chlorides, and increased to about one order of magnitude at 4.5% and 6.0% of chlorides."*

6. **Field Comparison of the Installation and Cost of Placement of Epoxy-Coated and MMFX 2 Steel Deck Reinforcement: Establishing a Baseline for Future Deck Monitoring - S. Sharp, A. Moruza - VTRC 09-R9 – May 2009 (84 Pages):** This study identifies and compares differences in the installation practices and comprehensive placement costs of epoxy-coated reinforcing steel (ECR) and MMFX 2 (ASTM A1035/AASHTO MP 18), as part of the FHWA Innovative Bridge Research and Construction Program (IBRCP). The report was based on costs associated with Virginia DOT's construction of the Route 123 Bridge over the Occoquan River. Two separate bridge decks were constructed as part of the project: A. southbound deck using ECR, and the northbound deck using MMFX 2, a corrosion-resistant reinforcing steel (CRR). Field surveys conducted after completion of construction resulted in crack sealing of certain spans of the ECR portion of the deck and modification for added bolster material above one of the northbound (MMFX 2) abutments. Final installation costs,

including cracking sealing of certain ECR deck span sections and the additional work for the MMFX deck, indicated that that total direct in place unit costs for ECR were $0.90/lb and MMFX were $0.87/lb. The report indicates that indirect costs (i.e. VDOT inspection, special traffic control, and public travel delay) for required sealing of ECR deck cracking placed the total installed ECR unit cost between $2.34 and $2.90/lb. Labor records for the contract's ironworkers indicated that they placed: 329.9 lb/labor hour for ECR and 358.8 lb/labor hour for MMFX 2. The study notes: "*Average labor productivity estimates from this study suggested that the handling requirements of ECR led to additional supervisory costs and additional ironworker costs relative to those associated with uncoated CRR. Inspectors' records indicated that the subcontractor billed 15% more supervisor hours to place ECR in the southbound deck than to place MMFX 2 in the northbound deck, yet almost 16% less ECR than MMFX 2 was placed by weight …. The special handling requirements for ECR are a plausible explanation for the lower average labor productivity in the placement of ECR compared to that for MMFX 2…"* The report concludes by stating: *"ECR appears to have been far less cost-effective per unit than MMFX 2 when both anticipated and unanticipated costs of ECR in this study are estimated. MMFX 2 showed both labor productivity and comprehensive in-place cost advantages over ECR in this application."*

7. **Risk of Macro-Cell Corrosion Associated with Black Bar – MMFX 2 (ASTM A1035) Combinations in Concrete - W. H. Hartt - Hartt and Associates, Inc. - May, 2009 (10 pages):** This report was based on testing of concrete specimens to determine if adverse dissimilar metal effects occur when connecting MMFX 2 (ASTM A1035) bars to black steel bars. The report makes the following statement: "… *there is no technical reason why black bar and MMFX2 reinforcements cannot be combined in concrete construction, including situations involving, first, field repairs and, second, new construction."*

8. **Corrosion Resistant Alloys for Reinforced Concrete – FHWA HRT 09-020 – W. Hartt, R. Powers, P. Virmani et. al – May 2009 (150 pages)** This report documents the findings of a 6 year study of the corrosion resistance of various concrete reinforcing bars using four specimen types: simulated deck slabs (SDS), macrocell slabs (MS), 3 Bar tombstone columns (3BTC) and Field columns (FC) and three types of concrete mixtures: STD 1 (5 bag W/C 0.50), STD 2 (7 bag W/C 0.41) and STD 3 (7 bag W/C 0.50) Reinforcements included stainless steels: 316, 304, 2304, 2101, and 3Cr12 ; two types of 316 clad, AASHTO MP 13M/MP 13-04, and MMFX-2 (ASTM A1035); and BB (ASTM A615), with BB used a comparator. The report indicates: "*The reinforcements, other than BB, were classified into two groups as either improved performance*" … (alloys with corrosion initiation during project) "*or high performance*" (alloys without corrosion initiation during project). *"Improved performers were 3Cr12, MMFX-2, and 2101 …. These alloys ranked according to time for corrosion to initiate as BB < 2101 < 3Cr12 < MMFX-2." "Chloride threshold for corrosion initiation of 3Cr12 and MMFX-2 reinforced SDS specimens was about four times greater than for BB specimens and slightly less than four times greater in the case of 2101 specimens. For STD2 MS specimens, however, $T_i$ for MMFX-2 and 2101 was from 3.4 to more than 5.7 times greater than for BB (limited data precluded this determination for 3Cr12)."*

9. **Effect of Concrete Crack Width on Corrosion of Embedded Reinforcement – W. H. Hartt - Hartt and Associates, Inc. - March, 2009 (10 pages):** This commentary reviews existing literature pertaining to the effect of concrete crack width on reinforcement corrosion in various project environments with different exposure zones encountered in the Middle East. The literature indicates that crack width does not significantly influence long-term durability of reinforced concrete, for crack widths up to 1.6 mm (0.063 in.). The report indicates that the time to corrosion initiation is six times greater and the corrosion rate for MMFX 2 (ASTM 1035) is six times less than that for black steel in cracked concrete.

10. **Effect of crack width on corrosion of reinforcing steel – D. Darwin - February, 2009 (2 pages):** This report states: "*Within the range of 0.1 to 0.6 mm, crack width does not affect the corrosion of reinforcing steel. Corrosion is, however, affected by concrete cover, water-cement ratio, and the orientation of the crack with respect to the reinforcing steel.*" This discussion notes that the steel's corrosion rate is not affected when crack widths are under 0.6mm but are by their critical chloride

threshold level. A 75mm concrete cover, the report indicates "…*provides protection against not only corrosion in the presence of cracks abut also against carbonation* …" and states "*For severe chloride exposure conditions, the ACI Building Code limits the water-cement ratio to a maximum of 0.40*."

11. **Periodic Overload Corrosion Fatigue of MMFX and Stainless Reinforcing Steels – S. DeJong, P. Heffernan, C. MacDougall - Journal of Materials in Civil Engineering, Vol. 21, No. 1, January 2009 (9 pages)** "*This study presents the periodic overload and corrosion-fatigue resistance of machined specimens made from two corrosion resistant reinforcing steels: MMFX Microcomposite [ASTM A1035/ASSHTO MP18] and 316LN stainless steel. MMFX had reduced constant amplitude performance in the corrosive environment, whereas 316LN stainless steel showed no environmental reduction under constant amplitude loading (except at high loads). Corrosion fatigue reduced the periodic overload performance of both materials, although both materials retained their intrinsic fatigue limit (250 MPa stress range) in the corrosive environment, a drastic improvement over the periodic overload corrosion-fatigue performance of conventional reinforcing steel*."

12. **Concrete and Steel Type Influence on Probabilistic Corrosion Service Life - G. Williamson, R. Weyers, et. al. - ACI Materials Journal V. 106, No. I, January-February 2009 (7 pages):** This technical paper presents comparative service life predictions for Microcomposite (MMFX 2/ASTM A1035), stainless steel (SS), galvanized steel (GS) and carbon (black) steel reinforcing bars, utilizing low-permeability concrete (LPC with admixtures) and standard (without admixtures) concrete. Service lives were established using a computer model based on: a. time to corrosion initiation of 2% of the reinforcing steel; b. time from corrosion initiation to concrete cracking and spalling of the concrete over 2% of the reinforcing steel; and c. time for corrosion propagation from 2% to 12%. ASTM A1035 steel was noted to provide > 200 years of service life when used in conjunction with LPC; and 2 to 3 times the service life of black steel depending on the surface chloride concentration levels of standard concrete. (Copy of this paper may be obtained from the American Concrete Institute (ACI), Farmington Hills, MI.)

13. Evaluation of Corrosion Resistance of Steel Dowels Used for Concrete Pavements **- M. Mancio, C. Carlos, J. Zhang, J. Harvey, P. M. Monteiro, and A. Ali- JOURNAL OF MATERIALS IN CIVIL ENGINEERING – October 2008 (9 pages**) This study investigated the corrosion performance of several types of steel dowels cast in concrete beams using accelerated laboratory tests This paper indicates: " *that the microcomposite [ASTM A1035] steel dowels exhibit much greater resistance to corrosion propagation than carbon steel dowels, but not as much as the stainless clad and stainless hollow bars*". In addition the study states: "*Visual inspections of the corroded dowels revealed heavy and mostly uniform corrosion along the carbon steel dowels, light corrosion in the microcomposite steel dowels, and no visible corrosion in the stainless steel clad and stainless steel hollow bars. For the epoxy coated dowels, the visual inspections generally revealed that visible corrosion was not widespread, but did occur at a few localized defective areas, generally at holidays and at the edges of the bar ends. No significant difference was observed on the performance of nonflexible and flexible epoxy-coated dowels*."

14. **Electrochemical and in-situ SERS study of passive film characteristics and corrosion performance of microcomposite steel in simulated concrete pore solutions - University of California Berkeley (UCB) – M. Mancio, G. Kusinski, et. al. – March 2008 (104 pages).** This testing program provides the basis for proposed AASHTO SOM specification Annex A "Test Method for Comparative Qualitative Corrosion Characterization of Steel Bars Used in Concrete Reinforcement." The report states: *"After passivation, the current density for microcomposite steel [ASTM A1035] was around 11 μA/cm$^2$ while that for carbon steel was about 140 μA/cm$^2$ (~13 times higher). If these values were used to estimate corrosion rates, one would get approximately 1627 μm/yr (1.63 mm/yr) for carbon steel and 128 μm/yr (0.128 mm/yr) for microcomposite steel [ASTM A1035]."*

15. **Comparative Corrosion Testing and Analysis of MMFX 2 Rebars for Reinforced Concrete Applications – Wiss, Janney, Elstner Associates, Inc. - Final Report WJE No. 2003.0707.0 – F. Cui, P. Krauss, et. al - January 2008 (57 pages)** This report is based on ASTM G109 and time-to-

corrosion (a.k.a. Southern Exposure) tests, stating: *"MMFX 2 steel bars have higher chloride thresholds than A615 bars, but less than Type 304 stainless steel. The ASTM G-109 test program suggested that the chloride threshold of MMFX bars is about three times of that of black bars. …. The removal of mill scale was found to have slightly increased the corrosion resistance of MMFX bars in the G-109 test. … Modeling analyses of a marine pile and a northern bridge deck exposed to deicers showed that the use of MMFX bars in lieu of black bars may extend the structure service life by about 1.8 times, assuming a chloride threshold for the MMFX bars of three times that of the A615 black bars. Slower corrosion rates for the MMFX bars during the propagation period could increase the service life further, to about twice that of A615 bars."*

16. **Corrosion of Reinforcing Bars in Concrete - R&D Serial No. 3013 Portland Cement Association - C. Hansson, A. Poursaee, S. Jaffer – 2007 – (33 pages):** The primary focus of this report is chloride-induced corrosion of steel reinforcement: the factors affecting it and its influence on durability. This review describes the corrosion process, the lack of a single chloride threshold concentration for initiation of corrosion and the relative contributions of micro-cell and macro-cell corrosion in sound concretes. The report indicates that a two-fold approach to corrosion resistant structures should include:
    *"The use of high performance concrete (HPC) to lower concrete's permeability and reduce the rate of ingress of chlorides or carbonation and, thereby, increase the effectiveness of the physical barrier.*

    *The use of more resistant reinforcing bar materials to provide better chemical resistance. In those parts of structures exposed to very severe chloride environments, stainless steel is recommended. Despite the initial expense, it is a cost effective solution in these circumstances when both direct and indirect costs (such as user costs) are taken into account. In the somewhat less severe chloride environments, corrosion resistant alloys such as MMFX or 2101LDX, which are more resistant to chlorides than black steel - but less corrosion resistant and much less costly than stainless steel - should be considered."*

17. **Critical Choloride Corrosion Threshold for Galvanized Reinforcing Bars - SL Report 07-2 – Univ. of Kansas Center for Research – D. Darwin, J. Browning et. al. - Dec. 2007 (36 pages).** This report prepared for the International Lead Zinc Research Organization indicated the following: "*… test results show that galvanized reinforcement has an average critical chloride corrosion threshold of 2.57 lb/yd$^3$, which is greater than conventional steel (1.63 lb/yd$^3$) and lower than MMFX[ASTM A1035] steel (6.34 lb/yd$^3$)." "Based on chloride surveys of cracked bridge decks in Kansas, galvanized steel can be expected to increase the average time to corrosion initiation at crack locations from 2.3 years for conventional steel to 4.8 years for bars with 3 in. of concrete cover. Corrosion initiation can be expected to occur at an average age of 14.8 years for MMFX [ASTM A1035] steel. All three systems will exhibit significantly longer times to corrosion initiation in uncracked concrete." …."the average times to corrosion initiation in uncracked regions on bridge decks would be 26, 41, and 100 years for conventional, galvanized, and MMFX reinforcement, respectively, demonstrating that uncracked concrete provides excellent protection against chloride penetration. These values closely match those used in life-cycle models in which chloride penetration is based on diffusion through uncracked concrete."*

18. **Corrosion Resistant Alloy Steel (MMFX) Reinforcing Bar in Bridge Decks – Mich DOT Report R-1499 – Steve Kahl, PE – Sept. 2007 (36 pages).** This report compiles the findings of Mich DOT corrosion research and structural analysis (See Appendix B "MMFX Reinforced Bridge Deck LRFD Design Example") of bridges using MMFX 2 (ASTM A1035) reinforcing bars. The report states: "*..MMFX steel does exhibit corrosion resistance, higher yield strength, and a lower life cycle cost than epoxy coated reinforcement. Due to the high yield strength, MMFX use in bridge deck construction should be limited to structures that are designed in accordance with AASHTO LRFD code, and for 75 ksi steel reinforcement design yield strength…*" This statement was made after making an economic analysis that compared a MMFX 2 (ASTM A1035 Gr 75) AASTHO LFRD design to an epoxy-coated rebar (ECR) design using Michigan's standard design (LFD).

19. **Corrosion Resistant Alloys for Reinforced Concrete - FHWA-HRT-07-039 - W. Hartt, R. Powers**

**et. al. - July 2007 (135 pages).** This test program included MMFX-II™ (sic.) (ASTM A1035), solid stainless steels 3Cr12 (UNS-S41003), 2201LDX (ASTM A955-98), 2205 (UNS 31803), and two 316L (UNS S31603) alloys; and two 316 stainless steel clad black bar products, black bar (ASTM A615) reinforcement included for comparison purposes. The report states: "*For black bar slabs, it was considered that active corrosion commenced once potential dropped to −280 mVSCE, at which point the average macro-cell current density was about 0.26 μA/cm$^2$. If it is assumed that this same current density denotes onset of active corrosion for the other reinforcement types as well, then the corresponding potentials are −390, −350, and −195 mVSCE for 3Cr12, MMFX -II™, and 2201, respectively. These potentials were achieved after 35 days (black bar), 64 to 140 days (3Cr12), 91 to 140 days (MMFX-II™), and 64 to 94 days (2201).*"

20. [Laboratory Evaluation of Corrosion Resistance of Steel Dowels in Concrete Pavement]() **– Final Report UCPRC-RR-2005-10 – FHWA No S/CA/RI-2006/27 – Mauricio Mancio, John Harvey, PhD et al.- Pavement Research Center - UC Berkeley and Davis - January 2007 (127 pages)**: This pavement dowel corrosion report indicates that Microcomposite (MMFX 2) pavement dowel bar had approximately 35 times the polarization resistance of carbon steel dowels. The report makes the following recommendations: **"***It is recommended that the use of stainless steel-clad, hollow stainless steel, or microcomposite [MMFX 2] steel dowels be considered for locations with high risk of high chloride exposure (such as on mountain passes and marine environments)..."* Furthermore the report states: "*Epoxy dowels present some risk of corrosion, primarily localized at holidays and the ends of the bars."* The report notes that*:* **"***Bar ends should be coated with epoxy and care must be taken with epoxy-coated dowels during shipping, storage, and installation. Corrosion will be exacerbated if the bar ends are not coated (observed on various Caltrans construction sites) or if the coated ends are damaged during storage, transport, and installation."*

21. [Comparative Performance of MMFX Microcomposite Reinforcing Steel and Other Types of Steel with Respect to Corrosion Resistance and Service Life Prediction in Reinforced Concrete Structures]() – **D. R. Morgan - AMEC Earth & Environmental - June 2006 (48 pages):** This report makes the following conclusion after evaluating 14 studies and reports concerning the corrosion resistance properties of MMFX 2 (Microcomposite) Steel reinforcement and other products: *"Studies evaluated in this report indicate that MMFX corrosion resistance is similar to or better than that of certain stainless steels such as 2101 and 3Cr12. … stainless steels (i.e. SS304 and SS316 series) appear to be more effective than MMFX for use in bridge and other structures exposed to chlorides, the lack of availability in North America of many the types of stainless steel evaluated, and their high costs compared to MMFX, make them less attractive from a life-cycle cost perspective for most applications."*

22. [Summary Report on the Performance of Epoxy-Coated Reinforcing Steel in Virginia]() - **Richard Weyers, Michael Sprinkel , Michael Brown , - VTRC Report 06-R29 - June 2006 (37 pages)**: This report based on 14 years of research by VTRC of corrosion resistant reinforcing steel alternates states: *"because ECR cannot provide adequate corrosion protection for structures designed for a 100-year+ service life as currently recommended by FHWA, the report recommends that the Virginia Department of Transportation amend its specifications regarding the use of ECR to require the use of corrosion-resistant metallic reinforcing bars such as MMFX 2, ..." "Based on the times to cracking, MMFX2 reinforcement is worth 5 times more than ECR."* This study reiterated some of the findings of Hansson, Haas et al ([ref A. 33]()) concerning epoxy-coated rebar (ECR)

23. [Evaluation of Corrosion Resistance of Different Steel Reinforcement Types]() **- Final Report - Iowa State University Bridge Center - CTRE Project 02-103 - May 2006 (75 pages):** Voltage and current results from field monitoring of a instrumented bridge constructed half with MMFX steel and half with ECR indicated: 1. The MMFX half remained within the normal range at less than 100mV; appeared to have no ongoing corrosion activity. 2. In contrast, ECR had readings that were two times greater than MMFX, close to 200 mV. This led to the report's speculation that defects in the coatings had occurred during construction.

24. [ASM Handbook, Volume 13C, Corrosion: Environments and Industries]() **Corrosion in Bridges**

**and Highways –ASM International – J. Tinnea, W. Hartt, F. Pianca et. al. - 2006 (39 pages):** This handbook chapter discusses the various aspects of corrosion associated with bridge structural elements in corrosive environments and describes alternative corrosion-resistant reinforcement systems. ASTM A1035 (MMFX 2 Steel) is noted as having the same $Cl^-/OH^-$ ratio of 4.9, as 316 stainless steel cladded reinforcement, as a measure of its corrosion resistance. (Copy of this reference is available from the American Society for Metals - ASM).

25. **Evaluation of MMFX Steel For NCDOT Concrete Bridges – FHWA/NC/2006-31, NCDOT Report 2004-27 – S. Rizkalla, P. Zia et. al. – December 2005 (131 pages):** This publication states the following conclusions based on testing of full scale bridge deck sections and corrosion tests at North Carolina State University: *"1. Substituting MMFX steel directly for Grade 60 steel in a design … is an overly-conservative approach. 2. MMFX steel [ASTM A1035] can be used as the main flexural reinforcement for cast-in-place concrete bridge decks at a reinforcement ratio corresponding to 33% less than that required for Grade 60 steel. Therefore, a design of reinforced concrete bridge decks using MMFX steel may utilize an equivalent yield stress of 90 ksi for the MMFX steel bars. 3. Design of concrete bridge decks utilizing the high tensile strength characteristics of the MMFX steel should satisfy all minimum reinforcement ratios required by the AASHTO LRFD Bridge Design Specifications as well as the serviceability requirements of the specifications. 4. MMFX steel [ASTM A1035] has a much lower corrosion rate compared to conventional Grade 60 steel. Therefore, the use of MMFX steel could increase the service life of concrete bridges and lower repair costs."*

26. **Corrosion Resistance of Duplex Stainless Steels and MMFX Microcomposite Steel for Reinforced Concrete Bridge Decks - University of Kansas Center for Research, Inc. - SM Report No.80- J. Ji, D. Darwin et. al - December 2005 (507 pages):** This report indicated that MMFX 2 (ASTM A1035) bars had ½ the corrosion rate of conventional black bar and approximately 3 to 4 times black bars critical chloride threshold value. 2101 stainless steel (SS) was reported to have 1.35 times the corrosion rate of black bar in an unpickled surface condition, with a slight higher corrosion rate as ASTM A1035 with a pickled surface condition.

27. **New Technologies Proven in Precast Concrete Modular Floating Pier for U.S. Navy – PCI Journal - Michael W. LaNier, PE, FPCI, Preston S. Springston et.. al. - July-August 2005 (26 pages):** This article notes that the Navy's Modular Hybrid Pier (MHP) project received Precast/Prestressed Concrete Institute's (PCI's) Henry N. Edwards award and updates - Preston Springston's ASCE paper. Project review procedures are discussed demonstrating why MMFX rebar was included in one of the project's two Navy MHP modules. The article noted that use of MMFX saved approximately $2.8 million over the original proposed design, while providing a 75-yr service life. MMFX's corrosion resistance performance was analyzed by the STADIUM computer model.

28. **The Long Term Performance of Three Ontario Bridges Constructed with Galvanized Reinforcement – Ontario Ministry of Transportation – F. Pianca and H. Schell – June 2005 (29 pages)**: This report makes the following conclusions: *"Corrosion of galvanized reinforcing bars was initiated soon after the chloride corrosion threshold (for black steel) was reached…"* [and] *"…caused significant damage to the concrete, in the form of delamination and cracking." "…they* [galvanized bars] *do not provide effective long-term protection from corrosion."*

29. **Surface Condition Effects on Critical Chloride Threshold of Steel Reinforcement – D. Trejo, R. Pillai - ACI Materials Journal 102- M12 – March – April 2005 (6 pages):** This publication compared the critical chloride threshold level (CCTL) values of various uncoated steel reinforcement types using their as-received (with mill scale) and polished surface conditions. MMFX 2 (ASTM A1035) was determined to have approximately 9 times the CCTL value of A615 in the as-received condition and approximately 12 times the CCTL of A615 in the polished condition. These values were determined using the accelerated chloride threshold (ACT) test procedure developed at Texas A&M University. (Copy of this paper may be obtained from the American Concrete Institute (ACI), Farmington Hills, MI)

30. **Comparing the Chloride Resistances of Reinforcing Bars - Gerardo Clemeña Ph.D. and Paul**

**Virmani Ph.D. – Concrete International - November 2004 (11 pages):** This article evaluates new, economical metallic reinforcement for its ability to withstand high salt concentration. The comprehensive study, on which the article is based shows that the chloride threshold of MMFX Microcomposite bars is about 5 to 6 times better than A615 steels and approximately 2 times chloride threshold of stainless steel 2101 LDX bars. (Copy of this paper may be obtained from the American Concrete Institute (ACI), Farmington Hills, MI)

31. **Evaluation of Mechanical and Corrosion Properties of MMFX Reinforcing Steel for Concrete - University of Kansas Center for Research, Inc. Report No. FHWA-KS-02-8 - SM Report No. 70 – L. Gong, D. Darwin et. al. - February 2004 (132 Pages):** This report based on Southern Exposure corrosion testing, indicated that MMFX 2 (ASTM A1035) has a corrosion rate of approximately 30% less than that of black (ASTM A615) steel bars.

32. **Investigation of the Resistance of Several New Metallic Reinforcing Bar to Chloride-Induced Corrosion In Concrete - Virginia Transportation Research Council (VTRC) Report 04-R7 - Gerardo Clemeña Ph.D. – December 2003 (27 pages):** This report describes testing, analysis and recommendations concerning various metallic bars, including MMFX 2, that were found to be more durable and corrosion resistant than epoxy-coated rebar, with the program's investigation serving as the basis for an ACI Materials Journal paper co-authored by Dr. Gerardo Clemeña of the VTRC and Dr. Y. Paul Virmani of the FHWA. In conclusion, the report recommends MMFX 2 rebar for use by Virginia DOT in corrosive environments.

33. **Appraisal Report High Corrosion Resistance MMFX Microcomposite Reinforcing Steels-CIAS (Concrete Innovations Appraisal Service) Report 03-2 – Prof. Paul Zia, Prof. Theodore Bremner, Dr. V. M. (Mohan) Malhotra, Morris Schupack, P.E., Paul G. Tourney, P.E. – May 2003 (50 pages):** This document reports on the findings of the CIAS's MMFX corrosion panel concluding that MMFX 2's corrosion resistance provides a longer service life and is more cost effective than A615 reinforcement.

34. **Corrosion Protection Strategies for Ministry Bridges - Final Report Amended - University of Waterloo - C.M. Hansson, R. Haas, R. Green, R.C. Evers, O.K. Gepraegs, and R. Al Assar - July 2000 (210 pages)**: This report states: "*Major concerns exist with the inability of maintaining a flaw-free coating on ECR during handling, placement and compaction of the concrete, and with disbondment of the coating ... In turn, concern exists that this provides easy access to chlorides and, thus, allows corrosion at flaws and along the bar under the disbonded coating. … There is additional concern regarding the difficulty of monitoring the condition of ECR and of repair/rehabilitation cycles over the 75 years." …. "The conclusion is that options involving ECR present no cost or performance advantages over BSR [Black Steel Reinforcement]. … the further use of ECR is not recommended on the basis of both technical and life cycle cost analysis."*

## B. Structural Test Reports, Papers and Analysis References

**1.** **[Design Guide for Use of ASTM A1035 High-Strength Reinforcement in Concrete Bridge Elements with Consideration of Seismic Performance](#) – H. Russell, S. K. Ghosh, M. Saiidi - August 2011 – (25 pages) –** This study evaluates the maximum strengths of reinforcement that may be used in the design of the different structural elements of bridges in Seismic Zones 1, 3 and 4. The report's conclusions are summarized the Table 1 (below), based on the information presented in this report, which differentiates Seismic Zone 1 conclusions from Seismic Zones 3 and 4. It is noted that the application of high-strength reinforcing steel in bridges Seismic Zone 2 was beyond the scope of this study.

The report states: "*In view of the fact that (1)* ***bridge decks, girders, and bent cap beams*** *are capacity-protected, (2) satisfactory performance in field studies has been documented, and (3) research findings that the use of MMFX bars in close proximity with black steel bars in chloride-contaminated environments does not lead to enhanced corrosion of the reinforcing bars, there should be no reservation about permitting MMFX reinforcing bars in bridge decks, girders, and bent cap beams in Seismic Zones 3 and 4, provided the guidelines in Part 1 of this report are followed*.
*Pending further testing, MMFX steel should not be used as longitudinal reinforcement in* ***bridge columns*** *in Seismic Zones 3 or 4. The use of MMFX steel as transverse reinforcement in such members should be permitted, provided the transverse reinforcement yield strength is restricted to no more than 60 ksi for the purposes of computing shear strength. The full yield strength of the transverse reinforcement may be utilized for purposes of confinement of the concrete.*
*The above recommendation should also apply to* ***pier walls, back walls, and wing walls****, which are preferable locations for inelastic behavior in most bridges.*
*The welding of ASTM A1035 reinforcement should be prohibited in plastic hinge regions of columns and other structural members that are not capacity-protected in bridges located in AASHTO Seismic Zones 3 and 4, until approved procedures for butt-welding of hoops become available.*
*In general, MMFX reinforcing bars should be permitted to be used in any* ***foundation element such as a footing or a Type II pile shaft*** *in Seismic Zones 3 and 4 that is capacity protected, provided the guidelines in Part 1 of this report are followed.*
*When MMFX reinforcing bars are used as transverse reinforcement in pile shafts, the transverse reinforcement yield strength should be restricted to no more than 60 ksi for the purposes of computing shear strength. The full yield strength of the transverse reinforcement may be utilized for purposes of confinement of the concrete."*

**Table 1 Maximum Tensile Strengths of Reinforcement for Use in Design**

| Yield Strength, ksi | Foundations | | | Columns/Walls | | Decks | Beams/Girders | | |
|---|---|---|---|---|---|---|---|---|---|
| | Abutments | Piles | Pile Caps | Vertical | Confine-ment | Top and Bottom | Tension | Compres-sion | Shear |
| Non-Seismic (Zone 1) | | | | | | | | | |
| 100 | X | X | X | X | X | X | X | X | X |
| 75 | | | | | | | | | |
| 60 | | | | | | | | | X(1) |
| Seismic (Zones 3 and 4) | | | | | | | | | |
| 100 | X | X | X | N(2) | X | X | X | X | X |
| 75 | | | | N(2) | | | | | |
| 60 | X(3) | X(3) | X(3) | N(2) | X(3) | | | | X(1) |

(1) Yield strength limited to of 60 ksi for shear-friction calculations.
(2) Not recommended.
(3) Yield strength of transverse reinforcement limited to 60 ksi for shear strength computations.
Note: Application of high-strength reinforcement in bridges located in Seismic Zone 2 was beyond the scope of this study.

2. **Design of Concrete Structures Using High-Strength Steel Reinforcement - National Cooperative Highway Research Program - NCHRP Report 679 – B. Shahrooz, R. Miller, K. Harries, H. Russell – April, 2011 - Pages 83:** This report, prepared as part of NCHRP Project 12-77, provides an evaluation of existing *AASHTO LRFD Bridge Design Specifications* relevant to the use of high-strength reinforcing steel. The report identifies aspects of reinforced-concrete design and of the AASHTO specifications that may be affected by the use of high-strength reinforcing steel. Experimental and analytical studies, conducted as part of the program, provide the background and engineering basis to support recommendations for changes to the specifications necessary for the use of high-strength reinforcing steel. The report includes proposed recommended language which specifically permits the use of high-strength reinforcing steel for yield strengths not greater than 100 ksi. This study did not address seismic applications and therefore, is limited in its application to Seismic Zone 1.

   The report's supporting documents include the following: Appendix A—*Material Properties*, Appendix B—*Flexural Resistance of Members with Reinforcing Bars Lacking Well-Defined Yield Plateau*, Appendix C—*Strain Limits for Tension-Controlled/Compression-Controlled and Strains to Allow Negative Moment Redistribution*, Appendix D—*Flexure Specimens*, Appendix E—*Fatigue of High-Strength Reinforcing Steel*, Appendix F—*Shear Specimens*, Appendix G—*Analytical Studies of Columns*, Appendix H—*Beam Splice Specimens*, Appendix I—*Crack Control*, Appendix J—*Survey Instruments and Results*, Appendix K—*Design Examples*, Appendix L—*Proposed Changes to Section 5 of the AASHTO LRFD Specification*, Appendix M—*2010 AASHTO Bridge Committee Agenda Item.*

   The following conclusions are made as part of this report; which cover the ensuing design aspects based on the program's experimental and analytical studies: A. Yield Strength **–** "*A value of yield strength, fy, not exceeding 100 ksi was found to be permissible without requiring significant changes to the specifications*." B. Flexure- *"All beam specimens met and exceeded their designed-for strength and ductility criteria and exhibited predictable behavior and performance similar to beams having conventional reinforcing steel".* C. Fatigue-"…*tests…and a review of available published data demonstrate that presently accepted values for the fatigue or 'endurance' limit for reinforcing steel are applicable, and likely conservative, when applied to higher strength bars*." D. Shear – "T*he use of current specifications procedures for calculating shear capacity were found to be acceptable for values of shear reinforcement yield fy ≤ 100 ksi.* E. Shear Friction - "…*restriction that fy be limited to 60 ksi when calculating shear friction capacity must be maintained regardless of the reinforcing steel used."* F. Compression - "*Results indicate the current specifications requirements for both longitudinal and transverse reinforcement design in compression members are applicable for fy ≤ 100 ksi*." G. Bond and Development **–** *"…it is recommended that development, splice, and anchorage regions be provided with cover and confining reinforcement based on current design requirements when high-strength bars are used."* H. Serviceability—Deflections and Crack Widths - "*Based on the results of the flexural tests conducted in this study, deflections and crack widths at service load levels were evaluated. Both metrics of serviceability were found to be within presently accepted limits and were predictable using current specifications provisions*."

3. **Cyclic Response of Concrete Columns Reinforced with High-Strength Steel - 10th Canadian Conference on Earthquake Engineering - Paper No 996 - J. Rautenberg, S. Pujol et. al – July 2010 – (9 pages)**: This paper compares the results of columns designed with ASTM A1035 120 ksi longitudinal reinforcement to those of columns with ASTM 706 60 ksi reinforcement and variable axial loads with all columns having the same confinement steel. It is reported that the flexural strength of these columns is controlled by the strength of the steel; and that two sections with different grades of steel have similar moment capacities as long as the product of reinforcement ratio and yield stress is similar for both sections. Tests of columns under cyclic load reversals show that columns reinforced with ASTM A1035 120-ksi steel reinforcement can reach drift ratios of 4%; and have smaller drift capacities than columns reinforced with (twice as much) A706 60-ksi steel.

4. **Design Guide for the Use of ASTM 1035/A1035M Grade 100 (690) Steel Bars for Structural Concrete - ACI ITG-6R-10 - *ACI Innovation Task Group 6:* P. Zia, A. Luba, S. K. Ghosh, C.**

**Paulson, A. Lepage, H. Russell, K. Luttrell, J. Sanders, R. Mast - August 2010 (90 pages)**: This guide provides recommendations on appropriate design procedures for the use of ASTM A1035 Grade 100 high-strength deformed reinforcing bars, for reinforced concrete members with regard to safety and serviceability. It was developed to address certain requirements in ACI 318-08 that limit more efficient use of high-strength steel bars.

This document includes a discussion of the material characteristics of ASTM A 1035 steel bars and recommends design criteria for beams, columns, slab systems, walls, and footings in low and moderate seismic applications (Seismic Design Category A, B, or C). For high seismic areas, the application of this guide is currently limited to slab systems, foundations, and structural components not designated as part of the seismic-force-resisting system but explicitly checked for the induced effects of the design displacements. The only exception to this, is the use of transverse reinforcement for concrete confinement with a specified yield strength, $f_{y,}$ up to 100,000 psi (690 MPa) as permitted by Section 21.1.5.4 of ACI 318-08.

Design examples are included as part of this document to illustrate design procedures and proper applications of the recommended design criteria. Also included as part of these design examples are commentaries, which are provided to highlight the differences in design when using ASTM A1035 high-strength steel bars as opposed to the conventional ASTM A615 steel bars.

5. **Flexural Behavior And Design With High-Strength Bars And Those Without Well-Defined Yield Point - Transportation Research Board Annual Meeting - 2010 Paper #10-1599- Jan. 2010 - B. Shahrooz, K. Harries, H. Russell et al.- (16 Pages):** This paper focuses on behavior and design of flexural members reinforced with high-strength reinforcement (ASTM A1035) as well as other types of steel without well-defined yield plateaus, as part of National Cooperative Highway Research Program (NCHRP) Project 12-77 *Structural Concrete Design with High-Strength Steel Reinforcement*. Analytical formulations and experimental testing of full-scale beams are reported. The following conclusions were made from these formulations and experimental testing. The results of this study make the following general conclusions

   - *"For beams with reinforcement ratios less than 3%, flexural capacity of members reinforced with high-strength and other grade bars with no clear yield point can be established by using well-established strain compatibility analysis procedures in which the steel stress-strain behavior is idealized as being elastic-perfectly plastic with the yield point taken as the stress at strain equal to 0.0035 or 0.005. For beams with reinforcement ratios larger than 3% and concrete strength exceeding 69 MPa (10 ksi), the use of stress corresponding to strain equal to 0.0035 is conservative and recommended. For A1035 reinforcing bars, the yield strength at this strain maybe taken as 100 ksi.*
   - *The strain limit to achieve tension-controlled behavior for members using high-strength reinforcement should be taken as 0.008 (instead of the current value of 0.005). The corresponding strain limit for compression-controlled members is 0.004 (versus 0.002 in current AASHTO LRFD Bridge Design Specifications).*
   - *Members reinforced with high-strength ASTM A1035 bars exhibit adequate ductility and do not suggest any unexpected response characteristics."*

6. **Bond and Anchorage of High Strength Reinforcing Steel, TRB 2010 Paper #10-1328, K. Harries, B, Shahrooz, H. Russell, et al January 2010, 12 pages:** This paper, which was prepared as part of TRB's NCHRP 12-77 project: *Structural Concrete Design with High-Strength Steel Reinforcement***,** stated: **"***The study clearly demonstrates that the present AASHTO, and indeed ACI requirements for both straight bar tension development and hooked anchorage tension development may be extended to develop bar stresses of at least 125 ksi (860 MPa) for concrete strengths up to 10 ksi (69 MPa). In using higher strength steel, greater bar strain and slip will occur prior to development of the bar. The results of this study and previous work clearly indicate that confining reinforcement should always be used when developing, splicing or anchoring ASTM A1035 reinforcing steel."* The results reported in this paper will be part of NCHRP 12-77 Project Report 679, which will provide an evaluation of existing *AASHTO LRFD Bridge Design Specifications* relevant to the use of high-strength reinforcing steel and other grades of reinforcing steel having no discernable yield plateau. NCHRP Report 679

will include recommended language to the *AASHTO LRFD Bridge Design Specifications,* Sections 3, 5 and 9 that specifically permits the use of high-strength reinforcing steel with specified yield strengths not greater than 100 ksi.

7. **Use Of High-Strength Steel Reinforcement In Shear Friction Applications - Masters Thesis Univ. of Pittsburg- Gabriel Zeno - November 2009- (Pages 91):** This thesis reports the results of a study associated with Task 8.4b of the National Cooperative Highway Research Program (NCHRP) Project 12-77 *Structural Concrete Design with High-Strength Steel Reinforcement*. This study's test results showed that the shear friction mechanism occurs in stages and that the concrete component contributes to the majority of the shear friction capacity prior to cracking when the steel component develops. Therefore, the concrete and steel components of the shear friction mechanism do not act simultaneously as implied by the present AASHTO shear friction equation. In addition, the test results showed that, contrary to the assumptions of the AASHTO and ACI equations to calculate the shear friction capacity of concrete members, the interface steel reinforcement never reaches its yield strain. Therefore, the use of high-strength reinforcing steel does not affect the shear friction capacity of concrete members because the clamping force is a function of the elastic modulus of the steel rather than its yield strength. Based on these findings and using the experimental data from current and previous tests, an equation was proposed as an alternative to the existing AASHTO and ACI equations to calculate the shear friction capacity of concrete members. While the proposed equation is still semi-empirical, it represents the actual shear friction behavior better than the existing equations

8. **Bond Characteristics of ASTM A1035 Steel Reinforcing Bars - ACI Structural Journal, Jul/Aug 2009 - J. Jirsa, D. Darwin, S. Rizkalla, P. Zia, et al. (10 Pages): –** This paper states: **"***The study shows that using high-strength steel [ASTM A1035] alters the mode of failure from diagonal tension to shear compression failure and results in higher shear strength compared with using conventional steel. It was also found that the current ACI shear design provisions are unconservative for large-size concrete beams without web reinforcement".* Among the paper's conclusions are the following: "*The use of transverse reinforcement to confine the spliced bars allowed splitting cracks to develop along the spliced bars and spalling of the cover was more gradual."* – This conclusion is made when comparing beams with and without transverse reinforcement. "*By confining the ASTM A1035 spliced bars with transverse reinforcement, bar stresses at bond failure of up to 150 ksi (1035 MPa) were reached for No. 8 and No. 11 (No. 25 and No. 36) bars." … "The ACI Committee 408 equation provides a reasonable estimate of the strength for both unconfined and confined splices using a strength reduction factor (φ-factor) of 0.82 and design parameters (cover, spacing, and concrete strengths) comparable to those used in this test program. The design equations in ACI 318 are less conservative, with a large percentage of the developed/calculated strength ratios below 1.0, and should not be used for development and splice design with high-strength reinforcing steel in their present form*" (Copy of this paper may be obtained from the American Concrete Institute (ACI) Farmington Hills, MI)

9. **Rigid Pavement 100 KSI Steel Lane Tie Bar Substitution Analysis and Design - CME Transportation Group – July 2009 - Timothy Biel, P.E. (10 Pages):** This report provides an analysis and design methodology for substituting 100 ksi corrosion resistant MMFX 2 (ASTM A1035/AASHTO MP 18) bars for either lower strength (i.e. 60 ksi) coated or uncoated black steel bars. Design procedures provide a new economical procedure for optimizing lane tie bar materials and installation costs by utilizing MMFX 2's high strength and corrosion resistant material properties.

10. **Behavior of High-Performance Steel as Shear Reinforcement for Concrete Beams - ACI Structural Journal, Mar/Apr 2009 - M. Sumpter S. Rizkalla, P. Zia (7 Pages):** This document states: **"***This paper describes the behavior of high-performance (HP)[ASTM A1035] steel as shear reinforcement for concrete beams. HP steel is characterized by enhanced corrosion resistance and higher strength in comparison to ASTM A615-06 Grade 60 steel."... "Test results indicate that using HP steel reinforcement increases the shear capacity and enhances the serviceability in terms of strength gain and reduction of shear crack width. Current design codes can conservatively be used for the design of HP steel using a yield strength of 80 ksi (552 MPa)."* Among the paper's conclusions are the following: *"Direct replacement of conventional Grade 60 stirrups with ASTM A1035 steel*

*stirrups increased the shear load capacity of flexural members and enhanced the serviceability in terms of distributing cracks and reducing crack width." "Direct replacement of conventional Grade 60 longitudinal reinforcement with ASTM A1035 longitudinal reinforcement further increased the shear strength and enhanced serviceability;" "Shear crack widths were within the allowable limit of 0.016 in. (0.41 mm) using an increased service stress level of 48 ksi (331 MPa) for all beams reinforced with HP steel;" "The ACI, CSA, and AASHTO LRFD design codes can conservatively predict the shear behavior of concrete beams reinforced with HP steel using a yield strength of 80 ksi (552 MPa)." "Current research could not fully use the strength of ASTM A1035 steel stirrups beyond 80 ksi (552 MPa) because the failure was controlled by crushing of the concrete in the strut. Pairing high-strength concrete with ASTM A1035 steel could provide a better use for HP steel;"* (Copy of this paper may be obtained from the American Concrete Institute (ACI) Farmington Hills, MI.)

**11.** **Mechanical Properties of ASTM A1035 High Strength Steel Bar Reinforcement - Wiss, Janney, Elstner Associates, Inc. - WJE No. 2008.9901.0 –S. Graham, C. Paulson - December 2008 (49 pages)**: This report indicates the results of laboratory tests to measure mechanical properties of ASTM A1035 steel reinforcing bars with specified yield strengths of 100,000 psi (Grade 100) and 120,000 psi (Grade 120). The tests were performed in support of the activities of ACI Innovation Task Group 6 (ITG-6) - *High Strength Reinforcing Steel.* Tests measured axial tension stress (ASTM A370), at 0.0035 in/in strain, yield strength (0.2% offset), and ultimate tensile strength, along with axial compression (ASTM E9) stress at 0.0035 in/in strain, and yield strength (0.2% offset). The following table compares the average tensile test results to ASTM A1035 required values. Individual test specimen elongation curves are included as part of the report. Modulus of Elasticity (E) tests were conducted in accordance with ASTM E111, indicating ASTM A1035's E value of 29,000 ksi is similar to carbon steel.

Average Tensile Test Properties of ASTM A1035 Bars

| ASTM A1035 Bar Grade | Stress corresponding to extension of 0.0035 in./in. | Yield strength (0.2% offset) (ksi) | Tensile Strength (ksi) | Total Elongation (percent) |
|---|---|---|---|---|
| Ave Gr 100 Bar Tests | 92.4 | 126.2 | 158.1 | 9.0 |
| A1035 Gr 100 Spec | 80 | 100 | 150 | 7 |
| Ave Gr 120 Bar Tests | 94.4 | 137.0 | 172.9 | 10.6 |
| A1035 Gr 120 Spec | 90 | 120 | 150 | 7 |

**12.** **Analytical Evaluation of Structural Concrete Members with High-Strength Steel Reinforcement - Masters Thesis – University of Cincinnati – E. Ward – December 2008 (352 pages):** This report investigates the use of reinforcing steel, which exhibits no well-defined yield plateau, in the design of structural concrete members through analytical studies. Steel reinforcement considered includes ASTM A1035, A955 (stainless steel), A706, A496, and A82. This study made the following conclusions and observations: "*The analytical studies suggest that concrete members designed with a yield strength of 100 ksi behave similarly to members designed with a yield strength of 60 ksi. Therefore, allowing concrete members to be designed with reinforcing bars having a yield strength of 100 ksi is deemed reasonable. Because the stress-strain diagram for A1035 reinforcing steel has no well-defined yield plateau, the currently accepted strain limits of 0.005 and 0.002 were reevaluated. … the strain limits for tension-controlled behavior and compression-controlled behavior of members reinforced with A1035 bars were found to be, respectively, 0.008 and 0.004. Columns designed with A1035 transverse reinforcement and using the current equations for transverse steel spacing behave in the same manner as columns designed with A615 reinforcement. A1035 shear reinforcement with a yield strength of 100 ksi provides adequate shear resistance while maintaining acceptable diagonal crack widths and pattern."*

**13.** **Towards Earthquake-Resistant Concrete Structures With Ultra High-Strength Steel Reinforcement – 14th World Conference on Earthquake Engineering–A. Lepage, H. Tavallali, S.**

**Pujol, J. Rautenberg - October 2008 – (9 pages):** This paper describes a collaborative experimental program between Penn State University and Purdue University is underway to investigate the deformation capacity of reinforced concrete members reinforced with ultra high-strength steel reinforcement well in excess of 80 ksi (550 MPa). Test beams and columns are subjected to combined shear, moment, and axial load, applied through controlled increasing displacement reversals. Main variables of the experiments include: yield strength of main longitudinal reinforcement, 60, 100, and 120 ksi [410, 690, and 830 MPa]; yield strength of transverse reinforcement, 60, 120, and 185 ksi [410, 690, and 1280 MPa]; spacing of transverse reinforcement, *d*/2 and *d*/4; volume fraction of steel fibers, 0 and 1.5%; ratio of compression-to-tension longitudinal reinforcement, $\rho'/\rho$ = 0.5 and 1.0; and type of loading, monotonic and cyclical. Within the range of code-accepted limits on reinforcement ratios, shear stress levels, and length-to-depth ratios, it is expected that the deformation capacity of ultra high-strength steel reinforced concrete members is going to be increased by (1) reductions in spacing of transverse reinforcement; (2) increases in the ratio of compression-to-tension longitudinal reinforcement, and/or (3) addition of engineered fibers.

14. **Flexural Strength Design of Concrete Beams Reinforced with High-Strength Steel Bars - ACI Structural Journal, Sep/Oct 2008 - B. Mast, M. Dawood, S. Rizkalla, P. Zia (8 Pages):** This paper presents a methodology for the flexural strength design of concrete beams reinforced with high-strength reinforcing steel that conforms to the requirements of ASTM A1035-07 (MMFX 2 bars). The design method is based on simple analysis techniques that satisfy fundamental principles of equilibrium and compatibility. Strain limits for tension-controlled sections and compression-controlled sections are proposed that are consistent with the approach of the current and past ACI 318 Codes. The proposed method is compared with experimental results previously reported by others. The application of the proposed method is demonstrated by a numerical design example. (Copy of this paper may be obtained from the American Concrete Institute (ACI) Farmington Hills, MI)

15. **Shear Behavior of Concrete Beams Reinforced with High Performance Steel Shear Reinforcement - Masters Thesis - North Carolina State Univ. – Constructed Facilities Laboratory – A. Munikrishna – July 2008 (152 pages):** This paper reports on a program utilizing the strength of ASTM A1035 (MMFX 2) as shear reinforcement for reinforced concrete flexure members at selected yield strengths of 80 ksi and 100 ksi in comparison to conventional reinforcement designed at 60 ksi, which were tested to failure under static loading conditions. Conclusions from this program are: *"1. The shear capacity of flexural members can be achieved with lesser amount of MMFX stirrups … attributed to the higher tensile strength of the MMFX steel in comparison to Grade 60 steel. 2. The beams reinforced with MMFX steel exhibited the same deflections at service load as the beam reinforced with Grade 60 steel. 3. Shear crack widths measured for all tested beams reinforced with MMFX steel designed with yield strength of 80 ksi and 100 ksi were within the allowable limit specified by the ACI Code. 4. The ACI, CSA and AASHTO LRFD design codes can conservatively predict the shear behavior of concrete beams reinforced with MMFX steel. 5. Design stress up to 100 ksi can be for MMFX transverse reinforcement for flexure members without impairing the ultimate load carrying capacity and serviceability."*

16. **Review of Port Authority of NY & NJ (PANYNJ) Testing of MMFX Reinforcing Steel, #11 rebars – S. K. Ghosh (S. K. Ghosh) – April 2008 (Pages 44):** This report is based on the included PANYNJ's report and "Material Test Report – ASTM A1035 – Grade 120." The review notes A1035 Grade 120's certified: tensile, yield (0.0035 strain and 0.2% offset) and elongation at facture properties, indicating that all 30 test specimens exceeded the certified values. The author concludes: "*Overall, I think the results are quite reassuring. The shape of the stress-strain curve should not matter until we get into high-seismic applications. And it can be accounted for in design. There is now an Innovation Task Group (ITG) within ACI, working on a comprehensive design document for concrete structural members using MMFX steel. Such a document is expected to be available within the next year or so."*

17. Shear Behavior of Large Concrete Beams Reinforced with High-Strength Steel **- ACI Structural Journal, Mar/Apr 2008 – T. Hassan, Rizkalla, P. Zia et. al. (7 Pages):** This paper states: **"***The study shows that using high-strength steel alters the mode of failure from diagonal tension to shear*

*compression failure and results in higher shear strength compared with using conventional steel. It was also found that the current ACI shear design provisions are unconservative for large-size concrete beams without web reinforcement."* Among the paper's conclusions are the following: "*Despite the reduction in the reinforcement ratio by 40%, the shear strength of concrete beams reinforced with high-strength steel was significantly higher than that of the beams reinforced with Grade 420 MPa (60 ksi) steel. The high yield strength of the material maintained the capacity of the tension tie, and thus enabled the beams to resist more load until crushing of the diagonal strut occurred ;" "A significant reserve in strength was observed for beams reinforced with high-strength steel after diagonal cracking. Failure was due to crushing of the diagonal concrete strut at much higher loads compared with beams reinforced with conventional steel;" "The ACI 318-05 simplified expression for the shear contribution of concrete is unconservative for large-size concrete beams without web reinforcement. The expression needs to account for the size effect and the reinforcement characteristics.*" (Copy of this paper may be obtained from the American Concrete Institute (ACI) Farmington Hills, MI)

18. **Behavior of Concrete Bridge Decks Reinforced with High-Performance Steel - ACI Structural Journal, V. 105, No. 1, January-February 2008 – G. Lucier, S. Rizkalla, P. Zia, Paul, H. Hatem (9 pages):** This paper describes the behavior of concrete bridge decks reinforced with MMFX 2 (ASTM A1035) high-performance (HP) steel, characterizing its high strength in comparison with conventional ASTM A615-06 Grade 60 steel The paper makes the following conclusions: *"1. The ultimate load-carrying capacity of the three bridge decks investigated in this study was on the order of 10 times the service load prescribed by the AASHTO Specifications; 2. Punching shear was the primary mode of failure for the three bridge decks. Due to continuity used in the test models, flexural-shear failure was observed as a secondary mode of failure; 3. The cracking load of the three tested bridge decks was more than twice the service load prescribed by the AASHTO Specifications. Hence, under service load level, the three bridge decks behaved as uncracked sections. Therefore, using 33% less HP [ASTM A1035] steel should not alter the serviceability behavior of concrete bridge decks; 4. The bridge deck reinforced with 33% less HP steel developed the same ultimate load-carrying capacity as that reinforced with Grade 60 steel. This performance is attributed to the higher strength of HP [ASTM A1035] steel compared with Grade 60 steel; and 5. Behavior of bonded HP [ASTM A1035] steel bent bars is similar to the behavior of straight bars. Debonded bent bars exhibit similar behavior to straight bars, including the linear and the nonlinear behavior up to a strain of 1.5%. Its ultimate strength, however, is reduced by 6% and its ultimate strain by 70%." The papers also makes the following design guideline recommendations: "1. Substituting HP [ASTM A1035] steel directly for conventional Grade 60 steel in a design,…is a conservative approach; 2. HP [ASTM A1035] steel can be used as the main flexural reinforcement for cast-in-place concrete bridge decks at a reinforcement ratio corresponding to 33% less than that required for Grade 60 steel. Therefore, design of reinforced concrete bridge decks using HP [ASTM A1035] steel can use a yield stress of 90 ksi (621 MPa) for the HP [ASTM A1035] steel bars; 3. Reduced reinforcement ratio of HP [ASTM A1035] steel shall satisfy all minimum reinforcement ratios prescribed by the AASHTO Specifications. In addition, the reduced reinforcement ratio of HP [ASTM A1035] steel must comply with the crack control requirement of the AASHTO Specifications; and 4. HP [ASTM A1035] steel bars can be bent up to 90 degrees without reducing their ultimate strength or strain provided that the bend is fully encased and bonded to concrete."*

19. **Behaviour of Concrete Deep Beams With High Strength Reinforcement - Structural Engineering Report 277 - University of Alberta -.J. Garay-Moran, A. Lubell - January 2008- (315 Pages):** This paper reports on the testing of large-scale beams containing ASTM A1035 steel, at an effective yield strength of 860 MPa (125 ksi) as the main tension reinforcement. The program's testing examined the adequacy of CSA A23.3-04, ACI 318-05 and Eurocode 2 design models predict the behavior of reinforced concrete deep beams containing high strength steel reinforcement. The report conclusions indicated: "*Capacity predictions made using the Strut and Tie Method provisions from the CSA A23.3-04, ACI 318-05 and Eurocode2 were in good agreement with the results from deep beam specimens constructed with ASTM A1035 reinforcing steel. … Current design yield strength limits (500 MPa for CSA A23.3-04 and Eurocode 2 and 550 MPa for ACI 318-05) can be increased to magnitudes closer to the effective yield strength according to the 0.2% offset method*."

20. **Bond Behavior of MMFX (ASTM A 1035) Reinforcing Steel – Cooperative Research Program – NC State Univ. - S. Rizkalla et. al – Univ. of Kansas, D. Darwin et. al. – Univ. of Texas Austin, J. Jirsa et. al – November 2007 (32 pages):** This report summarizes the findings of a cooperative research program on the bond behavior of MMFX (ASTM A1035). Findings indicate, based on sixty-six MMFX (ASTM A 1035) test specimens, that: *"… ACI 318-05 code design equation overestimates the strength of unconfined spliced MMFX bars, especially for high strength concrete. On the other hand, the bond equation for design recommended by ACI Committee 408 (as best-fit to the database but including a strength-reduction factor φ of 0.82) underestimates the stresses for unconfined spliced bars for all but two out of 31 cases, but with less scatter than those obtained using the ACI 318-05 equation. … ACI Committee 408 equation with a strength-reduction factor φ of 0.82 is recommended for development and splice design using MMFX steel."*

21. **Report on Structural Design and Detailing for High-Strength Concrete in Moderate to High Seismic Applications - ACI ITG – 4.3R-07 - ACI Innovation Task Group 4 (S. K. Ghosh, Chairman) - 2007 (Pages 62)**: This report presents a literature review on seismic design using high-strength concrete. Included as part of the report are a series of recommended modifications to "Building Code Requirements For Structural Concrete" ACI 318-05. Subsequently, ACI 318-08 allowed an upper limit of 100 ksi (690 MPa) on the yield strength of high-strength confinement reinforcement for members resisting earthquake-induced forces in structures assigned to SDC (Seismic Design Category) D, E, or F. (Copy of this report may be obtained from American Concrete Institute (ACI), Farmington Hills, MI)

22. **High-Strength Rebar Called Revolutionary – McGraw Hill Construction - Engineering News Record - July 22, 2007 (2 pages)** This magazine article describes the first use of MMFX 2 (ASTM A1035) rebar in a high seismic zone (Seattle, WA) high rise building for column and shear wall boundary element confinement. The article notes that use of ASTM A1035 at 100 ksi design, reduced rebar requirements by 40% in comparison to conventional design practices. In addition, use of ASTM A1035 rebar simplified the project's beam to column connections, reducing the construction time to make these connections by up to 25%.

23. **Behavior of High Performance Steel as Shear Reinforcement for Concrete Structures – Final Report – North Carolina State Univ. – Constructed Facilities Laboratory – M. Sumpter, S. Rizkalla, P. Zia – June 2007 (91 pages):** This report concludes that: *1. "Direct replacement of conventional Grade 60 longitudinal reinforcement with MMFX [ASTM A1035] longitudinal reinforcement showed an optimum design by further increasing the shear strength and enhancing serviceability." 2. "The use of MMFX [ASTM A1035] steel, with a yield strength of 80 ksi, increases the allowable service stress level to 48 ksi. Shear crack widths measured for all tested beams reinforced with MMFX steel were within the allowable limit specified by the ACI Code."*

24. **Evaluation of Bond Characteristics of MMFX Steel – North Carolina State Univ. – Constructed Facilities Laboratory, Technical Report No. RD-07-02 – H. Seliem, A. Hosny, S. Rizkalla – June 2007 (71 pages):** This report concludes that: A. Stress levels of 90 and 70 ksi can be achieved by No. 8 and No. 11 ASTM A1035 spliced bars without the use of transverse reinforcement (confinement). B. Spliced bar transverse reinforcement was able to develop a stress of 150 ksi for No. 8 and No. 11 A1035 bars and increased the ultimate load and ductility of the beams. C. Increasing the splice length, proportional to the square root of the ratio of the splice length and the bar diameter, increased the strength of the splice. D. Increasing the concrete cover by the square root of the ratio of the cover to the bar diameter, increases the stress developed in the spliced bars. E. Use of ACI 408 equation provides better prediction of stresses and less scatter than use of the ACI 318-05 equation.

25. **Effects of Confinement and Gauging on the Performance of MMFX High Strength Reinforcing Bar Tension Lap Splices – Masters Thesis - University of Texas (Austin) – K. Hoyt – May 2007 (65 pages):** This program reports on testing of beam-splice specimens using ASTM A1035 No. 8 bar splices in a constant moment region, with varied amounts of No. 4 Grade 60 transverse reinforcement

and spacing. It was found that: 1. ACI 408 equation provided a good estimate of failure stresses at high stress levels, but with predicted lower strengths than measured in beams with confinement. 2. The linear nature of the current development length code equation is acceptable. 3. Behavior of the interior splices was nearly identical to that of the exterior splice. 4. High steel stresses resulted in greater crack widths than currently acceptable for service load stresses using Grade 60 steel. The equation used to determine serviceability limits only appears to be effective for stress levels of 60 ksi or less.

**26.** Performance of Tension Lap Splices with MMFX High Strength Reinforcing Bars **- University of Texas (Austin) – G. Glass – May 2007 (141 pages):** This paper reports on tests from beam-splice specimens at the University of Texas, North Carolina State University, and the University of Kansas, making the following conclusions concerning ASTM A1035 reinforcement: A. A1035 lap splices developed bar stresses up to 155 ksi. B. ACI 408 development length equation provided relatively accurate estimates of failure stresses for splices with and without confining transverse reinforcement. C. ACI 318 and AASHTO LRFD development length equations provided unconservative calculated failure stresses for unconfined splices, while providing reasonable calculated failure stresses for confined splices. D. The addition of confining transverse reinforcement provided an increase in failure stress and was greater than predicted by either the ACI 408 or ACI 318 equation. E. The addition of confining transverse reinforcement provided an increase in beam deflections at failure; and was greater than proportional to the increase in confining reinforcement. F. Service level crack widths were greater than the limits used as a basis for serviceability provisions included in pre-1999 editions of ACI 318. G. Bar splices with stresses greater than 75 ksi should be designed using the ACI 408 development length equation with the modification factor, $\phi$, equal to 0.82. H. A minimum level of transverse reinforcement should be included for all splices above 75 ksi except for those with No. 5 or smaller bars with large bar spacing and cover.

**27.** Behavior of Concrete Bridges Reinforced with High-Performance Steel Reinforcing Bars **– Dissertation – North Carolina State Univ. – H. Seliem – 2007 (287 pages):** This paper describes the testing of reinforced concrete structural members with MMFX 2 (ASTM A1035) reinforcing bars and made the following conclusions: "*Yield strength of 90 ksi (621 MPa) can be used in design of bridge decks reinforced with MMFX steel reinforcing bars without impairing the ultimate load carrying capacity or altering the serviceability behavior. … Up to #8 (NO. 25), spliced MMFX reinforcing bars can develop a stress of 90 ksi (621 MPa) without the use of confinement by transverse reinforcement. … Minimum amount of transverse reinforcement is required to confine spliced bars to ensure a ductile behavior of concrete members with spliced bars as well as sufficient warning prior to failure. … MMFX steel bars can be bent up to 90 degrees without impairing their ultimate strength if they are fully bonded to concrete. "*

**28.** Behavior of Minimum Length Splice of High Strength Reinforcement **– Honors Thesis - University of Texas (Austin) – K. Donnelly – 2007 (37 pages):** This paper describes testing of MMFX (ASTM A1035) beams, using No. 5 MMFX bars spliced with minimum splice lengths and varying levels of transverse reinforcement. It was concluded that splice length designs using ACI 408 equations with transverse reinforcement were more accurate than use of ACI 318, while ACI 318 designs were better suited for unconfined splice designs.

**29.** Fatigue Behaviour of MMFX Corrosion-Resistant Reinforcing Steel **– S. DeJong, C. MacDougall Department of Civil Engineering, Queen's University, Ontario, Canada 7th International Conference on Short and Medium Span Bridges, Montreal, Canada - 2006 (11 pages):** This study indicates that MMFX 2 was tested to have a fatigue life of $1 \times 10^6$ cycles at a stress range of approximately 310 MPa [45 ksi], compared to conventional steel $1 \times 10^6$ cycles at a stress range of approximately 166 MPa [24 ksi]. The study made the following conclusion: "*Thus, MMFX exhibits superior fatigue resistance under constant amplitude loading in an air environment than conventional steel reinforcing bars*."

**30.** Bond Characteristics of High-Strength Steel Reinforcement **- ACI Structural Journal Vol. 103, No. 6 - R. El-Hacha, H. El-Agroudy, S. Rizkalla - November - December 2006 (12 pages):** This paper summarizes the findings of a study concerning the bond characteristics of MMFX 2 steel bars, based on testing of a series of beam end specimens, comparing MMFX 2 bars to A615 Grade 60. The bond behavior of the MMFX 2 bars was found to be similar to that of A615 Grade 60 ksi steel up to the proportional limit of 80 ksi, using splice length to bar diameter ($L_s/d_b$) of 30 db. A splice length of 45 $d_b$ was found to be adequate for a MMFX 2 bar yield strength of 110 ksi. (Copy of this paper may be obtained from American Concrete Institute (ACI), Farmington Hills, MI).

31. **Shear Behavior of Concrete Beams Reinforced with MMFX Steel without Web Reinforcement – S. Rizkalla, H. Seliem, et. al – Technical Report: IS-06-08 - NC State Univ. – April 2006 (13 pages)**: This study tested large size concrete beams reinforced with MMFX steel without web reinforcement under static loading up to failure to evaluate their shear behavior. Among the report's conclusion were: "*reduction of the longitudinal reinforcement area (40 percent less) of MMFX [ASTM A1035] steel used, the shear capacity of the beams with a/d ratio of 1.79 and reinforced with MMFX steel was 80 percent higher than those reinforced with grade 60 steel. For the beams with a/d ratio of 2.6, the beam reinforced with MMFX steel had a capacity of 12 percent more than the beam reinforced with conventional Grade 60 steel. The higher failure loads achieved by the beams reinforced with MMFX steel compared to the beams reinforced with Grade 60 steel is due to the high-strength characteristics of the MMFX steel which is more than twice of the Grade 60 steel.*"

32. **Application of ASTM A 1035 MMFX Steel Reinforcement in Building Applications: An Appraisal – S.K. Ghosh - S.K. Ghosh Associates Inc. - April 2006 (19 pages):** This report examines various design aspects for use of MMFX 2 rebar in building structural applications, relating the design to appropriate ACI 318 Sections. Conclusions of the report describe considerations for: a. allowable flexural tension design at 100 ksi, 80 ksi in flexural compression, and 60 ksi for shear strength, and b. one-way slab tension design at 100 ksi limitations, among design aspects presented.

33. **Evaluation of MMFX Steel For NCDOT Concrete Bridges – FHWA/NC/2006-31, NCDOT Report 2004-27 – S. Rizkalla, P. Zia et. al. – December 2005 (131 pages):** This publication states the following conclusions based on testing of full-scale bridge deck sections and corrosion tests at North Carolina State University: *"1. Substituting MMFX steel directly for Grade 60 steel in a design … is an overly-conservative approach. 2. MMFX steel [ASTM A1035] can be used as the main flexural reinforcement for cast-in-place concrete bridge decks at a reinforcement ratio corresponding to 33% less than that required for Grade 60 steel. Therefore, a design of reinforced concrete bridge decks using MMFX steel may utilize an equivalent yield stress of 90 ksi for the MMFX steel bars. 3. Design of concrete bridge decks utilizing the high tensile strength characteristics of the MMFX steel should satisfy all minimum reinforcement ratios required by the AASHTO LRFD Bridge Design Specifications as well as the serviceability requirements of the specifications. 4. MMFX steel [ASTM A1035] has a much lower corrosion rate compared to conventional Grade 60 steel. Therefore, the use of MMFX steel could increase the service life of concrete bridges and lower repair costs."*

34. **MMFX Rebar Evaluation for I-95 Service Road Bridge 1-712-B – University of Delaware- M. Chajes, M. McNally et. al – March 2005 (162 pages):** The following is a summary of results from the four point bending tests of the "standard" beam [60 ksi yield design], "MMFX4" beam [same reinforcement as 60 ksi yield design], "MMFX2" beam [100 ksi yield design], and the "CFRP" beam [ACI 440.1 R-01 design guideline]. Both ultimate loads and mode of failure were predicted with good accuracy using traditional equations for the MMFX reinforced beams. Yield deflection calculations were smaller and load at L/800 calculations were greater than the actual measured yield deflection and load at L/800 values for all beams. This may have been due to early cracking. All beams cracked at a similar load level. Both MMFX beams failed in the desired mode. For both beams, the MMFX rebar yielded prior to failure.

35. **Tensile Test – Coupled Reinforcing Steel Bars (w/ Stress vs. Strain Graphs) – Smith Emery Laboratories – February 2005 (26 pages):** This report covers the successful testing of #4, #8, #9, #10, and #11 MMFX Bars fitted with Barsplice® couplers. The report covers test results and photographs of tested samples.

36. **[Tensile Testing of Mechanical Bar Splices for MMFX Steel] – Florida DOT - Antonis Michael - February 2004 (15 pages):** Two types of commercially available mechanical splices for #6 bars were tested to establish compatibility with MMFX 2 rebar. Both splice types exceeded the capacity of the MMFX bar and failure occurred in the steel bar. The average stress in the bars at failure was 173.6 ksi.

37. **[Seismic Behavior of Bridge Columns Built Incorporating MMFX Steel] – University of California, San Diego – Report No. SSRP – 2003/09 – Bernd Stephan, Jose Restrepo, Frieder Seible – October 2003 (37 pages):** Testing was performed on two similar column units constructed using ASTM A706 Grade 60 and MMFX 2 reinforcing bars. The ASTM unit was designed according to the CALTRANS Bridge Design Specifications (July 2002) and the MMFX unit incorporated MMFX's design strength resulting in approximately half the steel requirement of the ASTM unit. The tests conclusively showed that both units can be designed to form ductile flexural plastic hinges and can sustain drift levels of approximately 4% without failure and complied with CALTRANS column seismic failure criteria. (See also – "**Seismic Testing of Bridge Columns Incorporating High-Performance Materials" – ACI Structural Journal Vol. 103, No. 4 - J. I. Restrepo, F. Seible, B. Stephan, M. J. Schoettler - July-August 2006 - 9 pages**) (Copy of this paper may be obtained from American Concrete Institute (ACI), Farmington Hills, MI)

38. **Development Length of Micro-composite (MMFX) Steel Reinforcing Bars Used In Bridge Applications - University of Massachusetts Amherst – S. Peterfreund - June 2003 (59 pages):** This study reports on the laboratory testing of beams using MMFX (ASTM A1035) No. 4 and No. 5 bars for tensile reinforcement, varying the lap splice length in the constant moment region. Tests were compared to ACI 318-02 development length code (Equation 6-1); and the tested lap splice lengths were determined to be *"more than adequate to develop the flexural capacity of the beam"*

39. **Fundamental Material Properties of MMFX Steel Rebars - North Carolina State University, NCSU-CFL Report No. 02-04 - Raafat El-Hacha Ph.D. and Sami Rizkalla Ph.D. - July 2002 (61 pages):** This report provides preliminary data for the fundamental mechanical material properties of MMFX steel reinforcing rebars. The testing focused on the mechanical properties in tension and in compression, shear strength, fatigue strength, effect of bend on tensile strength of the bent rebar (stirrup), bond strength and development length, and the behavior of MMFX rebars as compression steel in reinforced concrete columns.

40. **Bending Behavior of Concrete Beams Reinforced with MMFX Steel Bars - Constructed Facilities Center - West Virginia University - Vijay P.V., Ph.D. et. al - July 2002 (34 pages):** Theoretical moments can be predicted very well using current theories. Beams exhibited a significant amount of elongation before compression failures (secondary) occurred. Deflection values can be well approximated up to a stress level of 75 ksi (within the serviceability stress limits) using actual stiffness of the bar at a given stress level and also by accounting the corresponding increase in strain as compared to $Es = 29x10^6$ psi. The crack width values evaluated by using stress in tension steel and also by accounting for the corresponding strain value at that stress level led to very good prediction of crack widths.

## C. Supplemental References

1. "**Product Guide Specification – Microcomposite (MMFX 2) Steel Uncoated, Plain and Deformed Bars For Concrete Reinforcement**" **– MMFX Technologies Corporation – September 2011 (10 pages):** This guide product and construction specification provide a guideline to assist design engineers in specifying MMFX 2 rebar, referencing applicable codes and standards that apply to it, along with MMFX 2's material properties and recommendations for fabrication, and field installation.

2. **ASTM A1035/A1035M-09 Specification "Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement" - American Society For Testing And Materials - West Conshohocken, PA 19428 – 2009 (5 pages):** This ASTM specification, which MMFX 2 rebar qualifies as, was prepared by ASTM's 1.05 Committee based on material properties that MMFX 2 rebar possesses. Bars are of two minimum yield strength levels as 100 ksi [690 MPa], and 120 ksi [830 MPa] designated as Grade 100 [690] and Grade 120 [830], respectively. Document available through ASTM (American Society for Testing and Materials).

3. **AASHTO MP 18 M/MP 18-09 Standard Specification: "Uncoated, Corrosion-Resistant, Deformed and Plain Alloy, Billet-Steel Bars for Concrete Reinforcement and Dowels" – 2009 (15 pages):** This specification was prepared in conjunction with AASHTO SOM (Subcommittee on Materials) Technical Section 4g "Concrete Reinforcement". ASTM A1035 (MMFX 2) and stainless steel reinforcing bars are included in this specification, which defines corrosion resistant bars by testing them in accordance with the document's Annex A, **"Test Method for Comparative Qualitative Corrosion Characterization of Steel Bars Used in Concrete Reinforcement."** Document available through AASHTO (American Association of State Highway and Transportation Officials).

4. **Quality Assurance Manual 5**th Edition **– MMFX Technologies Corporation –August 2011 (12 pages): This manual provides the quality control basis for the manufacture of all MMFX 2 Ste**el bars while ensuring that the manufacturing practice**s and tolerances used in MMFX 2's production, provide b**oth the certified chemical composition and mechanical properties are met or exceeded.

5. **Smith Emery Laboratories – Certificates of Compliance**

   **ASTM A615/615M Grade 75 Deformed Reinforcing Steel – February 2003**
   **ASTM A1035/A1035M Deformed Reinforcing Steel - August 2004**
   **Smith-Emer**y Laboratories – P. John Latiolait:

   These test results took place at an ICC (International Code Council) certified commercial material testing laboratory; and confirm that MMFX 2 rebar meets or exceeds the requirements for ASTM A615/615M Grade 75 and ASTM A1035/A1035M for bar sizes 4 through 11.

6. **Chemical, Mechanical Analysis, Tests and Measurements performed on Bar numbers 3, 4, 5, 6, 7, 8, 9, 10 and 11 MMFX-2 (AASHTO MP 18/ASTM A 1035) grade 100 steel rebar samples – Professional Service Industries, Inc. (PSI)- PSI Project: 0689492-2a- Paul Irish - June 2011 (6 pages)**: This test report provides results of mechanical and other testing of MMFX 2 (AASHTO MP 18/ASTM A1035) bar sizes 3 through 11, certified to AASHTO MP 18 and ASTM A1035 in accordance with AASHTO MP 18 Sections 6, 7, 8, 9, 10, 12 13 and 21. All test bars met the requirement of AASHTO Standard Specification M18 as indicated in the test data table included in the report.

7. **MMFX 2 (ASTM A 1035, GRADE 100) Steel Rebar Corrosion Performance Testing in Accordance with AASHTO MP 18M/MP 18-09 – Tourney Consulting Group (TCG) – Report TCG # 11072- August 2011 (29 pages)** This test report indicates the result of corrosion test of AASHTO MP 18/ ASTM A1035 certified bars in accordance with AASHTO MP 18's – Annex A polarization resistance and potentiodynamic polarization tests on No. 3 through No. 11 test bars. Results of these corrosion tests indicated that all bars met the corrosion test requirement s of AASHTO MP 18

In addition, micrographs of etched specimens were taken as an index for confirmation of the microstructure for each of the test bars. The metallographic examination showed Martensite, fine grain microstructure structure for each of the MMFX 2 test bars at a 500x magnification