Use of Vitreous Enamel Coated Bars in Structural Concrete Subjected to Corrosive Environment

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Abstract: Steel-reinforced structural concrete is a common building material that has proven itself to be versatile, economical and affordable. Under a spectrum of operating conditions and circumstances, steel-reinforced concrete can be categorized as being both strong and durable thereby enabling in maintenance-free service during its life span. However, corrosion, or environment-induced degradation, of the steel reinforcement embedded in concrete is of concern particularly in aggressive environments, to include both aqueous and gaseous. A gradual degradation of the steel within concrete causes several problems ranging from cracking to spelling of the concrete coupled with reduced bond strength between the steel bars and the surrounding concrete. A reduction in bond strength contributes to a gradual loss in strength coupled with increased deformation, ease of initiation of flaws spanning both microscopic and macroscopic, and concurrent growth of the flaws through the microstructure. An evaluation of steel reinforcing bars coated with a new and emerging coating material is presented in this paper. Two potential applications for this type of coated bars include (a) the role of enamel-coated dowel bars for use in concrete pavements, and (b) enamel coated bars as viable reinforcement for structural concrete. The results of the study are aimed at evaluating and understanding the influence of environment on corrosion resistance of enamel coated steel reinforcing bars with concomitant influence on mechanical performance of reinforced concrete structure is presented, and comparisons are made with the performance of structural concrete reinforced with conventional steel reinforcing bars. Structural tests on beam specimens reinforced with enamel-coated steel reinforcing bars demonstrated the role of vitreous enamel coating on steel reinforcing bars and proved that the performance of reinforced concrete beams with such bars is marginally better in terms of improved flexural strength and shear strength.

Keywords: Corrosion resistant coating, vitreous enamel-coated steel reinforcing bars, flexural strength of beams, corrosion tests.

1. INTRODUCTION

In the period spanning the last four decades, since the early 1980's, sustained research and development efforts have been made with the primary objective of both understanding and determining a potentially viable solution for the problem of corrosion, experienced by steel dowel bars when embedded in concrete pavements and for steel-reinforced concrete structures. This certainly provided the much-needed interest, inclination, inspiration and impetus for not only engineering the development but also ensuring the emergence of methods, such as the use of:

(i) Galvanized bars,

(ii) Stainless steel bars,

(iii) Cathodic protection,

(iv) Coated bars,

(v) Non-metallic bars such as fiber-reinforced polymer bars.

These are attractive, commercially viable and economically affordable alternatives to steel-reinforced bars so as to minimize the problem due to environment-induced degradation, or corrosion, experienced by the reinforcing material. Up until now, a spectrum of studies have shown that the use of galvanized bars, stainless steel, epoxy coated bars did not prove to be completely effective in either minimizing or obviating the problems arising from environment-induced degradation. Such measures also add premium to the cost of the structures.

The technique of using coatings as a commercially viable alternative to minimize material-environment interactions and concomitant degradation has been demonstrated to be promising. In this connection, several researchers and scientists working independently on this aspect have attempted to both engineer and recommend the use of a new and improved type of corrosion resistant enamel coating for purpose of both ease of application and eventual use on steel dowel bars that are used in concrete pavements. Any new and improved coating must be

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experimentally evaluated with the primary purpose of establishing its intrinsic resistance to degradation induced by the surrounding environment. Due to its non-metallic nature, the coating by itself is both impermeable and resistant to environmental attack. Any evidence of the occurrence of corrosion initiation and resultant growth, or propagation, would be facilitated should the coating have fine microscopic cracks and/or an array of defects [1].

The purpose of cover concrete is to seal and/or protect the steel reinforcements from degradation induced by the environment stemming from prolonged exposure to the environment, spanning a range of aggressiveness. This then makes the reinforced concrete structure to function effectively as a long-term viable and reliable structure [2]. The reinforced concrete (RC) structures when exposed to an aggressive environment, such as de-icing salt, are easily susceptible to premature deterioration necessitating a need for regular maintenance. A key factor responsible for material-environment interactions often resulting in the onset of this problem and concomitant effects is chloride-induced corrosion of the steel reinforcements. The occurrence of gradual corrosion of the steel bar-reinforced concrete structures does allow the expansive corrosion products to induce tensile stress in the surrounding concrete. When the local tensile stresses become large it favors the initiation of cracking at both the fine microscopic level and macroscopic level culminating in a gradual deterioration of the reinforced concrete structure [3].

2. REINFORCED CONCRETE STRUCTURE-ENVIRONMENT INTERACTION

In recent years, reinforced concrete (RC) has become a common building material primarily because it can be easily categorized as being both versatile and economical among several other attributes it must offer. Under a spectrum of operating conditions, reinforced concrete provides a synergism of strength and durability to ensure maintenance-free service over a lengthy life span. However, material-environment interactions and concomitant degradation, or corrosion, is a problem of concern in aggressive environments spanning both aqueous and gaseous. A gradual deterioration of the steel reinforcement that is embedded in concrete due to interactions with environment does induce a spectrum of problems such as:

I. Cracking,

II. Spalling, and,

III. Weakening of the bond between the reinforcing steel bars and the surrounding concrete.

Reduced bond strength results in reduced moment strength flexural members coupled with preferential susceptibility to enhanced deformation and resultant growth of both the fine microscopic and macroscopic cracks through the reinforced concrete structure [4-8].

In this connection, several projects have been undertaken to study the use of corrosion resistant reinforcing bars in concrete. A few such bars that are currently available [9-15] include the following:

(a) Stainless steel rebar,

(b) MMFX rebar,

(c) Galvanized rebar,

(d) Dual-coated Z-Bar,

(e) Epoxy-coated bar,

(f) Fiber-Reinforced Polymer (FRP) composite rebar, and,

(g) Stainless steel-clad bar.

While each type of these bars has noticeable corrosion resistant properties to offer, there does exist a few to several disadvantages associated with each type. For example: (i) the MMFX bars lack ductility when compared one-on-one with the other steel bars; (ii) The FRP bars can be characterized by their low modulus of elasticity, low creep rupture strength, and linear stress-strain behavior up until failure.

Epoxy-coated bars are commonly chosen for use in several environmentally sensitive and/or corrosion susceptible applications. Recent studies have demonstrated that epoxy-coated bars do not provide the expected corrosion protection, and moreover, increase maintenance costs and life-cycle costs when used in bridge decks [15]. The crack widths in concrete bridge decks reinforced with epoxy-coated bars are substantially larger than the crack widths of identical bridge decks reinforced with uncoated black bars [8]. The bond between epoxy-coated bars and the surrounding concrete is practically weak or non-existent under conditions of impact loading [16]. Therefore, in applications of importance to the Department of Defense (DoD) [such as: (i) concrete structures, (ii) bridges, (iii) marine facilities, and (iv) other structures subjected to ballistic or blast loading],

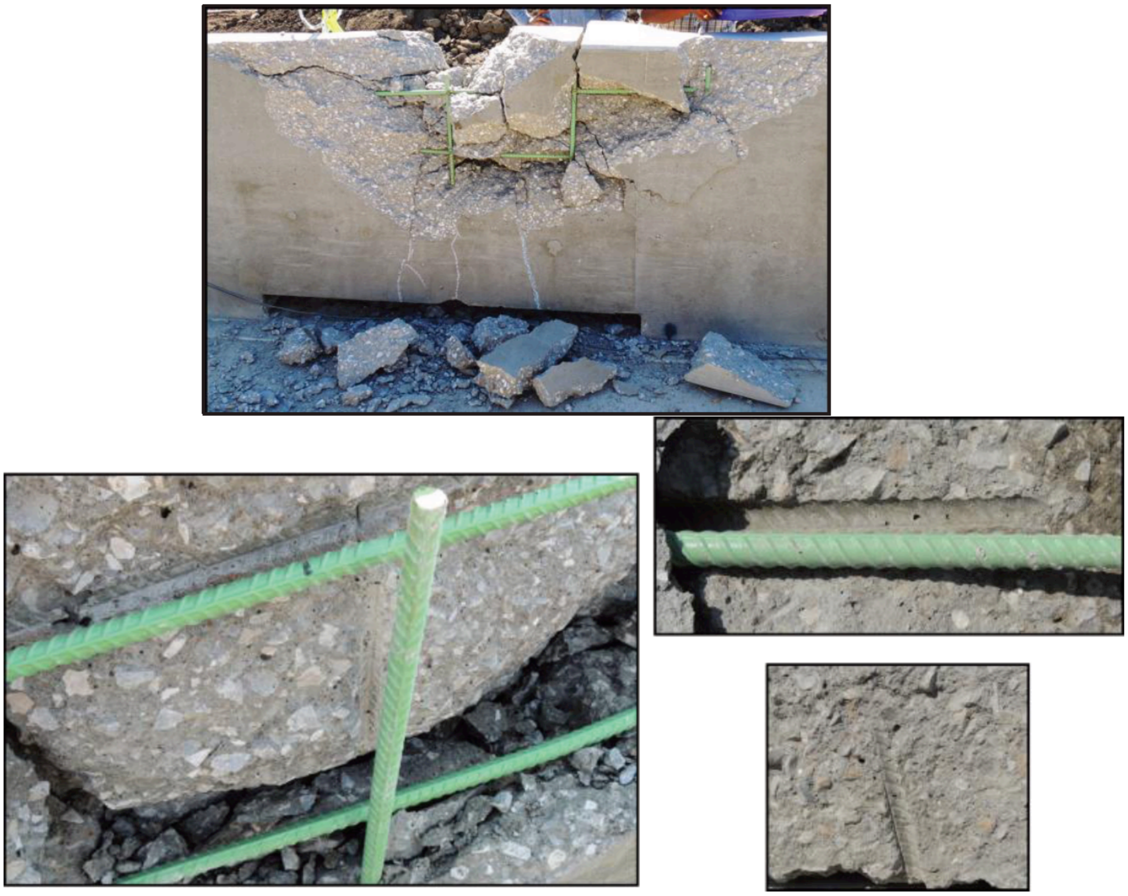

Figure 1: The failure mode of cast-in-place concrete barriers after impact loading.

the epoxy-coated bars are not particularly suitable for structures that are required to possess good impact resistance (see Figure **1**). The performance of reinforcing bars under such loading conditions require superior bond between the reinforcing bars and the surrounding concrete to facilitate energy absorption. The overall bond degradation experienced as a direct consequence of material-environment interactions is much more critical under conditions of impact or blast loading than under static loading.

3. VITREOUS ENAMEL COATING DEVELOPED BY US ARMY CORPS OF ENGINEERS

The US Army Corps of Engineers have developed a vitreous enamel coating for the primary purpose of reinforcing steel bars that is further coated with either cementitious particles or clinker. The clinker reacts with the surrounding concrete during the hydration process and produces a chemical reaction with the moist concrete to facilitate enhanced chemical bond. The coating is provided for the prevention of corrosion of the underlying steel by enabling the formation of a thin layer of impermeable insulator that does not easily delaminate from the core steel. A schematic of a typical vitreous enamel coated bar is shown in Figure **2**. This

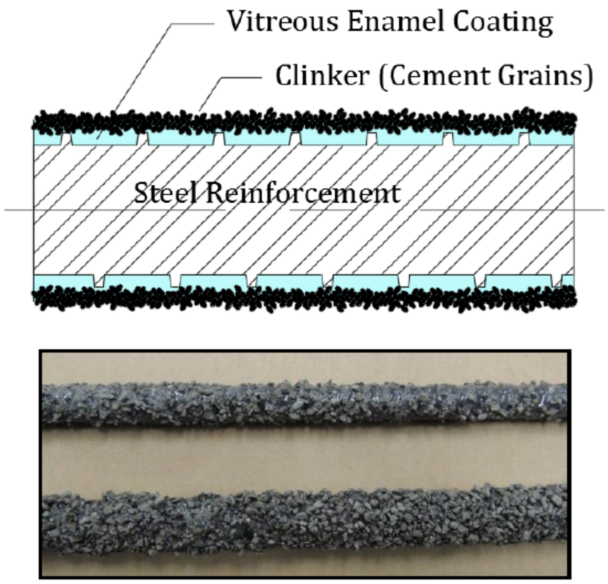

Figure 2: (a); A schematic of vitreous enamel coating developed by US Army Corps of Engineers, and (b); The steel reinforcing bars coated by the material provider [Panel. Suppliers, Inc].

is made possible by the fusion of glass to steel at temperatures between 750°C and 850°C thereby forming a true interlayer of glass that is rich in iron on the surface of the steel [9,17,18]. The USACE considers this coating to be the most durable that can be applied to a reinforcing steel bar. The vitreous enamel coating is molten glass fused to the metal substrate. Composition of the glass can be altered to enable changes in the following: (a) chemical resistance, (b) bonding properties, and (c) coefficient of expansion. Cobalt and nickel-rich glasses are suitable to bond tightly to the reinforcing steel by forming an iron-rich interface.

In this paper, the results of a study aimed at comparing the pull-out strength of vitreous enamel coated bars with that of bars having no coating is presented and discussed. Also presented are results obtained from a study of the flexural performance of the concrete members reinforced with vitreous enamel coated ribbed bars and compared one-on-one with that of beams made using reinforcing bars with no coating.

4. EXPERIMENTAL PROCEDURES

4.1. Pull-Out Tests

For the pull-out tests, the reinforcing bars were embedded in concrete cubes that had a dimension of 6"x 6"x 6" (150x150x150 mm). Four test specimens were prepared:

(A) One each from #4 and #5 steel reinforcing bars with a coating, and

(B) One each from #4 and #5 steel reinforcing bars without a coating.

The test set-up that was used for the pull-out test is shown in Figure **3**. A dial gage was installed at the top of the test specimen for purpose of determining the slip at the end of the bar relative to the concrete cube. In each specimen, stirrups were provided in order to provide confining effect in the concrete around the reinforcing bar. The length of the coated bars provided by Panel Suppliers was found to be inadequate for gripping the bars in the test machine. Therefore, a mechanical coupler was used to splice the rebar to facilitate adequate gripping within the test machine used in this study.

The variation of load with slip and the failure load of the test specimen were established for two sets of pull-out tests. The test results revealed the pull-out strength of the vitreous enamel coated rebars to be about thirty percent greater than the corresponding strength of the uncoated bars. The variation of slip (in inches) on the

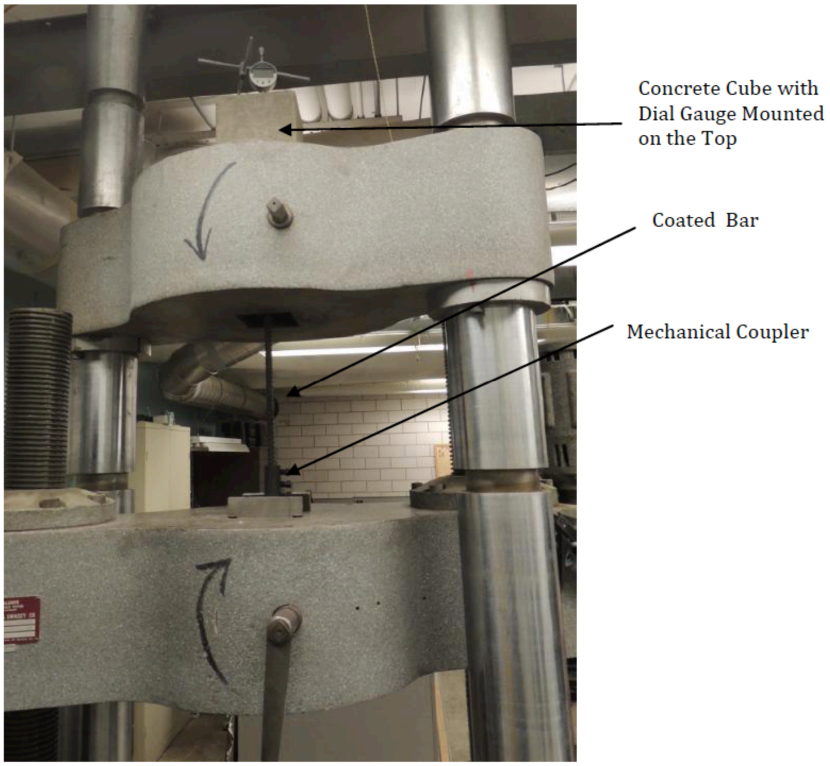

Figure 3: The test set-up for the pull-out tests.

X-axis with bond stress (in psi) on the Y-axis is shown in Figure **4**.

The deformed test specimens were then saw cut for visual examination of the interface between the reinforcing steel bar and the surrounding concrete. Careful examination, over a range of low magnifications, revealed the coating on the reinforcing steel bars to be well adhered to the concrete as seen in Figure **5**.

4.2. Beam Tests

Eight beams were made and tested in bending. The details of these flexural tests are summarized in

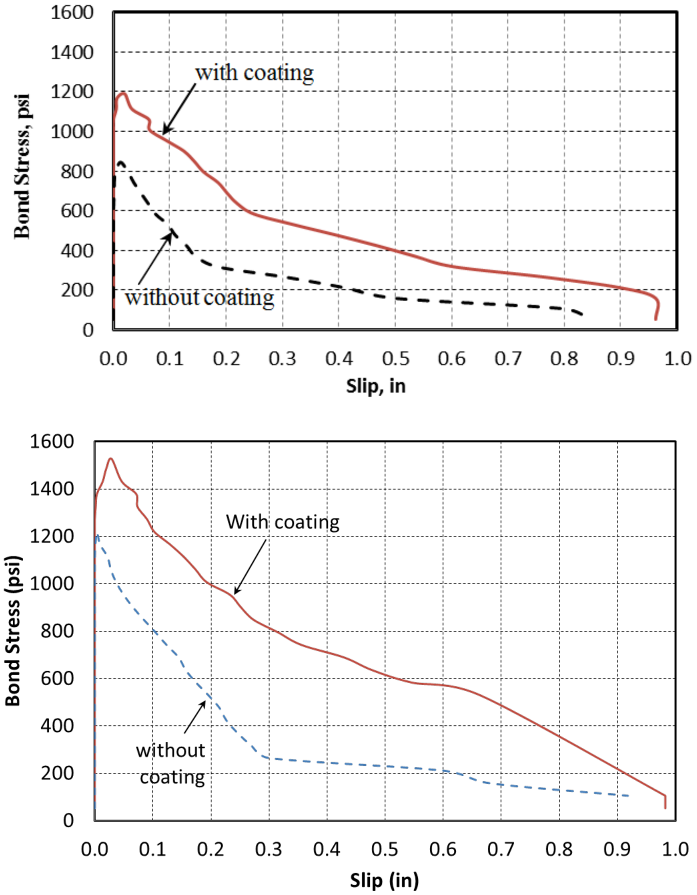

Figure 4: (a); Influence of coating on the variation of bond stress with slip for #4 rebar (b); Influence of coating on the variation of bond stress with slip for #5 rebar 1 inch = 25.4 mm 1,000 psi = 6.895 MPa.

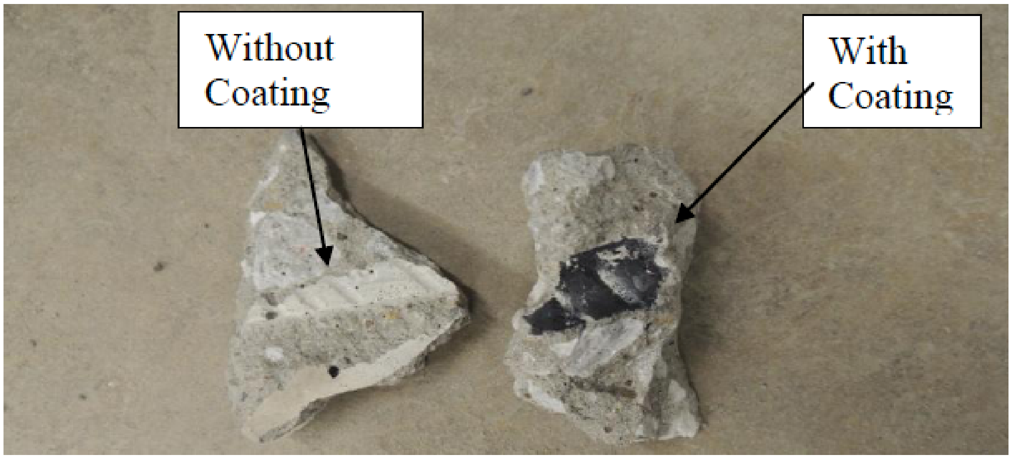

Figure 5: Concrete Surface at the Bar Interface.

Table **1**. A typical flexural test setup is shown in Figure **6**. The length of coated bars provided by Panel Suppliers was found to be too short to make 7′-0" [175 mm] long beams. Therefore, mechanical couplers were used to splice compatible size bars at the ends of the shorter length coated steel bars as shown in Figure **7**.

A variation of load with deflection is as shown in Figure **8** for one set of beams without stirrups. The

Table 1: List of Beam Specimens

Beam Name	Description	Maximum Loading (lb.)	Failure Type
B5	#4 Rebar with coating with stirrups	9,588	Flexure
B7	#4 Rebar without coating with stirrups	12,690	Flexure
B6	#4 Rebar with coating without stirrups	8,742	Shear
B8	#4 Rebar without coating without stirrups	9,024	Shear
B1	#5 Rebar with coating with stirrups	9,024	Flexure
B3	#5 Rebar without coating with stirrups	16,920	Flexure
B2	#5 Rebar with coating without stirrups	10,434	Shear
B4	#5 Rebar without coating without stirrups	10,152	Shear

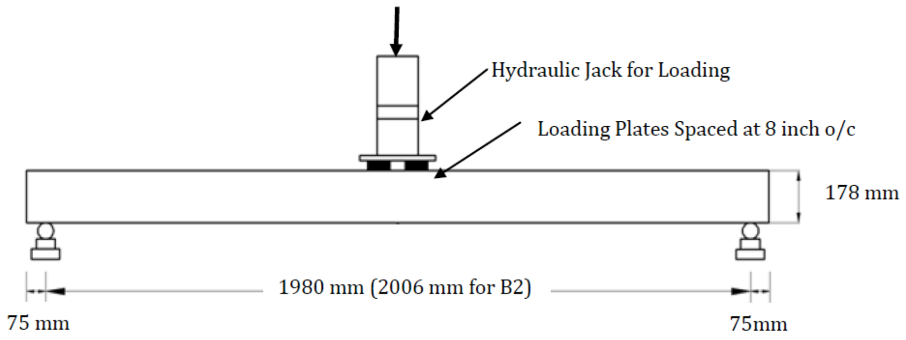

Figure 6: A schematic of the flexure beam test set-up.

Figure 7: Coated Rebar with Stirrups Note: Couplers were used to splice the coated bars.

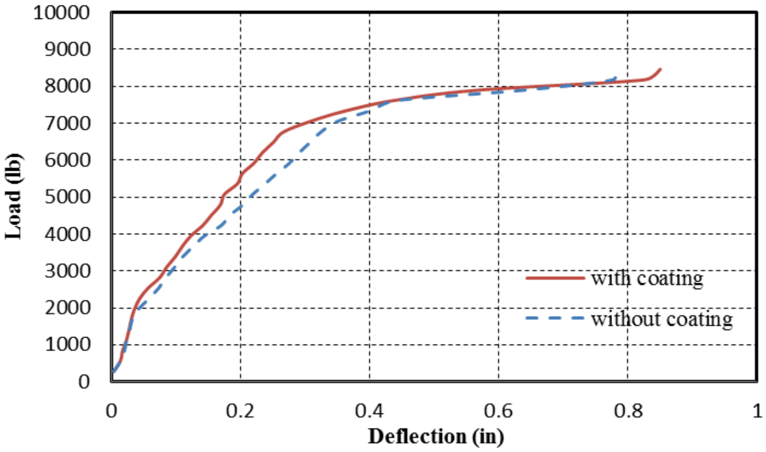

Figure 8: Variation of load with deflection for the beams reinforced from #4 Rebar [both with and without a coating; and without shear reinforcement], 1 inch = 25.4 mm 1000 lb. = 4.448 kN.

Figure 9: Beams from #4 Rebar without and with coating; and without stirrups.

failure mode experienced by the resultant test beam is shown in Figure **9**. The extent and severity of cracking along the length of the test specimens were significantly reduced for beams that were reinforced with coated steel bars.

5. CONCLUDING COMMENTS

The results of a study aimed at comparing the performance of vitreous enamel coated bars with that specimens reinforced with bars having no coating provide the following key highlights:

1. The pull-out tests described in this paper revealed that coated steel bars have over thirty-percent higher bond strength with the surrounding concrete when compared one-on-one with the uncoated bars.

2. Flexural tests revealed the crack widths to be tighter and the cracks to be more evenly distributed for the beams and slabs made using coated steel bars when compared one-on-one with those made using uncoated steel bars. This finding establishes the superior bonding behavior of the coated bars. Deflections experienced by the beams reinforced with coated bars were comparable with that of the uncoated bar.

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