COMPARATIVE EVALUATION OF EPOXY TREATED REINFORCEMENT AND ENAMEL TREATED REINFORCEMENT

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Abstract

TMT steel reinforcements were introduced in India during late 1970s.but these steel are affected by the corrosive environments. Considering the above issue, researchers developed application of fusion bonded Epoxy coating to steel reinforcing care to protect the steel from corrosion in a moist, humid,& aggressive environment. But these steels are so expensive due to a critical manufactureing process and not easily available in the country like India, Where as proper enamel coating to (TMT)steel reinforcement is a good substitute of epoxy coated reinforcement. This paper presents the comparative evaluation results conducted to assess in protecting the steel from corrosive environments.

Therefore, this study focused on the corrosion resistance of three different enamel coatings, along with a standard epoxy coating, each of which were applied to both smooth and deformed steel bars and included both short-term and long-term test methods.
The three enamel coatings tested within this study were: reactive enamel, pure enamel, and double enamel. The reactive enamel was obtained by combining pure enamel with calcium silicate (cement) at a 1-to-1 ratio by weight. The double enamel was composed of an inner layer of pure enamel and an outer layer of reactive enamel.

Results obtained from the tests revealed that the pure and double enamel coatings provided a superior amount of protection when compared to the 50/50 enamel coating.

However, the overall performance of the pure and double enamel coatings was limited by the manufacturing process, which resulted in significant variations in coating thickness.

Keywords: Corossion,Enamel,Epoxy,Reinforcement.

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1. INTRODUCTION

Generally,concrete detorioration is a gradual process and dependinf on their service and environment, reinforced cement concrete can stand for years before the corrosion of steel. Structure of concrete is porus which contains moisture and oxygen,due to its high alkalinity(a pH level of 11 or higher),hydroxyl ions(OH-) in the pore water of sorroundind concrete form a protective,passive oxide layer on the reinforcing steel that reduces the corrosion rate to a negligible level. if the concrete cover that protecys the reinforcing steel is damaged and the bond between the concrete and steel is broken, the steel's passive layer will break down and active corrosion ofsteel will start. The understanding of concrete durability issues has improved significantly in the last 50 years,and particularly the causes of, assessment,and treatment of steel reinforcement corrosion, Three well known types of corrosion resistant steel reinforcing bars have evolved. They are epoxy-coated rebar (ECR), galvanized steel rebar, and stainless steel rebar.

By the mid 1990's, a consensus was formed about the field performance of damaged epoxy-coating reinforcement as a result whenthe coating is damaged, and ECR is continuously saturated with water, a loss in adhesion between the coating and the steel substrate will occur. As a result, the steel beneath the coating is no longer protected from corrosive elements, for the elements are now able to travel along the epoxy-steel interface. Although this consensus does exist, the significance of this phenomenon, in terms of the degree to which it affects the epoxy's ability of providing long-term corrosion protect, has not yet been fully established.

Today, enamel is commonly applied to steel surfaces to protect the material from corrosive environments. This application is widely seen in household appliances, such as microwaves, ovens/stove tops, washing machines, hot-water heaters, etc. Enamel-coated steel has also been successfully incorporated into the construction industry in the form of interior and exterior cladding along buildings and tunnels . Recently, a new form of enamel has been developed that is specifically designed for steel reinforcing bars embedded within concrete. Through additional testing, it was also discovered that the cement particles embedded within the reactive enamel were capable of sealing cracks that were deliberately created along the surface of the coating. This showed that not only does the reactive enamel protect the steel from corrosion, but it also possessed a "self-healing" ability.

Fig-1 Different types of enamel coatings.

2. LITERATRE REVIEW

It is seen that when steel is unprotected and exposed to atmospheric conditions, itl will corrode. Steel corrodes under the above conditions, becuse as a material, steel is unstable due to in the process by which it is manufactured. Processing steel requires large amounts of heat energy to produce iron from ore. By which the iron is placed within a high temperature state that results in the material being unstable when stored within an atmospheric condition [Carino, 1999]. The iron will react naturally with its surrounding environment to reach alower, more stable, energy state such as iron oxide or rust [Smith, 1977]. In an effort to prevent this reaction from occurring, protective epoxy and enamel coatings are commonly applied to steel. Indirectly, steel is also protected from corrosion when placed within concrete.

3. TESTING METHODS

Corrosion is a complex and highly unpredictable process which is often affected by numerous factors. These factors are often difficult to quantify and/or account for, which makes classifying and understanding a material's corrosion resistance extremely difficult. Therefore, when trying to characterize a material's ability to postpone the corrosion process, it may be beneficial to conduct a series of tests in hope that the results may lead to a clear and indisputable conclusion. This section describes the three tests which were used to study the corrosion resistance of various protective coatings. They are: the AASHTO T259 ponding test, the ASTM B117 salt spray test method.

3.1 Ponding Test

Understanding a concrete's resistance toward the action of destructive chloride ions is highly beneficial when attempting to design a durable reinforced concrete structure. Many factors within the concrete's design, along with the environmental in which the concrete is placed, must be taken into account when trying to quantify a concrete's ability to resist the action of chlorides. Therefore, a standard concrete ponding test has been developed by both the American Association of State Highway and Transportation Official's AASHTO and ASTM International. Both the AASHTO T259 and ASTM C1543 standard involve the casting and curing of several concrete slabs made of the same concrete that are capable of retaining a 3 percent saltwater solution upon their surface for a predetermined period of time. Depending upon which standard is used, a

minimum of two (ASTM C1543) or four (AASHTO T259) slabs must be cast for each concrete under investigation with each slab having a thickness of approximately 3 in. (7.6 cm). The surface area of each slab shall be at least 28 in.2 (175 cm2) or 46 in.2 (300 cm2) in order to satisfy the AASHTO T259 or ASTM C1543 standard, respectively.

Once casting is complete, both standards require the slabs to be moist-cured for 14 days, at which time the slabs are to be air dried for two weeks (14 days) at a temperature of 73 ± 4°F (23 ± 2°C) and relative humidity of 50 ± 5 percent. Drying of the specimens is a critical step within both standards, as the concrete's ability to absorb the initial saltwater solution can be significantly altered when the slabs are not properly dried in accordance with the standards. Therefore, the procedures conducted after removing the slabs from the moist room and before initiating ponding must be closely followed. After the saltwater has been placed within a slab's reservoir, a glass plate or a piece of polyethylene sheeting may be used to cover the specimen in order to prevent evaporation of the saltwater; however, the bottom surface of each slab shall remain unobstructed to promote air-flow around the specimen. The slabs are to be stored in this arrangement until the completion of the test, which may be for 90 days .However, once the test has been completed, the saltwater shall be removed immedietly to promote drying of the specimens. Once dry, a wire brush shall be used to remove any salt that may have crystallized along the surface of a slab's reservoir. After the surface has been cleaned, chloride analysis upon the slabs may be performed. The AASTHO T259 standard requires that the acid soluble (total) chloride content be determined upon concrete powder that was collected from depth ranges of 0.063 to 0.5 in. (0.16 to 1.3 cm) and 0.5 to 1.0 in. (1.3 to 2.5 cm). The ASTM C1543 standard requires that the acid soluble chloride content be determined from four concrete powder samples collected from the following depth ranges: 0.4 to 0.8 in. (1.0 to 2.0 cm), 1.0 to 1.4 in. (2.5 to 3.5 cm), 1.6 to 2.0 in. (4.0 to 5.0 cm), and 2.2 to 2.6 in. (5.5 to 6.5 cm). As clearly stated within each standard, this test is meant to provide information pertaining to a concrete's ability to slow down or prevent the action of chlorides when an adjustment has been made to the mix design. The test is not, however, intended to provide a quantitative value for the lifespan of a reinforced concrete structure.

3.2 Salt Spray Test

In this test a salty fog is injected into the enclosed chamber through a nozzle or atomizer centrally located along the chamber's floor. The atomizer is continually supplied with a 5 percent saltwater solution, that is stored within a reservoir positioned along one side of the chamber, and a steady stream of clean compressed air. The distribution of the salt fog throughout the chamber shall have a fallout rate such that1.0 to 2.0 mL is collected upon a horizontal surface measuring 80 cm2. Temperature within the chamber shall be maintained (via heaters) 55 ± 2°C. The lid of the chamber shall be sloped to prevent any solution that has accumulated along the inner surface of the lid from falling upon the specimens lying below. Specimens within the chamber shall

be oriented at an angle of 15° to 30° from the vertical and positioned in such a manner that prevents the specimens from contacting one another. A specimen's exposure to the salt fog shall be unobstructed. Solution that accumulates inside the chamber may be disposed of through a drain positioned within the chamber's floor. Prior to opening the chamber, a ventilating system may be used to expel any salt fog lingering within the chamber; however, opening of the chamber shall be held to a minimum.

Although the test has been standardized and today's cabinets are designed to operate in accordance with the ASTM standard, variations within test results may be reported when testing identical specimens in multiple chambers. This phenomenon has been widely studied throughout the standard's existence, in large part by the American automotive industry, and although information gathered from these studies may have led to adjustments within the standard, the issue still exists today. Even though the test is imperfection for some applications, it still has the ability to detect faults that may have resulted from the coating process. Such faults may include thinly coated areas, uniformity issues, and/or pores that are present within the coating. The validity of the test may also be established by examining standard test specimens, of known performance, alongside specimens whose performance has not yet been established.

4. RESULTS

4.1 Ponding Test

4.1.1 Concrete Resistivity Measurements

The overall average resistivity of specimens group over the course of the 54 weeks of testing is shown in Figure 2. Each data point in the figure is an average value that represents the overall resistance of a specimen group during the 54 weeks of testing. A data set consisted of four individual sets of six resistivity values which were gathered from the four specimens contained within each specimen group. Therefore, a data point's was equal to the standard deviation of these 24 resistivity values divided by the square root of 24. A table of the resistivity values concern to a specific specimen within a specimen group.

4.1.2 Corrosion Potential Measurements

Corrosion potential measurements for the five groups of reinforced specimens is shown in Figure 3. Each data point within the plot represents an final average potential value for the four specimens contained within each group. A data set consisted of four individual sets of twelve potential measurements which were gathered from the four specimens contained within each specimen group.   Throughout the 54 weeks of testing, the two groups containing epoxy-coated bars reported the greatest corrosion resistance (more positive half-cell potential) of the five groups, while the lowest corrosion resistance (more negative half-cell potential) was reported by the uncoated group. The two 50/50 enamel groups reported a corrosion resistance (half-cell potential) between the epoxy and uncoated specimens. Furthermore,

the two enamel groups reported similar potential values throughout the test, with the "perfect" 50/50 enamel group consistently reporting the lower (more negative) of the two potential values. During the 30 weeks that followed, the potential of each specimen group gradually decreased and by week 54 each group reported an average potential of less than -350 mV, which would indicate a high probability of corrosion. Of the five groups, both the "perfect" epoxy group and damaged epoxy group reported the greatest distribution in potential measurements; whereas the potential measurements collected from the uncoated group showed the smallest distribution.
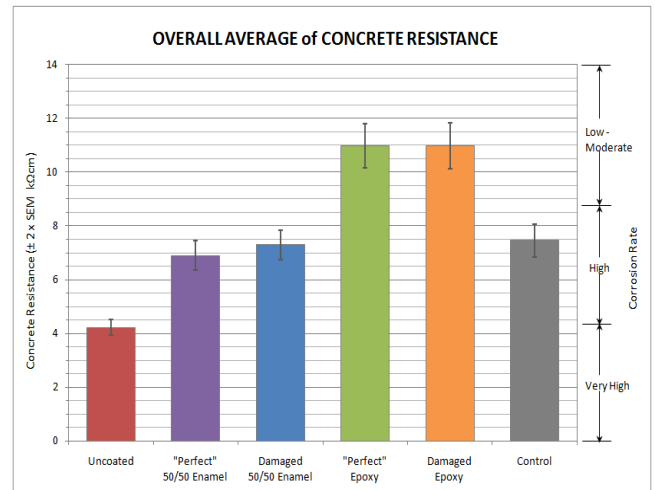

Fig-2 The overall average resistance of each specimen type throughout the testing period.
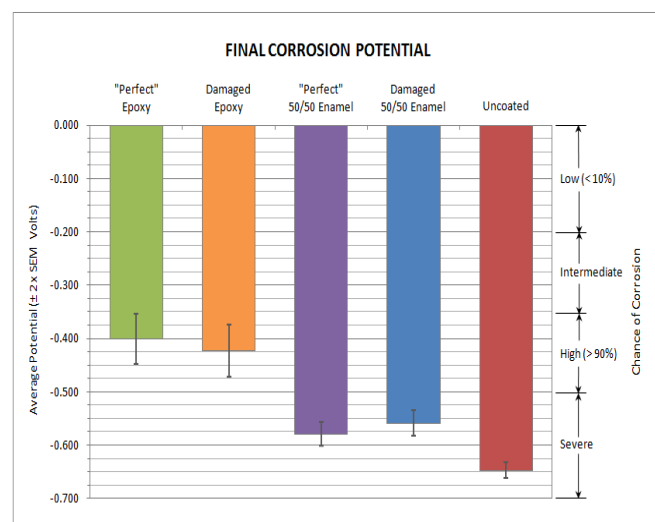

Fig-3 An average representation of the final corrosion potential of each specimen group at week 54.
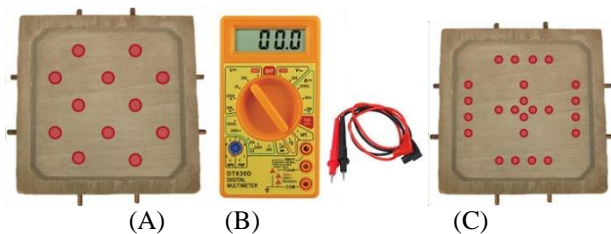
(A)   (B)   (C)

Fig 4: A-Locations along a specimen where corrosion potential measurements were taken., B-Mutimeter used for both measurements., C-Locations where resistivity measurements were taken.
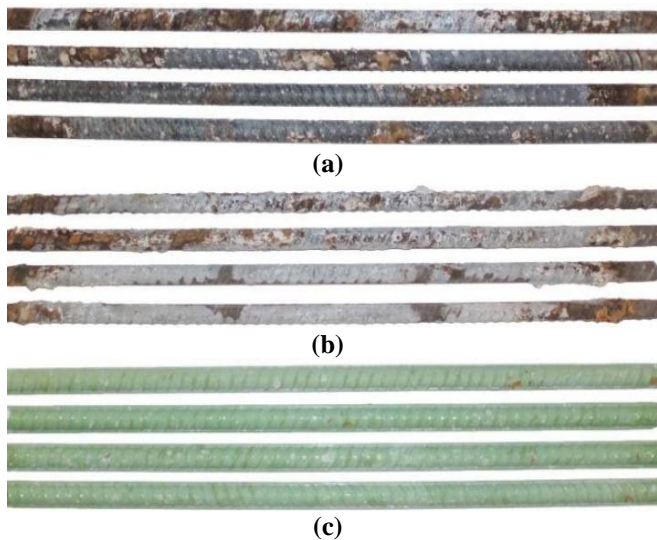

(a)

(b)

(c)

Fig-5: (a) A typical set of uncoated reinforcing bars after being removed from a ponding specimen., (b) A typical set of "perfect" 50/50 enamel-coated bars after being removed from a specimen., (c) The condition of a typical set of epoxycoated bars after being removed from a specimen.

4.2 Salt Spray Test

The results discussed within this section are based on visual observations during the course of the salt spray testing, as well as microscopic examination of sections taken at the conclusion of the test period. Values stated within this section are approximate unless otherwise noted. Photographs indicating the overall condition of each specimen.

4.2.1 50/50 Enamel

The deformed 50/50 enamel-coated specimens performed relatively well up until the 6th week of testing, with each specimen only showing minor amounts of "pin sized" areas of corrosion that can be seen in Figure 6 (a). However, during the 6 weeks of testing that remained, each specimen gradually began to show increased amounts of corroded areas along both the transverse and longitudinal ribs. By the 10th week, the 50/50 enamel coating began to crack along a portion of the transverse ribs that had previously shown signs of corrosion. This cracking of the coating is shown in Figure 6 (b) below.
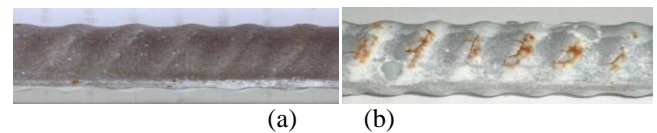

(a)   (b)

Fig 6: The condition of a typical deformed 50/50 enamel-coated specimen after the fifth and twelfth week of testing. (a) Fifth week. (b) Twelfth week.

When the test was complete, it was determined that most, if not all, of the visible corrosion had taken place along the transverse and longitudinal ribs of each specimen. On average, 57 percent of a specimen's transverse ribs and 12 percent of its longitudinal ribs showed signs of corrosion.

4.2.2 Double Enamel

The deformed double enamel coated specimens showed "minor" signs of corrosion along a random portion of the transverse ribs within the first four weeks of testing. These areas of corrosion became more significant over the course of the remaining eight weeks. By the time the test was complete, 18 percent of the transverse ribs along an average specimen exhibited "moderate" signs of corrosion and 31 percent showed "minor" signs of corrosion. Therefore, after the twelve weeks of testing, a total of 49 percent of an average specimen's transverse ribs showed either "minor" or "moderate" signs of corrosion. The difference between "minor" and "moderate" signs of corrosion along a corroding rib may be seen in Figure 7. The longitudinal ribs of each specimen showed minimal signs of corrosion with only one or two "pin sized" areas throughout each rib.
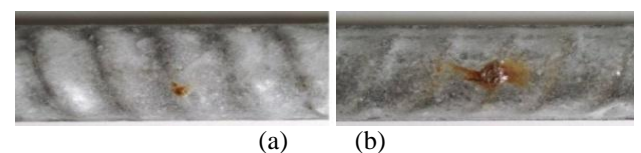

(a)   (b)

Fig 7 : Areas along a deformed double enamel-coated specimen showing various amounts of corrosion. a "Minor." b "Moderate."

4.2.3 Pure Enamel

Within the first three days of testing, three out of the eight deformed pure enamel-coated specimens showed moderate signs of corrosion. By the second week, it was evident which of the eight specimens were performing well and which ones were not. A visual comparison between a specimen that had performed well and one that performed poorly may be seen in Figure 8 Of the three specimens that showed a poor performance throughout the test, 83 percent of their transverse ribs showed signs of either "minor" or "significant" corrosion after the test was finished. The difference between "minor" and "significant" corrosion for the deformed black enamel-coated specimens is shown in Figure 9 An average 58 percent of the transverse ribs that exhibited signs of corrosion along the three specimens were labeled as "significant" and 31 percent of the area along the specimens' longitudinal ribs showed extensive signs of

corrosion. On average, 7 percent of the transverse ribs along the five remaining specimens showed "minor" signs of corrosion while 2 percent of the longitudinal ribs showed "significant" signs of corrosion. Among these five specimens, the average longitudinal rib showed corrosion along 3 percent of its length.

Fig 8: A visual comparison between a deformed pure enamel-coated specimen that performed well and one that performed poorly.
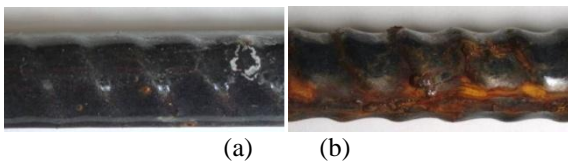

(a)   (b)

Fig 9: Areas along a deformed pure enamel-coated specimen showing various amounts of corrosion. a "Minor." b "Significant."

4.2.4 Epoxy

Both the deformed and smooth epoxy-coated specimens performed well throughout the duration of the test. After testing, each specimen showed minor spots of corrosion that were between 2 and 16 mils (50 and 400 μm) in diameter. Typically these spots were uniformly distributed throughout the length of each specimen, as shown in Figure 10, with an average deformed and smooth specimen having approximately 50 and 65 spots, respectively. The spots tended to increase in quantity and size along areas of the coating that appeared to have been degraded by excessive light exposure, as shown in Figure 10(b) below.
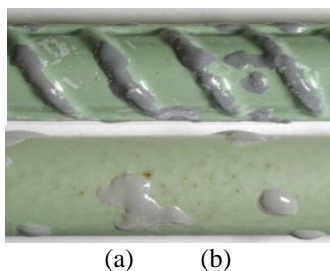

(a)   (b)

Fig 10: Typical spots of corrosion along deformed and smooth epoxy-coated specimens. (a) Deformed specimen. (b) Smooth specimen showing signs of degradation within the epoxy coating.

5. FINDINGS

5.1 Ponding Test

5.1.1 Concrete Resistivity Measurements

After evaluating the concrete resistivity results, it was determined that the concrete resistance of a reinforced specimen was a function of the type of coating that was applied to the specimen's reinforcement. On average, a specimen containing either "perfect" or damaged epoxy coated reinforcement reported a resistance that was 1.47 times that of an unreinforced specimen's resistance. On average, specimens belonging to either the "perfect" or damaged 50/50 enamel group reported similar resistivity values to that of an unreinforced specimen. The group containing uncoated reinforcement reported an average resistance that was 44 percent lower than the average resistance of an unreinforc ed specimen. The significance of these values is as a relative indication of the corrosion resistance of the concrete/rebar system for each coating type. The 50/50 enamel-coated bars provided a degree of resistance between that of the epoxy and uncoated bars.

5.1.2 Corrosion Potential Measurements

The epoxy coating provides the greatest degree of resistance, while the uncoated bars offer the least. The 50/50 enamel-coated bars offer a degree of resistance between that of the epoxy and uncoated bars. An average 4 percent increase in corrosion resistance was seen when comparing the damaged 50/50 enamel group to that of the "perfect" 50/50 enamel group throughout the course of the 54-weeklong test. The final set of corrosion potential measurements indicated a "high > 90% " probability that the reinforcement contained within each specimen group was actively corroding. With a severe chance that the reinforcement contained within the two 50/50 enamel groups and the uncoated group had begun to corrode.

5.2 Salt Spray Test

It was found that the performance of the three enamel coatings largely depended upon the coating's thickness and the concentration of calcium silicate within the coating. The uniformly coated smooth specimens, with an average coating thickness of around 8 to 16 mils (200 to 400 μm), outperformed the inconsistently coated deformed specimens that possessed thinly coated areas along their transverse and longitudinal ribs. However, although the 50/50 enamel-coated specimens shared similar coating distribution patterns as the pure and double enamel-coated specimens, it was seen that the deformed specimens outperformed the smooth specimen. This can best be explained by the large quantity of calcium silicate within the coating. When a large quantity of calcium silicate is added to a pure enamel mixture and then fired to create 50/50 enamel, a porous material is created.

The pores throughout the 50/50 enamel provide pathways for oxygen, moisture, and chlorides to reach the steel. The iron oxide formed during the corrosion process then slowly begins to outwardly diffuse toward the exterior surface of the coating . Therefore, the time it takes for a 50/50 enamel specimen to show any significant signs of corrosion is a function of the coating's thickness and the rate of diffusion of both the corrosive elements and the iron oxide. This would explain why the inconsistently coated, deformed, 50/50 enamel specimens outperformed the uniformly coated, smooth, 50/50 enamel specimens and why the overall performance of the smooth specimens decreased dramatically between the 8th and 10th week of testing. The pure enamel, double enamel, and epoxy specimens all performed relatively well throughout the testing period. However, the deformed double enamel-coated specimens did show areas of weakness along a portion of their

transverse ribs. These areas of weakness were thinly coated with what appeared to be an amalgamation of the two applied coatings. This mixing of the two coatings would, at times, lead to large concentrations of calcium silicate within the thinly coated sections of the coating.

As a result, the coating along these sections exhibited similar properties to that of the 50/50 enamel. The performance of a deformed pure enamel-coated specimen directly correlated to the minimum thickness of the applied coating along that specimen. The three specimens that performed poorly during the test had a minimum coating thickness of 2 mils (50 μm); where as the five specimens that performed well during the test had a minimum coating thickness of 8 mils (200 μm). When damaged, the pure enamel coating maintained its bond with the steel and no undercutting was observed. Both the deformed and smooth epoxy-coated specimens were uniformly coated and no significant signs of corrosion were observed along the surface of the specimens.

6. CONCLUSION

Based on the previously stated findings, the following conclusions can be drawn in reference to both the corrosion resistance and properties of the three enamel coatings when applied to smooth steel dowels or deformed steel reinforcing.

1.The 50/50 enamel coating is more susceptible to impact damage than that of the epoxy coating.

2. When embedded in concrete, the 50/50 enamel coating can reduce the electrical conductivity of a steel bar. However, the insulating properties of the coating are lower than that of an epoxy coated steel bar.

3. When embedded in chloride contaminated concrete, the 50/50 enamel coating can reduce the occurrence of the anodic reaction; however, not to the same extent as that of an epoxy coated steel bar.

4. An area of damage, measuring approximately 0.2 in.2 (1.3 cm2) in size, will have no influence upon a 50/50 enamel-coated bar's performance during a ponding test.

5. Of the three enamel coatings, the 50/50 enamel coating provides the least amount of protection to the underlying steel, while the double enamel provides the highest amount of protection, and the pure enamel provides a degree of protection between the double and 50/50 enamel coatings.

6. When the double enamel coating is applied to a deformed bar, the two separately applied layers of enamel may mix with one another to form what appears to be a single layer of reactive enamel that contains a substantial amount of calcium silicate throughout its thickness. This phenomenon occurs when the coating is thinly applied and will typically occur near a bar's transverse rib.

7. The overall performance of the three enamel coatings depended significantly the minimum thickness of each coating.

8. The excellent bond created between the steel reinforcement and both pure and double enamel coatings actively prevents corroding areas from traveling along the steel-coating interface whereas, the epoxy coating is unable to do so.

9. When undamaged and properly applied, both pure and double enamel coatings can protect steel reinforcement from chloride induced corrosion; whereas, the 50/50 enamel coating cannot.

RECOMMENDATIONS

Based on the findings and conclusions stated in the previous sections, the following recommendations were derived in regards to the future development and usage of enamel-coated steel reinforcement for concrete:

1. When attempting to protect a reinforced concrete structure or pavement from chloride induced corrosion, the 50/50 enamel coating is not recommended. However, the pure enamel and double enamel coatings show great promise provided a method of production exists that results in a more uniform coating thickness.

2. To obtain the maximum corrosion resistance of a reactive enamel coating, the calcium silicate included within the coating should be located as far away from the steel surface as possible.

3. An additional ponding test should be conducted in order to further classify the corrosion performance of both deformed pure enamel-coated and deformed double enamel-coated steel reinforcement.

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