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PARAMETERS GOVERNING THE CORROSION PROTECTION EFFICIENCY OF FUSION-BONDED EPOXY COATINGS ON REINFORCING STEEL

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OVERVIEW

In 2008, a report sponsored Virginia Transportation Research Council was published that reached conclusions regarding the manufacture and durability of epoxy-coated reinforcing steel[1]. However, review of this report found that that many of the conclusions reached by the authors of that report cannot be supported and inappropriate techniques were used to evaluate the extracted bars. Despite concerns, the report indicates that epoxy-coated reinforcing steel continues to perform well at high chloride contents.

REPORT SUMMARY

The Report outlines work conducted using bars obtained from 27 bridges, built between 1984 and 1991. Bridges were 12 to 19 years old when inspected. The specified w/c for the bridges was 0.45 and some of the concrete contained pozzolanic materials. The bridges were selected from 6 geographic regions throughout Virginia. The parameters investigated were: chloride content at the bar depth, coated bar corroded area, corrosion product color under the coating, epoxy coating adhesion, coating color, coating damage (holidays and holes), coating thickness, Thermogravimetric analysis (TGA), Differential Scanning calorimetry (DSC) and Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS.

Conclusions presented within the report and a discussion of these conclusions is presented below.

1. ***ECR coating samples extracted from concrete exhibited extensive cracking compared to the new ECR samples in which the coating cracking was limited to only one sample.***
   a. ***The coating cracking correlated with the amount of chloride at bar level, residual adhesion of the epoxy to the steel surface, and the percent moisture in the coating.***

Response: Coating cracking was assessed using SEM at a magnification of 2000 times and observed cracking was assigned numbers between 1 and 4. While surface crazing was observed, the researchers failed to demonstrate or refer to work by others that the surface crazing in any way corresponds to loss coating performance. Presumably, should such crazing penetrate to the steel surface, the electrical resistance of the coating would be lost and holidays would be detected; however, this was not shown to be the case.

2. ***The coating cracking is also related to the change in color of the epoxy and this indicates that the epoxy coating degradation in concrete influences the surface condition of the coating.***

Response: It is common knowledge that changes in coating color are normally a result of excessive UV exposure prior to embedment into concrete and is the result of the UV bleaching coloring dye within the polymer. Epoxy powder is naturally white. Coating color for bars has not been standardized and varies by manufacturer. In addition, variations in coating color may also be a function of the age at which the powder was at the time of use. Data reported in the report does not support the assertion that degradation is occurring within the concrete.

3. ***The DSC results showed that both the extracted epoxy coating samples as well as new samples are not fully cured during the manufacturing process.***

Response: Careful review of the DSC data and descriptions used found that the DSC method used by the researchers did not follow standard industry practice that includes a thermal relaxation step. When checking cure of a coating sample, samples are heated to the coatings glass transition temperature (Tg) and held for a short period, about 1 minute. Not running this step can lead to a broad transition and a slightly lower Tg. Running the relaxation step does not heat the coating to a sufficient temperature to allow more cure to take place.

All but one bar showed a significant Tg shift. A few were in the range that would be considered instrument variance (up to 4°C Tg shift) but for the most part they were 8-15°C shift. If this were a result of under-cure, the coated bars would exhibit extremely poor flexibility and subsequently failed the ASTM coating bend flexibility tests. This factor would have been found when bars were fabricated.

Figure 4 of the report shows a typical DSC scans for a coating. It is stated that since the second scan (bottom curve) is flat and the first one was not, this shows that the coating was not cured. However, upon close examination of this curve, the peak represents an endothermic reaction (heat is absorbed by the system). During cure, epoxy coatings give off heat and thus residual cure of coatings show up as an exothermic reaction on DSC. This means that if the assertion was correct the bend in the upper curve should be downward, not upward. The endotherm observed by the researchers is likely due to heat needed to be put into the system to evaporate the water. Thus, the assertion reached regarding poor curing of the coatings cannot be supported.

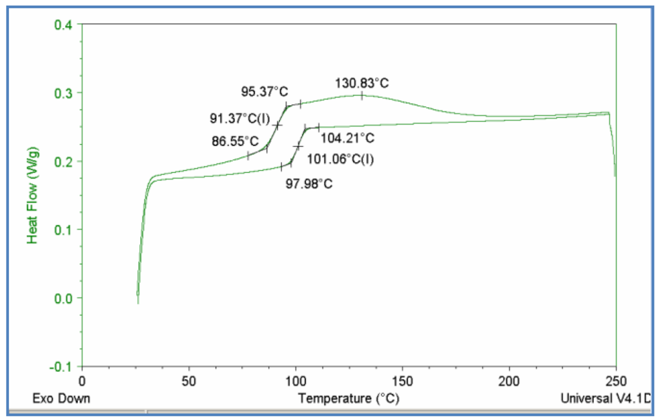

Figure 1: DSC Result from Figure 4 of paper

4. ***The extracted epoxy-coated samples presented significant permanent adhesion loss with little or no epoxy coating residue present on the bar surface (p iii)***

Response: This assertion has been presented for many years by the researchers. Essentially the idea is that if the epoxy coating isn't fully bonded to the steel, then corrosion of the carbon steel is rapid, even without the presence of chloride ions. This assertion has not been supported in field studies of this report and others.

There are a number of factors that may result in poor coating adhesion. A principal cause is contamination of the steel surface prior to coating, either from salts or dust from blast media. In the first generation of epoxy-coated reinforcing steel, this was not uncommon. Surface contamination was addressed in the CRSI certification program, adopted in 1991, and this program is now used by almost all epoxy-coated bar plants.

Coating adhesion may also be affected by the storage conditions of epoxy powder prior to use. The CRSI program now requires appropriate storage of the powder prior to use and requires manufacturers of the powder to provide "use-by" dates for these materials.

Finally, time and time again, this question regarding the correlation between adhesion and corrosion has been investigated in many reports and not established. There is poor correlation between adhesion and corrosion performance and many structures with poor adhesion and exhibiting excellent corrosion performance.

5. ***EDS analysis showed that once adhesion is lost, corrosion will proceed unimpeded under the coating even in the absence of chlorides.***

The report reaches this conclusion based upon EDS observation outlined in Tables 15, 16 and 17 where instances of high atomic oxygen was found on the steel surface. While it is agreed the presence of oxygen indicates the presence of an oxide, the oxide is likely the result of poor surface preparation during manufacture leaving mill scale on the surface of the bar, and not an indication of ongoing corrosion. The assertion that corrosion will proceed unimpeded under the coating even in the absence of chlorides cannot be supported.

6. ***Observed corrosion activity correlated with***
   a. ***number of holidays***
   b. ***number of damaged areas per unit length of bar***

The report found that 82 percent of the specimens were in concrete that had chloride levels that were below that generally assumed for corrosion of black bars; however, it ignores the performance of the remaining 18 percent of the bars were in concrete at chloride levels greater than that assumed for black bars. Despite this high percentage of bar in high chloride levels, delamination and spalling of the bridge decks were not observed.

The average corrosion percentage for the bars was reported to be 0.66 percent. However, this level of corrosion could well have occurred prior to placing the bars into concrete. Current specifications require all damaged and exposed bar to be repaired prior to placement of concrete; however, this was not the case for specifications used when many of the bridges were built.

7. ***The results also show a distinct loss of quality control in the handling and possibly storage of new coated bars.***

The researchers used flawed methods to reach this conclusion including DSC, discussed earlier in this document and SEM. Cure of coatings is commonly checked by powder manufacturers and this is not a substantial issue for the industry. Tests for bond and adhesion are routinely conducted at the manufacturing locations. Programs, such as that established by CRSI have been reviewed by departments of transportation and deemed appropriate for ensuring that plants are able to produce product that meets required standards.

8. ***The new ECR samples had significantly higher damage density than the samples extracted from concrete, while there was no change in the number of holidays and cure condition.***

It is widely known that damage to bars will reduce performance; however, damage levels observed in the sample bars are well outside current practice. The epoxy industry has been an advocate of best handling practices for many years. Many documents have been produced that demonstrate simply implemented changes that minimize coating damage.

OTHER COMMENTS

Holidays plotted in Figure 15 show a significant departure from a normally distributed curve. Use of normal distribution statistics for this data is incorrect and 95 percent confidence data presented in Figure 14 is incorrect.

Damage areas plotted in Figure 18 show a significant departure from a normally distributed curve. Use of normal distribution statistics is incorrect and 95 percent confidence data presented in Figure 17 is incorrect.

The coating cracking is assessed on a scale of 1 – 4; yet Figure 20 presents a 95 percent confidence interval for this discrete distribution. This data is meaningless.

The percent cracking and porosity of each structure is presented in Figure 21. This shows that for many of the samples, the 95% confidence includes negative values. This data is meaningless.

Results obtained by ImageJ are highly dependent on the sample preparation and post-processing procedures used. Such data should be used carefully to avoid meaningless interpretations. Such care is not described in the report.

The coating color is assessed on a scale of 1 – 5, yet Figure 11 presents a 95 percent confidence interval for this discrete distribution. Such data is meaningless.

The authors conclude that the majority of coating cracking occurs in the concrete. This is not substantiated by any information within the report. In addition, there is no indication that the surface cracking or crazing results in reduced performance of the coating.

Conclusions based upon the observations of pores cannot be substantiated. It is stated that the presence of a pore network makes observed surface cracks in the coating irrelevant; however, the researchers fail to demonstrate that the pores form a continuous or a discrete network. Should an ionic conductive path have been formed, a holiday detector would ring continuously.

A discussion is made regarding line speed and coating cure. Adhesion and bond to the steel surface are now routinely evaluated during manufacture using cathodic disbondment tests and bend tests. Poorly cured coatings are less flexible than well cured coatings and this would be discovered during production and/or fabrication.

The report states: *The corrosion rates for the majority of the structures are between 1 and 10 µA/cm^2 and that in that region, damage to concrete due to corrosion activity is expected to take place between 2 and 10 years. Two of the structures exhibit significantly higher corrosion rates, with values between 16.8 and 21.1 µA/cm.^{2} In these structures, concrete damage due to corrosion activity is expected to occur within 2 years or less.* This data presents a dire forecast for decks in Virginia. However, if these corrosion rates were actually the case, then repair activities to decks containing epoxy-coated bars would already be significant within Virginia. To date, no such activities have been reported.

The authors fail to discuss backside contamination of the coatings. Analysis of the backside of coatings would provide substantial information regarding the quality of coated bars. As with all industries and products, improved understanding of critical features results in the implementation of better production practices.

While the authors are quick to point out that 82 percent of the samples had chloride levels less than threshold, they fail to indicate that this would mean that 18 percent have chloride levels above threshold. Should these structures be manufactured using black bar, corrosion distress would have already been noted.

Finally, the report concludes with a comment about a material (MMFX) and claims that it will have a costs equal to ECR and that it provides better performance. In fact, recent reports of bid prices from VDOT indicate that installed price is at least twice that of the epoxy-coated reinforcing.

SUMMARY AND CONCLUSIONS

On behalf of the epoxy-coated reinforcing industry, a detailed review was conducted by corrosion, coating and chemistry experts who have worked in this field for many years. Conclusions reached by this review determined:

- While surface cracks in the coating were observed, the assertion that the cracks propagate to the steel surface and thus reduce corrosion performance has not been established.
- The DSC method and conclusions reached used by the researchers are fundamentally flawed
- Coating gloss and color are not good indicators of performance and conclusions based upon these observations do not indicate reduced performance of these materials.
- Statistical methods used are inappropriate

The report has found that at least 18 percent of the samples were in chloride levels greater than that required for black bar corrosion, yet widespread damage to the decks was not reported.

To conclude, the epoxy-coated bar industry continues to improve its product and its installation via appropriate testing and plant evaluation. To date, epoxy-coated reinforcing bars continue to prove that they provide a low-cost effective method of corrosion protection of steel in concrete.

REFERENCES

1. Ramniceanu, A., et al., *Parameters Governing the Corrosion Protection Efficiency of Fusion-Bonded Epoxy Coatings on Reinforcing Steel*. 2008: Virginia Polytechnic Institute and State University, Blacksburg, Virginia Transportation Research Council, Virginia Department of Transportation. 70p.