VERIFICATION OF EFFECTIVENESS OF EPOXY-COATED REBARS

PENNSYLVANIA DEPARTMENT OF TRANSPORTATION

PROJECT NO. 94-05

FINAL DRAFT REPORT
November 24, 1998

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Pennsylvania Department of Transportation
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13. Abstract (Maximum 200 words)
A two year program was initiated in 1996 to document the condition of epoxy coated rebars in Pennsylvania and New York. The objectives of this program were i) to investigate the field performance of epoxy coated reinforcing steel in select bridge decks in Pa and NY, ii) determine if ongoing or progressive corrosion and/or a reduction in coating adhesion were occurring, with a 95% confidence level, in more than 3% of the deck area in either state, and iii) define variables associated with exposure conditions, concrete properties, and epoxy coated rebar properties which predict the presence or absence of corrosion and/or adhesion reduction. Results from the study showed that the existing condition of epoxy coated rebars in bridge decks in Pa and NY State was very good. The frequency of occurrence of progressive corrosion was less than 3% in PA and at least 3% in NY. Coating adhesion reduction or loss was found to be more prevalent and extensive. Probability distribution analyses showed that more than 50% of epoxy coated rebars in bridge decks in Pa and NY State exhibit some degree of adhesion reduction within 6 to 10 years of placement in concrete. It should be pointed out that, although progressive corrosion must be accompanied by complete adhesion loss, coating adhesion alone was not found to be good predictor of corrosion condition in this study. Performance of epoxy coated rebars was evaluated with respect to two mechanisms for corrosion initiation and propagation on epoxy coated rebars, "Failures from Coating Defects" and "Failure by Adhesion Reduction". Due to the relatively low average age (10 years) of the sample population the performance of the epoxy coated rebars with respect to either of the failure mechanisms at an acceptable confidence level could not be statistically ascertained.

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The authors express their deep appreciation to Mr. Donald R. Jackson, Senior Project Manager, Federal Highway Administration, for financial support, through Demonstration Project No. 84, to conduct electrochemical impedance spectroscopy tests. This additional information was an asset to the overall project and is expected to be very useful in future research efforts on epoxy-coated reinforcing steel.

The authors would also like to acknowledge and thank the following CONCORR, Inc. personnel for their outstanding efforts during this project: Ms. Joanna Viarengo (field evaluation and laboratory procedures), Mr. Mike Bowers (field and laboratory evaluation), Mr. Billy Payne (field evaluation), Mr. Ken Allen (laboratory evaluation), Mr. Garry Graham (field evaluation), and Mr. Todd Barton (field evaluation).

DISCLAIMER

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1. Among all the variables included in the analyses, logarithm of EIS, number of holidays, and number of bare spots were found to be the best predictors of corrosion condition rating, but in all cases the correlation's were weak. These same parameters were also found to have statistically significant relationships with adhesion reduction, but again the correlation's were weak.

2. Corrosion condition rating did not correlate with coating thickness, clear concrete cover, color of epoxy, or bridge deck condition rating.

3. Adhesion reduction or loss is irreversible at least after a 7 day drying period. There is a higher probability of adhesion reduction adjacent to areas with visible coating defects compared to those with no visible defects. In addition, the deformation pattern on the bars has some impact on adhesion reduction.

4. A good correlation between concrete resistivity and coulombs passed was found and the following equation can be used to describe the relationship:

$$\text{Coulombs Passed} = 2E{+}09 * \text{A/C Resistivity}^{-1.4539}$$

5. Results of pH testing in rebar traces and pencil hardness testing on the coating did not provide any useful information.

1.4 Recommendations for Future Research

The distinction between existing condition, performance to date, and projections of future performance should be clearly defined in the objective of any field research project involving epoxy coated reinforcing steel. If the primary goal is to investigate existing condition, a sampling plan similar to that employed in this study (i.e. a statistical sample of the global population) is appropriate. However, if the primary objective is to assess performance to date or project future performance, the sample population should consist of older structures in areas with the highest deicing salt usage only. In either case, variables such as type of epoxy, presence of overlays, and epoxy coated rebar in both mats of reinforcing steel versus the top mat only should be considered.

The same structures included in this study should be reevaluated after approximately 10 years of additional service. Performance of the epoxy coated bars could then be more accurately assessed.

Finally, similar data obtained from past studies by other researchers should be combined and analyzed using the procedures described in this report. This would eliminate differences in the data analysis approach and interpretation and should provide insight into the existing condition and performance of epoxy coated reinforcing steel over a large geographical area.

bridge decks in Pennsylvania and New York State exhibit some degree of adhesion reduction within 6 to 10 years of placement in concrete. It should be pointed out that, although progressive corrosion must be accompanied by complete adhesion loss, coating adhesion alone was not found to be a good predictor of corrosion condition in this study.

Performance of epoxy coated rebars can only be evaluated after the bars have been exposed to a corrosive environment for a sufficient length of time. Two mechanisms for corrosion initiation and propagation on epoxy coated rebars have been proposed:

1. **Failure from Coating Defects** - Corrosion initiates at coating defects once sufficient levels of chloride are present. Corrosion then progress underneath the coating adjacent to the defects. The coating in these areas may or may not be disbonded at the time corrosion initiates in the defect.

2. **Failure by Adhesion Reduction** – This corrosion mechanism first requires a reduction in coating adhesion. Once sufficient levels of chloride are present, corrosion initiates and propagates under the disbonded coating.

These mechanisms were used to analyze the performance of epoxy coated rebars in this study. Due to the relatively low average age (10 years) of the sample population, 80% of the bars tested had no exposure time to the chloride threshold of 1.2 pcy. Thus, in the analysis of "Failure from Coating Defects," only 49 bars with known defects and a chloride exposure of at least 1.2 pcy for more than 5 years were identified. Similarly, only 41 bars with adhesion reduction followed by chloride exposure of at least 1.2 pcy for more than 5 years were identified to analyze "Failure by Adhesion Reduction." The number of samples in each of these subsets were not sufficient to statistically evaluate the performance of the epoxy coated rebars with respect to either of the failure mechanisms at an acceptable confidence level. However, only 2 bars (less than 5%) in each subset exhibited progressive corrosion as indicated by the corrosion condition ratings. This minimal number of failures may be attributed to one or more of the following:

a) The epoxy coating on the bars in the subsets has provided acceptable corrosion protection to date.

b) The assumptions used in terms of chloride exposure and chloride content threshold were not sufficiently severe to detect the transformation from corrosion initiation to propagation.

c) Parameters other than those considered in this study play a primary role with regard to the corrosion mechanisms investigated.

No correlation was found with corrosion condition rating and chloride exposure time or chloride content. This is most likely attributable to the age and chloride content distribution of the study population and/or satisfactory performance of the epoxy coated bars.

Other pertinent findings were as follows:

A detailed methodology for randomly locating and collecting three cores from each of the 80 spans (total of 240 cores) was developed. Prior to collecting the cores, delamination and crack surveys were performed in a one square foot area surrounding each core sampling location. Although an effort was made to avoid collecting cores from areas that contained cracks, 16% of the extracted cores contained cracks. In each core, two intersecting rebars were extracted for evaluation. The condition of the bridge deck in each span was visually evaluated by the researchers using a deck condition rating scheme similar to NBIS. The methodology also included procedures for shipping and storing cores prior to testing in the as-extracted condition as much as possible. The field evaluations and sampling plan were conducted from September 4 to 19, 1996 in New York and from September 30 to October 15, 1996 in Pennsylvania.

A detailed laboratory methodology was also developed and implemented to document the condition and specific properties of the cores, concrete, and epoxy coated rebars. Standard test methods were used when available. Measurements and tests were performed on each core and the two extracted rebars over a two-year period. Core evaluations and concrete property evaluations were performed on 240 cores and epoxy coating condition and property evaluations were conducted on 473 rebars.

Documentation of core properties included core conditions (i.e. delaminations, cracks, rust staining, and/or honeycombing), dimensions, electrochemical impedance spectroscopy measurement, and clear concrete cover over the top rebar. Measurement of concrete properties encompassed specific gravity, permeability, absorption, percent volume pore space, pH, and chloride ion content. Tests and observations on the epoxy coated rebars included color of epoxy, defects such as mashed areas, blisters, bare areas, and holidays, deformation pattern, coating thickness, coating hardness, corrosion condition rating, and adhesion rating.

1.3 Findings

The sampling plan was designed to detect progressive corrosion even if the frequency of occurrence was less than 3% of the global population. Results from the study showed that the frequency of occurrence of progressive corrosion is less than 3% in Pennsylvania and at least 3% in New York. A total of 409 rebars showed no evidence of corrosion, 62 bars had a number of small, countable corrosion spots, and only 2 rebars, both in New York, exhibited significant visible corrosion. In addition, corrosion products were observed under the coating on approximately 7% of the bars tested. However, in most cases, corrosion products found under the coating were not the result of ongoing corrosion. Therefore, the existing condition of epoxy coated rebars in bridge decks in Pennsylvania and New York State was found to be very good from a corrosion point of view.

Coating adhesion reduction or loss was found to be more prevalent and extensive. Only 47% of the bars tested had no reduction in adhesion. Over 13% exhibited a complete loss of adhesion and the remaining 40% had varying degrees of adhesion reduction. Probability distribution analyses showed that more than 50% of epoxy coated rebars in

SECTION 1

EXECUTIVE SUMMARY

1.1 Project Objectives

The objectives of this project were i) to investigate the field performance of epoxy coated reinforcing steel in select bridge decks in Pennsylvania and New York State, ii) determine if ongoing or progressive corrosion and/or a reduction in coating adhesion were occurring, with a 95-percent confidence level, in more than 3-percent of the deck area in either State, and iii) define variables associated with exposure conditions, concrete properties, and epoxy coated rebar properties which predict the presence or absence of corrosion and/or adhesion reduction.

The following definitions were used throughout the study:

a) Existing Condition – The condition of an epoxy coated bar at the time it is examined.

b) Performance - The effectiveness of the coating in providing corrosion protection after the bar has been exposed to a corrosive environment for some time period. The existing condition of an epoxy coated bar may be excellent, but if it has not been exposed to a corrosive environment for a sufficient length of time its performance cannot be assessed.

c) Progressive Corrosion - A corrosion process that is presently ongoing. Visible rust, for example, indicates that a steel element has corroded, but it may or may not still be corroding.

1.2 Approach and Scope of Project

Bridge inventory, inspection, and management systems were examined to identify the study population in each state (i.e. bridge decks constructed with epoxy coated reinforcing steel between 1977 and 1993, inclusive). Construction dates preceding 1977 were omitted in order to eliminate decks constructed with "Flintflex" epoxy coating. In New York, 1,425 bridge decks with a total of 3,360 spans representing 16.6 million square feet of deck area were identified. The analysis in Pennsylvania found 2,290 bridge decks with a total of 6,062 spans comprising 26 million square feet of deck area. For logistic purposes, a "sampling population" was then defined. The distribution of decks in the sampling population was representative of the study population in terms of age, salt usage, and deck condition rating. Based on this sampling plan, 40 spans in New York State and 40 spans in the State of Pennsylvania were selected. To meet the requirements of the statistical sampling plan, 3 cores had to be collected from each of the 80 spans.

SECTION 2

INTRODUCTION

2.1. Background

Fusion bonded epoxy coating technology has been the primary defense used by most state agencies, including the Pennsylvania Department of Transportation (PennDOT) and the New York State Department of Transportation (NYSDOT), to protect reinforcing steel in concrete from corrosion. However, results from recent research activities[1-3] cast doubt on the ability of epoxy coatings to provide long-term corrosion protection to steel in concrete exposed to chlorides. The projected problem has been attributed to the number and size of breaks or defects in the coating and reduction in adhesion between the epoxy coating and steel substrate.

Coating breaks or defects are represented by holidays, narrow cracks, mashed areas, and bare areas that occur during coating application, fabrication bending, transportation, handling, and concrete vibrating. Reduction of the adhesion bond between the epoxy coating and underlying steel has been widely observed. Occurrence of this phenomenon has been found to be independent of the level of chlorides at the reinforcing steel depth and may or may not be associated with corrosion underneath the coating. While there is a consensus on the occurrence of these problems, their significance with regard to the long-term performance of epoxy coated reinforcing steel in concrete bridge structures exposed to salt in-service is not completely understood, and thus, much controversy remains.

Effective corrosion protection performance of epoxy coated reinforcement after up to 20 years of service, particularly in structures exposed to deicing salt environments, has been reported in several field studies.[4,5] On the other hand, isolated failures have been reported in deicing salt environments after 10 to 15 years of service.[4] The sampling effort in some of these field studies intentionally focused on locations representing a worse case scenario.[5] Consequently, the question is whether the reported failures are precursors to a widespread corrosion problem or the result of relatively unique situations, which are not indicative of the general population of all bridges.[4]

In light of the above discussion, PennDOT and NYSDOT decided to conduct a joint research effort to survey and evaluate in-service bridge decks constructed with epoxy coated reinforcing steel by way of a statistically based sampling plan. Project funding was provided through a regional pool fund and the Federal Highway Administration.

2.2. Project Objectives

Specific project objectives were as follows:

SECTION 3

SELECTION OF BRIDGES AND CORE SAMPLE LOCATIONS

3.1. General Information

A statistically based sampling plan was developed by NYSDOT. Details regarding the selection of bridge decks, specific spans to be sampled, and the exact locations for extracting cores are discussed in a complete report by NYSDOT.[1]

Basic elements of the sampling plan were as follows:

- The sampling unit was defined as the epoxy coated reinforcing steel contained in a one square foot area of bridge deck. This area would be sampled by extracting one, 4 inch diameter core.
- In each state, 40 spans were selected to be as representative of the study population as possible.
- Sampling in each span involved extracting three, 4-inch diameter core samples at randomly selected locations.

It was believed that the resulting 120 cores per state would be sufficient to determine if ongoing or progressive corrosion and/or a reduction in coating adhesion had occurred in over 3-percent of the deck area in either state.

3.2. Selection of Bridges

The first step in the span selection process involved development of age and salt usage strata for the available sample population. Thus, two age strata, decks with 3 to 11 years of service (constructed between 1985 and 1993) and others with 12 to 19 winters of service (constructed between 1977 and 1984) were defined. The age of bridge decks that had been replaced as part of rehabilitation efforts was calculated from the replacement date as opposed to the original construction date. Selection of these age strata was based on an assumption regarding the expected chloride content at the reinforcing steel depth and eliminated the possibility of obtaining samples coated with 'Flintflex'; use of this coating was terminated prior to 1977. No other effort was made to control the type of epoxy coating sampled. In addition, no distinction was made between bridge decks with epoxy-coating only on the top mat of reinforcing steel versus those with coated steel in both mats. Similarly, although the bridge decks were not expected to be overlaid with asphalt, the presence, or lack thereof, of any overlay on the decks was not treated as a variable in the sample selection process.

Statewide data on annual deicer usage per lane mile were analyzed and each county in each state was then classified into one of the salt usage categories described below.

For New York:

High - more than 20 tons per lane-mile per year.
Medium - between 15 and 20 tons per lane-mile per year.
Low - less than 15 tons per lane-mile per year.

For Pennsylvania:

Medium - more than 15 tons per lane-mile per year.
Low - between 9 and 15 tons per lane-mile per year.
Extra-Low - less than 9 tons per lane-mile per year.

Bridge inventory, inspection, and management systems were then examined to identify the study population in each state (i.e. bridge decks constructed with epoxy coated reinforcing steel between 1977 and 1993, inclusive). In New York, 1,425 bridge decks with a total of 3,360 spans representing 16,599,290 square feet of deck area were identified. The analysis in Pennsylvania found 2,290 bridge decks with a total of 6,062 spans comprising 26,026,417 square feet of deck area. The number of bridges and spans and the total bridge deck area in each of the six age and salt usage strata were then determined for each sample population. Since the sampling unit was defined as epoxy coated reinforcing steel in one square foot of deck area, the number of spans to be cored for each combination of age strata and salt usage category was determined by a proportional allocation based on the percentage of deck area represented.

The next step involved selection of a subset of bridge decks to be used as the 'sampling population' within each combination of age and salt usage stratum. A subset of bridge decks was required in order to minimize travel costs associated with the sampling process. Selection of the subset was accomplished using intuitive judgment and trial-and-error until the several criteria listed below were satisfied. Also, bridges in NYSDOT Region 11 were excluded from the subset due to traffic considerations.

- The condition of epoxy coated reinforcing steel in the sampling population should be representative of the condition in the strata populations.

- Each sampling population should consist of a sufficient number of bridge decks to sample from (i.e. much larger than the actual number to be sampled).

- The sampling population should be concentrated, as much as possible, within a geographically compact area.

- The overall sampling population (i.e. the sampling population for all six strata) should also be concentrated in as geographically compact an area as possible.

The first two criteria were considered so that the study objectives and statistical integrity of the sampling plan would not be compromised. The other goals were included to address the aforementioned issue regarding travel costs during the sampling effort.

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A detailed methodology for randomly locating and collecting three cores from each of the 80 spans (total of 240 cores) was developed. Prior to collecting the cores, delamination and crack surveys were performed in a one square foot area surrounding each core sampling location. Although an effort was made to avoid collecting cores from areas that contained cracks, 16% of the extracted cores contained cracks. In each core, two intersecting rebars were extracted for evaluation. The condition of the bridge deck in each span was visually evaluated by the researchers using a deck condition rating scheme similar to NBIS. The methodology also included procedures for shipping and storing cores prior to testing in the as-extracted condition as much as possible. The field evaluations and sampling plan were conducted from September 4 to 19, 1996 in New York and from September 30 to October 15, 1996 in Pennsylvania.

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1.3 Findings

The sampling plan was designed to detect progressive corrosion even if the frequency of occurrence was less than 3% of the global population. Results from the study showed that the frequency of occurrence of progressive corrosion is less than 3% in Pennsylvania and at least 3% in New York. A total of 409 rebars showed no evidence of corrosion, 62 bars had a number of small, countable corrosion spots, and only 2 rebars, both in New York, exhibited significant visible corrosion. In addition, corrosion products were observed under the coating on approximately 7% of the bars tested. However, in most cases, corrosion products found under the coating were not the result of ongoing corrosion. Therefore, the existing condition of epoxy coated rebars in bridge decks in Pennsylvania and New York State was found to be very good from a corrosion point of view.

Coating adhesion reduction or loss was found to be more prevalent and extensive. Only 47% of the bars tested had no reduction in adhesion. Over 13% exhibited a complete loss of adhesion and the remaining 40% had varying degrees of adhesion reduction. Probability distribution analyses showed that more than 50% of epoxy coated rebars in bridge decks in Pennsylvania and New York State exhibit some degree of adhesion reduction within 6 to 10 years of placement in concrete. It should be pointed out that, although progressive corrosion must be accompanied by complete adhesion loss, coating adhesion alone was not found to be a good predictor of corrosion condition in this study.

Performance of epoxy coated rebars can only be evaluated after the bars have been exposed to a corrosive environment for a sufficient length of time. Two mechanisms for corrosion initiation and propagation on epoxy coated rebars have been proposed:

1. **Failure from Coating Defects** - Corrosion initiates at coating defects once sufficient levels of chloride are present. Corrosion then progress underneath the coating adjacent to the defects. The coating in these areas may or may not be disbonded at the time corrosion initiates in the defect.

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These mechanisms were used to analyze the performance of epoxy coated rebars in this study. Due to the relatively low average age (10 years) of the sample population, 80% of the bars tested had no exposure time to the chloride threshold of 1.2 pcy. Thus, in the analysis of "Failure from Coating Defects," only 49 bars with known defects and a chloride exposure of at least 1.2 pcy for more than 5 years were identified. Similarly, only 41 bars with adhesion reduction followed by chloride exposure of at least 1.2 pcy for more than 5 years were identified to analyze "Failure by Adhesion Reduction." The number of samples in each of these subsets were not sufficient to statistically evaluate the performance of the epoxy coated rebars with respect to either of the failure mechanisms at an acceptable confidence level. However, only 2 bars (less than 5%) in each subset exhibited progressive corrosion as indicated by the corrosion condition ratings. This minimal number of failures may be attributed to one or more of the following:

a) The epoxy coating on the bars in the subsets has provided acceptable corrosion protection to date.

b) The assumptions used in terms of chloride exposure and chloride content threshold were not sufficiently severe to detect the transformation from corrosion initiation to propagation.

c) Parameters other than those considered in this study play a primary role with regard to the corrosion mechanisms investigated.

No correlation was found with corrosion condition rating and chloride exposure time or chloride content. This is most likely attributable to the age and chloride content distribution of the study population and/or satisfactory performance of the epoxy coated bars.

Other pertinent findings were as follows:

1. Among all the variables included in the analyses, logarithm of EIS, number of holidays, and number of bare spots were found to be the best predictors of corrosion condition rating, but in all cases the correlation's were weak. These same parameters were also found to have statistically significant relationships with adhesion reduction, but again the correlation's were weak.

2. Corrosion condition rating did not correlate with coating thickness, clear concrete cover, color of epoxy, or bridge deck condition rating.

3. Adhesion reduction or loss is irreversible at least after a 7 day drying period. There is a higher probability of adhesion reduction adjacent to areas with visible coating defects compared to those with no visible defects. In addition, the deformation pattern on the bars has some impact on adhesion reduction.

4. A good correlation between concrete resistivity and coulombs passed was found and the following equation can be used to describe the relationship:

$$\text{Coulombs Passed} = 2E{+}09 * \text{A/C Resistivity}^{-1.4539}$$

5. Results of pH testing in rebar traces and pencil hardness testing on the coating did not provide any useful information.

1.4 Recommendations for Future Research

The distinction between existing condition, performance to date, and projections of future performance should be clearly defined in the objective of any field research project involving epoxy coated reinforcing steel. If the primary goal is to investigate existing condition, a sampling plan similar to that employed in this study (i.e. a statistical sample of the global population) is appropriate. However, if the primary objective is to assess performance to date or project future performance, the sample population should consist of older structures in areas with the highest deicing salt usage only. In either case, variables such as type of epoxy, presence of overlays, and epoxy coated rebar in both mats of reinforcing steel versus the top mat only should be considered.

The same structures included in this study should be reevaluated after approximately 10 years of additional service. Performance of the epoxy coated bars could then be more accurately assessed.

Finally, similar data obtained from past studies by other researchers should be combined and analyzed using the procedures described in this report. This would eliminate differences in the data analysis approach and interpretation and should provide insight into the existing condition and performance of epoxy coated reinforcing steel over a large geographical area.

SECTION 2

INTRODUCTION

2.1. Background

Fusion bonded epoxy coating technology has been the primary defense used by most state agencies, including the Pennsylvania Department of Transportation (PennDOT) and the New York State Department of Transportation (NYSDOT), to protect reinforcing steel in concrete from corrosion. However, results from recent research activities[1-3] cast doubt on the ability of epoxy coatings to provide long-term corrosion protection to steel in concrete exposed to chlorides. The projected problem has been attributed to the number and size of breaks or defects in the coating and reduction in adhesion between the epoxy coating and steel substrate.

Coating breaks or defects are represented by holidays, narrow cracks, mashed areas, and bare areas that occur during coating application, fabrication bending, transportation, handling, and concrete vibrating. Reduction of the adhesion bond between the epoxy coating and underlying steel has been widely observed. Occurrence of this phenomenon has been found to be independent of the level of chlorides at the reinforcing steel depth and may or may not be associated with corrosion underneath the coating. While there is a consensus on the occurrence of these problems, their significance with regard to the long-term performance of epoxy coated reinforcing steel in concrete bridge structures exposed to salt in-service is not completely understood, and thus, much controversy remains.

Effective corrosion protection performance of epoxy coated reinforcement after up to 20 years of service, particularly in structures exposed to deicing salt environments, has been reported in several field studies.[4,5] On the other hand, isolated failures have been reported in deicing salt environments after 10 to 15 years of service.[4] The sampling effort in some of these field studies intentionally focused on locations representing a worse case scenario.[5] Consequently, the question is whether the reported failures are precursors to a widespread corrosion problem or the result of relatively unique situations, which are not indicative of the general population of all bridges.[4]

In light of the above discussion, PennDOT and NYSDOT decided to conduct a joint research effort to survey and evaluate in-service bridge decks constructed with epoxy coated reinforcing steel by way of a statistically based sampling plan. Project funding was provided through a regional pool fund and the Federal Highway Administration.

2.2. Project Objectives

Specific project objectives were as follows:

1. Investigate the field performance of epoxy coated reinforcing steel in selected bridge decks in Pennsylvania and New York State using the methodology and sampling processes provided by PennDOT and NYSDOT.

2. Determine if ongoing or progressive corrosion and/or a reduction in coating adhesion is occurring on the epoxy coated rebars utilizing a sampling plan which provides at least a 95-percent probability of detecting these characteristics if they occurred in more than 3-percent of the deck area in either state.

3. Statistically analyze all the data elements investigated to reveal any relationships between these and corrosion condition and/or adhesion reduction.

2.3. Approach and Scope of Project

The NYSDOT developed a statistical sampling plan that included a cross-section of bridge structures, stratified by age and deicer usage in terms of annual average salt usage per lane mile. This sampling plan involved taking a total of 240 cores from 80 bridge deck spans (40 spans in each state) at pre-determined sample locations. The approach and scope of work for the field and laboratory evaluations included:

a) developing and implementing a detailed methodology and sampling plan to collect the core samples containing epoxy coated rebars,

b) developing and implementing a detailed laboratory methodology to perform tests on the concrete and epoxy coated rebars in the cores,

c) creating a database of all data obtained from the field and laboratory evaluations, and

d) analyzing the database using appropriate statistical procedures.

Measurements in addition to those originally included in the scope of work were believed to be useful, but beyond the fiscal provisions for the project. Consequently, the Federal Highway Administration, through Demonstration Project No. 84, agreed to sponsor electrochemical impedance spectroscopy tests on select cores.

The methodology details, results, and conclusions of this investigation are provided in the following sections.

REFERENCES

1. Sagues, A.A., 'Corrosion of Epoxy Coated Rebar in Florida Bridges,' Final Report to Florida Department of Transportation, WPI No. 0510603, University of South Florida, Tampa, FL, May 1994.

2. Clear, K.C., Hartt, W.H., McIntyre, and Lee, S.K., 'Performance of Epoxy Coated Reinforcing Steel in Highway Bridges,' NCHRP Report No. 370, Transportation Research Board, Washington, D.C., 1995.

3. Weyers, R.E., Pyc, W., Zemajtis, J., Liu, Y., Mokarem, D., and Sprinkel, M.M., 'Field Investigation of Corrosion-Protection Performance of Bridge Decks Constructed with Epoxy Coated Reinforcing Steel in Virginia,' Transportation Research Record No. 1597, Transportation Research Board, Washington, D.C., 1997, pp. 82-90.

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5. Smith, J.L., and Virmani, Y.P., 'Performance of Epoxy Coated Rebars in Bridge Decks,' Report No. FHWA-RD-96-092, Federal Highway Administration, Turner-Fairbank Highway Research Center, McLean, VA, August 1996.

SECTION 3

SELECTION OF BRIDGES AND CORE SAMPLE LOCATIONS

3.1. General Information

A statistically based sampling plan was developed by NYSDOT. Details regarding the selection of bridge decks, specific spans to be sampled, and the exact locations for extracting cores are discussed in a complete report by NYSDOT.[1]

Basic elements of the sampling plan were as follows:

- The sampling unit was defined as the epoxy coated reinforcing steel contained in a one square foot area of bridge deck. This area would be sampled by extracting one, 4 inch diameter core.
- In each state, 40 spans were selected to be as representative of the study population as possible.
- Sampling in each span involved extracting three, 4-inch diameter core samples at randomly selected locations.

It was believed that the resulting 120 cores per state would be sufficient to determine if ongoing or progressive corrosion and/or a reduction in coating adhesion had occurred in over 3-percent of the deck area in either state.

3.2. Selection of Bridges

The first step in the span selection process involved development of age and salt usage strata for the available sample population. Thus, two age strata, decks with 3 to 11 years of service (constructed between 1985 and 1993) and others with 12 to 19 winters of service (constructed between 1977 and 1984) were defined. The age of bridge decks that had been replaced as part of rehabilitation efforts was calculated from the replacement date as opposed to the original construction date. Selection of these age strata was based on an assumption regarding the expected chloride content at the reinforcing steel depth and eliminated the possibility of obtaining samples coated with 'Flintflex'; use of this coating was terminated prior to 1977. No other effort was made to control the type of epoxy coating sampled. In addition, no distinction was made between bridge decks with epoxy-coating only on the top mat of reinforcing steel versus those with coated steel in both mats. Similarly, although the bridge decks were not expected to be overlaid with asphalt, the presence, or lack thereof, of any overlay on the decks was not treated as a variable in the sample selection process.

Statewide data on annual deicer usage per lane mile were analyzed and each county in each state was then classified into one of the salt usage categories described below.

For New York:

High - more than 20 tons per lane-mile per year.
Medium - between 15 and 20 tons per lane-mile per year.
Low - less than 15 tons per lane-mile per year.

For Pennsylvania:

Medium - more than 15 tons per lane-mile per year.
Low - between 9 and 15 tons per lane-mile per year.
Extra-Low - less than 9 tons per lane-mile per year.

Bridge inventory, inspection, and management systems were then examined to identify the study population in each state (i.e. bridge decks constructed with epoxy coated reinforcing steel between 1977 and 1993, inclusive). In New York, 1,425 bridge decks with a total of 3,360 spans representing 16,599,290 square feet of deck area were identified. The analysis in Pennsylvania found 2,290 bridge decks with a total of 6,062 spans comprising 26,026,417 square feet of deck area. The number of bridges and spans and the total bridge deck area in each of the six age and salt usage strata were then determined for each sample population. Since the sampling unit was defined as epoxy coated reinforcing steel in one square foot of deck area, the number of spans to be cored for each combination of age strata and salt usage category was determined by a proportional allocation based on the percentage of deck area represented.

The next step involved selection of a subset of bridge decks to be used as the 'sampling population' within each combination of age and salt usage stratum. A subset of bridge decks was required in order to minimize travel costs associated with the sampling process. Selection of the subset was accomplished using intuitive judgment and trial-and-error until the several criteria listed below were satisfied. Also, bridges in NYSDOT Region 11 were excluded from the subset due to traffic considerations.

- The condition of epoxy coated reinforcing steel in the sampling population should be representative of the condition in the strata populations.

- Each sampling population should consist of a sufficient number of bridge decks to sample from (i.e. much larger than the actual number to be sampled).

- The sampling population should be concentrated, as much as possible, within a geographically compact area.

- The overall sampling population (i.e. the sampling population for all six strata) should also be concentrated in as geographically compact an area as possible.

The first two criteria were considered so that the study objectives and statistical integrity of the sampling plan would not be compromised. The other goals were included to address the aforementioned issue regarding travel costs during the sampling effort.

In addition, to ensure that the condition of bridge decks in the sampling population was not distinctly different than the condition of decks which were not included, comparisons of monolithic deck surface rating (for New York bridges) and deck condition rating (for Pennsylvania bridges) were made.

The final sample was drawn randomly from spans in the sampling populations of each of the six age and salt usage stratum. In New York, the final sample consisted of 40 spans on 37 bridges located in 13 counties in NYSDOT Regions 1, 2, 3, 4, and 9. The final sample in Pennsylvania included 40 spans on 40 bridges located in 16 counties in PennDOT Districts 1, 2, 4, and 9. The final list of spans in New York and Pennsylvania is presented in Appendix A.

3.3. Selection of Core Sample Locations

Once the final list of spans had been developed, the exact coring locations on each span had to be determined. First, to simplify traffic control requirements, coring locations were restricted to only one driving lane, that is the right driving lane in the direction of traffic. For structures with traffic in both directions, the traffic direction in which a driving lane was to be cored was randomly selected first. Second, a x-y coordinate system was used to define the exact location for coring within the selected driving lane and span. Longitudinal distances (x-coordinates) were determined by dividing the span length into three equal sections and then randomly selecting one core location in each section. The corresponding transverse distance (y-coordinates) for each location was randomly generated using either known or assumed lane widths. In each case, an alternate coring location within each section was also determined using the same procedures. Alternate locations were to be used if the primary location was not accessible, was located outside the designated lane, or disqualified for coring for some other reason.

The field procedures used to identify the selected span(s) on each bridge, determine the lane to core, and pinpoint the pre-selected coring locations are discussed in Section 4 of this report.

REFERENCES

1. Sandhu, D., "Sampling Plan for Verification of Effectiveness of Epoxy Coated Rebars," Transportation Research and Development Bureau, New York State Department of Transportation, July 24, 1996.

SECTION 4

FIELD EVALUATION AND SAMPLING

4.1. General Information

A detailed methodology and sampling plan to collect a total of 240 concrete core samples containing epoxy coated reinforcing steel from the selected 77 bridge decks was developed. The complete report is provided in Appendix A. In summary, the methodology and sampling plan included the following:

A. Detailed scheduling information for sampling in each state.

B. Traffic control plans and details for each structure.

C. Procedures for locating and documenting exact core sample locations.

D. Procedures for locating rebars and conducting visual and delamination surveys at core sample locations.

E. Procedures for coring including a) collection, b) photographing (including inside core holes), c) labeling, d) packaging, e) handling, f) shipping, and g) storing.

F. Procedures for re-sampling in the event the epoxy coated rebars were damaged while retrieving them or if the core did not contain a rebar.

G. Procedures and materials for patching core holes.

H. Procedures for photographing the overall bridge structures and decks.

I. Data sheets for documenting general bridge information, sampling information, core locations, and the visual condition of cores and decks.

4.2. Field Evaluation and Sampling

A bridge information form was prepared for each structure and this included a schematic drawing showing the direction of traffic, lane and span to be sampled, the x-y coordinates for each primary and alternate core location, a 'begin bridge' reference point, and traffic control requirements. Sample bridge information forms are shown in Appendix A.

Each sampling location was pinpointed using the pre-selected x-y coordinates and the drawing provided on the bridge information form. A circle drawing template was then used to outline an area for each core sample. At this point, primary sampling sites were excluded only if no reinforcing steel could be found within the outlined circular area or if they were spalled, patched, located within one foot of the edge of the traffic control boundary (for safety reasons) or outside the traffic control area. Spalled areas were not sampled since exposed bars had been subjected to an extremely severe environment for an unknown period of time; this situation was not considered representative of typical conditions. Similarly, it was not known if rebars in repaired areas would be coated or, if they were coated, what process was used to apply the coating or how long it had been in service. In the unlikely event that both the primary and alternate coring locations disqualified for coring, a second set of alternate coordinates was randomly selected for each core location and these were included on the aforementioned bridge information forms.

Any cracks, delaminations, or other deterioration within each outlined area were then documented. The exact core location within each outlined area was selected so that the core would contain intersecting rebars (or a single rebar if no intersecting bars were found) closest to the center of the circle. The sampling plan provided by the NYSDOT stated that, when selecting coring sites, no preference should be given to cracks or any other concrete deterioration found. However, prior to initiating the field sampling effort, the State DOT project panel decided that cracks should be avoided. If a selected core location contained a crack visible to the naked eye, then an alternate location was to be used. The primary coring site was not disqualified, however, if it was delaminated, but uncracked.

Core samples were collected using a vacuum apparatus, where possible, for securing the core drill in place and tap water for cooling the core bit. Cores were extracted after drilling to a depth of six inches or to the top of the bottom mat of reinforcing steel, whichever was less. All core holes were patched with a fast setting; prebagged, cementitious concrete material.

Upon extraction, cores were surface dried and the visual condition of the cores and any exposed rebar segments was documented immediately. The cores were then labeled, photographed, wrapped in dry burlap, and sealed in an air tight sample bag. Cores were packaged and shipped to the laboratory on a weekly basis. If cores were broken or otherwise damaged upon retrieval (i.e. due to the core extraction process or a delamination at the rebar level), and epoxy coated rebars exposed, all pieces were individually surface dried, labeled, wrapped in burlap, and sealed in an air tight sample bag. The entire sample was then shipped by overnight delivery to the laboratory. In such instances, all bar coating tests and measurements were performed within 24 hours after receipt in the laboratory.

In addition to obtaining core samples at each site, the condition of the deck surface was visually rated as follows:

Rating	Description
N	**Not applicable** (concrete surface is not visible, for example, due to an overlay or sealer)
9	**Excellent Condition** (no problems noted, generally used for a new structure)

8 **Very Good Condition**
(no problems noted, generally used for an old structure)

7 **Good Condition**
(some minor problems)

6 **Satisfactory Condition**
(less than 2% spalls or sum of all deteriorated deck concrete less than 20%)

5 **Fair Condition**
(less than 5% spalls or sum of all deteriorated deck concrete 20% to 40%)

4 **Poor Condition**
(greater than 5% spalls or sum of all deteriorated deck concrete 40% to 60%)

3 **Extensive Deterioration**
(greater than 5% spalls or sum of all deteriorated deck concrete greater than 60%)

The field evaluations and sampling plan were conducted from September 4 to 19, 1996 in New York and from September 30 to October 15, 1996 in Pennsylvania.

SECTION 5

LABORATORY TESTING METHODOLOGY

5.1. General Information

A detailed laboratory evaluation methodology to perform specific tests on the concrete cores containing epoxy coated rebars was developed (a complete report can be found in Appendix B). The methodology addressed the following issues:

A. Logging, handling, and storage of cores in the laboratory.

B. Testing sequence.

C. Procedures and data sheets for each test.

D. Documentation of test results including design of a database for managing the data.

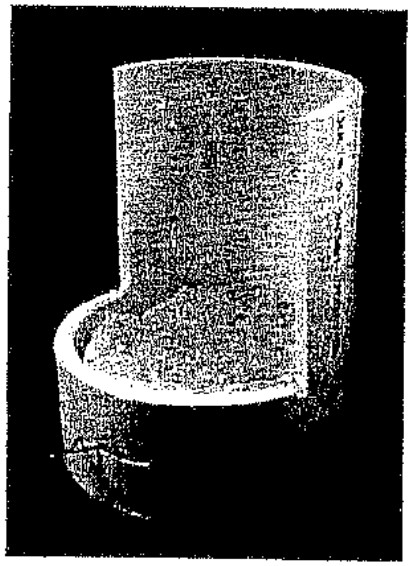
E. Quality control procedures.

5.2. Laboratory Testing Methodology

Upon receipt in the laboratory, cores that were intact were frozen until testing was initiated. For fractured cores with exposed epoxy coated rebars, all bar coating tests and measurements were performed within 24 hours after receipt in the laboratory. Frozen cores were tested in groups of six to fifteen. In each case, a group of cores was removed from the freezer and allowed to thaw to room temperature. Within 24 hours after thawing, the cores were prepared for testing, electrochemical impedance spectroscopy (EIS) testing was conducted, and powdered concrete samples were extracted for chloride content analysis.

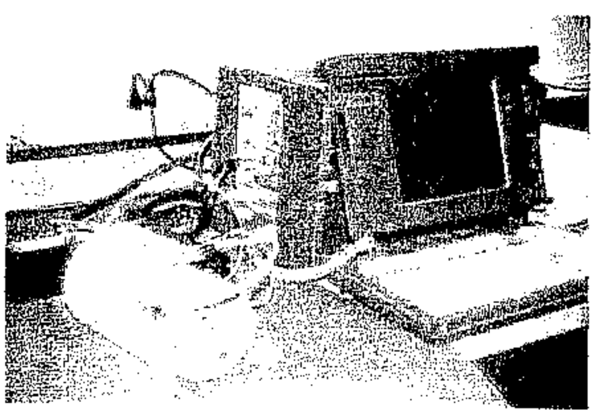
Core preparation involved surface drying, visual examination, documenting physical characteristics, measuring the concrete cover over the topmost bar, photographing, and drilling and tapping the bar ends to facilitate direct connections for testing purposes. EIS measurements involved a specially designed test probe as shown in Figure 5-1. Powdered concrete samples were obtained in a manner that permitted accurate determination of the chloride content at the depth of both intersecting bars (see the detailed laboratory evaluation methodology in Appendix B).

Testing proceeded with the extraction of epoxy coated rebars from the cores. Rebar traces (i.e. the indentation left on the concrete surface when a rebar is removed) were then visually examined and photographed; pH testing was conducted on the rebar traces and any visible liquid on the bars or traces; and epoxy coated bars were visually examined and photographed.



a) EIS test probe

b) Test probe with core removed



c) EIS test in progress

Figure 5-1. EIS test setup: a) test probe,
b) test probe with core removed, and c) test in progress.

Bars were extracted by dry saw cutting small groves into the sides of the core and then splitting the core using a hammer and chisel. Litmus paper was used to measure the pH of any liquid observed on the bars or traces and pH pencils and liquid pH indicators were used to measure the pH of the concrete within the rebar trace area. Visual inspection of epoxy coated rebars involved documenting the deformation pattern, recording mashed areas, bareareas, and blisters, and rating the overall condition of the coating and reinforcing steel using the rating system shown in Table 5-1.

Table 5-1. Visual Rating System for Epoxy Coated Rebars.

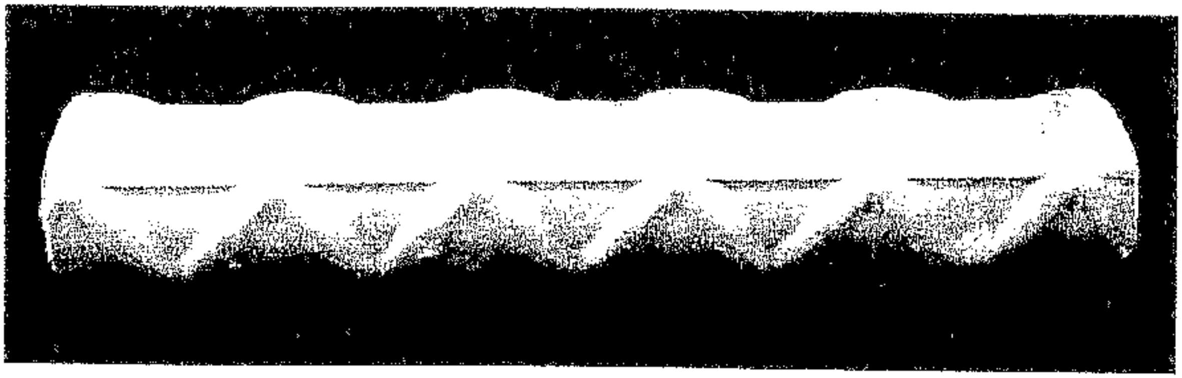
Rating	Description
1	No evidence of corrosion.
2	A number of small, countable corrosion spots.
3	Corrosion area less than 20% of total ECR surface area.
4	Corrosion area between 20% to 60% of total ECR surface area.
5	Corrosion area greater than 60% of total ECR surface area.

Figure 5-2 shows photographic examples for some of the visual rating categories. The visual examination was followed by a series of coating tests: a) holiday detection, b) coating thickness, c) coating hardness, and d) wet and dry knife adhesion tests.

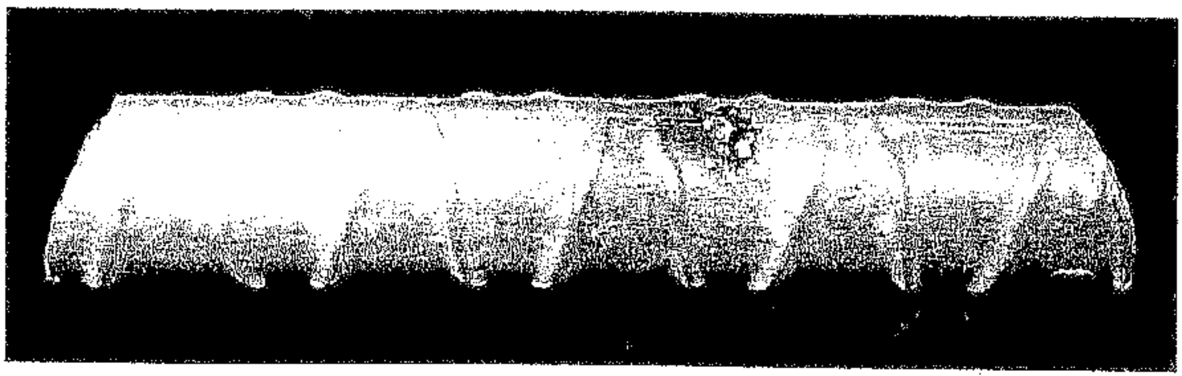
Holiday detection was performed in accordance with ASTM 62 – Method A. A small (1/4 inch square) sponge was used in order to differentiate between closely spaced holidays.

Coating thickness was measured using the procedures described in ASTM A 775 and ASTM D 3963 except that a correction factor could not be determined (i.e. clean uncoated steel bar of the same size and from the same lot was not available to define a correction factor). Coating thickness measurements were also taken on top of bar deformations for comparison with results obtained between bar deformations.

Coating hardness and adhesion tests were performed in accordance with NACE Standards TM0174 – Section 6.1.5 and TM0185 – Section 5.3.2 respectively. The latter involves only dry knife adhesion tests (i.e. tests are conducted after the bars are placed in a desicator for 7 days). In addition, wet adhesion tests (i.e. bars are tested without a 7 day drying period in a desicator) were performed to insure that the extent of any reduction in adhesion was not underestimated if adhesion was re-established upon drying. The wet adhesion test represents in-service conditions while the dry test provides standardized results under controlled conditions. In both cases, tests were conducted in damaged and undamaged areas. If insufficient total bar area and/or damaged area was available, emphasis was placed on the dry knife adhesion test to facilitate direct data comparisons. The adhesion tests also involved visual examination of the steel surface at locations where the coating was removed.



Corrosion Rating 1



Corrosion Rating 2

Corrosion Rating 4

Figure 5-2. Photographs depicting the visual condition of bars with corrosion ratings of 1, 2, and 4.

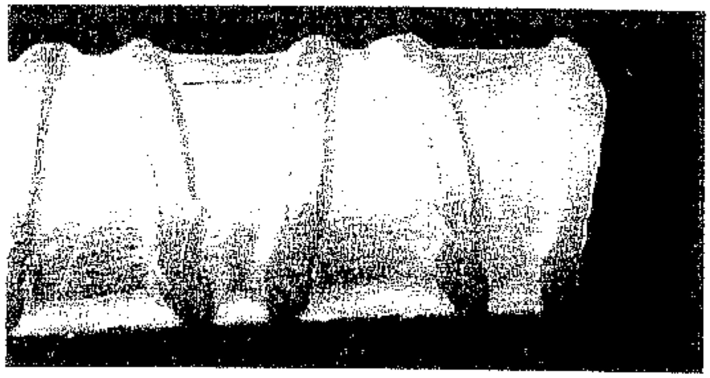
The rating scheme presented in Table 5-2 was used to record adhesion test results. Figure 5-3 shows a typical visual example of each adhesion rating. Once started, all the above (i.e. from extracting the bars from the cores to the wet knife adhesion tests) was completed within 24 hours.

Table 5-2. Rating System Used for Knife Adhesion Tests.

Rating	Description
1	Well adhered coating that cannot be peeled or lifted from the steel substrate.
3	Coating that can be pried from the steel substrate in small pieces, but cannot be peeled off easily.
5	Coating that can be peeled from the steel substrate easily, without residue.

Additional testing of the concrete portion of cores was also conducted. This included acid soluble chloride content analyses, determination of the specific gravity, absorption, and voids, rapid chloride permeability testing, and concrete resistivity measurements. Chloride content analyses were performed in accordance with AASHTO T260-94 – Procedure A. Specific gravity, absorption, and voids were determined using concrete from the bottom portion of cores and the procedures described in ASTM C 642-90. Rapid chloride permeability tests (AASHTO T 277-93) were conducted on the upper portion of the core samples. In instances where the concrete cover was less than or greater than two inches, a correction factor based on the actual sample thickness was applied to the test results (see the detailed laboratory evaluation methodology in Appendix B). Concrete resistivity was calculated using AC resistance measurements taken at specific times during the rapid chloride permeability test.

Upon completion of all testing for each group of cores, all concrete was stored in an airtight sample bag at room temperature. Epoxy coated rebars were individually wrapped with plastic wrap and stored in an airtight sample bag at room temperature.



Adhesion Rating 1

Adhesion Rating 3

Adhesion Rating 5

Figure 5-3. Photographs showing the typical condition observed for each adhesion rating.

SECTION 6

RESULTS AND DISCUSSION

6.1 Summary of Data Collected

A total of 240 cores, 3 from each of 80 bridge deck spans, were obtained and analyzed. Each core contained two intersecting epoxy coated rebars from the top mat reinforcement, thus a total of 480 rebars were extracted for evaluation. Of these, 7 were too small to perform the prescribed laboratory procedures. As a result, the database generated in this study consists of 473 sets of data; one for each rebar evaluated.

The intersecting rebars in each core were comprised of one longitudinal and one transverse bar. With the exception of six cores, from 2 spans in Pennsylvania, the transverse rebars were closer to the top surface of the deck. For the purpose of this report, the rebar in each core that was closest to the surface of the deck was labeled the top bar and the other rebar was labeled the bottom bar.

The data obtained in this study were grouped into four categories; 1) bridge information, 2) core information, 3) concrete properties, and 4) epoxy coated rebar condition and properties. Several measurements were performed using more than one procedure. To simplify data analysis, results obtained from all procedures were compared in each case and if no significant differences were observed, only results from one of the procedures were used for the data analyses presented herein. In addition, all prescribed concrete laboratory tests could not be performed on all samples, as the dimension and/or condition of some samples were not within the required specifications. Instances where all laboratory procedures could not be performed on all 473 rebars are discussed below.

6.1.1 Bridge Information

With the exception of the bridge deck rating, all information in this category was obtained from the local agencies responsible for the bridge structures or the appropriate State DOT. The visual condition of the deck in each span was rated during the field evaluation.

1. **Location:** Each structure's location was defined using the following geographical descriptions:

   i. County

   ii. District

   iii. State

   The selected spans were distributed over 13 counties in 5 districts in the State of New York and 16 counties in 4 districts in the State of Pennsylvania. Table 6-1 shows the distribution of spans by State, District, and County.

Table 6-1. Distribution of Spans by State, District, and County.

STATE	DISTRICT	COUNTY	Total Spans
New York	1	ALBANY	4
		GREENE	3
		SCHENECTADY	1
		WASHINGTON	1
	District 1 Total		**9**
	2	FULTON	2
		HERKIMER	2
		ONEIDA	2
	District 2 Total		**6**
	3	ONONDAGA	6
		OSWEGO	1
	District 3 Total		**7**
	4	LIVINGSTON	8
		MONROE	6
	District 4 Total		**14**
	9	BROOME	2
		SULLIVAN	2
	District 9 Total		**4**
Total Spans in New York			**40**
Pennsylvania	1	CRAWFORD	3
		ERIE	2
		FOREST	2
		MERCER	7
		WARREN	2
	District 1 Total		**16**
	2	CAMERON	1
		CENTRE	1
		CLEARFIELD	2
	District 2 Total		**4**
	4	SUSQUEHANNA	5
		WAYNE	1
		WYOMING	1
	District 4 Total		**7**
	9	BEDFORD	3
		BLAIR	2
		FULTON	5
		HUNTINGDON	2
		SOMERSET	1
	District 9 Total		**13**
Total Spans in Pennsylvania			**40**

2. **Salt Strata:** To account for variations in deicing salt applications, the four salt strata shown in Table 6-2 were defined and used in the selection of spans for sampling. In some cases, variations in salt usage between the two states resulted in different levels of salt usage for the same salt stratum. The distribution of bridges in each salt stratum is presented in Table 6-3.

Table 6-2. Description of Salt Strata.

Salt Strata	New York tons/lane-mile/year	Pennsylvania tons/lane-mile/year
1	> 20	
2	15 < x < 20	> 15
3	< 15	9 < x < 15
4		< 9

3. **Average Daily Traffic (ADT):** This information was obtained from State DOT databases and the resulting distribution is presented in Table 6-3.

4. **Age Strata:** Two age strata were defined and used in the span selection process. Spans constructed from 1985 to 1993 were categorized as Age Stratum 1 and those constructed from 1977 to 1984 were categorized as Age Stratum 2. The distribution of bridges by age stratum is provided in Table 6-3.

   The age of each selected bridge structure was obtained from appropriate State DOT databases. Some of the older structures had undergone deck replacement. In such cases, the age was calculated from the date of deck replacement. Table 6-3 presents a summary of the age distribution for all spans included in this study and statistical information is shown in Table 6-4.

Table 6-4. Statistics for Bridge Information.

	N	Min.	Max.	Avg.	Median	Std. Dev.
Age, years	80	3	19	10	10	4
Deck Rating	79	6	7	7	7	1.1

5. **Deck Condition Rating:** Visual evaluation of the deck surface in the selected spans was performed during the sample collection effort. One span in New York was not rated due to an asphalt overlay. The distribution of spans by deck condition rating is presented in

Table 6-3. Distribution of Spans by Salt Strata, ADT, Age Strata, Age and DCR.

	STATE	
	New York	Pennsylvania
Salt Strata		
1	16	
2	10	2
3	14	18
4		20
Total Spans	**40**	**40**
Average Daily Traffic (ADT)		
0 to 9,999	26	38
10,000 to 19,999	6	2
20,000 to 29,999	3	0
30,000 to 39,999	4	0
40,000 to 49,999	0	0
50,000 to 60,000	1	0
Total Spans	**40**	**40**
Age Strata		
1	22	28
2	18	12
Total Spans	**40**	**40**
Age (years)		
less than 5	8	9
6 to 10	14	18
11 to 15	14	13
16 to 20	4	0
Total Spans	**40**	**40**
Deck Condition Rating (DCR)		
6	1	15
7	9	25
8	29	
Not Rated	1	
Total Spans	**40**	**40**

Table 6-3 and statistical information is shown in Table 6-4. The ratings shown in these tables are described below.

Rating 6	Satisfactory Condition: less than 2% of the deck surface is spalled or the sum of all deteriorated deck concrete is less than 20% of the deck surface area.
Rating 7	Good Condition: some minor problems
Rating 8	Very Good Condition: no problems noted

Minor spalling, which was not related to reinforcing steel corrosion, was observed on one deck which was given a rating of 6. Freeze-thaw damage was also observed on this span. All other ratings of 6 were associated with cracking on the deck surface and the only difference between a rating of 6 and 7 was the degree of cracking. No investigation was conducted to determine the cause of the cracks.

6.1.2 Core Information

Data in this category were collected from within the circular sampling area and from the extracted core samples.

1. **Delaminations:** A delamination survey was performed within each circular sampling area. No delaminations were found at any of the sampling locations.

2. **Cracks:** Cracks within the circular sampling area were observed and attempts were made to locate cores in areas with no cracks. The State DOT project panel decided that it would be more prudent to evaluate the performance of epoxy coated rebars in uncracked concrete areas. Although effort was made to avoid cracks, 16% (39 cores) of the extracted cores contained cracks.

3. **Visual Observation of Cores:** Due to the drilling depth used to extract cores, several cores unintentionally contained bottom mat reinforcement (not the bottom bar of the top mat, but the bar from the second layer of steel in the deck). In some cases, the bottom mat steel was epoxy coated and in others it was not (i.e. black or uncoated reinforcing steel). All bridge decks in New York have black bottom mat reinforcing steel. In Pennsylvania, a given bridge deck may have black or epoxy coated reinforcing steel in the bottom mat depending on the date of construction.

   Each core was visually observed for the presence of rust staining and/or honeycombing. Rust staining was observed on 7 cores and honeycombing was noted on one core. Rust staining on 2 of the 7 cores was directly related to corrosion of the epoxy coated bars. In 2 other cores the rust staining was related to corrosion of steel chairs supporting the bottom mat reinforcement. In the remaining 3 cores, the rust stains were caused by corrosion of uncoated bottom mat steel which was extracted with the cores.

4. **Cover:** Clear concrete cover over the top rebar was measured. The concrete cover over the bottom rebar was calculated by adding the diameter of the top rebar to the cover measurement for the top rebar. Three cores had a concrete overlay and three other cores

had a thin asphalt overlay. Statistical information for top and bottom rebar cover is shown in Table 6-5.

Table 6-5. Statistics for Core Information.

	N	Min.	Max.	Avg.	Median	Std. Dev.
Top Bar Cover, in.	238	1.6	4.0	2.7	2.7	0.4
Bot. Bar Cover, in.	235	2.2	4.5	3.3	3.3	0.4
EIS, kΩ	178	3	155,000	1,724	108	12,236

5. **EIS:** Electrochemical impedance spectroscopy testing was conducted on 178 cores and the impedance obtained at 0.1 Hz was documented[1]. The EIS technique is a non-destructive test method that has been successfully used to study the deterioration of coated metals, although its application to ECR in concrete is still being investigated. Consequently, no data interpretation guidelines are available. Theoretically, high impedance values would be indicative of an effective coating. The primary purpose of conducting EIS tests in this study was to determine if EIS test results could accurately provide information regarding the condition of epoxy coated reinforcing steel in concrete. Statistical EIS test results are presented in Table 6-5.

6.1.3 Concrete Properties

Concrete properties were measured or calculated as discussed below. The standard test method ASTM C-642 requires that the concrete sample weigh a minimum of 800 gms. Of the 240 cores tested, the concrete sample from 94 of the cores weighed less than 800 gms. Consequently, absorption and percent pore volume data for these cores were not included in any data analyses. However, the weight of the sample was not considered particularly critical with respect to determining specific gravity, therefore specific gravity results were used in the analysis. Statistical results for ASTM C-642 and concrete permeability testing are presented in Table 6-6.

Table 6-6. Statistics for Concrete Properties.

	N	Min.	Max.	Avg.	Median	Std. Dev.
Unit Weight, pcf	240	64	206	134	135	10
Permeability, coulombs	236	419	23,775	5,275	4,012	3,761
Absorption, %	146	3.5	9.4	6.5	6.6	1.0
Volume Pore Space, %	146	8.3	21.7	14.1	14.2	2.0

1. **Specific Gravity:** The standard test method measures specific gravity in four different ways; bulk dry specific gravity, bulk specific gravity after immersion, bulk specific gravity after immersion and boiling, and apparent specific gravity. Descriptive statistics for each of these were very similar. Since bulk dry specific gravity provides a better estimate of concrete unit weight, this parameter was selected for the data analyses presented herein. The data in Table 6-6 show the bulk dry specific gravity results after conversion to concrete unit weight.

2. **Permeability:** A total of 236 cores were tested. Due to difficulties encountered in performing the test, 4 cores were not tested. Based on the test results, cores were categorized as 51% high (greater than 4000 coulombs) permeability, 39% moderate (2000 to 4000 coulombs), 9% low (1000 to 2000 coulombs), and 1% very low (100 to 1000 coulombs).

   To investigate any relationship between concrete resistivity and coulombs passed, the A/C resistance of each sample was measured prior to the start of the test. Measured resistances were converted to concrete resistivity using:

   $$R=\rho L/A^2$$

   where R is the measured resistance, ρ is the concrete resistivity, L is the thickness of the sample, and A is the surface area of the sample. A good correlation between concrete resistivity and coulombs passed was observed and the following equation can be used to describe the relationship found:

   $$\text{Coulombs Passed} = 2E{+}09 * \text{A/C Resistivity}^{-1.4539} \qquad r^2 = 0.83$$

3. **Absorption:** Although 240 cores were tested, results for only 146 cores were included in the analysis as the weight of the other cores did not meet the requirements of the test method. Absorption was measured in two ways; absorption after immersion and absorption after immersion and boiling. No statistically significant difference was found between these measurements. Since absorption after immersion and boiling should provide a better measure of true absorption, it was used in the data analyses presented herein.

4. **Percent Volume Pore Space:** The volume of permeable airspace for the 146 cores with a sample weight in excess of 800 gms was measured.

5. **pH:** The concrete pH in rebar traces was measured using two techniques; standard indicating solutions and pH pencils. Also, pH measurement of any liquid observed on the rebar traces was planned, but no liquid was observed. Measurements obtained with standard indicator solutions are more accurate and were thus used in all data analyses. Of the 459 traces available for testing, 99% had a pH of 11. A total of 14 traces were not available for testing. In some cases where cores fractured upon retrieval, the trace for the bottom bar was not extracted with the core. In other cases, traces were damaged when bars were removed from the cores. Statistical results for pH measurements are presented in Table 6-7.

Table 6-7. Statistics for Concrete Properties.

	N	Min.	Max.	Avg.	Median	Std. Dev.
Rebar Trace pH	459	11	13	11	11	0.1
Total Chloride Content, pcy	457	0.00	11.37	0.95	0.47	1.34
Chloride Exposure, yrs	473	0	16	1	0	3

6. **Chloride Ion Content:** Chloride ion content data were obtained for a total of 457 rebars. In some cores sufficient concrete was not available to collect the required sample. Statistical information for the chloride ion content at the rebar depth is shown in Table 6-7. Figure 6-1 presents the percent of rebars that had a chloride content in the surrounding concrete at or greater than a given level. Percent chloride content was converted to pounds per cubic yard (pcy) using the measured bulk dry specific gravity of the concrete in each core. To identify the percentage of bars that had a chloride content of 1.2 pcy or more at the rebar depth, Table 6-8 was generated using the plot in Figure 6-1.

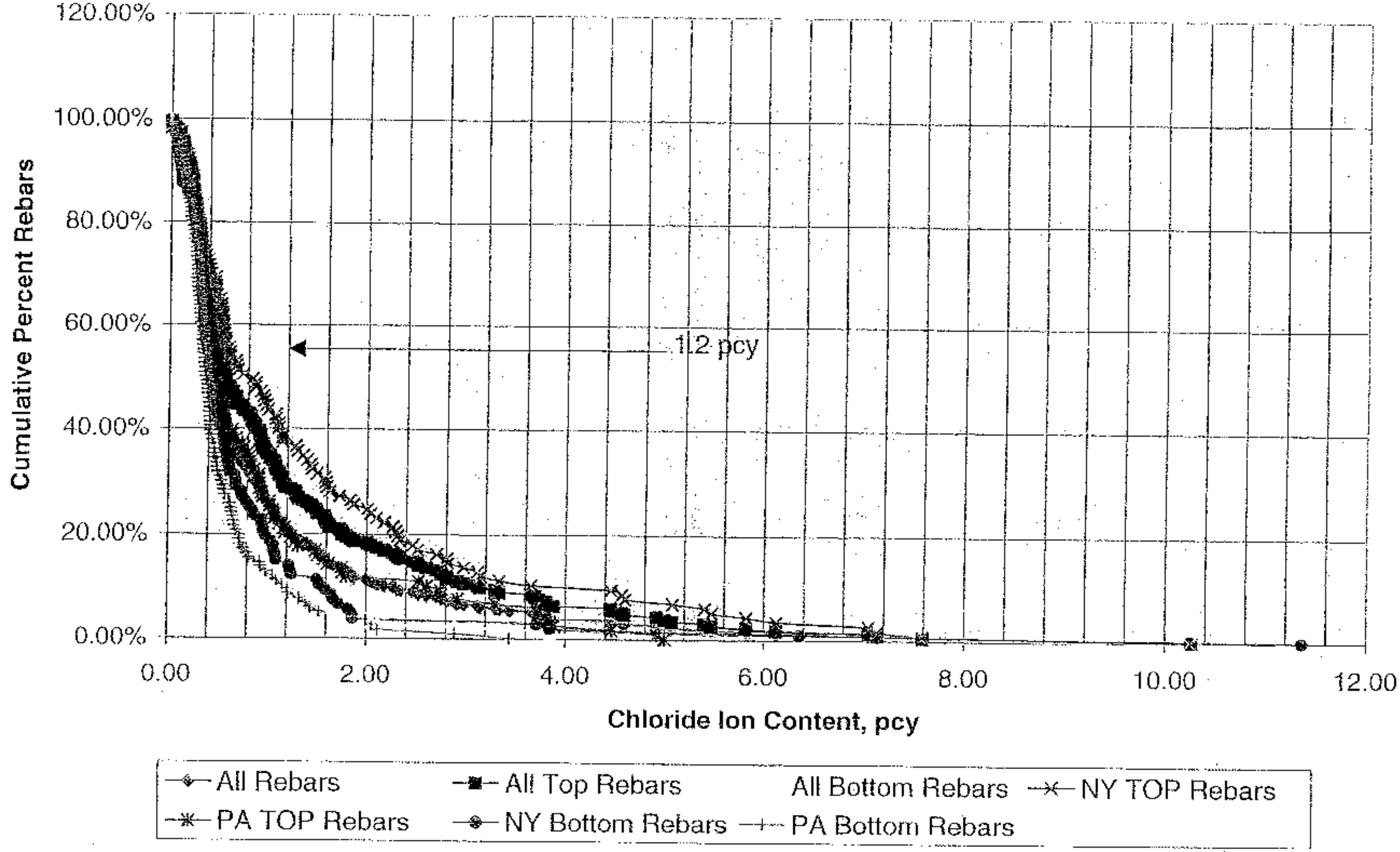
   If one considers all top rebars tested, Table 6-8 shows that 29% of these had a chloride content at the steel depth of 1.2 pcy or greater. If the chloride content threshold is changed to 2 pcy, the number of top bars with 2 or more pcy of chloride would reduce to 18% (see Figure 6-1). Similarly, if the chloride content threshold is increased to 5 pcy, the number of top bars with 5 or more pcy of chloride would reduce to 4%.

Table 6-8. Summary of Rebars with >= 1.2 pcy Chloride.

Types of Rebar	Percent
All Rebars	21%
All Top Rebars	29%
All Bottom Rebars	14%
Top Rebars New York only	37%
Top Rebars-Pennsylvania only	15%
Bottom Rebars-New York only	15%
Bottom Rebars-Pennsylvania only	14%

7. **Time of Exposure to Chloride Content Equal to or in Excess of 1.2 pcy:** Determination of the time that rebars have been exposed to at least 1.2 pcy chloride concentration (for brevity, this is termed **chloride exposure** in this report) is difficult as this is a function of concrete quality and exposure conditions (salt application rate,

Figure 6-1. Cumulative Distribution of Chloride Ion Content.



environment, etc.). Chloride exposure can best be estimated using Fick's law of diffusion. A diffusion constant was calculated for each rebar using the following mathematical expression:

$$C_{(x,t)} = C_o\left(1 - erf\frac{d}{2\sqrt{D_c t}}\right)$$

where,

$C_{(x,t)}$ = the chloride ion content at the rebar depth. Results from chloride ion content analyses were used for each rebar.

C_o = a constant used to account for deicing salt applications and the near surface chloride ion content[2,3]. With the exception of two rebars from New York, the C_o values for all rebars in the States of New York and Pennsylvania were assumed to be 10 pcy and 8 pcy respectively. These values for C_o were selected based on the range of values provided in Reference 2. Conservative values for C_o were selected to ensure that chloride exposure was not overestimated. For two of the rebars from New York, the chloride ion content at the rebar depth was already in excess of 10 pcy. Therefore, C_o values of 11 and 12 pcy were selected after a trial and error process of obtaining acceptable diffusion constants.

d = the rebar depth.

D_c = the diffusion constant to be calculated.

t = the age of the deck at the time chloride samples were collected.

Once the diffusion constants were calculated, the same equation was used to calculate the age at which the chloride ion content at the rebar depth reached 1.2 pcy. If the results of this calculation were less than the age of the structure, the result was subtracted from the age of the structure to obtain the chloride exposure for 1.2 pcy. If the calculation resulted in a value greater than the age of the structure, the chloride exposure was considered to be zero. Statistical information for chloride exposure is presented in Table 6-7 and the resulting continuous cumulative distribution is presented in Figure 6-2. The ordinate of this plot shows the median chloride exposure for each range except for chloride exposure of zero.

6.1.4 Epoxy Coated Rebar Condition and Properties

Epoxy coating properties and the condition of epoxy coated rebars are summarized in Table 6-9. The average and median length of the extracted rebars was 3.7 with a standard deviation of 0.2. Therefore, the number of coating defects, including holidays, was used in the analysis without normalizing the data by bar length.

Figure 6-2. Continuous Cumulative Distribution of Chloride Exposure.

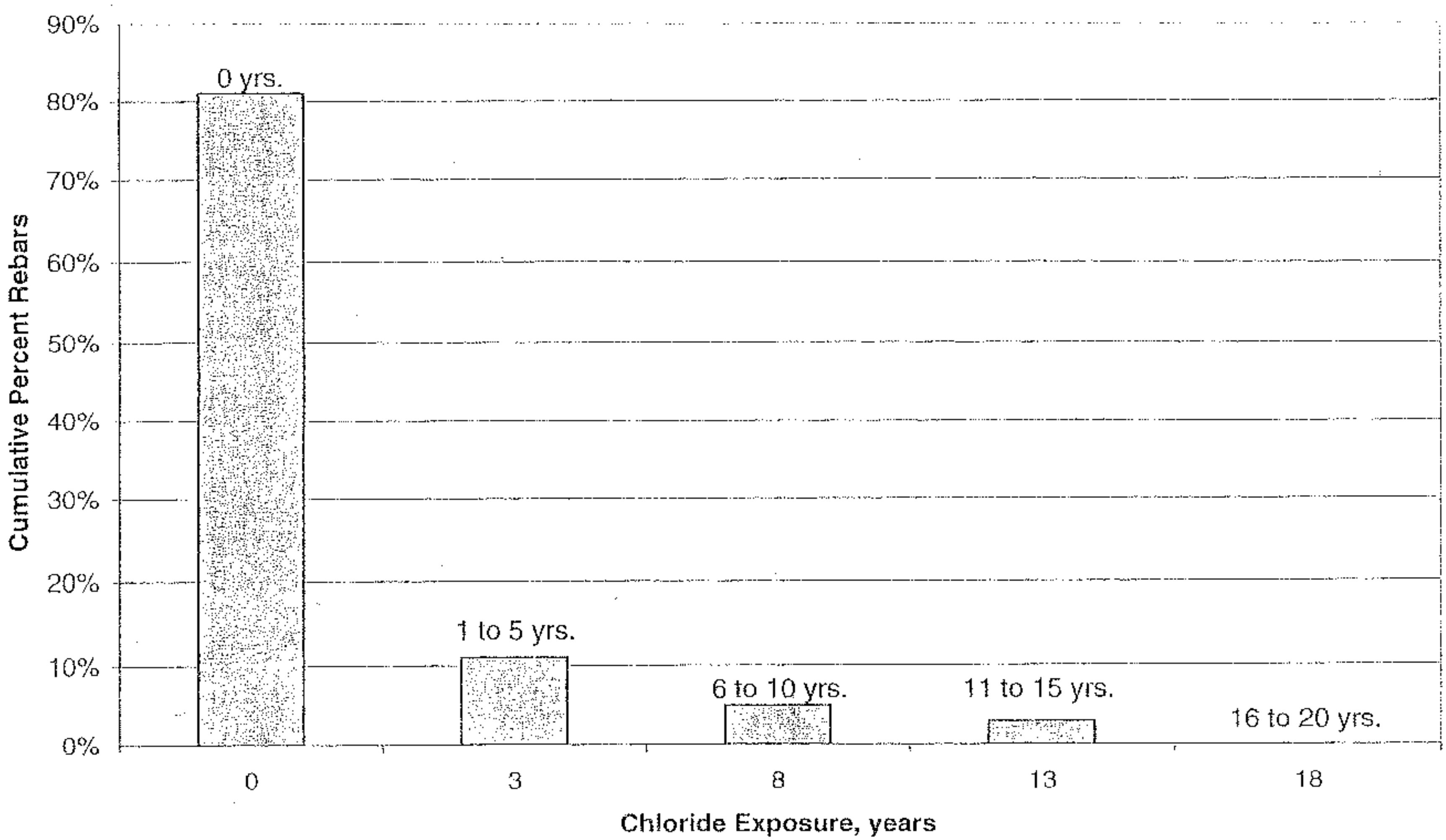


Table 6-9. Statistics for Epoxy Coated Rebars.

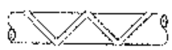
	N	Min.	Max.	Avg.	Median	Std. Dev.
# of Mashed Areas	473	0	20	2.1	2.0	2.2
# of Bare Areas	473	0	21	2.4	2.0	2.6
# of Holidays	473	0	156	7.7	3.0	15.8
Coating Thickness, mils	473	2.4	21.9	11.2	11.1	2.8
Pencil Hardness	473	6 (3B)	10 (F)	9.0 (HB)	9.0 (HB)	0.18
Corrosion Condition Rating	473	1	4	1.1	1.0	0.4
Adhesion Rating	473	1	5	2.2	2.0	1.4

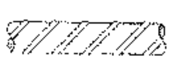
1. **Color:** The epoxy coating on extracted rebars had two different colors; green (351 bars) and brown (122 bars). The green colored epoxy was considered to be Scotchkote 213. Sufficient information was not available to determine the exact source(s) of the brown epoxy coating. It is believed that the majority of the brown coating is Scotchkote 214 and that the remaining may be Armstrong R349.

2. **Number of Mashed Areas, Blisters, Bare Areas, and Holidays:** The number of each of these coating defects was documented for each extracted rebar. No blisters were detected on any of the rebars tested. The size of each bare area was not documented as this was beyond the scope of the study. When a continuous beep was heard during holiday detection, the length of the bar was divided by the width of the sponge used (0.25 in.) to obtain the number of holidays in that area.

3. **Deformation Pattern:** The deformation pattern on each rebar was classified by one of the following descriptions:

   Type X  Used when consecutive ribs formed a 'X' shape.

   Type V  Used when consecutive ribs formed a 'V' shape.

   Type P  Used when consecutive ribs were parallel to each other.

   This categorization resulted in 219 Type X bars, 149 Type V bars, and 105 Type P bars.

4. **Coating Thickness:** Coating thickness was measured on four different sections of each rebar. Each bar was divided into a top half (closest to the deck surface) and a bottom half. In each of these sections, coating thickness was measured at three locations on the ribs and in the valleys between ribs. The data were then averaged to provide a total of four coating thickness results for each bar. No variation in coating thickness between the

two bar sections was expected and none was detected. However, minor variations in coating thicknesses on ribs compared to valleys were noted (coating thickness on ribs averaged 1.2 mils more than in the valleys). Since no significant differences were found, coating thickness data obtained on ribs in the top half of the bars were randomly selected for the data analyses presented herein.

5. **Pencil Hardness:** The pencil hardness test method provides the following measures of hardness ranging from soft to hard: 6B, 5B, 4B, 3B, 2B, B, HB, F, H, 2H, 3H, 4H, 5H, 6H, 7H, 8H, and 9H. For analysis purposes, a numerical value was assigned to each measure of pencil hardness starting with 3 for 6B and ending with 19 for 9H. Of the 473 bars tested, 98% had a pencil hardness of HB or 9. These results are not significantly different from those obtained on epoxy coated bars collected from job sites prior to concrete placement[4].

6. **Corrosion Condition Rating:** The distribution of corrosion ratings as a percent of the total number of rebars tested and the epoxy coating color is provided in Table 6-10. The ratings shown in this table are described below.

Rating 1	No evidence of corrosion.
Rating 2	A number of small, countable corrosion spots.
Rating 3	Corrosion area less than 20% of the total ECR surface area.
Rating 4	Corrosion area between 20% and 60% of the total ECR surface area.
Rating 5	Corrosion area greater than 60% of the total ECR surface area.

This table shows that 87% of the bars had a rating of 1 and that the corrosion condition ratings were independent of epoxy coating color.

7. **Coating Adhesion:** Coating adhesion was measured in the wet (as-recieved condition) and dry (after exposure for 7 days in a desicator) conditions. The following rating scheme was used to document the test results:

Rating 1	Well adhered coating that cannot be peeled or lifted from the steel substrate.
Rating 3	Coating that can be pried from the steel substrate in small pieces, but cannot be pealed off easily.
Rating 5	Coating that can be peeled from the steel substrate easily without residue.

Test locations included areas with no visible coating defects and areas directly adjacent to visible coating defects. Testing in areas with no visible defects involved a total of three measurements in the valleys between ribs for both the wet and dry conditions. In each case, the data were averaged to provide a single adhesion rating; one rating each for the wet (termed wet-no defects) and dry (termed dry-no defects) conditions. In some cases, averaging resulted in ratings of 2 and 4. All 473 rebars were tested for both wet and dry adhesion in areas with no visible coating defects.

Table 6-10. Summary of Corrosion Condition Ratings.

Corrosion Rating	Color of Epoxy	# of Rebars	% of Same Color	% of Total Bars
1	Brown	105	86.1	22.2
	Green	304	86.6	64.3
Total for Rating 1		***409***		***86.5***
2	Brown	16	13.1	3.4
	Green	46	13.1	9.7
Total for Rating 2		***62***		***13.1***
3	Brown	0	0.0	0.0
	Green	0	0.0	0.0
Total for Rating 3		***0***		***0.0***
4	Brown	1	0.8	0.2
	Green	1	0.3	0.2
Total for Rating 4		***2***		***0.4***
5	Brown	0	0.0	0.0
	Green	0	0.0	0.0
Total for Rating 5		***0***		***0.0***
Total		473		100.0

The number of tests adjacent to visible coating defects was limited by the total number of defects observed. If the number of visible coating defects did not exceed 3, testing adjacent to defects was conducted only in the dry condition. If more than one rating was obtained in the wet or dry condition, the data were averaged to provide a single adhesion rating; one rating each for the wet (termed wet-defects) and dry (termed dry-defects) conditions. In some cases, averaging resulted in ratings of 2 and 4. Wet-defect and dry-defect adhesion ratings were obtained on a total of 225 and 423 bars respectively.

The presence or absence of corrosion product under the portions of coating removed during adhesion testing was noted. Although the total number of adhesion tests on a given rebar varied from 6 to 12, only one result regarding the presence or absence of corrosion product was recorded for each bar. If corrosion product was observed at any of the adhesion test locations, the rebar was considered to have corrosion product under the coating. Using this criterion, 31 of the 473 bars tested had corrosion product under the coating.

As shown in Table 6-11 and Figure 6-3, descriptive statistics, correlation analyses, and the continuous cumulative distribution of adhesion ratings were not significantly different for wet versus dry conditions (wet-no defects vs. dry-no defects and wet-defects vs. dry-defects). This implies that adhesion reduction or loss is irreversible at least after a 7 day drying period. The data analysis also confirmed a higher probability of adhesion reduction adjacent to areas with visible defects compared to those with no visible defects. However, statistical correlation's with corrosion rating and age for both cases were not significantly different. These findings, coupled with the larger data set available for the no-defect adhesion ratings, resulted in selection of the wet-no defect adhesion ratings for the data analyses presented herein.

Table 6-11. Correlation Analyses of Various Adhesion Ratings.

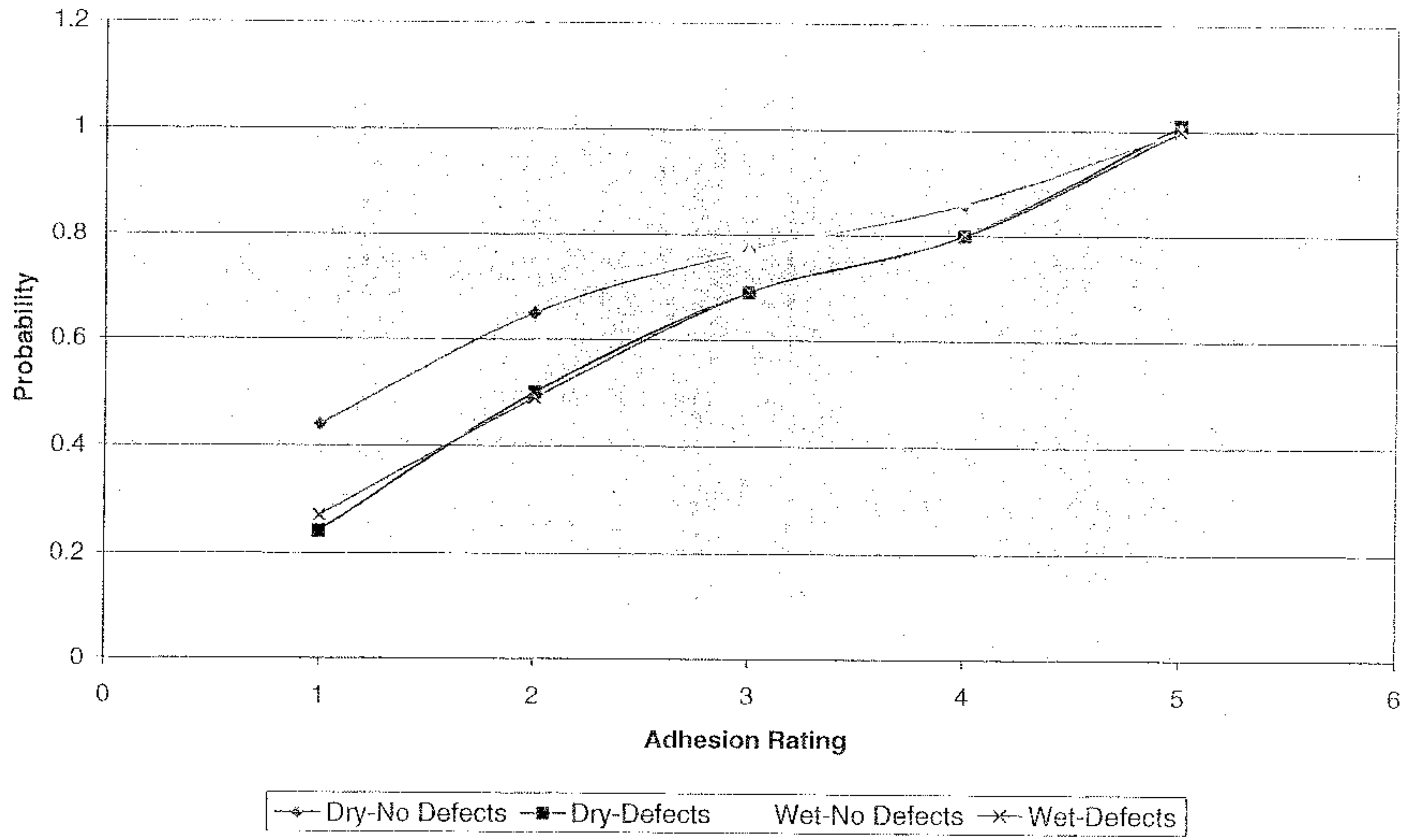
	Avg. Rating	Median Rating	Std. Dev.
Wet – No Defects	2.21	2.00	1.45
Wet – Defects	2.75	3.00	1.46
Dry – No Defects	2.28	2.00	1.45
Dry – Defects	2.79	3.00	1.45
	Coefficient of Correlation, r		
	Wet – No Defects	Wet – Defects	Dry – No Defects
Wet – No Defects	------	------	------
Wet – Defects	0.74	------	------
Dry – No Defects	0.82	0.71	------
Dry – Defects	0.69	0.81	0.75

The distribution of wet-no defect adhesion ratings for the 473 bars tested was as follows:

Rating 1	46.5%
Rating 2	22.2%
Rating 3	8.0%
Rating 4	10.0%
Rating 5	13.3%

It has been reported in recent investigations on existing structures that adhesion reduction is a function of age.[3,5] To determine if the data obtained in this study exhibited such a relationship, several statistical analyses were performed. First, a correlation analysis of all sets of adhesion rating and age data was performed. A statistically significant, but weak relationship was found (coefficient of correlation r = 0.195). An analysis of all individual adhesion ratings versus age strata 1 and 2 was then performed using the

Figure 6-3. Cumulative Probability Distribution Function for Adhesion Ratings



nonparametric Kruskal-Wallis test and the two sample t-test. Results from these tests showed that adhesion exhibited by rebars from structures in the two age strata investigated were significantly different and that age stratum 1 exhibited much lower adhesion ratings compared to age stratum 2 (medians of 1.0 and 2.3 and means of 1.99 and 2.52 for age strata 1 and 2 respectively). These analyses suggest that adhesion reduction or loss is related to some threshold age or ages.

To further analyze this relationship, individual ages were grouped into the four age categories shown in Table 6-3. Each age category was then given a number for the analysis as follows:

1 Less than 5 years old.
2 From 6 to 10 years old.
3 From 11 to 15 years old.
4 From 16 to 20 years old.

Each individual adhesion rating was then assigned to the appropriate age group. Finally, a correlation analysis of all individual adhesion ratings and their assigned age group was then performed. A much stronger statistical relationship was found compared to the first analysis (coefficient of correlation $r = 0.525$).

A probability distribution analysis of adhesion reduction for the four age groups above was then performed. First, individual adhesion ratings were grouped into two categories; one representing no adhesion reduction and the other representing varying degrees of adhesion reduction. Thus, all adhesion ratings of 1 were assigned a value of 0 and ratings of 2 or more were assigned a value of 1. The frequency at which the value of 1 occurred in each age category was then determined and the probability of the value of 1 occurring in each age category was calculated (see Figure 6-4). The results showed that a value of 1 occurred with a 24% probability in age group 1. This probability progressively increased to 54%, 63% and 70% for age groups 2, 3, and 4 respectively. An estimate of the resulting probability function for the age groups investigated is represented by the following mathematical relationship:

$$\text{Probability} = -0.0575*\text{Age Group}^2 + 0.4345*\text{Age Group} - 0.1275$$

The coefficient of correlation, r, between the mathematical relationship and the actual probability distribution data was calculated to be 0.993. This strong relationship is only valid for the four age groups used in the analysis.

6.1.5 Data Statistics by State

To identify any significant differences among all the tests and measurements obtained on the cores, concrete, and epoxy coated rebars in Pennsylvania and New York, the data statistics presented in Sections 6.1.2 through 6.1.4 were separated by State (see Table 6-12). The most notable differences included concrete permeability and total chloride content at the rebar depth. The average and median concrete permeability and chloride content at the rebar depth

Figure 6-4. Probability of Adhesion Reduction as a Function of Age Group.

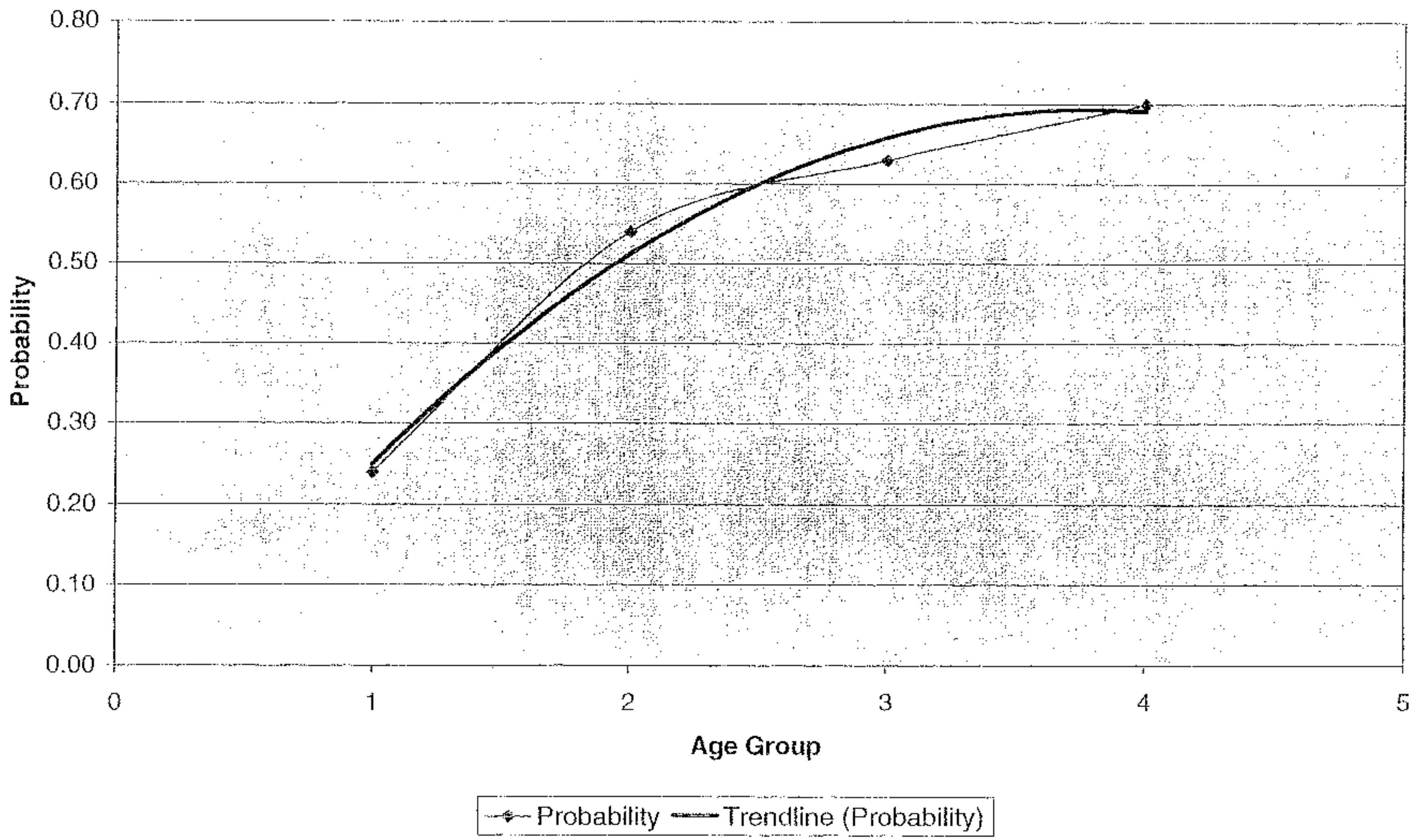


Table 6-12. Breakdown of Statistics By State for Core Information, Concrete Properties, and Epoxy Coated Rebar.

	New York						Pennsylvania					
	N	Min.	Max.	Avg.	Median	Std. Dev.	N	Min.	Max.	Avg.	Median	Std. Dev.
Top Bar Cover, in.	118	1.7	4.0	2.7	2.7	0.4	120	1.6	3.8	2.8	2.9	0.4
Bot. Bar Cover, in.	117	2.3	4.5	3.3	3.3	0.4	118	2.2	4.4	3.4	3.4	0.4
EIS, Kohm	104	3	155,000	2,488	116	15,860	74	10	20,899	651	85	2,476
Unit Weight, pcf	120	106	206	135	136	8	120	64	158	133	135	11
Permeability, coulombs	117	1,132	23,775	6,033	4,621	4,148	119	419	19,272	4,530	3,828	3,182
Absorption, %	63	3.5%	8.3%	6.5%	6.6%	1.0%	83	3.5%	9.4%	6.5%	6.5%	1.0%
Volume Pore Space, %	63	8.3%	21.2%	14.1%	14.3%	2.2%	83	8.3%	18.4%	14.0%	14.1%	1.8%
Rebar Trace pH	227	11	12	11	11	0.1	232	11	13	11	11	0.2
Total Chloride Content, pcy	223	0.00	11.37	1.18	0.55	1.66	234	0.00	5.00	0.74	0.41	0.89
Chloride Exposure, yrs.	223	0	16	1	0	3	234	0	12	1	0	2
# of Mashed Areas	235	0	12	2.2	2.0	2.0	238	0.0	20.0	2.1	2.0	2.3
# of Bare Areas	235	0	13	2.4	2.0	2.5	238	0.0	21.0	2.3	2.0	2.7
# of Holidays	235	0	156	8.2	3.0	18.7	238	0.0	85.0	7.3	3.0	12.4
Coating Thickness, mils	235	5.2	21.9	11.1	11.0	2.7	238	2.4	18.8	11.4	11.2	2.9
Pencil Hardness	235	8	10	9.0	9.0	0.1	238	6.0	10.0	9.0	9.0	0.2
Corrosion Condition Rating	235	1	4	1.1	1.0	0.4	238	1	2	1.1	1.0	0.4
Adhesion Rating	235	1	5	2.1	2.0	1.3	238	1	5	2.3	2.0	1.6

were higher in New York. The average EIS measurement was also significantly different between the two States, but the implications of this observation are not known.

6.2 Existing Condition and Performance Assessment of Epoxy Coated Rebars

To properly analyze the existing condition and assess the performance of epoxy coated rebars based on corrosion condition and adhesion ratings, the implications of each rating need to be fully understood. With regard to the corrosion condition rating, a rating of 1 signifies that no visible corrosion was observed on the bar. A rating of 2 indicates that small spots of corrosion were visible in coating defect areas only. Neither rating describes the condition of the steel underneath the coating. At the same time, both of these ratings indicate that, if corrosion has initiated under the coating, it has not progressed to the point to cause visible coating damage. In addition, analysis of all samples with a corrosion rating of 1 or 2 did not reveal any significant difference in chloride ion content at the rebar depth, chloride exposure, or age. The primary difference between these bars was the number of defects in the coating. Rebars rated 2 had three times the number of holidays than those rated 1 and twice the number of bare areas. Bars are given a rating of 3 if corrosion is observed over less than 20% of the total bar surface area. Assuming that the bar did not have coating defects over a large portion of its surface area at the time it was placed in concrete, some degree of the observed corrosion must have occurred under the coating. Therefore, a rating of 3 is indicative of progressive corrosion. Ratings of 4 and 5 represent still further progression of the corrosion process.

Similarly, the adhesion ratings used in the data analyses represent an average of three separate tests. To obtain an average rating of 1, all individual ratings must also be 1. Therefore, an average rating of 1 indicates that excellent adhesion was found at all test locations. Likewise, an average rating of 5 represents complete adhesion loss at all test locations since this can only be obtained when all individual ratings are 5. Average ratings of 2 and 3 result when individual ratings are some combination of ratings 1, 3, and 5. Consequently, with the exception of all three individual ratings being 3, average ratings of 2 and 3 imply that adhesion varied from one location to another and that excellent adhesion was found at a minimum of one test location. An average rating of 4 can only be obtained when individual ratings are some combination of ratings 3 and 5. Therefore, this rating indicates that adhesion reduction or loss occurred at all test locations and that complete adhesion loss was found at a minimum of one location.

6.2.1 Existing Condition of Epoxy Coated Rebars

Analysis of the corrosion condition ratings indicates that the epoxy coated rebars are currently in very good condition in both Pennsylvania and New York. A total of 409 rebars were given a corrosion condition rating of 1, 62 bars were rated 2, no bars were rated 3, only two rebars (both in New York) were rated 4, and no bars were rated 5. With respect to coating adhesion, the existing condition of the epoxy coated rebars was poor. Only 47% of the bars had no reduction in adhesion. Over 13% exhibited a complete loss of adhesion and the remaining 40% showed varying degrees of adhesion reduction. A correlation analysis of all sets of corrosion condition and adhesion ratings was performed and a statistically significant, but weak relationship was found (coefficient of correlation $r = 0.173$).

One of the primary objectives of this study was to determine if ongoing or progressive corrosion and/or a reduction in coating adhesion were occurring on the epoxy coated rebars in three or more percent of the bridge deck area in each State. The sampling size used in the study was selected in order to accomplish this objective at a confidence level of 95%. From a statistical point of view, if progressive corrosion or adhesion reduction was found in a single core for either State, then the frequency of occurrence would be 3% or greater of the total deck surface area in that State. If progressive corrosion or adhesion reduction were not found in even a single core, then the frequency of occurrence would be less than 3% of the total deck surface area in that State. If a corrosion condition rating of 3 or more identifies the occurrence of progressive corrosion on epoxy coated rebars, results from the cores showed that the frequency of occurrence of progressive corrosion was less than 3% in Pennsylvania and 3% or more in New York. The frequency of occurrence of adhesion reduction or loss in both States was more than 50%.

6.2.2 Performance Assessment of Epoxy Coated Rebars

Evaluation of the performance of epoxy coated rebars to date requires samples that have been exposed to a corrosive environment for a sufficient length of time. To define a corrosive environment for epoxy coated rebars, the mechanisms for corrosion initiation and propagation on epoxy coated rebars must first be explored. Two such mechanisms have been proposed:[3,6]

1. **Failure from Coating Defects** - Corrosion initiates at coating defects once sufficient levels of chloride are present. Corrosion then progress underneath the coating adjacent to the defects. The coating in these areas may or may not be disbonded at the time corrosion initiates in the defect.

2. **Failure by Adhesion Reduction** – This corrosion mechanism first requires a reduction in coating adhesion. Once sufficient levels of chloride are present, corrosion initiates and propagates under the disbonded coating.

These mechanisms may occur independently or simultaneously.

It should be noted that the age of the spans sampled in this study varied from 3 to 19 years, with an average and median of 10 years and a standard deviation of 4 years. Also, no distinction was made between spans with epoxy coated rebar in the top mat only versus spans with epoxy coated rebar in both the top and bottom mat. However, it is known that all bridge decks in New York have black bottom mat reinforcing steel and in Pennsylvania, a given bridge deck may have black or epoxy coated reinforcing steel in the bottom mat depending on the date of construction.

Failure from Coating Defects

For corrosion initiation to occur by this mechanism, coating defects must be present and the chloride content at the steel depth must equal or exceed 1.2 pcy (assuming the chloride threshold for corrosion of black steel applies at coating defects). A sufficient time of exposure to 1.2 pcy chloride must then occur in order to detect the transformation from corrosion initiation in defects to corrosion propagation under the coating. As discussed earlier, the exposure time (in years) to at least 1.2 pcy is termed "chloride exposure" in this report.

Epoxy coatings are not expected to provide corrosion protection in areas where defects in the coating exist. Therefore, to judge the performance of epoxy coated reinforcing steel, it is necessary to determine if corrosion that initiated in defects propagated into areas with no defects. If the coating is able to limit corrosion to areas containing defects, then it would be considered effective.

If coating defects include mashed areas, bare areas, and holidays, 441 of the 473 rebars tested in this study had one or more defects (average number of defects was 13 with a median of 9). Analysis of chloride exposures (see Section 6.1.3) for these 441 rebars resulted in the frequency distribution provided in Table 6-13.

Table 6-13. Frequency Distribution of Chloride Exposure for Bars with Defects.

Chloride Exposure, yrs	No. of Samples
1 to 5	48
6 to 10	26
11 to 15	19
16 to 20	4

Although the distribution shown in Table 6-13 is not an ideal one, there are a sufficient number of samples with acceptable levels of chloride exposure. If one assumes that the transformation from corrosion initiation in defects to corrosion propagation under the coating can be detected after 5 years of chloride exposure, the sample size reduces to 49. Due to the relatively low average age (10 years) of the 473 bars, the number of rebars meeting the required criteria (i.e. presence of known defects and chloride exposure for more than 5 years) is limited from a statistical point of view. Thus, it is not possible to statistically evaluate performance of the global population with regard to "Failure from Coating Defects" at an acceptable confidence level. However, it should be noted that the corrosion condition ratings for these 49 bars (listed below) indicate that progressive corrosion occurred on only 2 bars.

Rating 1 42 bars.
Rating 2 5 bars.
Rating 3 0 bars.

Rating 4	2 bars.
Rating 5	0 bars.

This minimal number of failures may be attributed to one or more of the following:

1. The epoxy coating on these bars has provided acceptable corrosion protection to date.

2. The assumptions used in terms of chloride exposure and chloride content threshold were not sufficiently severe to detect the transformation from corrosion initiation in defects to corrosion propagation under the coating.

3. Parameters other than those considered in this study play a primary role with regard to "Failure from Coating Defects."

Failure by Adhesion Reduction

This corrosion mechanism requires adhesion reduction followed by sufficient chloride exposure. Corrosion in the initial stages is not visually observable until a break in the coating occurs or the coating is removed and the steel surface is exposed. If coating breaks occurred, the bar would have a corrosion condition rating of 3 or more and would be considered ineffective. If the coating is removed and corrosion is observed, it then becomes necessary to determine if the corrosion products are the result of an ongoing corrosion process. One possible way of establishing the presence of progressive corrosion is to observe the transition from corrosion initiation to propagation. This may be achieved by studying the distribution of corrosion condition ratings as a function of chloride exposure after adhesion reduction for a large sample. Failure of ECR by this corrosion mechanism would then be confirmed if a positive correlation between corrosion condition rating and chloride exposure after adhesion reduction was found.

To assess failure of the epoxy coated rebars by this corrosion mechanism, adhesion reduction must have occurred. It was assumed that a sample population with a minimum of 50% of the samples having adhesion reduction was sufficient to detect the presence or absence of this corrosion mechanism. Figure 6-4 shows that epoxy coated rebars that have been in service for more than 5 years have a higher than 50% probability that adhesion reduction has occurred. Therefore, samples from all structures in age groups 2 and above (see Section 6.1.4 and Table 6-3) were selected for the analysis.

This sample population was then reduced by excluding any samples that had an adhesion rating of 1 (i.e. no adhesion reduction). Chloride exposure was then recalculated for samples that had 1.2 pcy chloride at the steel depth in less than 5 years of service, so that only chloride exposure after 5 years of service (i.e. after adhesion reduction was assumed to have occurred) was used. For example, for a 14 year old structure with a time to reach 1.2 pcy chloride at the steel depth of 3 years, the chloride exposure in the previous analysis was 11 years (14 minus 3), whereas the revised exposure would be 9 years (14 minus 5). The frequency distribution for the resulting sample population is shown in Table 6-14.

Table 6-14. Frequency Distribution of Chloride Exposure for Bars with Adhesion Reduction.

Chloride Exposure, yrs	No. of Samples
1 to 5	58
6 to 10	30
11 to 15	11
16 to 20	0

Although the distribution shown in Table 6-14 is not an ideal one, there are a sufficient number of samples with adhesion reduction and acceptable levels of chloride exposure. If one assumes that the transformation from corrosion initiation to propagation can be detected after 5 years of chloride exposure subsequent to adhesion reduction, the sample size reduces to 41. Due to the relatively low average age (10 years) of the 473 bars, the number of rebars meeting the required criteria (i.e. adhesion reduction followed by chloride exposure for more than 5 years) is insufficient to perform the required correlation at an acceptable confidence level. However, it should be noted that the corrosion condition ratings for these 41 bars (listed below) indicate that progressive corrosion occurred on only 2 bars.

Rating 1	34 bars.
Rating 2	5 bars.
Rating 3	0 bars.
Rating 4	2 bars.
Rating 5	0 bars.

This minimal number of failures may be attributed to one or more of the following:

1. The epoxy coating on these bars has provided acceptable corrosion protection to date.

2. The assumptions used in terms of chloride exposure and chloride content threshold were not sufficiently severe to detect the transformation from corrosion initiation to propagation in areas of adhesion reduction.

3. Parameters other than those considered in this study play a primary role with regard to "Failure by Adhesion Reduction."

<u>Presence of Corrosion Products Under the Epoxy Coating</u>

Corrosion products were observed under the coating at a minimum of one adhesion test location on 31 of the 473 rebars. To investigate if this observation was indicative of chloride induced corrosion, the chloride concentration for each of the rebars was analyzed. This was based on the assumption that a sufficient chloride content (i.e. 1.2 pcy) must be present in order to attribute the observed corrosion to an ongoing process. For 2 of the 31 rebars, it was obvious that the corrosion under the coating was a result of an ongoing corrosion process since these bars had a corrosion rating of 4 and a chloride content of 3.34 pcy and 10.27 pcy. Whether the corrosion process initiated in defects or in areas of reduced adhesion or a combination of both could not be determined however. The chloride ion content for the remaining 29 bars is summarized below.

Chloride content less than 0.5 pcy	19 bars.
Chloride content between 0.5 and 0.9 pcy	7 bars.
Chloride content greater than 1.2 pcy	3 bars.

The 3 bars that had a chloride content greater than 1.2 pcy also had sufficient chloride exposure and thus, corrosion initiation on these bars can be attributed to chloride induced corrosion. Whether the corrosion process was caused by defects or adhesion reduction or both could not be determined however. Corrosion products found under the coating on the remaining 26 bars cannot be attributed to chloride induced corrosion.

6.3 Analysis of Variable Interrelationships

The final objective of this study was to statistically analyze all data elements to reveal any interrelationships. In each case, two data elements were considered. Results of corrosion condition rating versus adhesion rating are presented first. This is followed by analyses of all data elements versus corrosion condition rating. Finally, analyses of all data elements versus adhesion rating are presented.

Statistical analyses were performed using correlation analyses at a 95% confidence level, the non-parametric Kruskal-Wallis procedure, classical one way analysis of variance, Tukey's pairwise comparisons, regression analysis, stepwise regression analyses, and analysis of means as appropriate. The discussion below is limited to those analyses that revealed a statistically significant relationship. Results used in previous Sections of this report are not reiterated.

The following binary variables were also created for the analyses:

Corrosion1 (Corrosion Condition Rating Greater Than 1): In order to perform meaningful correlation's, this variable considers a condition rating of 2 or more as failure (i.e. there were only 2 bars rated greater than 2). A value of 1 was assigned to all rebars with a corrosion condition rating greater than 1 and a value of 0 was assigned to all bars with a rating of 1.

Adhesion3 (Adhesion Rating Greater Than or Equal to 3): This variable was created to assess relationships with adhesion reduction (as opposed to complete adhesion loss). Considering the possible combinations of individual adhesion ratings that result in an average rating of 2, 3, or 4, an average rating of 3 best represents adhesion reduction. Therefore, a value of 1 was attributed to all rebars with an adhesion rating of 3 or more and a value of 0 was assigned to all bars with a rating less than 3.

Adhesion5 (Adhesion Rating Equal to 5): This variable was created to assess relationships with complete adhesion loss (i.e. all three individual adhesion ratings were 5). Therefore, a value of 1 was attributed to all rebars with an adhesion rating of 5 and a value of 0 was assigned to bars with a rating less than 5.

Correlation analyses results that exhibited statistically significant relationships are presented in Table 6-15. In each set of correlation results, the top number is the correlation coefficient (or r value) and the bottom number represents statistical significance (or p value). The value of r signifies the degree of correlation (zero represents no correlation and 1 represents a perfect correlation). A value of p less than 0.05 signifies a statistically significant relationship at a 95% confidence level.

Relationship Between Corrosion Condition Rating and Adhesion Rating

To be an effective barrier, it is believed that the epoxy coating should be well adhered to the steel. Any reduction in the bond between the coating and steel is considered by many to be a precursor to corrosion initiation. If this was true then a good correlation between corrosion condition rating and adhesion rating should exist. As shown in Table 6-15, both corrosion condition variables have a statistically significant relationship with all three adhesion variables, but the correlation is weak. In other words, coating adhesion is one parameter that has some influence on corrosion condition rating, but the correlation analysis suggests that coating adhesion is not, by itself, a good predictor of corrosion condition. However, it should be noted that in both failure mechanisms discussed earlier, if progressive corrosion occurs, it must be accompanied by complete adhesion loss. Also, the strongest correlation was found between corrosion condition rating and complete adhesion loss.

Corrosion Condition Rating Analyses

Logarithm of EIS, number of holidays, and number of bare spots were the only variables that exhibited a statistically significant relationship with corrosion condition rating and Corrosion1, and in all cases the correlation's were weak (see Table 6-15). A decrease in EIS value corresponded to an increase in corrosion condition rating.

A logistic regression analysis was also conducted. Among all the variables included in the analyses, logarithm of EIS, number of holidays, and number of bare spots were found to be the best predictors of corrosion condition rating.

Analysis of means showed that the binary variable had a higher mean (0.17) for top bars compared to bottom bars (0.10).

Adhesion Rating Analyses

Age, logarithm of EIS, number of holidays, and number of bare spots were the only variables that exhibited a statistically significant relationship with adhesion rating, and in all cases the correlation's were weak (see Table 6-15). A decrease in EIS value corresponded to an increase in adhesion rating.

Table 6-15. Correlation Matrix.

	Adhesion Rating	Adhesion3	Adhesion5	Corrosion Condition Rating	Corrosion1	Number of Holidays	Number of Bare Areas	Logarithm of EIS
Adhesion3	0.912 0.000							
Adhesion5	0.756 0.000	0.581 0.000						
Corrosion Condition Rating	0.173 0.000	0.127 0.006	0.241 0.000					
Corrosion1	0.147 0.001	0.106 0.021	0.209 0.000	0.943 0.000				
Number of Holidays	0.224 0.000	0.224 0.000	0.125 0.006	0.291 0.000	0.282 0.000			
Number of Bare Areas	0.202 0.000	0.171 0.000	0.073 0.113	0.269 0.000	0.282 0.000	0.354 0.000		
Logarithm of EIS	-0.211 0.000	-0.226 0.000	-0.121 0.023	-0.256 0.000	-0.230 0.000	-0.140 0.008	-0.254 0.000	
Age	0.195 0.000	0.163 0.000	0.066 0.154	0.014 0.758	-0.009 0.838	0.178 0.000	0.248 0.000	-0.089 0.096

In the Kruskal-Wallis test, coating thickness was found to be comparatively higher (median coating thickness of 11.30 compared to 10.38) for rebars rated 0 in Adhesion3.

Adhesion ratings in some counties were found to be statistically different from the others in the Kruskal-Wallis test. Three counties in Pennsylvania (Bedford, Cameron, and Warren) and one county in New York (Sullivan) had comparatively lower adhesion ratings, whereas two counties in Pennsylvania (Centre and Mercer) and two counties in New York (Fulton and Livingston) had comparatively higher adhesion ratings.

Both the Kruskal-Wallis test and analysis of variance showed that bars with a 'P' deformation pattern had higher adhesion ratings than those with a 'X' pattern. The Tukey pairwise comparison test confirmed that the mean adhesion ratings for deformation patterns 'P' and 'X' were significantly different. However, the three tests were not conclusive regarding statistical differences between deformation patterns 'V' and 'P' or 'V' and 'X'

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SECTION 7

CONCLUSIONS

AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 *Existing Condition of Epoxy Coated Rebars in Pennsylvania and New York State*

1. The sampling plan was designed to detect progressive corrosion even if the frequency of occurrence was less than 3% of the global population. Results from the study showed that the frequency of occurrence of progressive corrosion is less than 3% in Pennsylvania and at least 3% in New York. A total of 409 rebars showed no evidence of corrosion, 62 bars had a number of small, countable corrosion spots, and only 2 rebars, both in New York, exhibited significant visible corrosion. In addition, corrosion products were observed under the coating on 31 of the 473 rebars. However, the corrosion products observed on 26 of these bars could not be attributed to chloride induced corrosion since they had no exposure to the threshold level of chlorides required to initiate corrosion. Therefore, the existing condition of epoxy coated rebars in bridge decks in Pennsylvania and New York State is very good from a corrosion point of view.

2. Only 47% of the bars tested had no reduction in adhesion. Over 13% exhibited a complete loss of adhesion and the remaining 40% had varying degrees of adhesion reduction. Probability distribution analyses showed that more than 50% of epoxy coated rebars in bridge decks in Pennsylvania and New York State exhibit some degree of adhesion reduction within 6 to 10 years of placement in concrete. If progressive corrosion occurs, it must be accompanied by complete adhesion loss. Correlation analyses of corrosion condition ratings and adhesion ratings indicated that reduction in coating adhesion does have some relation to corrosion condition, however, coating adhesion alone was not found to be a good predictor of corrosion condition.

7.2 *Performance of Epoxy Coated Rebars in Pennsylvania and New York State*

1. Performance of epoxy coated rebars can only be evaluated after the bars have been exposed to a corrosive environment for a sufficient length of time. Due to the relatively low average age (10 years) of the sample population, 80% of the bars tested had no exposure time to the chloride threshold of 1.2 pcy. Thus, in the analysis of "Failure from Coating Defects," only 49 bars with known defects and a chloride exposure of at least 1.2 pcy for more than 5 years were identified. Similarly, only 41 bars with adhesion reduction followed by chloride exposure of at least 1.2 pcy for more than 5 years were identified to analyze "Failure by Adhesion Reduction." The number of samples in each of these subsets were not

sufficient to statistically evaluate the performance of the epoxy coated rebars with respect to either of the failure mechanisms at an acceptable confidence level. However, only 2 bars (less than 5%) in each subset exhibited progressive corrosion as indicated by the corrosion condition ratings. This minimal number of failures may be attributed to one or more of the following:

a) The epoxy coating on the bars in the subsets has provided acceptable corrosion protection to date.

b) The assumptions used in terms of chloride exposure and chloride content threshold were not sufficiently severe to detect the transformation from corrosion initiation to propagation.

c) Parameters other than those considered in this study play a primary role with regard to the corrosion mechanisms investigated.

2. No correlation was found with corrosion condition rating and chloride exposure or chloride content. This is most likely attributable to the age and chloride content distribution of the study population and/or satisfactory performance of the epoxy coated bars.

7.3 Other Pertinent Findings

1. Among all the variables included in the analyses, logarithm of EIS, number of holidays, and number of bare spots were found to be the best predictors of corrosion condition rating, but in all cases the correlation's were weak. These same parameters were also found to have statistically significant relationships with adhesion reduction, but again the correlation's were weak.

2. Corrosion condition rating did not correlate with coating thickness, clear concrete cover, color of epoxy, or bridge deck condition rating.

3. Adhesion reduction or loss is irreversible at least after a 7 day drying period as no statistically significant difference was found between wet and dry adhesion ratings. There is a higher probability of adhesion reduction adjacent to areas with visible coating defects compared to those with no visible defects. Also, bars with a 'P' deformation pattern had more adhesion reduction or loss than those with a 'X' pattern. Results were not conclusive with regard to statistical differences between deformation patterns 'V' and 'P' or 'V' and 'X'.

4. A good correlation between concrete resistivity and coulombs passed was found and the following equation can be used to describe the relationship:

$$\text{Coulombs Passed} = 2E{+}09 * A/C\ \text{Resistivity}^{-1.4539}$$

5. Results of pH testing in rebar traces and pencil hardness testing on the coating did not provide any useful information.

7.4 Recommendations for Future Research

Recommendations for future studies are provided below. Each of the three main components (i.e. selection of a sample population, field testing and sampling, and laboratory testing) of any field related research project involving epoxy coated reinforcing steel in bridge structures are discussed separately.

Selection of Sample Population

The distinction between existing condition, performance to date, and projections of future performance should be clearly defined in the objective of any field research project involving epoxy coated reinforcing steel. If the primary goal is to investigate existing condition, a sampling plan similar to that employed in this study (i.e. a statistical sample of the global population) is appropriate. However, if the primary objective is to assess performance to date or project future performance, the sample population should consist of older structures in areas with the highest deicing salt usage only. In either case, variables such as type of epoxy, presence of overlays, and epoxy coated rebar in both mats of reinforcing steel versus the top mat only should be considered.

Field Testing and Sampling

The field testing and sampling plan used in this study is adequate for future research efforts with the primary exception being that cracks should not be purposefully avoided in selecting coring locations. Cracks are an inherent part of any concrete component, thus, for the epoxy on the bars to be effective as a corrosion protection system, it must provide protection even under cracks.

Laboratory Testing

Suggested improvements to the laboratory tests and procedures used in this study, when investigating the existing condition of epoxy coated rebars in bridge structures, are as follows:

1. Eliminate testing of concrete properties except for determination of the bulk dry specific gravity as this parameter is needed to accurately convert chloride analyses results to units of pounds of chloride per cubic yard of concrete. If concrete permeability is to be measured, AASHTO T 277 can be replaced by AC resistance measurements when the concrete sample is in a fully saturated, surface dry condition. The latter can then be used to estimate concrete permeability.

2. Eliminate pencil hardness testing, pH testing in rebar traces, and dry knife adhesion tests.

3. Use a more detailed corrosion condition rating scheme and include the condition of the steel underneath the coating. Also, when recording the number of bare areas on coated bars, document the surface area at each location.

4. Add investigations adjacent to areas exhibiting corrosion products to determine if adhesion reduction and/or undercutting corrosion has occurred. Also, determine the composition of any corrosion product found under the coating.

In addition to the above, studies that focus on the performance of epoxy coated rebars should include collection of powdered concrete samples at various depths from each core (including the top ½ inch and the depth of the epoxy coated bars) for total chloride ion content analyses. This would facilitate calculation of diffusion constants and chloride exposure times (i.e. the length of time that each bar was exposed to a given chloride content). To assess performance, it should also be recognized that chloride exposure time is the critical parameter, not the present chloride content. To project future performance, a deterioration model would also need to be developed once the corrosion mechanisms involved are fully understood.

Additional Recommendations

The same structures included in this study should be reevaluated after approximately 10 years of additional service. Performance of the epoxy coated bars could then be more accurately assessed.

In addition, similar data obtained from past studies by other researchers should be combined and analyzed using the procedures described in this report. This would eliminate differences in the data analysis approach and interpretation and should provide insight into the existing condition and performance of epoxy coated reinforcing steel over a large geographical area.

Appendix A

METHODOLOGY & SAMPLING PLAN

METHODOLOGY AND SAMPLING PLAN

INTRODUCTION

This report documents the methodology developed for locating sampling sites, and collecting, packaging, and shipping core samples containing epoxy coated rebars. The core samples are to be collected from 80 bridge spans located in the states of New York and Pennsylvania. The procedures described herein were developed to insure that the samples collected are statistically representative of the actual conditions of epoxy coated rebars in the bridge decks. The methodology also insures that the process of sampling does not impact the results of any tests or measurements to be conducted during laboratory evaluation.

Specific sampling sites including bridge decks, spans, lanes, primary sampling locations, and alternate sampling locations were provided in a report entitled "Sampling Plan for Verification of Effectiveness of Epoxy Coated Rebars," dated July 24, 1996 and authored by Ms. Deniz Sandhu of the Transportation Research & Development Bureau of the New York State Department of Transportation. The procedures described in that report were utilized in preparing bridge information sheets (BIS) which define the lane, span, and sampling sites to be cored. Typical BIS forms are attached at the end of this report. The final bridge selections for New York and Pennsylvania are shown in Tables A-1 and A-2 respectively.

A. Sequence of the Sampling Methodology

For each bridge to be sampled, CONCORR, Inc. will inform county personnel of scheduling and obtain approval for traffic control plans. Once approved, the bridge scheduled for sampling will be located. The sampling lane and span will be identified using the proper BIS form and traffic control will be set up. Once sampling sites have been located, visual and delamination surveys will be conducted and the bridge deck will be rated using the NBIS rating system. One concrete core containing epoxy coated rebars (ECR) will be extracted from each sampling site. Core holes will be patched and the cores will be stored for later delivery to the laboratory. Photos will be taken throughout the process. A flowchart depicting the Sampling Methodology is shown in Figure A-1.

Table A-1. Final Selection of Bridges in New York.

CONCORR BRIDGE ID NO.	BIN	COUNTY	SPAN TO BE CORED
NY-01	1022420	Albany	3
NY-02	1073090	Albany	1
NY-03	1073110	Albany	3
NY-04	1073570	Albany	2
NY-05	1017752	Greene	2
NY-06	1017762	Greene	2
NY-07	1017990	Greene	1
NY-08	1071580	Schenectady	2
NY-09	1071230	Washington	1
NY-10	1046150	Fulton	1
NY-11	1053730	Fulton	5
NY-12	1073640	Herkmer	1
NY-13	1074020	Herkmer	1
NY-14	4426030	Oneida	1
NY-15	4426332	Oneida	1
NY-16	1031671	Onandaga	13
NY-17	1031671	Onandaga	17
NY-18	1031672	Onandaga	8
NY-19	1061742	Onandaga	1
NY-20	1072571	Onandaga	1
NY-21	1072791	Onandaga	1
NY-22	1031850	Oswego	2
NY-23	1023720	Livingston	1
NY-24	1069902	Livingston	1
NY-25	1070100	Livingston	1
NY-26	1070100	Livingston	3
NY-27	1071160	Livingston	1
NY-28	1071752	Livingston	2
NY-29	1071760	Livingston	2
NY-30	1072492	Livingston	1
NY-31	1070092	Monroe	2
NY-32	1070312	Monroe	2
NY-33	1070312	Monroe	3
NY-34	1070900	Monroe	1
NY-35	1070950	Monroe	4
NY-36	1071962	Monroe	1
NY-37	1013271	Broome	3
NY-38	1013312	Broome	5
NY-39	1035410	Sullivan	9
NY-40	1063412	Sullivan	4

Table A-2. Final Selection of Bridges in Pennsylvania.

CONCORR BRIDGE ID NO.	BIN	COUNTY	SPAN TO BE CORED
PA-01	20002701401651	Crawford	1
PA-02	20007704601069	Crawford	1
PA-03	20007705200612	Crawford	1
PA-04	25009004440506	Erie	2
PA-05	25047400700952	Erie	1
PA-06	27006200900333	Forest	2
PA-07	27100300800000	Forest	1
PA-08	43001801300000	Mercer	1
PA-09	43007912201084	Mercer	2
PA-10	43007913141292	Mercer`	1
PA-11	43007913251071	Mercer	4
PA-12	43301200100580	Mercer	1
PA-13	43721706420909	Mercer	2
PA-14	43730288142313	Mercer	2
PA-15	61300900200000	Warren	1
PA-16	61600600201414	Warren	2
PA-17	12300200520000	Cameron	1
PA-18	14032203020723	Centre	1
PA-19	17008009852321	Clearfield	2
PA-20	17008010101880	Clearfield	3
PA-21	57008120611956	Susquehanna	2
PA-22	57008121111651	Susquehanna	3
PA-23	57008122402610	Susquehanna	1
PA-24	57008123011035	Susquehanna	3
PA-25	57100901200000	Susquehanna	1
PA-26	63019104300211	Wayne	4
PA-27	65002904300000	Wyoming	1
PA-28	5003005200000	Bedford	3
PA-29	5100800300000	Bedford	4
PA-30	5300101200000	Bedford	1
PA-31	7003602501911	Blair	1
PA-32	7401800300000	Blair	1
PA-33	29007015342382	Fulton	3
PA-34	29007015511798	Fulton	1
PA-35	29007016440466	Fulton	1
PA-36	29007016810235	Fulton	3
PA-37	29101200602065	Fulton	1
PA-38	31030500800000	Huntingdon	1
PA-39	31052203201965	Huntingdon	9
PA-40	55021908210000	Somerset	3

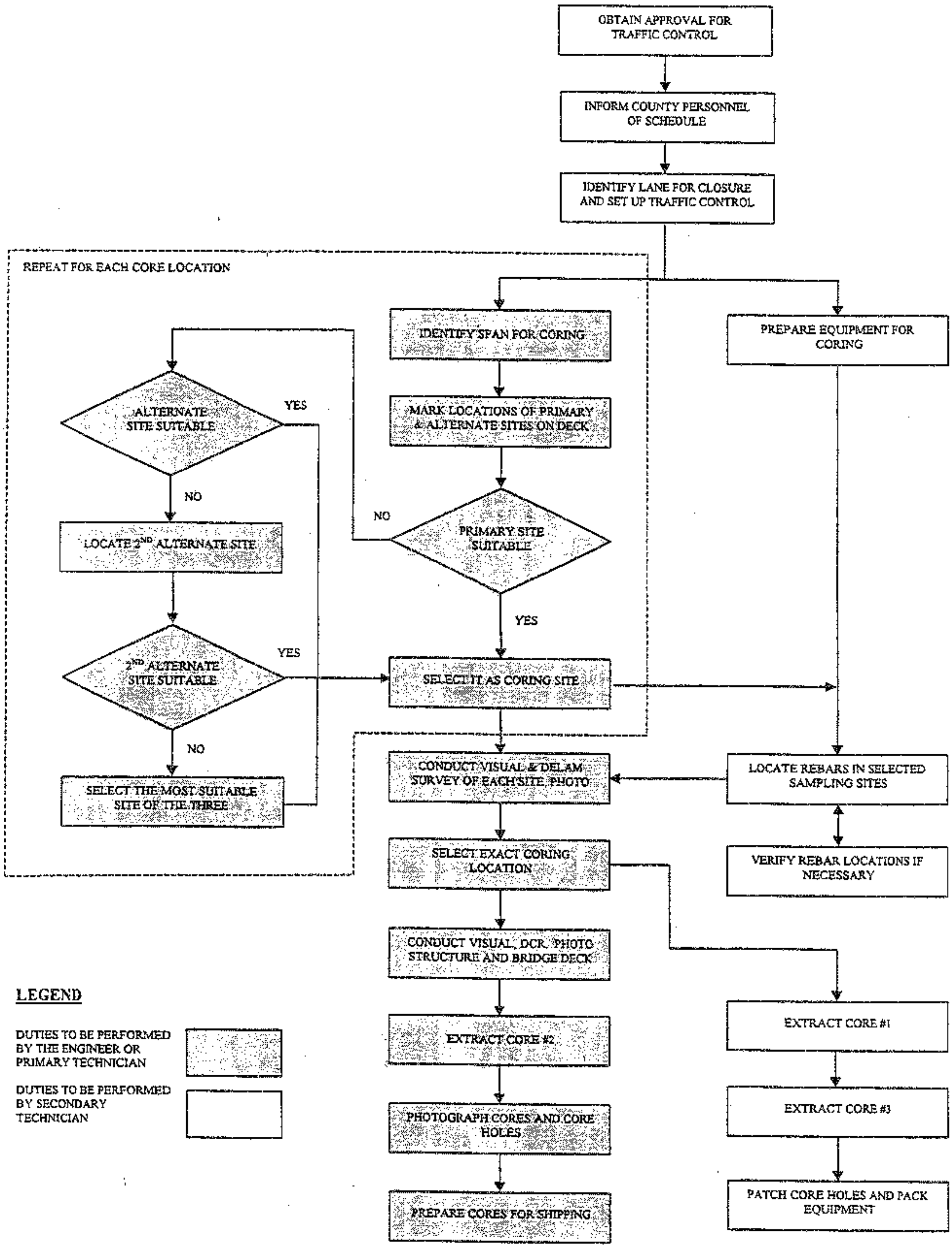


Figure A-1. Sampling Methodology Flowchart.

B. Scheduling

1. Provide contact persons (as shown on the BIS) with traffic control plans for the structures under their jurisdiction.

2. Obtain approval of traffic control plan for each bridge.

3. Inform contact persons and the following people of any change in the schedule:

   - Mr. Gerald J. Malasheskie, P.E. (Penn DOT)
   - Mr. Adam Sapp (Penn DOT)
   - Mr. William J. Winkler, P.E. (NY DOT)
   - Mr. Gerald R. Perregaux, P.E. (NY DOT)

C. Identification of Bridge and Lane to be Sampled

1. Stop before the approach abutment and document the compass reading in the direction of traffic.

2. Using the compass reading, locate your position on the drawing.

3. Verify Bridge Identification Number (BIN) as marked on the BIN plate attached to each bridge. Print New York BIN in the last seven spaces and Pennsylvania BIN in all 14 spaces of the data sheet.

4. If the BIN plate is missing, verify that you are on the correct structure; then write the BIN on a piece of paper and use this in the BIN plate photo.

5. Photograph the BIN plate. All subsequent photographs of that particular structure will be on that roll of film (i.e. one roll of film will be used for each bridge).

6. Identify the sampling lane and span marked on the BIS.[1]

[1] Lanes to be sampled on New York state bridges were selected as follows:

1. If the structure carried traffic in one direction, the right driving lane in the direction of traffic was selected.

2. If the structure carried traffic in both directions, the right driving lane carrying traffic in the direction listed in the sampling plan was selected.

Lanes to be sampled on Pennsylvania bridges were selected as follows:

1. If the structure carried traffic in one direction, the right driving lane was selected.

2. If the structure carried traffic in both directions, a coin was flipped to select the traffic direction and the right driving lane in that direction was selected.

D. Traffic Control Setup

1. Once the appropriate lane has been identified by the CONCORR, Inc. engineer or primary technician in charge, R.TnT personnel set up traffic control according to the plan number referenced on the BIS.

E. Identification of Span

1. Locate span as shown on the BIS.

F. Location of Sampling Sites

1. Identify and position yourself at the zero reference point marked on the corresponding BIS.

2. Mark the zero reference at the right corner as indicated in the BIS.[ii]

3. Place a measuring tape parallel to the right-most traveling lane in the direction of traffic with the zero of the measuring tape positioned at the zero reference mark.

4. Measure the longitudinal distance (X coordinate-shown on the corresponding BIS) for each primary and alternate sampling site along the right edge of the traveling lane and mark using the following color scheme[iii]:

    - Orange paint for primary sampling sites.

    - Yellow paint for alternate sampling sites.

5. At each X coordinate marked on the right edge of the lane, measure the corresponding Y coordinate (shown on the BIS) in the transverse direction (i.e. perpendicular to the right edge) and mark that spot on the deck using the above described color scheme.

[ii] Zero reference is located on the right edge of the traveling lane (when looking in the direction of traffic) of the target span approach.

[iii] The goal is to select three sites, one for each core. Core samples will be collected from their respective primary sampling sites, unless any of these are excluded for the reasons listed in step 7. It is possible that the actual lane widths may differ from that shown on the BIS, and sampling locations may fall outside the lane selected for sampling.

6. Using a circle drawing template, paint an orange circle at each primary site. Center the template over the mark made in step 4.

7. Exclude any primary sampling site that either contains a spall or a patch, is located outside the traffic control area, or is located within one foot of the edge of the traffic control boundary (for safety reasons) from further consideration as a sampling site. These are the only reasons that a primary sampling site can be excluded at this point.

8. If a primary sampling site is eliminated, substitute the primary site with the corresponding alternate site. Draw a circle around the alternate sampling site using yellow paint as described in step 6 above. If an alternate site is also excluded for any of the reasons stated in step 7, substitute it with the corresponding second alternate site.[IV] If a second alternate site is used, the circle shall be drawn using white paint.

9. If all three sites (primary, alternate, and second alternate) are not suitable, select the most suitable site amongst the three (i.e. the one with the least amount of spalling or patching and at least 1 foot inside the traffic control boundary).[V]

10. Locate all longitudinal and transverse rebars within the circle at each sampling site using a Soiltest Microcovermeter. All rebars found shall be marked with red keel. If difficulty is experienced in locating rebars, follow the procedure described in Section L.

11. If no bars are found within the circle at the primary sampling site, substitute the site with its corresponding alternate or second alternate site as appropriate, and then execute steps 7 through 10 on the new site.[VI]

12. Conduct a delamination survey within the circle at each site. All delaminations shall be marked with blue keel.

IV Second alternate sites are designed to be used as a backup plan. Coordinates were randomly generated by a computer.

V It is highly improbable that all sampling sites for a given core fall outside the traffic control boundaries. However, if they do, a new set of locations will be randomly generated using the new lane width.

VI It is considered highly improbable that no rebars will be identified within the circle.

13. For each site, document the presence or absence of any delaminations and/or other deterioration such as cracks, surface damage, etc. on the data sheet. Also document the site designation (primary, alternate, or second alternate) and core log # and core label. Core log # and labeling schemes are defined in Section H.

14. Photograph bar layout and delamination markings (if any) at each site. Use pre-made labels to identify each site. [VII]

15. At each site identify all intersecting transverse and longitudinal rebars.

16. Conduct a visual survey of each area identified in step 15.

17. Select the intersection which is closest to the center of the circle and contains no cracks for coring.

18. If there are no intersections devoid of cracks, select the location with the least amount of cracking.

19. If all intersections have the same amount of cracking, select the intersection closest to the center of the circle.

20. If no intersecting bars are identified within the circle, select a coring location that provides the maximum length of bar and is not cracked. If a crack cannot be avoided, select a coring location that would contain the longest section of a bar.

[VII] At each sampling site, a label showing the core # (i.e. Core 1, Core 2, or Core 3) shall be used in the photographs to identify the site. If more than one sampling span is located on a bridge, two separate rolls of film shall be used. The second photograph of each roll for such bridges will show the span number.

G. Core Extraction

1. Using a vacuum equipped core drill, center the core bit over the rebar(s) that were selected in steps 17 to 20 in Section F.

2. Once the vacuum between the core drill and the concrete surface is established, start the coring process. On some deck surfaces, a vacuum will not

work (e.g. tined surfaces). In these cases, the core drill will have to be anchored to the deck.

3. Use ample water to keep the core bit cool.

4. Core down 6 inches or to the top of the bottom mat reinforcement, whichever is less.

5. Break the core at its base using a specially designed tool.

6. Extract the core using hooked wires.

7. Document the orientation of the top bar and the bottom bar (longitudinal or transverse). Also document the condition of the core (i.e. full, broken, partial, or disintegrated.)

8. If the core breaks, extract all pieces of the core and follow the special handling procedures described in Sections H and K. Be certain to obtain as much of the bottom half of the core as possible.

9. If one of the following conditions apply to the core, discard it and follow steps 16 through 20 in Section F on the remaining intersections or bars in that sampling site, and all steps in Section G to obtain another core:[VIII]

    - no epoxy coated rebars are extracted.

    - core is comprised of poor quality concrete and the epoxy coated rebars were never fully embedded in concrete.

H. Labeling and Packaging of Cores

Intact Core

1. Surface dry the core with burlap. Label the core with its log # (a four digit numeric code) using an indelible marker pen.[IX]

[VIII] The situation in step 9 is considered highly improbable.

[IX] Cores from New York and Pennsylvania bridges will be marked with sequential log numbers starting at 1001 and 2001 respectively.

2. Photograph the core and all exposed surfaces of epoxy coated rebars.

3. Wrap each core in dry burlap and pack in a ziplock bag. Remove all air from the ziplock bag prior to sealing it.

4. Apply the appropriate pre-printed label to the interior of the ziplock bag.[x]

5. Place the ziplock bag in a storage box.

Broken, Partial, or Disintegrated Core

1. Surface dry every piece of the core including any epoxy coated rebars. Label all concrete pieces with the proper log #. Attach a tag to each loose rebar and label using the proper 7-digit code followed by an L or a T to signify longitudinal or transverse.[xi] Care should be exercised to avoid damage to the epoxy coating on the extracted bars.

2. Follow steps 2 through 4 in section H except that in step 2, wrap all pieces of the core in one piece of burlap and wrap bars individually in burlap. Place all concrete and bars in the same ziplock bag.

3. Document the concrete cover over the bars from the sides of the core hole.

I. Patching Core Holes

1. Vacuum all standing water from the core hole.

2. Patch with a fast setting, pre-bagged, cementitious concrete mix.

J. Deck Condition Survey

1. Rate the condition of the deck surface within the sampling span using the deck condition rating (DCR) system.[xii]

[x] The sample bag labels will contain a 7 character alphanumeric code. The first four characters will be the CONCORR, Inc. bridge ID number, the next two characters will signify the span and the last character will represent the core # (e.g. a Core #1 from structure NY-24, span 3 will be labeled as NY24-03-1).

[xi] As an example, bars will be labeled as follows:

NY24-03-1-L, for longitudinal bar, and NY24-03-1-T for transverse bar.

[xii] For DCR use the following codes:

- N **Not applicable** - concrete surface is not visible due to an overlay, sealer, etc.
- 9 **Excellent Condition** - no problems noted, generally used for new structure.
- 8 **Very Good Condition** - no problems noted, generally used for an old structure.
- 7 **Good Condition** - some minor problems.
- 6 **Satisfactory Condition** - <2% spalls or sum of all deteriorated deck concrete <20%.
- 5 **Fair Condition** - <5% spalls or sum of all deteriorated deck concrete 20% to 40%.
- 4 **Poor Condition** - >5% spalls or sum of all deteriorated deck concrete 40% to 60%.
- 3 **Extensive Deterioration** - >5% spalls or sum of all deteriorated deck concrete >60%.

2. If the engineer determines the NBIS rating to be less than 4, the appropriate District Engineer will be contacted to corroborate the rating.

3. Photograph the entire bridge and the deck. Also photograph any deck anomalies such as cracks, spalling, etc.

K. Shipping Core Samples

1. Pack cores with packing material to insure no damage occurs during shipping.

2. At the end of each week, ship all core samples to the laboratory via UPS.

3. If an extracted core is broken at the rebar level and the epoxy coated rebars are exposed, the core must be shipped the same day it is extracted to the laboratory via overnight service.[XIII]

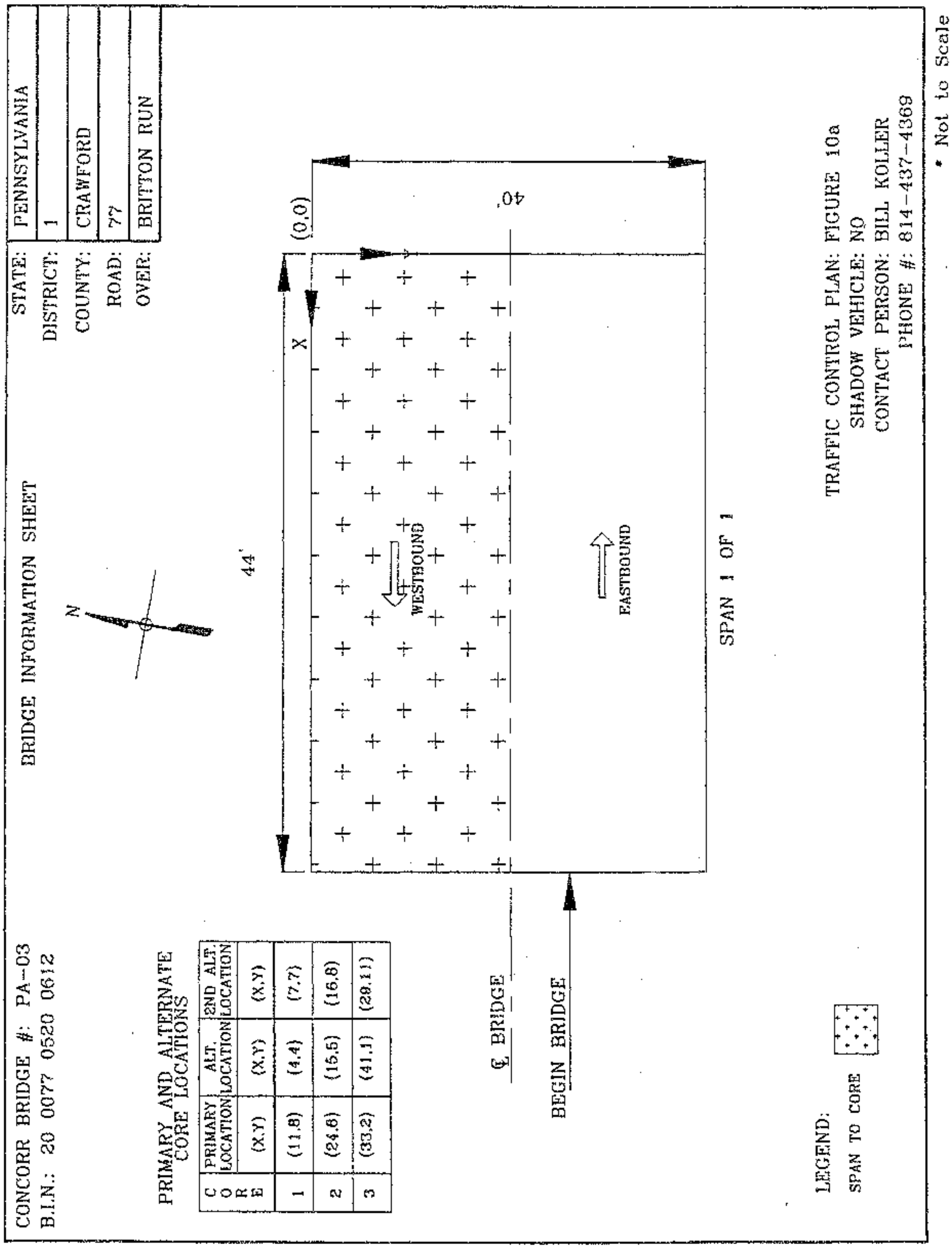
[XIII] If a core breaks at the steel level and the epoxy coated rebars are exposed, the core will be shipped to the laboratory via overnight mail and all bar coating tests and measurements will be performed the next day. This will insure that the test results reflect inservice conditions.

L. Verification of the Presence of Rebars

1. If problems are encountered in locating bars in the deck, verify the presence of the bars at the exact location to be cored by drilling down with a ¼ inch diameter bit approximately 6 inches away from the section of bar to be collected in the core.

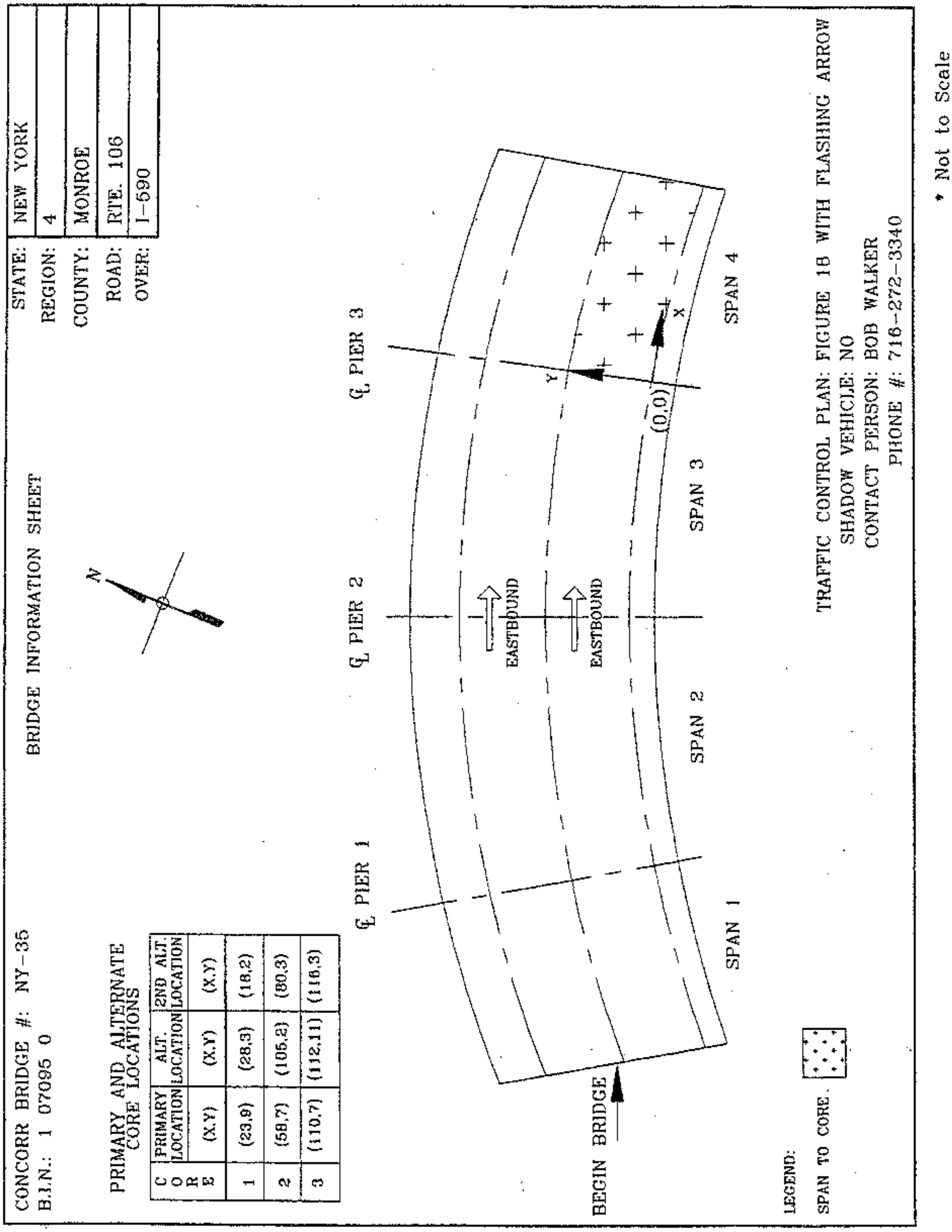
2. Select the intersection where the presence of bars has been verified or where a single bar has been verified.

3. Patch each hole with 100% solids epoxy.

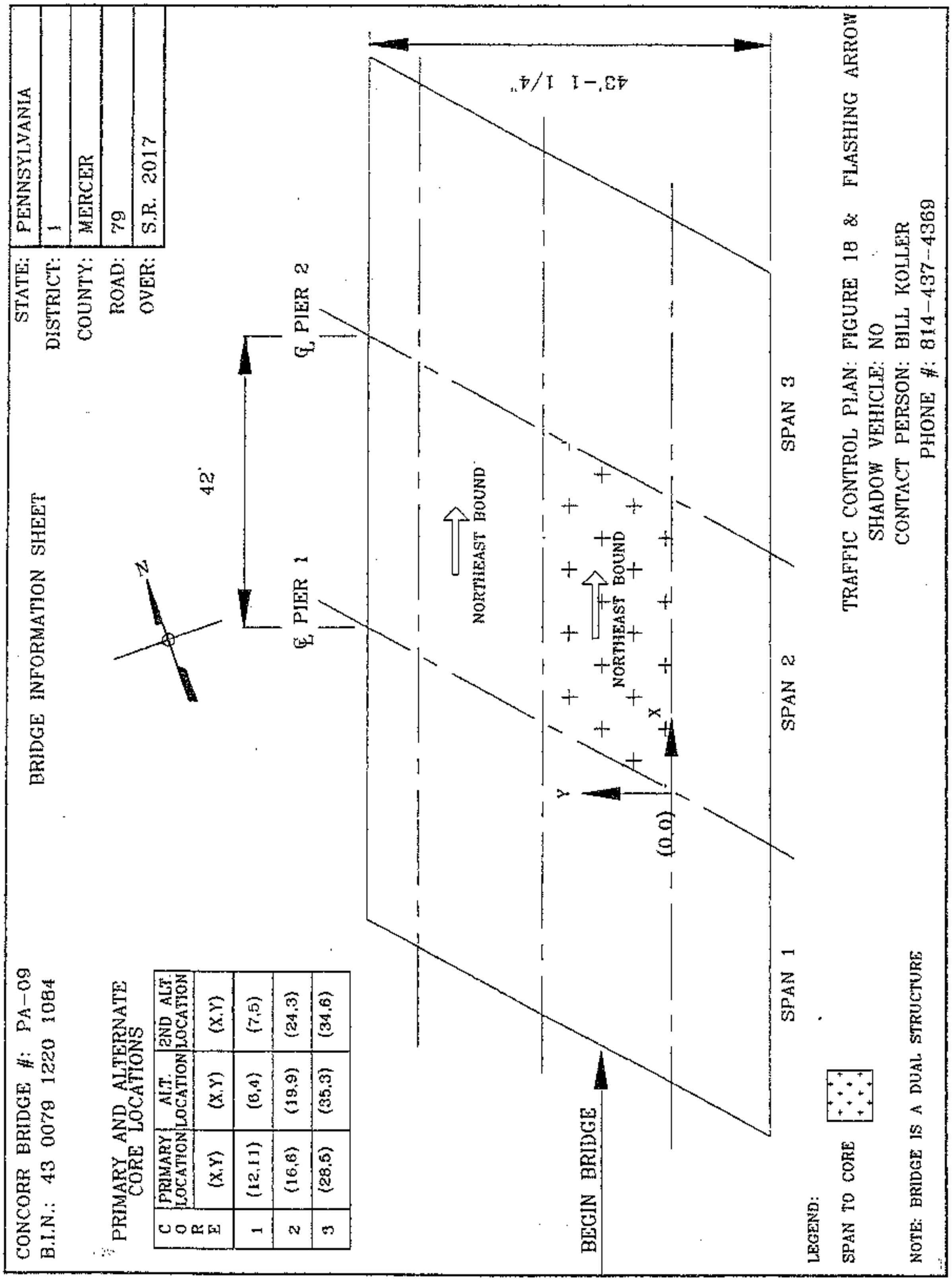


CORE	PRIMARY LOCATION	ALT. LOCATION	2ND ALT. LOCATION
	(X,Y)	(X,Y)	(X,Y)
1	(11,8)	(4,4)	(7,7)
2	(24,6)	(15,5)	(16,8)
3	(33,2)	(41,1)	(29,11)

Typical Bridge Information Sheet (BIS) for a straight bridge deck.



Typical Bridge Information Sheet (BIS) for a curved bridge deck.



CORE	PRIMARY LOCATION	ALT. LOCATION	2ND ALT. LOCATION
	(X,Y)	(X,Y)	(X,Y)
1	(12,11)	(6,4)	(7,5)
2	(16,6)	(19,9)	(24,3)
3	(28,5)	(35,3)	(34,6)

* Not to Scale

Typical Bridge Information Sheet (BIS) for a skewed bridge deck.

APPENDIX B

LABORATORY EVALUATION METHODOLOGY

LABORATORY EVALUATION METHODOLOGY

INTRODUCTION

This report describes the methodology developed for evaluating core samples collected from 80 bridge spans located in the states of New York and Pennsylvania (see Appendix A for details). The procedures described herein were developed to insure that the core samples are evaluated in conformance with the specifications and laboratory procedures described in the Request for Proposal (RFP).

A. Sequence of Laboratory Evaluation Methodology

During field work (see Appendix A), cores were sent to the laboratory on a weekly basis. When they arrived they were logged in on a data sheet and placed into a freezer for later testing. The only exception to this was if a core was broken during extraction from a bridge and epoxy coated rebars were exposed. If the latter scenario occurred, the core was shipped via overnight delivery to the laboratory so that it could be tested immediately.

Once laboratory evaluation begins, between six and fifteen cores will be removed from the freezer on a weekly basis for testing. Testing of the cores will begin when the cores have thawed for 24-hours and their surface temperature has risen to at least 60°F. The cores will be photographed and their physical properties and dimensions will be documented. Electrochemical Impedance Spectroscopy (EIS) tests will be run and two powdered concrete samples will be extracted from each core for later chloride analyses. Each core will then be strategically broken into two pieces and epoxy coated rebars will be carefully removed. The concrete traces left by the bars will be photographed, visual observations will be documented, and pH tests will be conducted on the rebar traces and any liquid found on the traces or the bars.

Bar testing begins by photographing and visually inspecting the bars. The visual inspection includes measuring the physical dimensions and counting the number of bare areas, mashed areas, and blisters. It also includes rating the bar for extent of corrosion. Holiday detection testing is then performed and this is followed in succession by coating thickness, coating hardness and wet adhesion tests. After wet adhesion testing is complete the bars will be placed into a desicator for seven days. Dry adhesion testing will be conducted after the seven day desicator period has elapsed. Specific gravity, percent volume, percent absorption, percent voids, and rapid permeability tests will be run on concrete samples and the two powdered samples taken earlier in the methodology will be tested for chloride content. Once all bar testing is complete, thirty bars will be randomly selected for microscopic coating thickness measurements. A flowchart depicting the Laboratory Evaluation Methodology is shown in Figure B-1.

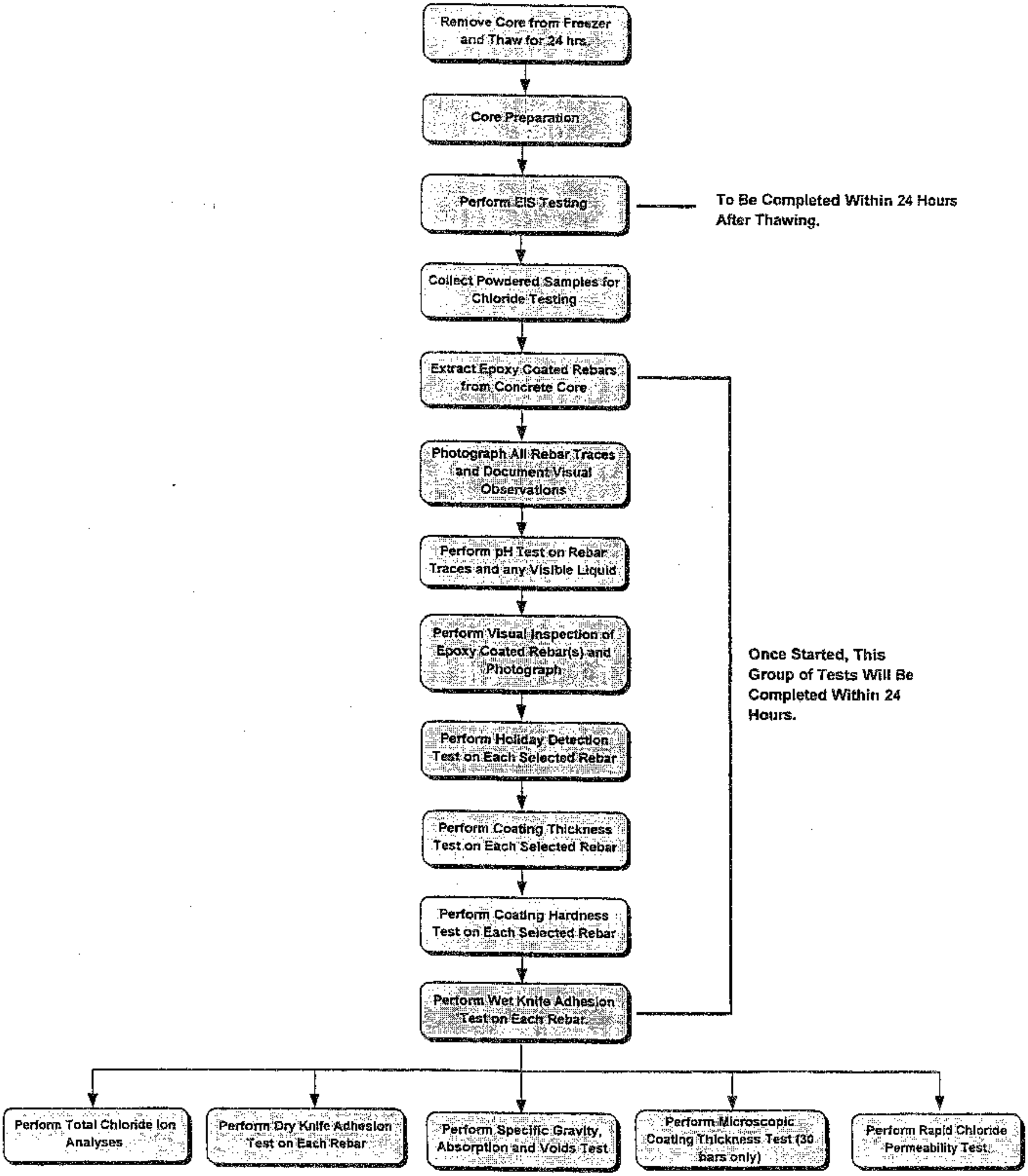


Figure B-1. Laboratory Evaluation Methodology Flowchart.

B. Core Preparation

1. Remove 6-15 cores from the freezer at a time and allow them to thaw to room temperature. All cores must be thawed for at least 24 hours.

2. Document the core # and date of initial testing on individual data sheets.

3. Measure the temperature of each core. If the temperature is less than 60°F allow further thawing until a minimum temperature of 60°F is attained.

4. Remove all moisture from the surface of the cores with Kimwipe tissues to insure that the surface is dry.

5. Document core information including diameter, height[I] (h_t), cover[II] over the topmost rebar, and height of concrete below the bottom most rebar (h_b). All lengths to be measured to one decimal place in English units.

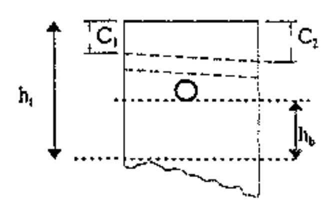
6. Visually observe the core to identify concrete damage such as cracking, honeycombing, and evidence of deterioration such as rust staining and delamination.

7. Label the core in multiple locations with its core #.

8. Photograph the core. The photograph is to include as many symptoms of deterioration as possible in one photograph.

[I] Height of a core can vary form one location to another due to irregular geometry of the broken surface. Thus, the maximum height of the core that contains the entire cross-section of the core shall be documented.

[II] Concrete cover will be measured at both ends of the topmost bar.



C. *Bar Selection and Preparation*

1. A maximum of two rebars shall be evaluated from each core.

2. Select the bars to be tested using the following criteria:

   - If more than two layers of rebars are found in a core, only the top two layers shall be selected for evaluation.

   - If a layer contains more than one rebar, one bar will be randomly selected for evaluation.

   - Any rebars that are not completely extracted (entire cross section) shall not be tested.

3. **All procedures described from this point forward shall only be conducted on the selected bars.**

4. With a black marker, paint the top half of one end of each selected rebar to designate its orientation in the core.

5. Drill and tap the other end of each selected rebar (the end that is not marked with a black marker). Install a screw and attach a pre-labeled tag.[III]

D. *Electrochemical Impedance Spectroscopy Measurement (EIS)*

1. Conduct EIS measurement within 24 hours of thawing.

2. Place one core at a time in the test probe[IV] and simultaneously connect the bars selected in section C to the working electrode of the EIS device.

3. Conduct EIS testing using Gamry Instrument's Impedance measuring device, Model # EIS 900.

[III] Each rebar extracted from the core will be labeled to identify the core # and whether the bar is the topmost or the bottommost bar. Labels will be of the following form:

1062 TOP

Where 1062 represents the Core # and TOP indicates that the bar was the topmost bar.

[IV] The EIS test probe is comprised of a 4 inch PVC tube and a titanium anode mesh sandwiched between two layers of sponge.

4. The EIS equipment will measure impedance at various frequencies. Save the results of each test as a separate file.

5. Document the impedance at 0.1 Hz on the data sheet.

E. Sampling for Chloride Ion Analysis

1. Two powdered concrete samples will be collected from each core. One sample will be extracted from the depth occupied by the topmost rebar and the other sample will be extracted from the depth occupied by the bottommost rebar. Each sample will come from four or more sampling sites located in such a way that an equal portion of the total sample comes from each quadrant of the core.[v] Each sampling site is to be located on cement paste. (e.g. drilling will not be done directly on exposed aggregate)

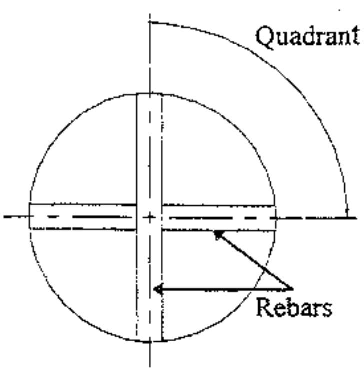
2. The locations of sampling sites within each rebar layer will be approximately spaced as follows:[vi]

    - top of the bar
    - $^1/_3$ of bar diameter from the top of the bar
    - $^2/_3$ of bar diameter from the top of the bar
    - bottom of the bar

3. Using a ¼ inch diameter drill bit, drill a ¼ inch deep hole at each sampling site. Discard powder from this drilling. Clean the bit and pan with a 50/50 mixture of alcohol and distilled water.

4. Using the same drill bit, continue drilling in the same holes to extract concrete powder. Store the two powdered concrete samples individually in labeled ziplock bags for future analyses. The label on each ziplock bag will be identical to the bar label.

v



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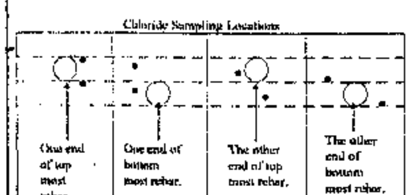


• center point of drill bit.

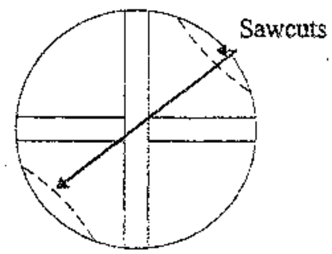
F. *Extraction of Epoxy Coated Rebars*

1. Dry saw cut a ½ to 1-inch deep groove in two diagonally opposing quadrants.[vii]
2. Break the core into two pieces along the sawcuts using a chisel and hammer.
3. Carefully remove the epoxy coated rebars from their traces. Insure that any liquid present on the rebars is not disturbed.

G. *Condition of Rebar Traces and pH*

1. Place the two halves of the core with the surface containing the rebar traces facing up on the lab table.
2. Photograph the rebar traces of both halves of the core simultaneously.
3. Record visual observations of each rebar trace individually.
4. If any liquid is identified on the epoxy coated rebar, under the epoxy coating, or on the rebar trace, use pH paper to define the pH of the liquid. If liquid is under a blister, prick a hole in the blister and squeeze out the liquid and then measure its pH.
5. Define the pH range of the trace using a pH pencil. Place a drop of water on the dry surface of the trace and swipe the pH pencil through the water along the surface of the trace. Use the color code provided with the pH pencil to determine the pH range.
6. Use one or more of the following indicators to more accurately define the pH in the trace:
   - 0.5% Phenolphthalein (pH range 8.2 to 10.0)
   - 0.04% Bromocresol Green (pH range 4.0 to 5.4)
   - Methyl Orange (pH range 5.0 to 6.5)

vii



- Methyl Red (pH range 4.2 to 6.2)
- 0.04% Bromothymol Blue (pH range 6.0 to 7.6)
- 0.02% Phenol Red (pH range 6.8 to 8.4)
- 0.10% Titan Yellow (pH range 11.0 top 13.0)

H. Visual Inspection of Epoxy Coated Rebars

1. Dry the epoxy coated rebar if necessary by wiping with Kimwipe absorbent tissue.

2. Record bar size, length, deformation pattern, and coating color for each ECR.

3. Deformations on rebars shall be characterized as type V, type X or type P.[VIII]

4. Place a rebar from each rebar layer with its top half facing up and photograph individually.

5. Place a rebar from each rebar layer with its bottom half facing up and photograph individually.

6. Visually observe the condition of the coating and the reinforcing steel and rate as follows:

Rating	Description
1	No evidence of corrosion.
2	A number of small, countable corrosion spots.
3	Corrosion area less than 20% of total ECR surface area.
4	Corrosion area between 20% to 60% of total ECR surface area.
5	Corrosion area greater than 60% of total ECR surface area.

7. Record the number of mashed areas, bare areas, and blisters for each rebar. Include comments for each rebar as necessary.

[VIII] Bar size and deformation pattern may impact the accuracy of coating thickness measurements. Thus, it is important to know the size and deformation pattern of each epoxy coated rebar.

Numerous deformation patterns are in use and therefore, it is impossible to document all types of deformation patterns one may come across in the bridge structures sampled.

Therefore, all deformation patterns will be characterized as either type V, type X or type P. These three patterns are the most common. All other patterns will be characterized as one of these three based on which one most closely matches the actual pattern.

I. Holiday Detection

1. Attach the ground wire of the holiday detector to the screw that was previously installed on the rebar.
2. KTA-Tator M/1, 60V holiday detector with a ¼ inch square sponge shall be used.
3. Perform holiday detection test on all surfaces of each bar in accordance with ASTM 62 - Method A.
4. When recording the number of holidays, distinguish between holidays located in bar ID areas from those not located in bar ID areas.[IX]

J. Coating Thickness

1. Measure coating thickness using Microtest IV, magnetic thumbwheel gauge.
2. Measure coating thickness in accordance with ASTM A 775 and ASTM D 3963 in undamaged areas with the exception of the following:
   - A clean uncoated steel bar of the same size and from the same lot will not be available to define a correction factor.
   - 1/8" wooden shims will be used to improve accuracy.[X]
3. Document coating thickness between the ribs (valleys) and on the ribs separately.
4. On each bar document the following coating thickness measurements:
   - Three measurements between ribs on the top surface of each bar.

[IX] During holiday detection, bare areas will also produce a beep. Areas previously categorized as bare areas will not be counted as holidays. If a holiday is detected over a mashed area the mashed area will be re-categorized as a bare area.

If a continuous beep is detected along a bar, then the number of holidays will be considered to be equal to the length of bar along the test trace divided by the width of sponge.

[X] Wood shims are used to keep the thickness gauge at the same angle relative to bars of different diameters. The research team believes that the accuracy of measurements is improved by using the shims. This has been verified using NIST coating thickness standards.

- Three measurements between ribs on the bottom surface of each bar.
- Three measurements on the top of ribs on the top surface of each bar.
- Three measurements on the top of ribs on the bottom surface of each bar.

5. Once a week the thumbwheel gauge will be calibrated against NIST coating thickness standards. The correction factor obtained from this calibration will be used to correct coating thickness readings made that week with the thumbwheel gauge.

K. Coating Hardness

1. Measure coating hardness at two locations on each bar in accordance with NACE TM0174 - Section 6.1.5, "Pencil Hardness Testing."
2. Record coating hardness for each bar.

L. Coating Adhesion

1. Measure coating adhesion in accordance with NACE TM0185 - Section 5.3.2, "Knife Adhesion Testing," with four modifications.[XI]
   - The sample will not be heated in an autoclave.
   - Use an "X" shaped groove in place of the "V" groove described.
   - Use a modified rating scale.
   - Store the samples in a desicator for 7 days prior to dry adhesion testing.

   Note: Procedures 2 and 3 below shall be performed if and only if their performance does not impact the ability to perform procedures 7 and 8. Also,

[XI] Modifications to the procedures in NACE TM0185 were required by the Pennsylvania Department of Transportation.

procedures 2 and 3 may be partially followed if possible (i.e. the number of tests may be reduced in order to maintain the ability to conduct procedures 7 and 8 in their entirety).

2. Conduct wet adhesion test in three undamaged areas.

3. If damaged coating areas are identified on the bar, conduct up to three additional wet adhesion tests adjacent to the damaged areas.

4. Record visual observations of the steel beneath the coating.

5. Rate all adhesion test areas as follows:

Rating	Description
1	Well adhered coating that cannot be peeled or lifted from the substrate steel.
3	Coating that can be pried from the substrate steel in small pieces, but cannot be peeled off easily.
5	Coating that can be peeled from the substrate steel easily, without residue.

6. Store each rebar in a desicator for 7 days.[xii]

7. Perform dry adhesion test in three undamaged areas.

8. If damaged coating areas exist, perform up to three additional dry adhesion tests adjacent to damaged areas.

9. Record visual observations of the steel beneath the coating.

Note: Sections F to L must be completed within a 24 hour period.

[xii] The knife adhesion test conducted prior to placing the bar in a desicator is termed the wet adhesion test. This test measures coating adhesion in an as-is condition.

The wet adhesion test must be completed within 24 hours from the time the rebars are extracted from the core.

The knife adhesion test conducted after 7 days of drying in a desicator is termed the dry adhesion test. This test provides standardized adhesion under controlled conditions.

M. Chloride Analysis

1. Perform total chloride ion analysis on the two samples extracted from each core in accordance with AASHTO T260-94 - Procedure A.[xiii]

2. Use procedures listed in paragraph 5.4.2 of AASHTO T 260-94, Method II: Gran Plot method for the total chloride ion analysis.

[xiii] With each set of chloride ion analyses include two blanks and two samples containing a known quantity of chloride ions.

N. Specific Gravity, Absorption, and Voids

1. On the piece of concrete obtained from the bottom half of the core perform testing in accordance with ASTM C 642-90, Standard Test Method for Specific Gravity, Adsorption, and Voids in Hardened Concrete.

2. Perform the test even if the sample does not meet the minimum size requirements specified in the Standard Test Method.[xiv]

[xiv] It will not be possible to obtain an 800 gram sample from the bottom half of each core to perform ASTM C 642-90.

The research team believes that a smaller size specimen will not significantly impact the accuracy of specific gravity measurements.

O. Rapid Chloride Permeability Test

1. If the top surface of the core has texturing or grooves, remove with a water-cooled saw.

2. Use the water-cooled saw to cut a 2 ± 0.1-inch slice from the top of the core. The cut should be made parallel to the top surface of the core. If the core is less than 2-inches thick, cut the thickest sample possible that maintains a flat surface and is parallel to the top surface.

3. Perform the rapid chloride permeability test in accordance with AASHTO T 277-93.

4. In addition to the procedures listed in the Standard Test Method, measure AC resistance prior to the application of 60v and 1 minute after the application of 60v. From the average of these measurements calculate resistivity in ohm-cm using a form constant.[xv]

5. If the thickness of the sample is not exactly 2.0 inches apply the following correction factor to each measured current:

$$I = I_m L_a/2$$

where I_m is the measured current in mA, L_a is the actual sample thickness in inches and I is the corrected current in mA.[xvi]

[xv] The form constant is calculated as

$$F=L/A$$

where F is the form constant, A is the surface area of the core in cm^2 and L is the height of the core in cm.

[xvi] The correction factor for sample thickness has been verified by performing measurements on 18 specimens cast from the same concrete, but of varying thickness.

P. Coating Thickness Measurement by Microscopic Examination

1. This test will be performed on 30 randomly selected epoxy coated rebar samples.

2. Encapsulate 1 ½ inches of one end of each ECR sample in epoxy.

3. After the epoxy cures, cut a 1 inch long segment of the encapsulated section through the diameter of the bar. The cut should be made through deformations. Cut off the remaining encapsulated section of the bar.

4. Polish the cross-section.

5. View the cross-section under a 70X microscope and measure coating thickness in undamaged areas around the cross section using a retical scale as follows:

- three measurements at the bar deformations (ribs).
- three measurements between bar deformations (valleys).

Q. Storage of Remaining Concrete and Rebars

1. Wrap all tested epoxy coated rebars in plastic-wrap. Insure that the rebar labels are wrapped inside the plastic-wrap.
2. Store all tested and untested pieces of concrete and all tested and untested rebars in a ziplock bag with an appropriate label.
3. Store the ziplock bags at room temperature.