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<table>
<thead>
<tr>
<th>NCHRP Report No.</th>
<th>Title</th>
<th>Page(s)</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A Critical Review of Literature Treating Methods of Identifying Aggregates Subject to Destructive Volume Change When Frozen in Concrete and a Proposed Program of Research—Intermediate Report (Project 4-3(2))</td>
<td>81</td>
<td>$1.80</td>
</tr>
<tr>
<td>2</td>
<td>Evaluation of Methods of Replacement of Deteriorated Concrete in Structures (Project 6-8)</td>
<td>56</td>
<td>$2.80</td>
</tr>
<tr>
<td>2A</td>
<td>An Introduction to Guidelines for Satellite Studies of Pavement Performance (Project 1-1)</td>
<td>19</td>
<td>$1.80</td>
</tr>
<tr>
<td>3</td>
<td>Guidelines for Satellite Studies of Pavement Performance 85 pp. 9 figs., 26 tables, 4 app.</td>
<td>$3.00</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Improved Criteria for Traffic Signals at Individual Intersections—Interim Report (Project 3-5)</td>
<td>36</td>
<td>$1.60</td>
</tr>
<tr>
<td>5</td>
<td>Non-Chemical Methods of Snow and Ice Control on Highway Structures (Project 6-2)</td>
<td>74</td>
<td>$3.20</td>
</tr>
<tr>
<td>6</td>
<td>Effects of Different Methods of Stockpiling Aggregates—Interim Report (Project 10-3)</td>
<td>48</td>
<td>$2.00</td>
</tr>
<tr>
<td>7</td>
<td>Means of Locating and Communicating with Disabled Vehicles—Interim Report (Project 3-4)</td>
<td>56</td>
<td>$3.20</td>
</tr>
<tr>
<td>8</td>
<td>Comparison of Different Methods of Measuring Pavement Condition—Interim Report (Project 1-2)</td>
<td>29</td>
<td>$1.80</td>
</tr>
<tr>
<td>9</td>
<td>Synthetic Aggregates for Highway Construction (Project 4-4)</td>
<td>13</td>
<td>$1.00</td>
</tr>
<tr>
<td>10</td>
<td>Traffic Surveillance and Means of Communicating with Drivers—Interim Report (Project 3-2)</td>
<td>28</td>
<td>$1.60</td>
</tr>
<tr>
<td>11</td>
<td>Theoretical Analysis of Structural Behavior of Road Test Flexible Pavements (Project 1-4)</td>
<td>31</td>
<td>$2.80</td>
</tr>
<tr>
<td>12</td>
<td>Effect of Control Devices on Traffic Operations—Interim Report (Project 3-6)</td>
<td>107</td>
<td>$5.80</td>
</tr>
<tr>
<td>13</td>
<td>Identification of Aggregates Causing Poor Concrete Performance When Frozen—Interim Report (Project 4-3(1))</td>
<td>47</td>
<td>$3.00</td>
</tr>
<tr>
<td>14</td>
<td>Running Cost of Motor Vehicles as Affected by Highway Design—Interim Report (Project 2-5)</td>
<td>43</td>
<td>$2.80</td>
</tr>
<tr>
<td>15</td>
<td>Density and Moisture Content Measurements by Nuclear Methods—Interim Report (Project 10-5)</td>
<td>32</td>
<td>$3.00</td>
</tr>
<tr>
<td>16</td>
<td>Identification of Concrete Aggregates Exhibiting Frost Susceptibility—Interim Report (Project 4-3(2))</td>
<td>66</td>
<td>$4.00</td>
</tr>
<tr>
<td>17</td>
<td>Protective Coatings to Prevent Deterioration of Concrete by Deicing Chemicals (Project 6-3)</td>
<td>21</td>
<td>$1.60</td>
</tr>
<tr>
<td>18</td>
<td>Development of Guidelines for Practical and Realistic Construction Specifications (Project 10-1)</td>
<td>109</td>
<td>$6.00</td>
</tr>
<tr>
<td>19</td>
<td>Community Consequences of Highway Improvement (Project 2-2)</td>
<td>37</td>
<td>$2.80</td>
</tr>
<tr>
<td>20</td>
<td>Economical and Effective Deicing Agents for Use on Highway Structures (Project 6-1)</td>
<td>19</td>
<td>$1.20</td>
</tr>
<tr>
<td>21</td>
<td>Economic Study of Roadway Lighting (Project 5-4)</td>
<td>77</td>
<td>$3.20</td>
</tr>
<tr>
<td>22</td>
<td>Detecting Variations in Load-Carrying Capacity of Flexible Pavements (Project 1-5)</td>
<td>30</td>
<td>$1.40</td>
</tr>
<tr>
<td>23</td>
<td>Factors Influencing Flexible Pavement Performance (Project 1-3(2))</td>
<td>69</td>
<td>$2.60</td>
</tr>
<tr>
<td>24</td>
<td>Methods for Reducing Corrosion of Reinforcing Steel (Project 6-4)</td>
<td>22</td>
<td>$1.40</td>
</tr>
</tbody>
</table>

* Highway Research Board Special Report 80.
CONTENTS

1 SUMMARY

4 CHAPTER ONE Introduction and Research Approach
   The Problem
   Study Design

5 CHAPTER TWO Airports
   General Trip Characteristics
   Trip Generation
   Trip Distribution
   Travel Impact on Highway Network
   Predicting and Testing Relationships
   Trends
   Conclusions

33 CHAPTER THREE Shopping Centers
   Data Characteristics and Analysis
   Some Interrelationships
   Shopping Centers and the Highway Network
   Estimating and Distributing Shopping Center Trips
   Conclusions

66 CHAPTER FOUR Industrial Plants
   General Trip Characteristics
   Trip Generation
   Trip Distribution Characteristics
   Travel Impact on Highway Network
   Predicting and Testing Relationships
   Trends
   Conclusions

87 CHAPTER FIVE Appraisal and Application
   Appraisal of Findings
   Application of Findings

88 CHAPTER SIX Conclusions and Suggested Research
   Airport Tripmaking
   Shopping Center Tripmaking
   Industrial Plant Tripmaking

90 REFERENCES

92 APPENDIX A Traffic Generation and Travel Patterns at Airports, Shopping Centers, and Manufacturing Plants: An Annotated Bibliography

102 APPENDIX B Summaries of Shopping Center and Manufacturing Plant Peak Traffic Data, Transportation Study Travel Survey Characteristics, and Plant Questionnaire Returns

105 APPENDIX C Regression and Backcheck Results

114 APPENDIX D Summaries of Shopping Center and Shopping Travel Characteristics
FIGURES

10  Figure 1. Monthly variation in air passengers as selected airports in selected years.
11  Figure 2. Fifty highest days, air passenger activity at Wold-Chamberlain Field, Minneapolis-St. Paul, 1958.
12  Figure 3. Total person trips to Atlanta, Chicago, Twin Cities, Seattle, and Washington airports, simple average of 3-hour moving averages, by day of week.
13  Figure 4. Home interview person trips to and from work, composite curve for selected airports.
14  Figure 5. Home interview person trips to and from social-recreation, composite curve for selected airports.
15  Figure 6. Home interview person trips to and from air travel, composite curve for selected airports.
16  Figure 7. Home interview person trips to and from all purposes, composite curve for selected airports.
17  Figure 8. Home interview auto driver trips to and from all purposes, composite curve for selected airports.
18  Figure 9. Internal truck trips to selected airports.
19  Figure 10. Internal taxi trips to selected airports.
20  Figure 11. Hourly accumulation of home interview auto driver trips to selected airports, all purposes.
21  Figure 12. Annual air passenger originations at selected airports, 1955-1964.
22  Figure 13. Annual air passenger originations per 100,000 population, 180 Standard Metropolitan Statistical Areas, 1960.
23  Figure 14. Home interview person trips per 1,000 population, composite curve on distance, all purposes.
24  Figure 15. Home interview auto driver trips per 1,000 population, composite curve on distance, by purpose.
25  Figure 16. Internal truck and taxi trips per 1,000 population, composite curve on distance, selected airports, all purposes.
26  Figure 17. Home interview person trips per 1,000 population, composite curve on travel time, all purposes.
27  Figure 18. Home interview auto driver trips per 1,000 population, composite curve on travel time, by purpose.
28  Figure 19. Home interview person trip origins, trips to Philadelphia International Airport, all purposes, all modes.
29  Figure 20. Home interview person trips to shop at the central business district, at all shopping centers, and at all other destinations, Pittsburgh, 1958.
30  Figure 21. Auto driver shopping trips to Center C, predicted and actual survey volumes, by travel time.
31  Figure 22. Auto ownership by travel time increment from Center Q.
32  Figure 23. Auto driver trips per 1,000 sq ft of floor space, by market area auto ownership.
33  Figure 24. Daily truck trips per 1,000 sq ft of floor space.
34  Figure 25. Auto driver trips to work by arrival time, three Miami shopping centers.
35  Figure 26. Auto driver trips to shop, by hour.
36  Figure 27. Auto driver trips to Denver center to shop, home-based and nonhome-based, daytime and evening shopping, by arrival hour.
37  Figure 28. All auto driver trips to three Miami centers, by arrival hour.
38  Figure 29. Auto driver trips to selected shopping centers, by day of week.
39  Figure 30. Auto driver trips to Buffalo centers for shopping goods, convenience goods, and all other purposes, cumulative distribution by travel time.
40  Figure 31. Home-based and nonhome-based auto driver shopping trips, frequency and cumulative distributions by distance, Centers O and P.
Figure 32. Total vehicle trips, and auto driver trips to shop, per person work trips.

Figure 33. Auto driver trips for convenience goods, shopping goods, and all other trips per 1,000 sq ft of floor space.

Figure 34. Auto driver trips to work, and all auto driver trips per 1,000 population, by total floor space.

Figure 35. Auto driver shopping trip rates, inside and outside zones, by distance, selected cities.

Figure 36. Auto driver shopping trip rates by goods type, by distance, Centers O and P.

Figure 37. Auto driver shopping trip rates by travel time, selected cities.

Figure 38. Auto driver shopping trip rates by goods type, inside and outside zones, Pittsburgh, by travel time.

Figure 39. Home-based auto driver trips per 1,000 autos owned, by distance, selected cities.

Figure 40. Auto driver shopping trip rates, inside zones, Buffalo, by distance.

Figure 41. Desire line map (unweighted by volume) of home interview auto driver trips to shop, Centers O and P.

Figure 42. Desire line map (unweighted by volume) of home interview auto driver trips to shop, Centers E, F, G, and H.

Figure 43. Traffic flow map of all auto driver trips to Center U.

Figure 44. Influence of highway improvements on central business district and shopping center market areas.

Figure 45. Home interview auto driver shopping trip rates, composite curves on travel time.

Figure 46. Auto driver shopping trips to Center B-B, predicted and survey volumes, by travel time.

Figure 47. Home interview auto driver trips to work at selected plants, by employment size groupings.

Figure 48. Home interview transit passenger trips to work at selected plants, by employment size groupings.

Figure 49. Internal truck trips to selected manufacturing plants.

Figure 50. Trip length frequency of home interview auto driver trips to work at selected plants.

Figure 51. Total person and total vehicle trips to selected plants per 1,000 sq ft of floor space.

Figure 52. Home interview auto driver work trip rates, by distance, to selected plants.

Figure 53. Home interview auto driver work trip rates, by distance, to selected plants, normalized by plant employment.

Figure 54. Actual vs predicted auto driver trips to work, by study area corridors, prediction on distance.

Figure 55. Home interview auto driver work trip rates, by distance, to selected plants, by "inside-outside" location.

Figure 56. Actual vs predicted auto driver trips to work, by study area corridors, prediction on distance, using "inside-outside" rates.

Figure 57. Home interview auto driver work trip rates, by travel time, normalized by plant employment.

Figure 58. Actual vs predicted auto driver trips to work, by study area corridors, prediction on travel time.

Figure 59. Home interview auto driver work trip rates, by travel time, to selected manufacturing plants in Pittsburgh (seven plants only).

Figure 60. Home interview person trips to work at Plant 4, Pittsburgh, blue collar vs white collar trip origins.
### TABLES

<table>
<thead>
<tr>
<th>Number</th>
<th>Table</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Table 1</td>
<td>Travel Mode Distribution of Trips to and from Selected Airports, All Purposes.</td>
</tr>
<tr>
<td>7</td>
<td>Table 2</td>
<td>Travel Mode Distribution of Person Trips to Selected Airports, by Purpose.</td>
</tr>
<tr>
<td>8</td>
<td>Table 3</td>
<td>Purpose Distribution of Person Trips to and from Selected Airports, All Travel Modes.</td>
</tr>
<tr>
<td>8</td>
<td>Table 4</td>
<td>Occupational and Car Ownership Class Distribution of Home Interview Transit Trips to Washington National Airport, All Purposes.</td>
</tr>
<tr>
<td>8</td>
<td>Table 5</td>
<td>Travel Mode Distribution, by Sex, of Person Trips to Selected Airports, All Purposes.</td>
</tr>
<tr>
<td>10</td>
<td>Table 6</td>
<td>Ratios of Truck and Taxi Trips to Person Trips, by Purpose, and to Auto Driver Trips, All Purposes, to Selected Airports.</td>
</tr>
<tr>
<td>14</td>
<td>Table 7</td>
<td>Ratio to Average Weekday Volume of Person Trips, by Purpose, to Selected Airports.</td>
</tr>
<tr>
<td>14</td>
<td>Table 8</td>
<td>Major Labor Force Component Percentages at Selected Airports.</td>
</tr>
<tr>
<td>19</td>
<td>Table 9</td>
<td>Home Interview Auto Driver Trip Length and Travel Time to Selected Airports.</td>
</tr>
<tr>
<td>19</td>
<td>Table 10</td>
<td>Reported Parking Characteristics of Home Interview Auto Driver Trips to Selected Airports.</td>
</tr>
<tr>
<td>20</td>
<td>Table 11</td>
<td>Average Car Loading Factors for Auto Driver Trips, by Trip Purpose.</td>
</tr>
<tr>
<td>21</td>
<td>Table 12</td>
<td>Peak Percentages and Directional Tendency of Trips to and from Selected Airports.</td>
</tr>
<tr>
<td>23</td>
<td>Table 13</td>
<td>Annual Air Passengers per 1,000 Population, Median Value for Selected Cities 1950.</td>
</tr>
<tr>
<td>23</td>
<td>Table 14</td>
<td>Resident Person Trip Generation Rates to Selected Airports.</td>
</tr>
<tr>
<td>29</td>
<td>Table 15</td>
<td>Air Travel Trip Rates per 1,000 Population, All Modes, by Ring.</td>
</tr>
<tr>
<td>29</td>
<td>Table 16</td>
<td>Proportion of Total Auto Driver Trips Originating Outside Study Areas.</td>
</tr>
<tr>
<td>30</td>
<td>Table 17</td>
<td>Proportion of Total Home Interview Person Trips to Airports with Origin in Central Business District, or Central Area, by Mode.</td>
</tr>
<tr>
<td>31</td>
<td>Table 18</td>
<td>Proportion of Resident Nonhome-Based Trips to Airports.</td>
</tr>
<tr>
<td>34</td>
<td>Table 19</td>
<td>Characteristics of Home Interview Shopping Trips in Pittsburgh, by Residence Ring and Mode.</td>
</tr>
<tr>
<td>34</td>
<td>Table 20</td>
<td>Characteristics of Home Interview Shopping Trips in Pittsburgh, by Car Ownership Class and Mode.</td>
</tr>
<tr>
<td>35</td>
<td>Table 21</td>
<td>Proportions of Travel and Capacity Used by Vehicular Trips to Selected Shopping Centers in the Pittsburgh Area.</td>
</tr>
<tr>
<td>39</td>
<td>Table 22</td>
<td>Distribution of Labor Force Components at Major Shopping Centers.</td>
</tr>
<tr>
<td>40</td>
<td>Table 23</td>
<td>Distribution of Travel Mode to Shop, by Sex of Tripmaker.</td>
</tr>
<tr>
<td>40</td>
<td>Table 24</td>
<td>Distribution of Home Interview Auto Driver Shopping Trips, by Origin.</td>
</tr>
<tr>
<td>44</td>
<td>Table 25</td>
<td>Shopping Center Entering Peak Hours and Proportions of Daily Volumes.</td>
</tr>
<tr>
<td>45</td>
<td>Table 26</td>
<td>Average Lengths of Auto Driver Trips for Shopping Goods and Convenience Goods.</td>
</tr>
<tr>
<td>45</td>
<td>Table 27</td>
<td>Distribution Characteristics of Auto Driver Shopping Trip Length for Selected Cities.</td>
</tr>
<tr>
<td>52</td>
<td>Table 28</td>
<td>Auto Driver Shopping Trip Rate by Mile Increment.</td>
</tr>
<tr>
<td>57</td>
<td>Table 29</td>
<td>&quot;Crosspull&quot; Between Major Chicago Shopping Centers.</td>
</tr>
<tr>
<td>60</td>
<td>Table 30</td>
<td>Directional Characteristics of Traffic to Shopping Centers, All Internal Auto Driver Trips.</td>
</tr>
<tr>
<td>61</td>
<td>Table 31</td>
<td>Trip Rates by Time Within Mile Increments, All Auto Driver Trips per 1,000 Autos Owned.</td>
</tr>
<tr>
<td>67</td>
<td>Table 32</td>
<td>Travel Mode Distribution, Home Interview Person Trips to Selected Plants, All Purposes.</td>
</tr>
</tbody>
</table>
ferent centers. But, in general, trip production rates are lower on the CBD side than on the suburban side of the centers—a uniform characteristic in all metropolitan areas studied.

12. The fact that trip rates differ between two zones equally distant from a center, when one zone is closer in time, shows that the highway system can affect the distribution of shopping center travel. However, speed of travel was not significant as one of the variables in multiple regression analysis of trip generation.

13. The effect of general urban highway improvements is to widen the market area coverage of the shopping center at a faster rate than that of the central business district.

14. Average daily traffic on a connector between two competing centers is generally low. Considering all shopping center trips to and from and between each of two centers studied, shopping center traffic did not exceed 15% of all traffic on any segment of connecting highway.

15. A trip distribution technique that appears to be dependable and useful in terms of its application to typical highway-shopping center study problems is proposed. The objective of the technique is to determine distribution by direction on approach highways rather than to assign trips specifically to residential zones of origin. Certain travel time and population data are the only requirements to develop solutions.

With respect to industrial plant travel:

1. About 95% of the daily trip making to most of the 51 plants studied consists of work trips.

2. About 10% of the employees of older plants, located in the highly built-up central cities, may walk to work, and a still larger percentage may take transit. But most employees of newer, suburban plants get to work by automobile. In general, car pooling is infrequent, and as more employees own cars the average car loading drops.

3. For every ten automobile trips to a given plant, on the average, there is one trip to drop off a passenger before continuing elsewhere.

4. Truck trips account for about 5% of total vehicular trip making of plants. Only 4% of the daily truck traffic occurs during the peaks when employees report to work.

5. Neither plant site area nor floor space singly provide reliable measures of total trip generation. Questionnaires reflect that plant areas may include a significant amount of vacant and inactive acreage: reserve storage space, railroad sidings, waste dumps, and so forth. Moreover, at least four types of floor space can be distinguished: production, storage, office, and service.

6. Plant employment is the best measure of total trip generation.

7. Multiple regression equations developed to predict modal split by plant indicate that employee characteristics are more influential than are characteristics of plant environments. High correlations were obtained, but large standard errors of the estimate showed that there was much variation from plant to plant.

8. Male employees have a greater propensity to drive to work than female employees. Females, blue collar workers, and workers from carless households have the greatest propensity to use transit.

9. Based on the 25 plants in the Pittsburgh and Buffalo areas, at least 60% of all transit trips to work are captive; that is, they are made by workers who do not own a car or cannot drive.

10. Most work trips are relatively long, averaging 5 to 6 miles and 20 to 30
min of travel time. Employee residences are highly scattered, even around mill towns where once most employees could walk to work. There is little grouping within residential areas by occupational classes.

11. There appears to be a reluctance for employees to cross major travel barriers such as river valleys. They tend to live on the side where the plant is located. They also tend to live on the suburban rather than on the CBD side of their plant.

12. Nevertheless, worker trip origins can be reasonably well predicted on the basis of population distribution about the plant, taking into account travel time or distance. Trip rate curves are presented which make allowance for the "nearside-farside" effect.

13. Although travel generated by a plant is usually a very small proportion of total travel in its metropolitan area, it may have significant local traffic impact.

With respect to general considerations:

1. Transportation study data, although subject to various degrees of sampling variability, can be used effectively to study the many characteristics of travel to specific major generator sites.

2. The findings in this report, whether for airports, shopping centers, or industrial plants, should not be construed as casting doubt on the effectiveness of the trip generation process at the traffic zone, district, ring, or sector level, where the aggregation of trips and land areas or floor space for a number of like land uses can produce meaningful indicators of trip generation. Rather, the findings reflect the difficulty of using floor space or acreages as single variables to predict trip generation at specific sites.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

THE PROBLEM

The following paragraphs, taken from the project statement, effectively summarize the general problem:

"The development of shopping centers, auditoriums, airports, industrial plants, and other large generators of urban travel increases traffic volumes and changes traffic patterns on the street networks which serve most traffic generators.

"It is desirable to determine criteria or values which establish the travel patterns created by these major traffic generators. Such information would be useful in forecasting the effect of various land uses on existing street networks; in providing a better basis for the design of new facilities; and in providing better criteria for the control of land use of this type."

The objective is "To evaluate the nature of the relationship between the travel patterns and influencing factors, such as:

(1) Travel time characteristics and other measures of

the adequacy of the street network serving the generator.

(2) Time distribution characteristics of the generated traffic.

(3) Characteristics of the traffic generator, including location, size, type, and intensity of land use.

(4) Modes of travel of the generated traffic.

(5) Competition of similar generators for the same street network.

(6) Socio-economic characteristics of the contributory area.

(7) Size, density, and degree of development of the contributory area."

STUDY DESIGN

The design of this project was determined by its expected application. It was felt that many factors bearing not only on highway design problems with respect to airports, major shopping centers, and major industrial plants, but also on forecasting and controlling their effect on highway development, could be developed from existing transportation
CHAPTER TWO

AIRPORTS

An airport can be among the most important and active single-site land uses in a metropolitan area. Perhaps the most specialized land use, the airport is a link to distant places. It can be the key to attracting new commerce and industry, as well as tourists. In this light, the economic impact of the airport upon the metropolitan area it serves can be much greater than is measurable by the number of passengers it serves or by the jobs available on its premises (1). Diverse activities at the airport site can create a tremendous amount of ground travel. People go there not only to fly, but also to work and for social-recreation activities. The longest trips in a metropolitan area are to airports (2), and they can be among the largest trip generators. Therefore, the travel impact on the highway network providing access to the airport can be considerable.

The broad purpose of this chapter is to present factors and relationships by which transportation planners, traffic engineers, and highway designers can be guided in providing efficient highway service to airports. Such relationships are needed not only for new airports, but also for older, still-expanding airports.

Ground travel at ten airports has been analyzed from the results of transportation studies in Atlanta, Buffalo, Chicago, Minneapolis-St. Paul, Philadelphia, Pittsburgh, Providence, San Diego, Seattle-Tacoma, and Washington, D. C. Airports in Salt Lake City and Miami have been analyzed to "test" predictive relationships derived from study of
TABLE 1
TRAVEL MODE DISTRIBUTION OF PERSON TRIPS TO AND FROM SELECTED AIRPORTS, ALL PURPOSES*

<table>
<thead>
<tr>
<th>AIRPORT</th>
<th>AUTO DRIVER</th>
<th>AUTO PASS.</th>
<th>TRANSIT PASS.</th>
<th>TAXI PASS.</th>
<th>AUTO DRIVER</th>
<th>AUTO PASS.</th>
<th>TRANSIT PASS.</th>
<th>TAXI PASS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlanta</td>
<td>81.8</td>
<td>15.7</td>
<td>0.7</td>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buffalo</td>
<td>53.3</td>
<td>42.4</td>
<td>2.1</td>
<td>2.2</td>
<td>49.3</td>
<td>43.0</td>
<td>1.2</td>
<td>6.5</td>
</tr>
<tr>
<td>Chicago (Midway)</td>
<td>52.1</td>
<td>34.4</td>
<td>9.4</td>
<td>4.1</td>
<td>44.6</td>
<td>37.1</td>
<td>9.4</td>
<td>8.9</td>
</tr>
<tr>
<td>Minneapolis-St. Paul</td>
<td>63.6</td>
<td>33.7</td>
<td>1.0</td>
<td>1.7</td>
<td>63.7</td>
<td>35.0</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>54.7</td>
<td>37.3</td>
<td>2.4</td>
<td>5.6</td>
<td>49.0</td>
<td>45.3</td>
<td>2.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Pittsburgh</td>
<td>61.3</td>
<td>34.0</td>
<td>1.9</td>
<td>2.8</td>
<td>57.8</td>
<td>28.2</td>
<td>3.8</td>
<td>10.2</td>
</tr>
<tr>
<td>Providence</td>
<td>59.0</td>
<td>41.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>San Diego</td>
<td>64.9</td>
<td>18.9</td>
<td>13.5</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seattle-Tacoma</td>
<td>67.5</td>
<td>29.3</td>
<td>1.3</td>
<td>1.9</td>
<td>62.1</td>
<td>34.5</td>
<td>1.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Washington (National)</td>
<td>57.3</td>
<td>31.5</td>
<td>9.6</td>
<td>1.6</td>
<td>51.9</td>
<td>34.4</td>
<td>9.6</td>
<td>4.1</td>
</tr>
</tbody>
</table>

* From transportation study data (home interviews) for the various cities. † Includes drivers of rental and company-owned cars. ‡ Includes truck passengers. ¶ Includes limousine and interurban bus passengers.

the first ten. All are commercial rather than general aviation or military airports.

The analyses are limited largely to tripmaking by residents of the metropolitan areas and surrounding regions considered, because short-term visitors from other metropolitan areas (particularly air travelers, lodging at hotels and motels) are frequently missed by standard origin-destination surveys. The resident tripmaking represents an average weekday, excluding Saturdays and Sundays, for the usual three- to six-month O-D survey period. Tripmaking by all means for all purposes is included. Total airport sites are considered, including those facilities related to general and military aviation, as well as to commercial aviation. In some instances it may have been impossible to sort out some trips to peripheral development not part of the airport site, but this is deemed a minor problem.

The major parts of this chapter consider, in order, general trip characteristics, trip generation, trip distribution, prediction and testing of relationships, trends, and the conclusions and implications that can be drawn.

GENERAL TRIP CHARACTERISTICS

Mode and Purpose of Person Travel

Mode, All Trip Purposes

Table 1 shows the striking dependence upon the automobile in getting to the airport.* Of the ten airports, the proportion of auto drivers ranges from Chicago's 52% to Atlanta's 82%.

The variation is hard to explain in terms of any single factor. Metropolitan area averages with respect to car ownership, family income and other household characteristics, or relative measures of highway versus transit accessibility, fail to suggest the answer.

An important factor is the percentage of trips to work; at every airport considered, the proportion of auto drivers is significantly higher for work trips than for other trips. Thus, other things being equal, the greater the relative importance of an airport as an employment center, the higher the proportion of auto driver trips it will attract.

The proportion of auto passengers ranges from Atlanta's 16% to Buffalo's 42%. Except for Atlanta and San Diego, the percentages do not differ greatly.

The proportion of transit passengers ranges from Providence's 0% to San Diego's 14%. Because of the relatively low total trip volumes to these two airports, sampling variability must be considered; a complete count would probably show Providence as having at least 1 to 2% limousine trips (although it had no public transit service in the trip survey year), and San Diego as having fewer than the 14% transit trips reported (although an upswing of servicemen using the airport during the Korean emergency, and possibly transit, has been offered as a possible explanation). The high percentages at Chicago and Washington will be traced subsequently to the work trip group.

At six of the ten airports there are higher proportions of taxi than transit passengers. The highs at Philadelphia (6%) and Chicago (4%) may reflect the proximity of both airports to the central business districts. But the San Diego airport, closest of all, reports only 1% taxi trips. Again, this may be due to sampling variability, as must be the Providence reporting of no taxi trips.

Table 1 also shows the percentage travel mode distribution of trips from the airport (it should be noted that for various reasons trips "from" were not requested of the Atlanta, Providence, or San Diego studies). Comparison with the "to" data shows the major difference to be a higher reported use of taxis, and a lower reported use of automobiles. Probably this is a function of home interview mechanics; the relatively few non-metropolitan area residents who are successfully interviewed can report their inbound trip but not their outbound trip. Such trips are likely to be by taxi, hence the inconsistency. For the same
TABLE 2

EFFECT OF SELECTED INORGANIC CORROSION INHIBITORS ON CORROSION CURRENT IN DIFFERENTIAL-AERATION CELLS

<table>
<thead>
<tr>
<th>INHIBITOR</th>
<th>CONC. (g/l)</th>
<th>CORROSION CURRENT (µA/in.²)</th>
<th>PENETRATION (mils/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>—</td>
<td>140</td>
<td>9.8</td>
</tr>
<tr>
<td>Na₂CrO₄·4H₂O</td>
<td>1</td>
<td>20</td>
<td>1.4</td>
</tr>
<tr>
<td>Ca₃(PO₄)₂</td>
<td>0.5</td>
<td>105</td>
<td>7.4</td>
</tr>
<tr>
<td>NaNO₂</td>
<td>0.5</td>
<td>90</td>
<td>6.3</td>
</tr>
<tr>
<td>NaNO₂</td>
<td>1</td>
<td>54</td>
<td>3.8</td>
</tr>
</tbody>
</table>

*The following conditions were constant: Deicing salt, CaCl₂ 10% solution, electrode 1, bare, deaerated; electrode 2, scale, aerated, polarity, electrode 1 is anode and corrodes, cathode-to-anode area ratio = 1.*

Alundum-tube cell operating as a differential-aeration cell. In addition, the surfaces of the electrodes were selected so as to give one of the more severe conditions as experimentally determined (see Table 1); that is, the nonaerated electrode was bare and the aerated electrode was coated with mill scale.

Both sodium and calcium chloride solutions were used. In some experiments, the sodium chloride solutions were made alkaline by saturating with calcium hydroxide. Calcium chloride solutions are alkaline as made up. The results of the experiments with a 10% calcium chloride solution are discussed in the following. The results in alkaline sodium chloride are equivalent to those obtained with calcium chloride.

Tables 2 and 3 contain the results of the screening tests for selected inhibitors.

Figure 5. Effect of cathode/anode area ratio on effectiveness of inhibitor.

Table 2 shows the effects in differential-aeration cells where a significant reduction in corrosion current was noted. It was observed in previous experiments that even without differential aeration, sufficient emf is generated as a result of surface conditions to cause corrosion. Accord-
Figure 6. Static electrode potentials and resistance values for concreted specimens with no inhibitor and immersed in 3½% NaCl solution.

Figure 7. Static electrode potentials and resistance values for concreted specimens with chromate inhibitor and immersed in 3½% NaCl solution.
ingly, inhibitors were added to cells in which both electrodes had access to air, but one electrode was bare and the other had mill scale on its surface. These results are summarized in Table 3. Chromates, Calgon, and sodium metasilicate appear to have promise. Sodium nitrite caused a reversal in polarity and the reason for this is not understood at this time.

The last columns in Tables 2 and 3 give the estimated corrosion in terms of mils (0.001 in.) per year penetration, as calculated from the corrosion-current density (microamperes per square inch). In converting from current density to penetration, the assumption was made that the current was uniformly distributed on the specimens, that the current efficiency was 100%, and that the anode reaction was \( \text{Fe} \rightarrow \text{Fe}^{++} + 2e^- \).

The effect of changing cathode to anode area ratios was studied without and with chromate inhibitor. In the former case the corrosion current increases linearly with increase in ratio. When chromate is present, the effect of the increase in ratio is largely offset, and the anodic areas corrode much less. This is shown graphically in Figure 5.

The foregoing results suggested that chromates might be added to the concrete mix. Accordingly, cement mortar specimens having inhibitor materials as an integral part of the cement were prepared. In mixing the mortar, distilled water was used in one set of specimens, a 5% aqueous chromate solution was used for another, and a 5% NaNO\(_2\) solution was employed in a third set. After curing in a fog chamber, static potential and resistance measurements were made in 3½% NaCl solution. The long-term results are shown in Figures 6, 7, and 8, respectively.

By taking the point at which the resistance curves level off, the time required for the NaCl solution to penetrate to the reinforcing steel can be estimated. The time for these three sets varied from about 25 to 50 hr. The static potential measurements give some indication of the inhibitive effect of the added material; the more electropositive the potential, the more effective is the inhibitor. The chromated specimens started becoming active at about the same time that the salt solution reached the steel. One of the nitrited specimens became active about 200 hr after the salt reached the steel, whereas the other started to become active at about the same time that the salt solution reached the steel. In these experiments none of the inhibited specimens appeared to be any more corrosion resistant than did the non-inhibited specimens.

**METALLIC COATINGS**

Metallic coatings for the protection of a basis metal such as iron fall into two broad classes—those which give sacrificial protection and those which do not. Metals that are more active than iron, such as zinc and cadmium, will give sacrificial protection to iron. This ability to provide sacrificial protection is of value where the coating metal is likely

---

**Figure 8.** Static electrode potentials and resistance values for concreted specimens with nitrite inhibitor and immersed in 3½% NaCl solution.
TABLE 4

<table>
<thead>
<tr>
<th>COUPLE</th>
<th>ANODE CURRENT DENSITY (μA/cm²)</th>
<th>PENETRATION OF ANODE (in./yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper-iron</td>
<td>MIN. 132</td>
<td>MAX. 0.017</td>
</tr>
<tr>
<td>Nickel-iron</td>
<td>MIN. 6.0</td>
<td>MAX. 0.0004</td>
</tr>
<tr>
<td>Lead-iron</td>
<td>MIN. 1.38</td>
<td>MAX. 0.0008</td>
</tr>
<tr>
<td>Zinc-iron</td>
<td>MIN. 4.8</td>
<td>MAX. 0.0065</td>
</tr>
</tbody>
</table>

Degrees of Corrosion as Estimated from Corrosion Currents Measured in Cells Containing Various Metal Couples in 3½ Percent NaCl Solution Saturated with Ca(OH)₂

Zinc, lead, copper, and nickel were individually coupled with steel. Each cell consisted of a 2-in. section of steel reinforcing bar and an electrode of one of these four metals immersed in a 3½% sodium chloride solution saturated with Ca(OH)₂. The areas of the coating metals (copper, nickel, lead, and zinc) were approximately six times those of the steel reinforcing bar specimen. This difference in area simulates the condition that arises when a break occurs in a metallic coating and the exposed area of the metallic coating is larger than that of the exposed steel. The choice of the ratios is arbitrary. Presumably, the ratio of coating area to steel area would be at a minimum in concreted steel because of the blanketing effect of the concrete. The results are given in Table 4.

Both copper and nickel were cathodic to steel under the conditions studied. On the basis of the experiments, copper would be expected to accelerate corrosion of the iron, resulting in a corrosion rate of from 17 to 60 mils per year, while the rate for iron coupled with nickel would be considerably less (2 to 6 mils per year).

The electrochemical measurements presented in Table 4 indicate that lead coatings are potentially useful. It should be noted that, unlike copper and nickel, lead is anodic to steel in alkaline solutions and would be expected to give sacrificial protection the same as zinc. In slightly acid solutions lead does not give sacrificial protection to steel. The low corrosion rate of lead in these experiments appears attractive. In view of the doubts concerning the use of lead in contact with wet cement or concrete, it would be necessary to study this metal further. In addition, the effect of lead on bonding is unknown.

Because the properties of zinc as a sacrificial coating are so well known, it was included in these galvanic cell experiments as a standard of comparison. It is to be emphasized that these data should be considered only in comparison with each other within this set of experiments.

The conclusions were to pursue the study of zinc and nickel as coatings for reinforcing rods.

Zinc Coatings

Zinc dissolves in both acid and alkaline solutions. There is an intermediate point at about pH 12 at which the corrosion of zinc drops to a very low value. The pH of the solution in the concrete pores is about pH 12.5, at which point the zinc dissolution rate is very low. This fortuitous condition favors zinc as a protective coating material for concrete reinforcing rods.

For this work, several reinforcing bar specimens were galvanized at a local commercial shop. Some of these were made up into the standard concrete-metal composite specimens. Others were used without concrete, but in solutions which simulated the chemistry of concrete. The latter experiments are described first.

The potentials of zinc-coated reinforcing bars were measured in 3% NaCl solution, 3% NaCl solution saturated with Ca(OH)₂, and the latter solution with chromate inhibitor added. The static potentials with respect to the saturated calomel electrode were approximately -1,060 millivolts (active); -800 mv (less active); and -450 mv (least active), respectively. These results indicated that the chromate might inhibit corrosion of the zinc. Chromate conversion coatings are widely used for zinc in the atmosphere and do improve the resistance of zinc to corrosion. It appeared from these preliminary experiments with non-concreted specimens that some beneficial effect might be expected from the addition of chromate to the concrete.

Two groups of standard concrete-zinc coated steel specimens were prepared, one with chromate and one without. Two specimens from each group were exposed in the same container to 3% NaCl solution for 288 days. During this time the static potentials were periodically measured, as was the resistance between the two specimens. The potential measurements, although erratic, were not significantly different for the two groups. The resistance dropped to the minimum value for both groups in less than 10 hr and remained fairly constant thereafter, indicating that the NaCl solution had penetrated to the steel in this time. After the 288 days had elapsed the concrete shells on the specimen were broken and the metal examined. The zinc-coated rod...
exposed to chromate was corroded less than the rod encased in nonchromated concrete. The latter specimens showed some white zinc corrosion products, and the zinc had darkened. However, the corrosion did not appear to be excessive. It is believed that the chromate does inhibit the corrosion of the zinc. No determination was made of the effect of the chromate on the properties of the concrete.

A differential-aeration cell using zinc-coated anode and cathode was studied. The polarization measurements (measurements with current flowing) were erratic, but one important fact was obtained: the zinc appears less susceptible than steel to differential-aeration effects. For example, with nitrogen bubbling through the anode compartment in a porous Alundum-tube cell and air bubbling through the cathode compartment, a difference of 100 to 200 mv was observed. When the air no longer bubbled through the cathode compartment but merely diffused in from the atmosphere, the potential difference was reduced almost to zero. This was not true of cells with iron electrodes, where diffusion alone was rapid enough to depolarize the cathode. This could be a strong factor in favor of the zinc coatings.

Zinc gives sacrificial protection over a wide range of pH, and at pH 12.5 corrodes at a minimum rate when uncoupled. However, zinc can corrode rapidly under certain conditions. As an example, it can be assumed that the reinforcing in a concrete section is galvanized and that the concrete cracks, exposing the reinforcing rod to a corrosive agent such as sodium chloride. In a small crack solution of Ca(OH)₂ may occur, giving rise to an alkaline pH. On the other hand, if the crack is large and the solution flows rapidly through the crack, insufficient Ca(OH)₂ is dissolved and the pH is neutral or slightly acid. The neutral or slightly acid pH condition would favor corrosion, as shown by the results of a series of experiments summarized in Table 5.

For these studies, zinc-coated reinforcing rods were exposed to slightly acid (pH 6) 3 1/2% NaCl solutions and to 3 1/2% NaCl solutions saturated with Ca(OH)₂ (pH 12.5). It was observed that the zinc coatings did corrode fairly rapidly in the pH 6 solutions and much more slowly in the pH 12.5 solution. In the first experiment listed in Table 5 the effect of the liquid-air-zinc interface is shown by the presence of iron corrosion products. In this case, the zinc is not providing complete sacrificial protection to the steel. The corrosion resistance of galvanized reinforcing steel is being evaluated at the University of California (20). This work is still in progress and final conclusions will be given at some future date.

Nickel Coatings

As discussed in a previous section, nickel is a more noble metal than iron and accordingly does not provide sacrificial protection. If a nickel coating has neither pores nor breaks it will give good protection to iron in a variety of environments. It has been used as a coating for dowel pins in highway construction (21, 22). However, in the case of reinforcing rod there is always the possibility that rough handling will cause a break in a coating. It was with this contingency in mind that the following experimental work was done.

It was estimated for the galvanic cell experiment summarized in Table 4 that nickel coupled to iron in 3 1/2% NaCl solution saturated with Ca(OH)₂ would cause only moderate corrosion of the iron. In subsequent experiments nickel-coated reinforcing rods having file cuts in the nickel coating so as to expose the underlying iron were exposed to 3 1/2% NaCl solution or to 3 1/2% NaCl solution saturated with Ca(OH)₂. In the former case, the iron corroded rapidly. In the alkaline solution little or no corrosion was observed after two months. It was concluded that under the alkaline conditions prevalent in sound concrete, a break in a nickel coating would not be a serious problem. The problem is with the sections of nickel-coated reinforcing bar exposed by large cracks where a neutral or slightly acid environment may prevail. This can be solved by using heavier coatings of nickel (3 to 5 mils thick). The heavier coating can resist rough handling. There is little probability of this coating being disrupted to the point where steel is exposed. Cut ends will, of course, expose the steel, but located as they are there is little threat to failure of the reinforcing rod even if corrosion does occur.

At present, nickel-coated reinforcing bars imbedded in concrete are undergoing test at the Harbor Island, N.C., installation of the International Nickel Co. (23). Also being tested are carbon steel, galvanized steel, nickel-copper high-strength low-alloy steel, and AISI 4340 steel. It may be some years before results are available. The nickel coating was rolled on in two thicknesses, 1 mil and 3 mils. These thicknesses are for a pure nickel layer. Beneath the pure nickel layer there is an iron-nickel alloy layer which was formed as a result of the rolling-on process. This layer also is capable of providing protection, at least in the outer, nickel-rich regions.

Further experiments on nickel coatings are reported in the section on polarization.

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>OBSERVATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Partially immersed in 3 1/2% NaCl solution.</td>
<td>Heavy corrosion of zinc. Iron corrosion products visible after less than 1 month. Iron corroding badly at liquid-air interface.</td>
</tr>
<tr>
<td>2. Completely immersed in 3 1/2% NaCl solution.</td>
<td>Heavy corrosion of zinc. Iron corrosion products after about 3 months.</td>
</tr>
<tr>
<td>3. Partially immersed in 3 1/2% NaCl solution saturated with Ca(OH)₂.</td>
<td>All of immersed surface covered with heavy zinc corrosion products. Some iron corrosion products.</td>
</tr>
<tr>
<td>4. Completely immersed in 3 1/2% NaCl solution saturated with Ca(OH)₂.</td>
<td>All of immersed surface covered with heavy zinc corrosion products. No iron corrosion products.</td>
</tr>
</tbody>
</table>
Polarization Studies on Uncoated Reinforcing Steel and Zinc- or Nickel-Coated Reinforcing Steel

On the basis of evidence presented thus far, both zinc and nickel coatings appear to have possibilities as protective coatings for reinforcing steel. A series of experiments was performed in which the polarization characteristics of reinforcing steel, nickel-coated steel, and zinc-coated steel were studied in 3½% NaCl solution saturated with Ca(OH)$_2$ over a wide range of potential and current values. A potentiostatic controller supplied the polarizing current to the specimens at a prearranged rate of change of potential. The experiments were then repeated using standard concrete specimens containing either reinforcing steel, nickel-coated steel, or galvanized steel reinforcing sections and immersed in 3½% NaCl solution. The objective of these experiments was to determine the reactions taking place under various conditions and to estimate whether or not they were favorable insofar as corrosion was concerned.

The method, as used in this work, consisted of immersing the test specimens and a platinum electrode in the electrolyte and applying a potential difference between them in order to make the test specimen more anodic or more cathodic. The potential of the test specimen was measured against an unchanging reference, which in this case was a saturated calomel electrode (SCE), and the current flowing in the circuit was recorded. The numerical value of the potential is associated with a specific reaction and the magnitude of the current indicates the degree of corrosion that can be expected for the given conditions.

Figure 9 shows the current density as a function of potential. The area was taken as 45.3 sq. cm, determined electrochemically on nickel-coated specimens (see Appendix B for method). The runs were started at —1.000 v (SCE scale) and the potential changed at a rate of 0.5 v/hr.

At the start of the first run the surface was uncorroded. When the current first became anodic several small spots appeared. The current increased until a potential of —0.675 v was reached and then decreased and became cathodic again at —0.600 v. The specimen remained the cathode until a potential of —0.430 v was reached, and then the current became very anodic.

A rerun of the same specimen after the anodic current had corroded approximately 35% of the surface yielded a curve that was anodic from a potential of —1.000 v.

Figure 10 shows the theoretical anodic and cathodic curves for iron. These were calculated, making certain assumptions. It was not possible to measure the cathodic reaction on the corroding steel because the anodic reaction, which was occurring simultaneously, masked the cathodic reaction. It was assumed that in the solution used the cathodic reaction on the steel surface would be the same as for the nickel surface. Because nickel was noncorroding in the alkaline chloride solution, it was possible to construct a cathodic polarization curve from direct measurements (Fig. 11). The anodic curves in Figure 10 are based on calculated current densities assuming 8% and 35% local anodes for the initial and rerun, respectively. The 35% was esti-
SUMMARY

The objective of the research reported herein was to evaluate and develop methods for reducing the corrosion of reinforcing steel in concrete in the presence of deicing salts.

The problem was attacked by a laboratory investigation featuring, for the greater part, electrochemical studies. This approach was prompted by the knowledge that corrosion of reinforcing steel is an electrochemical process, and because visual observation of the corrosion is precluded by the concrete envelope, thus necessitating use of an indirect method of observation.

The research began with a study of some of the factors which have a marked influence on the rate of corrosion of reinforcing steel. The effects of mill scale and differential aeration, for example, were noted. It became apparent from these experiments that corrosion did not result from a single process but was the consequence of a multiplicity of different galvanic cells or couples. Although these cells produce relatively small electrical currents, these currents may be of sufficient magnitude to cause appreciable dissolution of the anodic portion of the galvanic couple.

The complexities of corrosion of reinforcing steel in concrete pointed to the fact that a successful remedy would have to combat all of the many conditions which lead to corrosion. In view of this, inhibitors, coatings, and cathodic protection schemes were investigated.

Corrosion inhibitors such as sodium nitrite or chromates have been added to deicing salts to curtail metallic corrosion in vehicles. It would seem that such additions to the salt would be ineffectual in minimizing the corrosion of reinforcing steel because the inhibitor would not be expected to come in contact with the steel uniformly. After some preliminary studies, selected inhibitors were added to the cement mix from which reinforced concrete corrosion specimens were made. The measurements indicated that the inhibitor was effective only for short periods of time.

The research also included studies of coatings, both metallic and nonmetallic. In terms of protection from corrosion, there are two types of metallic coatings—sacrificial and nonsacrificial. The sacrificial type, of which galvanizing on steel is an example, dissolves in preference to the basis metal and thus gives sacrificial protection even if the coating is broken at some point, exposing the basis metal. The nonsacrificial type of coating provides a barrier only, and in the event of a rupture does not protect the basis metal; indeed, it often accelerates corrosion, because the coating is more noble than the steel.

Four metallic coatings were studied—copper, nickel, zinc, and lead. The first two are nonsacrificial, whereas the last two are of the sacrificial type. When undamaged, copper coatings will protect steel, but if a break occurs the steel will corrode rapidly, particularly if the corrodenent is acidic. Even near the neutral point, some attack may occur. It was not known how rapid the corrosion of the copper-steel couple would be in the alkaline environment provided by concrete. As it turned out, the rate of corrosion for the steel was excessively high in the alkaline chloride environment and was estimated from current measurements to range from 17 to 60 mils per year.
Zinc corrodes in both fairly strong acid and alkaline solutions. However, the rate of attack approaches a minimum near the pH of concrete (pH 12.5). If a break occurs in the zinc it provides sacrificial protection to the steel in both acid and alkaline solutions. In slightly acid solutions the zinc corrodes quite rapidly. Such a condition may be brought about by relatively large cracks in concrete in which the pH of the electrolyte cannot be maintained at 12.5 because the electrolyte is flowing in and out of the crack at too rapid a rate to leach sufficient Ca(OH)₂ from cement.

Comparison of the rate of corrosion of zinc-coated reinforcing steel in 3½% NaCl solution (pH about 6) and in 3½% NaCl solution saturated with Ca(OH)₂ (pH 12.5) showed the rate of corrosion of the zinc to be much faster in the pH 6 solution. Where breaks occur in the zinc coating, the zinc provides sacrificial protection to the steel for much longer periods in the alkaline solution than in slightly acid solutions because of the lower rate of zinc consumption. The addition of chromate to the cement mix appears to inhibit the corrosion of the zinc coating in the presence of chlorides.

A consideration of all the data suggests that zinc-coated rods would have a significantly longer service life than bare rods.

Nickel, although not providing sacrificial protection to steel, has been used in many applications as a barrier coating. In concrete highway construction nickel-coated dowel pins have been used. Nickel coating also appears to have merit in protecting reinforcing steel. The corrosion resistance of nickel is good in alkaline chloride solutions; even if breaks occur in the nickel coating the attack of the iron is not appreciably accelerated. Nickel has good resistance in neutral or slightly acid chloride solutions, and nickel coatings under these conditions provide protection to steel so long as no breaks or pores are present in the coating. On the other hand, if a break occurs in these environments the resulting galvanic couple accelerates the iron corrosion. It is suggested that the probability of having a rupture in a nickel coating is practically nonexistent providing the coating is 3 to 5 mils thick. With thinner coatings the number of holidays or pores increases significantly.

Lead will give sacrificial protection to steel in alkaline chloride solutions but not in neutral or slightly acid solutions. It appears to have merit as a potential protective material, but further studies are necessary before any recommendations can be made.

The experiments with nonmetallic coatings indicate that an asphalt-epoxy coating gives good protection to reinforcing steel. In addition to the inherent corrosion resistance of the coating, it has very high electrical resistance, which is instrumental in slowing the corrosion of the steel. Where breaks in the coating occur no sacrificial protection is given, nor is the corrosion of the steel accelerated because of galvanic coupling. There was some indication that sufficient material is leached out of the coating to provide an inhibitive effect. Asphalt-epoxy coatings protect the steel over the pH range encountered in the field.

Attempts to produce suitable insoluble silicate coatings were not successful.

Cathodic protection will probably be effective in minimizing corrosion in reinforcing steel. A laboratory investigation on cathodic protection was not undertaken for the reason that it is usually easy to make it work in simple laboratory models, whereas in practice the application is far more complicated, and each application is a separate problem.

It was concluded that the best candidates for protecting reinforcing steel from corrosion induced by deicing salts are zinc coating, nickel coating, or an asphalt-epoxy or some similar organic coating.

It is recommended that these coatings be tested in the field in a limited pilot test.
INTRODUCTION AND RESEARCH APPROACH

In recent years snow and ice have been removed from streets, highways, and bridge decks by the use of deicing salts such as sodium chloride and calcium chloride. Increased use of these salts has been accompanied by two principle deterioration problems in concrete structures: (1) salt scaling of concrete, and (2) corrosion of reinforcing steel. It is with the second of these problems that this investigation is concerned.

It has been the purpose of the research reported here to determine the factors responsible for corrosion of steel reinforcing, and through an understanding of the principles involved to suggest potential methods for minimizing the deterioration of the steel.

DISCUSSION OF PROBLEM

It is generally conceded that even in the presence of deicing salts corrosion of reinforcing rods is no problem where proper concreting practice is followed and where no subsequent injury to the concrete occurs. It is, however, recognized that although the first condition is desirable it is not always realized. At the 44th Annual Meeting of the Highway Research Board state highway engineers were almost unanimous in lamenting the poor concreting practices and in blaming them for many of the ills which beset the highway engineer. The second condition, injury of the concrete due to the pounding of vehicular traffic, is probably unavoidable. As a result of these combined events, the integrity of the concrete “envelope” is destroyed and, where deicing salts are used, corrosion of the reinforcing steel occurs in varying degrees. If it is assumed that uniform high-quality concreting is unlikely to be achieved or that highways which will resist the ravages of heavy vehicles will be designed, the problem must be solved by some other approach.

To do this, the mechanism or mechanisms by which the steel in concrete corrodes must be examined. An introductory explanation of the principles of corrosion is given in Appendix A for those readers unfamiliar with corrosion and its terms (also see 1, 2, 3, and 4).

On the basis of field observations and laboratory studies (5, 6, 7, 8, 9, 10, 11, 12, 13), it appears that the corrosion of reinforcing rods in concrete is electrochemical. A difference in potential (voltage) arises between two points in the reinforcing network, current flows, and the anodic portion of the steel corrodes. These differences in potential arise from various causes. Before considering the causes, however, it must be recognized that the reinforcing rods, although imbedded in concrete, are not insulated entirely from outside influence. The concrete may have varying porosity, orientation of coarse aggregate between steel surface and outer concrete surface may provide paths to the steel, and physical stresses caused by passing vehicles in time result in cracking of the concrete. Even in the absence of chloride salts, water fills the pores or cracks, and eventually becomes saturated with calcium hydroxide from the concrete, thus providing the cell electrolyte.

Possibly, one of the most prevalent causes of corrosion of reinforcing steel is differential oxygen concentration. Atmospheric oxygen has easy access to some portions of the steel and reaches other portions only with great difficulty. The latter areas become anodic and the former areas become cathodic. Corrosion resulting from the formation of such differential aeration cells has been observed.

In the presence of chlorides, the corrosion of the steel becomes more severe. As the salt penetrates the concrete, the chloride concentration varies from point to point, a condition which can also result in a difference in potential. However, the most important effects of the salt are to increase the electrolytic conductivity within the steel-concrete composite, and to activate the metal surface, thus intensifying the corrosion. Conductivity measurements made in this study show a 3 3/4% NaCl solution saturated with Ca(OH)$_2$ to be about seven times more conductive than saturated Ca(OH)$_2$ solution. High salt concentrations may also increase the differential aeration effect by lowering the solubility of oxygen in the electrolyte. High NaCl concentration is reported to lower the pH of Ca(OH)$_2$ solutions by 0.3 to 0.4 unit. Thus, differential pH is promoted and this in turn result in a potential difference.

Differences in the pH of the electrolytes can occur as a result of differences in availability of atmospheric CO$_2$ to react with the alkaline Ca(OH)$_2$ solution.

A final variable involves the rods which comprise the electrodes in the various cells. The rods are normally hot rolled and thus are covered with various thicknesses and types of mill scale. In addition, storage of reinforcing rods outdoors promotes the formation of additional corrosion products. Accordingly, the initial surfaces can vary considerably.

The foregoing discussion indicates only some of the factors to be considered and is not meant to be a complete delineation of the problem. It does, however, indicate the complexity of the problem arising from the variety of corrosion cells which can occur simultaneously.

The method or methods selected to prevent corrosion must ultimately meet economic restrictions. At present it is not deemed advisable to rule out any method solely on the basis of high cost, inasmuch as the costs must be balanced against the expected increase in highway life afforded by a given method.
RESEARCH APPROACH

In the study of the corrosion of reinforcing rods in concrete, the progress of the deterioration of the steel must be observed without being seen in the usual sense. In another sense, however, the steel can be "seen" by means of electrochemical measurements. Techniques based on electrochemical principles are well known in corrosion science. An insight into the electrochemical reactions associated with a given corrosion process has in the past frequently resulted in a method for minimizing corrosion. Such an approach would be expected to provide fundamental knowledge of the processes, indicate the relative influence of the various factors, and at the same time serve as a screening mechanism for evaluating various protective schemes.

CHAPTER TWO

EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results are discussed in the following. Details of apparatus and experimental methods are given in Appendix B.

CELL DESIGN

Electrochemical cells take various forms. For the problem at hand it was necessary to design a cell or cells that would simulate the conditions existing in reinforced concrete which has been wetted with a salt solution. Several designs were studied. The so-called sand-diaphragm cell and the steel-concrete cell were the first to be used. These are shown schematically in Figures 1 and 2. In Figure 1 the sand simulates the concrete which separates two portions of a reinforcing network. The anode and the cathode are separate sections of reinforcing steel which are in electrical contact through external connections. The anode and the cathode are surrounded by an aqueous solution which simulates the solution found in the pores of cement. Nitrogen (anode compartment) or air (cathode compartment) can be bubbled through the solution to simulate differential aeration. The electrodes can be surrounded by solutions of varying salt concentration or pH to simulate other conditions. The saturated calomel electrode is a reference standard for potential measurements. Its potential is constant and thus enables the investigator to determine the change in individual potential of the cell anode and cathode. Corrosion currents were measured by means of a zero-resistance ammeter.

In Figure 2 the setup is essentially the same, except that the concrete replaces the sand, and the cell now closely represents the reinforced-concrete situation. Eventually, a porous Alundum-tube cell, shown in Figure 3, was found to be most suitable for the electrochemical studies because it not only simulated the desired condition but also afforded ease of manipulation and provided acceptable reproducibility of results. To achieve differential aeration conditions, nitrogen is bubbled through the solution in the anode compartment and clean air is bubbled through the cathode solution.

For static (no current flowing) potential measurements, the cell shown in Figure 4 was used. In this cell two iden-
tactical standard cemented specimens were exposed simultaneously in a corrosive solution. The specimens were held rigidly at a distance of 3/4 in. from each other. Conductivity measurements were made, to obtain an estimate of the time required for the electrolyte to penetrate the pores of the concrete and reach the steel.

STUDIES OF FACTORS INFLUENCING CORROSION IN REINFORCING RODS

In accordance with the plan to study the principles involved in the corrosion of reinforcing steel in concrete, the experiments described in the following sections were run to determine the influence of various factors on the corrosion process.

Effects of Mill Scale

Reinforcing rods of the deformed type are hot-rolled in air and consequently have various types and amounts of mill scale on their surfaces. The mill scale does not form a continuous coating and bare areas of exposed steel are found where the scale has flaked off. Mill scale, being more noble than the steel, can act as the cathode of a couple whose anode is the basis steel. Thus the corrosion of the steel is accelerated. Scaled and bare surfaces combined with aeration or deaeration can result in a variety of cells. The various combinations were studied in the porous Alundum-tube cell, using a 10% NaCl solution. The results are summarized in Table 1. As expected, the different combinations of factors resulted in cells having a variety of corrosion characteristics. When using the cell currents as an indication of corrosion rate, the aggressive corrosion occurred when both electrodes were bare. The corrosion was least when the unaerated electrode had a scale coating and the aerated electrode was bare. In the cases cited the corrosion was under cathodic control; that is, the corrosion was limited by the reaction at the cathode. In cells 1, 2, and 4, this would mean that the reaction is controlled by the rate of diffusion of air to the cathode or by an activation energy. This is an energy needed, for example, by a surface to take part in a reaction, in this case a reduction or some step in the reduction reaction. Where the surface is slow in acquiring the needed energy, the reaction is correspondingly slow.

The experiments described in the foregoing demonstrate that the surface condition of the steel is an important factor and that under optimum conditions it can adversely affect the deterioration of reinforcing steel.

If mill scale formed a continuous coating and the coating

<table>
<thead>
<tr>
<th>TABLE 1</th>
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<tbody>
<tr>
<td>RESULTS OF POROUS-CELL STUDIES WITH 10% NaCl SOLUTION</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DETERMINATION</th>
<th>CELL 1</th>
<th>CELL 2</th>
<th>CELL 3</th>
<th>CELL 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) ELECTRODE 1 (100% N₂)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface condition</td>
<td>Scale</td>
<td>Bare</td>
<td>Scale</td>
<td>Bare</td>
</tr>
<tr>
<td>Potential (mv vs SCE):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polarity</td>
<td>Anode</td>
<td>Anode</td>
<td>Cathode</td>
<td>Anode</td>
</tr>
<tr>
<td>Polarization (mv)</td>
<td>40</td>
<td>50</td>
<td>13</td>
<td>40</td>
</tr>
<tr>
<td>(b) ELECTRODE 2 (100% Air)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface condition</td>
<td>Scale</td>
<td>Scale</td>
<td>Bare</td>
<td>Bare</td>
</tr>
<tr>
<td>Potential (mv vs SCE):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open-circuit</td>
<td>–570</td>
<td>–450</td>
<td>–710</td>
<td>–550</td>
</tr>
<tr>
<td>Polarity</td>
<td>Cathode</td>
<td>Cathode</td>
<td>Anode</td>
<td>Cathode</td>
</tr>
<tr>
<td>Polarization (mv)</td>
<td>60</td>
<td>220</td>
<td>2</td>
<td>120</td>
</tr>
<tr>
<td>Current density</td>
<td>13</td>
<td>27</td>
<td>0.7</td>
<td>38.5</td>
</tr>
</tbody>
</table>
could be maintained, improved corrosion resistance might be expected. Microscopic examination at low power of the surface of as-rolled reinforcing rods shows the coating to be irregular. Metallographic study of the cross section of reinforcing bars demonstrates variations in thickness and porosity. Thus, any attempt to utilize the mill scale as the basis for a protective coating would probably prove futile.

Effects of Differential Aeration and Differential Concentration

Differential aeration and differential concentration have been described as causes of corrosion of concrete reinforcing steel by several authors (5, 6, 7). Differential aeration occurs where one area of a metal surface has little or no air in contact with it while an adjacent area has a good supply of air. The result is that the area having little or no air will become anodic and will corrode. The other area will be cathodic and under most conditions will remain immune to corrosion.

In the case of concrete, differential-aeration effects can be abetted by variations in porosity, cracks, and differences in the amount of cover provided by the concrete.

The magnitude of the effect of differential aeration was studied by using the previously described porous Alumidum-tube cell. The electrodes were sandblasted reinforcing bars. Sandblasting was done to eliminate the complicating effects of mill scale. The electrolyte was 3½% NaCl solution saturated with Ca(OH)$_2$ and a small amount of solid Ca(OH)$_2$ was present to maintain saturation and alkalinity. Nitrogen was bubbled through the anolyte and air was bubbled through the catholyte in such a way that no bubbles accumulated on the electrodes. The anode and the cathode were weighed before and after the experiment. The electrodes were electrically connected to each other. The corrosion current was determined periodically, as were the weights of metal accumulations on the electrodes.

In this research, another reaction was observed at the cathode. This was evidenced by the red rust at the cathode and the weight loss observed after removal of rust. This is a complicating factor in the general scheme of corrosion of reinforcing bars. In addition to cathodic reactions, localized anodic reactions may be occurring on the cathode surface. The iron of the cathode corrodes to divalent iron at these anodic centers. The divalent iron, in turn, is readily converted to trivalent iron in the presence of air, and it is this trivalent iron that forms the familiar red rust.

An example of this type of corrosion was observed in the field by a highway engineer in one of the Northeastern states and reported to one of the authors. A reinforcing mat removed from a defective section of highway was observed to have corroded at one end with the formation of red rust and at the other end without the formation of red rust. The mat had been improperly placed and had about ¼ in. of concrete cover at the end where red rust formed and about 2 in. of concrete cover at the other end. This appears to be a case of differential aeration, with the anode having the greater cover.

During the differential-aeration studies attempts were made to "poison" the cathodic reactions so as to halt the cell action. None of these was effective, thus suggesting that the expedient way to halt or slow the cathode reaction is to use a coating which excludes oxygen or which in some way reduces the rate of the reaction.

Effects of pH on Corrosion of Reinforcing Steel

The pH of a corroding solution may have a marked influence on the corrosion rate of metals. Where sufficiently large cracks occur in reinforced concrete, salt-containing solutions from the surface have easy access to the interior. Furthermore, the solutions, in effect, may be flowing into and out of the crack. This latter condition makes it difficult to maintain the pH of about 12.5, resulting from saturation by Ca(OH)$_2$, which would exist in a crack if there were no flow. Where sodium chloride is the dissolved material, the pH may drop to between 6 and 7, and this tends to increase the rate of corrosion of steel and of other metals that might be used to coat the steel. Shalon and Raphael (14) have studied pH effects and have observed that the minimum pH for inhibition of steel varies from 11.5 to about 12.75, depending on the nature of the corrosive medium. Experiments which illustrate the effect of pH were performed in connection with zinc and nickel coatings and are reported under the appropriate heading.

INHIBITORS

Inhibitors are chemical substances which reduce the rate of corrosion. Inhibitors such as chromates or nitrites have been mixed with deicing salts to reduce corrosion of automobiles. Various organic and inorganic compounds have been added to cement mixes to inhibit the corrosion of the reinforcing steel (15, 16, 17).

Selected inhibitors have been studied in this work and were first subjected to screening experiments in the porous
METHODS FOR REDUCING CORROSION OF REINFORCING STEEL

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION
OF STATE HIGHWAY OFFICIALS IN COOPERATION
WITH THE BUREAU OF PUBLIC ROADS

SUBJECT CLASSIFICATION
GENERAL MATERIALS
MAINTENANCE, GENERAL
Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Commerce.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U.S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway Officials.

This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the research plan. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

The opinions and conclusions expressed or implied in these reports are those of the research agencies that performed the research. They are not necessarily those of the Highway Research Board, the National Academy of Sciences, the Bureau of Public Roads, the American Association of State Highway Officials, nor of the individual states participating in the Program.

NCHRP Project 6-4 FY '63
NAS-NRC Publication 1222
Library of Congress Catalog Card Number: 66-61520
Corrosion of reinforcing steel is a problem of ever-increasing magnitude. This report will be of interest to both maintenance and materials engineers because it contains the results of research into the relative effectiveness of various methods and materials for reducing corrosion. Determinations have been made of the factors responsible for corrosion, and the fundamentals have been examined for an understanding of the principles involved so as to arrive at potential corrective measures.

Corrosion of reinforcing steel is known to have contributed to the deterioration of some highway structures. This process occurs because corrosion environments develop within the region of the reinforcement due to several recognized causes, a major one being the penetration of chloride solutions into the structure and eventual contact with the reinforcement. Because deicing salts are extensively used in snow and ice control, serious and costly structure deterioration may continue to be a problem as it is not anticipated that this use will diminish in the foreseeable future. Although it is acknowledged that corrosion is not a serious problem when the integrity of the concrete surrounding the steel is maintained, it has been found extremely difficult to achieve such a condition in actual practice. Thus, while other research is concerned with the development of effective and economical deicing agents to replace chlorides, a parallel need has existed for a study of existing knowledge of methods for reducing corrosion of reinforcing steel and subsequent determination of the relative effectiveness and costs of various methods and materials.

The Battelle Memorial Institute approached this problem by first determining the factors responsible for corrosion of reinforcing steel and then, on the basis of the principles involved, investigating the potential of materials and methods. Following a state-of-the-art survey, the problem was principally attacked by a laboratory investigation based on electrochemical studies. Past experience indicated the likelihood that an investigation of electrochemical reactions associated with a given corrosion process could be expected to provide fundamental knowledge concerning the processes and the relative influence of various factors. It was conjectured that corrosion resulted from the interactions between different galvanic cells, and investigations were made of corrosion inhibitors to be added to deicing salts, metallic and nonmetallic coatings for the reinforcement, and cathodic methods of protection. Conclusions have been drawn concerning the most promising candidates, and recommendations have been made for field testing.

This document constitutes a final report on the research. Although a total solution to the problem of reducing corrosion has not been achieved, the reported material is of considerable value in that a narrow field of readily available candidates...
for reducing corrosion has resulted. The concept of pursuing the research further in either the field or laboratory is therefore well within the range of practicability for those who might be so inclined. It is felt, however, that any future experimentation with the recommended materials should principally be performed in the field under conditions representative of current highway practice.
CONTENTS

1 SUMMARY

3 CHAPTER ONE Introduction and Research Approach
   Discussion of Problem
   Research Approach

4 CHAPTER TWO Experimental Results and Discussion
   Cell Design
   Studies of Factors Influencing Corrosion in Reinforcing Rods
   Inhibitors
   Metallic Coatings
   Cathodic Protection
   Nonmetallic Coatings
   Protection of Reinforcing Steel in Prestressed Concrete

18 CHAPTER THREE Conclusions and Recommendations

19 REFERENCES

20 APPENDIX A An Introduction to Some of the Concepts of Electrochemical Corrosion as They Apply to Corrosion of Reinforcing Rods

21 APPENDIX B Materials Used, Preparation of Specimens, and Description of Apparatus
FIGURES

4 Figure 1. Sand-diaphragm cell.
4 Figure 2. Steel-concrete cell.
5 Figure 3. Porous Alundum-tube cell.
5 Figure 4. Cell for static potential and conductivity measurements.
7 Figure 5. Effect of cathode/anode area ratio on effectiveness of inhibitor.
8 Figure 6. Static electrode potentials and resistance values for concreted specimens with no inhibitor and immersed in 3½ % NaCl solution.
8 Figure 7. Static electrode potentials and resistance values for concreted specimens with chromate inhibitor and immersed in 3½ % NaCl solution.
9 Figure 8. Static electrode potentials and resistance values for concreted specimens with nitrite inhibitor and immersed in 3½ % NaCl solution.
12 Figure 9. Potentiometric curves for uncoated reinforcing steel in 3½ % NaCl solution saturated with Ca(OH)₂.
13 Figure 10. Theoretically derived current-voltage curves for uncoated reinforcing steel in 3½ % NaCl solution saturated with Ca(OH)₂.
13 Figure 11. Potentiodynamic curves for zinc-coated and nickel-coated reinforcing rod in 3½ % NaCl solution saturated with Ca(OH)₂.
14 Figure 12. Potentiodynamic curves for zinc-coated, nickel-coated, and uncoated reinforcing steel with concrete cover and immersed in 3½ % NaCl solution, showing type of control at various currents and potentials.
14 Figure 13. Potentiodynamic curves for zinc-coated, nickel-coated, and uncoated reinforcing steel with concrete cover, immersed in 3½ % NaCl solution, and based on estimated true metal area.
16 Figure 14. Static electrode potentials and resistance values for concreted specimens with asphalt coating and immersed in 3½ % NaCl solution.
17 Figure 15. Static electrode potentials and resistance values for concreted specimens with asphalt-epoxy coating and immersed in 3½ % NaCl solution.
21 Figure A-1. Schematic diagram showing anodic and cathodic reactions in a corrosion cell.

TABLES

5 Table 1. Results of Porous-Cell Studies with 10% NaCl Solution.
7 Table 2. Effect of Selected Inorganic Corrosion Inhibitors on Corrosion Current in Differential-Aeration Cells.
7 Table 3. Effect of Selected Inorganic Corrosion Inhibitors on Corrosion Current in Cells with Both Electrodes Aerated and Having Different Surface Conditions.
10 Table 4. Degree of Corrosion as Estimated from Corrosion Currents Measured in Cells Containing Various Metal Couples in 3½ % NaCl Solution Saturated with Ca(OH)₂.
11 Table 5. Corrosion of Zinc Coatings on Reinforcing Steel in Various Simulated Environmental Conditions after 6 Months' Exposure.
The information presented in this report will be very useful to highway planners, traffic engineers, and highway design engineers. The travel patterns studied for commercial airports, for regional shopping centers, and for major industrial sites will be of particular interest to those concerned with existing problems related to these three land uses as well as expected problems created by newly planned facilities and the proposed expansion of existing developments. These travel pattern studies include analyses of trip generation, trip distribution, and general trip characteristics which deal with mode and purpose of travel.

This research was initiated to determine the criteria or values which establish the travel patterns created by various major traffic generators. Such information is useful (a) in forecasting the effects of the various land uses on existing street networks, (b) in providing a better basis for design of new facilities, and (c) in providing better criteria for the control of various land uses.

The initial project specified the study of airports, shopping centers, and industrial areas in the cities of more than 50,000 population. The nature of the relationships between travel patterns and the various characteristics of the traffic generator, the transportation network, and the contributory area are evaluated for these three types of land use.

The researchers took advantage of travel data already collected for 15 transportation studies in different parts of the United States. The results reported are derived from the study of 12 commercial airports, 28 shopping centers, and 51 industrial plants, along with their related socio-economic, land use, and street system characteristics. The advantages and limitations of using transportation study data are carefully explained in the report.

Multiple regression analyses have been conducted for each of the three land uses studied in an effort to develop better predictive techniques. The results from these analytical computations are presented in the appendices, together with comparisons of travel data for similar land uses from studies not used in their derivation.

It is expected that the information presented on the use of different modes, for several trip purposes, by various time periods, will be most helpful to understanding the traffic situation created by the three types of land use. Although wide variations were found to exist between similar types of traffic generators, useful information is presented to help the engineer and planner understand the problems that may exist or that can be expected to occur. Various trends in pattern development are noted to assist the planner in predicting future travel characteristics.

An annotated bibliography highlights the most valuable literature found on
the traffic generation and travel patterns at airports, shopping centers, and industrial developments. This will be of particular interest to researchers, planners, and engineers who may wish to study in greater depth the effects of these traffic generators.

The agency is continuing the research into its next phase, which will include travel patterns for major office buildings, universities and colleges, hospitals, and state capitol complexes.
Figure 10. Theoretically derived current-voltage curves for uncoated reinforcing steel in 3½% NaCl solution saturated with Ca(OH)₂.

Figure 11. Potentiodynamic curves for zinc-coated and nickel-coated reinforcing rod in 3½% NaCl solution saturated with Ca(OH)₂.
Figure 12. Potentiodynamic curves for zinc-coated, nickel-coated, and uncoated reinforcing steel with concrete cover and immersed in 3½% NaCl solution, showing type of control at various currents and potentials.

These high currents were not resistance controlled because ions were initially available at the metal-concrete interface (Transient condition - not steady state).

![Potential Versus SCE, volts diagram](chart1)

Figure 13. Potentiodynamic curves for zinc-coated, nickel-coated, and uncoated reinforcing steel with concrete cover, immersed in 3½% NaCl solution, and based on estimated true metal area.
NICKEL-PLATED SPECIMEN IN 3½ % NaCl SOLUTION SATURATED WITH Ca(OH)$_2$

The results are shown in Figure 11. The specimen did not show corrosion. The cathodic portion of the curve shows that concentration polarization occurs; that is, the concentration of some reactant limits the cathodic current.

Possible reactions which can cause a limiting current are:

$$2H^+ + 2e → H_2 \quad (5)$$

$$O_2 + 2H_2O + 4e → 4OH^- \quad (3)$$

$$Ni(OH)_2 + 2e → Ni + 2OH^- \quad (6)$$

$$Ca(OH)_2 + ½O_2 + 2e → CaO + 2(OH)^- \quad (7)$$

Only the last two reactions are in the proper potential range. The Ni(OH)$_2$ reaction would use up the available reactant and the current would go to zero rather than create a limiting current. The final reaction appears to be the most logical. The anodic reaction may be controlled by the rate of diffusion of Ni$^{++}$ through an oxide film. In any event, the rate at which nickel dissolves anodically is slow, as shown by the relatively low current density (about 0.5 $\mu$A/sq cm compared to about 100 $\mu$A/sq cm for iron). When iron and nickel are coupled and immersed in 3½ % NaCl solution saturated with Ca(OH)$_2$, one would predict from Figures 9, 10, and 11 that the potential of the couple would be such that the iron would be held in a somewhat passive range (between −0.4 and −0.6 as shown in Fig. 9). In the experiments with galvanic couples described earlier, where the nickel area was about six times that of the iron area, the potential was within these limits and the corrosion rate was slow. This agrees with predictions based on the potentiodynamic studies.

INTERPRETATION OF POLARIZATION DATA FOR SERVICE

The polarization data obtained by potentiodynamic techniques using uncedmented specimens show that nickel becomes passive at a much lower current density than zinc. Accordingly, it would be expected to corrode at a much lower rate. Zinc will provide sacrificial protection to iron over the complete pH range; nickel does not give sacrificial protection to iron at all. There is some indication from this work that nickel can give anodic protection to iron in alkaline media. When nickel is coupled with iron the resultant cell potential may be in the range where iron becomes anodically passivated by the formation of a protective oxide film.

The resistance of the concrete was the major controlling factor in the experiments with concrete-coated specimens. Both the uncoated and the nickel-coated bars did show unmistakable reaction polarization, indicating that the electrochemical reactions observed in uncoated specimens were not entirely impeded by the concrete. The strong resistance control on the anodic side of Figure 12 emphasizes the
Figure 14. Static electrode potentials and resistance values for concreted specimens with asphalt coating and immersed in 3½% NaCl solution

CATHODIC PROTECTION

Cathodic protection is a widely used method for reducing corrosion to minimum values. It has been used to protect buried structures such as pipelines, and finds application in marine environments where, for example, ships' hulls and buoys require protection.

Essentially, this method consists of making a metal cathodic, so that it will not dissolve. This can be accomplished either by applying a current from a rectifier using inert anodes or by connecting the metal to sacrificial anodes and forming a galvanic system which generates its own current. The use of zinc coatings is a special case of this second type of cathodic protection.

Cathodic protection is easily applied in a laboratory setup, where it can usually be made to function with near 100% efficiency. In the field, however, it is much more difficult to achieve. Accordingly, in this work no laboratory experiments were attempted to develop a practical technique for cathodically protecting reinforcing bars.

One of the problems associated with cathodic protection is the difficulty in attaining a fairly uniform protective current and potential over the entire system. Variations in resistance throughout the system, for example, can cause variations in current that may result in inadequate protection for parts of a structure. If the current-potential relation is such that hydrogen is accidentally produced, the bond may be impaired; or, in the case of prestressed concrete, catastrophic failure may occur as a result of stress-corrosion cracking or hydrogen embrittlement of the steel wires.

Stratfull (24) applied cathodic protection to the reinforced concrete bridge beam and deck units of the 7-mile San Mateo-Hayward bridge. He used carbon anodes, and to insure good electrical contact with the concrete he surrounded the anodes with a backfill consisting of a slurry of 1 part by volume of raw gypsum, 4 parts steam-exploded mica, and approximately ½ part calcium chloride. After about 1 year the system appeared to be working effectively.

It is to be emphasized that each application of cathodic protection must be done on a "made-to-order" basis. Even adjacent sections of highway may require entirely different current-potential values because of differences in concrete characteristics.

The investigators' belief at the present time is that in seeking ways to protect reinforcing steel the initial emphasis should be on a self-regulating system such as a coating. However, for existing highways and bridges cathodic protection is probably the only way to mitigate corrosion. In such applications each case is a separate research project.
NONMETALLIC COATINGS

A variety of nonmetallic coatings has been applied to reinforcing steel in attempts to minimize its corrosion. These vary from dense cement mortar to the more sophisticated resin coatings (25, 26, 27, 28, 29, 30). All of the coatings are reported to reduce corrosion in varying degrees.

The nonmetallic coatings fall into the class of “barrier coatings,” so-called because they protect by keeping the corrosive agent away from the steel. If a break occurs in the coating, corrosion will, of course, occur.

Two materials representative of the bituminous-type coatings were selected for study. The first of these is a gilsonite-bearing paint* and the second is an asphalt-epoxy coating.\(^\dagger\) Gilsonite is a natural asphalt and is a very inert material. Both coatings were applied, by dipping, to sandblasted reinforcing rods. The coatings were approximately 10 mils thick. Both sets were air dried for several days, after which some from each group were made up into standard cemented specimens, as described in Appendix B.

The relative porosities of the coatings were estimated by using noncemented specimens. These were immersed in 3½% NaCl solution and the electrical resistance was measured with a platinum electrode and an a-c bridge. The resistance values given here can only be used to compare the two coatings under the conditions as described and are not to be used in comparison with the concreted specimens, for example. The gilsonite coating reached a resistance value of 18 ohms in less than 24 hr and remained at that value thereafter. The resistance of the asphalt-epoxy coating started at 500 ohms, went to a maximum of 1,300 ohms in 43 hr, then started a slow decrease, reaching 150 ohms in 84 days. Visual examination of the specimens showed voluminous rust accumulation at numerous pore sites in the gilsonite enamel and only a few minor rust spots on the asphalt-epoxy coating. It appears that the asphalt-epoxy coating is the better coating and that thinner coatings might prove effective. The static potential values were constant at about -600 mv with reference to the saturated calomel electrode. This is about 100 mv more noble than for the uncoated reinforcing steel in sodium chloride solutions and may indicate some passivating effect on the part of the coating.

The group of reinforcing rod specimens which were coated with asphalt or asphalt-epoxy and then with concrete were exposed to 3½% NaCl solution for 145 days. The results are shown in Figures 14 and 15. In less than 48 hr the electrical resistance between two asphalt-coated and cemented specimens dropped from 12,500 ohms to 130 ohms and stayed close to this value for the duration of the period. This is about the same resistance as observed with the standard uncoated specimens. The asphalt-epoxy-coated and concreted specimens had a resistance of 3,000 ohms after 145 days. In terms of behaving as an efficient barrier coating, the asphalt-epoxy coating appears superior. After 145 days the potentials of the asphalt-epoxy-coated and concreted specimens were 50 to 90 mv more noble than the asphalt-coated and concreted speci-

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* Gilso, manufactured by The Dean and Barry Co., Columbus, Ohio.
mens. This may indicate some inhibitive effect by the presence of small amounts of material dissolved from the coating. In experiments in which the coating was cut through so as to expose the steel, rust developed very slowly on the specimens in 3.5% NaCl solution.

Studies have been made of the effect of epoxy coatings on the strength of bond between reinforcement and concrete. The bond is at least as good as for uncoated reinforcing rods (6).

Some attempts were made to devise a silicate coating that would be compatible with cement mortar. It was hoped that a silicate coating would, in addition to forming a barrier, inhibit corrosion by providing small amounts of soluble silicates.

Starting with dilute commercial soluble sodium silicate solutions, various additions were made to form insoluble coatings. After hardening, these were then immersed in saturated Ca(OH)$_2$ solution to determine whether or not they would soften quickly at the pH of wet cement. Most of the coatings softened rapidly. One coating made by adding fluosilicate to sodium silicate held up fairly well. However, no coating was found which appeared satisfactory.

**PROTECTION OF REINFORCING STEEL IN PRESTRESSED CONCRETE**

In recent years the use of prestressed concrete sections has increased. This type of structure poses a somewhat different problem insofar as the corrosion of the reinforcing steel is concerned. The reinforcing steels used in prestressed concrete are of the high-strength type having ultimate strengths which may be in excess of 250,000 psi and are stressed initially up to 70% of this strength (28). In processing the wire to be used in prestressed concrete, a stress-relieving step is included to minimize the probability of occurrence of the phenomenon known as stress-corrosion cracking (SCC). SCC results in catastrophic failure of many metals because of cracks which go all the way through the steel in a direction normal to the applied stress. Failure takes place in high-strength steels which are highly stressed. The time required for failure varies, but is proportional to the stress applied.

After some years of studying the role of hydrogen in SCC at Battelle, it is certain that the presence of hydrogen is an important factor in causing SCC. Chlorides in contact with the steel also have a strong influence in inducing this phenomenon.

In the case where deicing salts are used on a prestressed concrete structure, the presence of chloride is accounted for. Hydrogen can be produced by certain cathodic corrosion reactions. In attempting to protect the steel with zinc coating, one may not get away from a hydrogen-producing situation. Bird (29) has shown that where a zinc coating is ruptured, a couple is formed and hydrogen is produced at the cathode, which in this case is the steel. These results have been duplicated in this research with the production of small amounts of hydrogen. Actually, only very small amounts are required for a SCC mechanism.

Accordingly, zinc coating may not be the answer to the problem of protecting high-strength prestressed reinforcing steel. If nickel is used as the coating material and a nickel-steel couple is formed, the nickel is the cathode; if hydrogen is produced it will collect on the nickel. However, in such a couple the nickel touches the steel, and it is conceivable that hydrogen can diffuse a short distance to the steel. All that can be said at this time is that prestressed concrete presents a potential source for SCC and other types of corrosion (30), and devising a means of protection would require further research.

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**CHAPTER THREE**

**CONCLUSIONS AND RECOMMENDATIONS**

The experimental investigation described in this report has shown that the corrosion of steel within a steel-concrete composite stems from a multiplicity of electrochemical cells. For economy and ease of construction it is desirable to have a single method to counteract these many forces which cause the corrosion. It has been concluded that for new reinforced concrete construction a protective coating is the best single means for keeping steel from corroding. Zinc, nickel, or an asphalt-epoxy appear suitable as potential coating materials.

It is recommended that limited field tests be made of these materials. This should be done in an area where heavy salting of the highway for long periods is the normal winter practice. The coatings should be compared with each other and with uncoated steel. The concreting must be carefully supervised so that it is uniform for all reinforcing under test and so that no variables are introduced which in themselves would be responsible for spurious results. All sections should have a uniform flow of vehicular traffic.

It is believed that such a test would serve better than additional laboratory tests in demonstrating which of the
recommended coatings is best suited to current highway practice from the standpoint of both corrosion control and economics.

The use of the previously recommended coatings will involve an increase in the cost of highway construction. Therefore, some estimates are given here purely for guidance, the increased cost for the nickel coating would forcing steel accounts for 5% of the total cost of highway per lb for uncoated bars. Assuming that the cost of reinforcing steel accounts for 5% of the total cost of highway construction, the increased cost for the nickel coating would add 1.65% to the total cost. If the coating added 50% to the life of the structure, this, of course, would be a good investment.

Hot-dip galvanizing, which would give a 2-mil-thick minimum zinc coating, would cost about $0.118 per lb as compared with $0.11 per lb for the uncoated steel, thus adding 0.44% to the over-all cost.

The cost for coating the rods with 10 mils of asphalt-epoxy would lie somewhere between the costs for nickel and zinc.

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REFERENCES

26. VAN OETEREN, K. A., “Should the Embedded Parts of


APPENDIX A

AN INTRODUCTION TO SOME OF THE CONCEPTS OF ELECTROCHEMICAL CORROSION AS THEY APPLY TO CORROSION OF REINFORCING RODS

It is generally conceded that the ordinary corrosion observed is electrochemical in nature, the electrochemical corrosion cell being analogous to the common carbon-zinc “dry” cell. It has the same basic components and it produces electricity at the expense of some metal (e.g., zinc in the familiar dry cell), which dissolves as the reaction proceeds.

To illustrate, consider a cell consisting of an iron rod and a copper rod, each dipping into the same aqueous solution of sodium chloride (Fig. A-1). The NaCl solution is called the cell electrolyte. If a high-resistance voltmeter is connected across the iron and copper electrodes, a difference of potential is observed, with the iron being the negative electrode and the copper being the positive electrode. This is said to be an open-circuit measurement. When the electrodes are connected by an external metal conductor, a current will flow as a result of the potential difference. In the electrolyte the current is carried by the positively charged sodium ions (Na⁺) and the negatively charged chloride ions (Cl⁻). If the solution is acidic, hydrogen ions (H⁺) will act as very mobile conductors. The iron dissolves according to

\[ \text{Fe} \rightarrow \text{Fe}^{++} + 2\text{e}^- \quad \text{(A-1)} \]

The electrode which dissolves is called the anode and the reaction occurring at the anode is termed oxidation. The electrons formed as a result of the iron dissolution are given up to the anode and give it a negative charge. These electrons travel via the external conductor to the nondissolving copper electrode, called the cathode, and are accepted there, provided that some reaction is taking place in which the electrons can be used. Such a reaction is called reduction. The reaction might be the reduction of hydrogen ions to hydrogen gas, as in

\[ 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2 \quad \text{(gas)} \quad \text{(A-2)} \]

If there is no possible reaction in which electrons can be used, the cells stop functioning. The greater the current, the more metal will dissolve in a given time. Therefore, it is desirable to keep the corrosion current to a minimum, or if possible to reduce it to zero.

A difference of potential can exist between two electrodes of the same metal if the separate solutions surrounding the electrodes are of different compositions, and the solutions make contact with each other. Such is the case with reinforcing rods imbedded in concrete; an example might be two parallel iron reinforcing rods imbedded in a concrete highway. These are the electrodes, connected electrically by a third rod at right angles to and in contact with them. If one of the parallel rods is in a dense concrete of low permeability, while the second rod is in a much more permeable concrete, the combined effects of weather and the application of deicing salts on this section of highway complete the cell by the presence of an electrolyte. In addition, air can diffuse easily to one rod and only with difficulty to the second. A potential difference is set up with the less easily aerated electrode being the anode, which dissolves in accordance with Eq. A-1. The cathode reaction involves...
the reduction of oxygen, possibly to form hydroxyl ions, in accordance with
\[
\frac{1}{2} \text{O}_2 + \text{H}_2\text{O} + 2e^- \rightarrow 2 \text{OH}^-
\] (A-2)
The hydroxyl ions can react with the Fe^{2+} ions to form Fe(OH)_3, which in the presence of air will oxidize to Fe(OH)_3 or FeO(OH), the familiar red rust.

The flow of current produces changes at one or both electrodes which result in changes in the potential. This is called polarization. Actually, polarization may be so severe as to stifle the current. This phenomenon, then, is an important one and if managed can help to control corrosion.

If polarization occurs equally at both anode and cathode, the corrosion is said to be under mixed control. If anodic polarization predominates, the corrosion is under anodic control. Cathodic control is also possible.

If one merely measures the potential difference (voltage) between the anode and cathode he cannot tell to what extent each electrode is polarizing. To determine this, the measurements are made with a reference electrode whose potential is constant.

The potential between this reference electrode and the anode and then the cathode is measured. Thus, it is possible to study individual electrode behavior. The reference electrode used in this work is the saturated calomel electrode (SCE).

By observing polarization behavior of the corrosion cell under widely varying conditions, the corrosion engineer or scientist is able to choose methods by which corrosion will be minimized or prevented.

For example, he may find that a certain condition promotes severe polarization at an extremely low current. He then has a clue as to what conditions should be set up to inhibit corrosion.

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**APPENDIX B**

**MATERIALS USED, PREPARATION OF SPECIMENS, AND DESCRIPTION OF APPARATUS**

**REINFORCING BAR**
The reinforcing bar used for preparing specimens for this work was procured from a local commercial outlet. The bar was of the deformed type, \( \frac{3}{4} \)-in. diameter, and was received in 4-ft lengths. It was sawed into whatever lengths were necessary for the preparation of specimens. The bars had the typical coating of mill scale with occasional spots of red rust.

**REINFORCING BAR SPECIMENS**
The specimens as prepared varied in length from 2 to 6 in. A hole, tapped for a \( \frac{1}{4} \)-20 thread, was machined in the center of one end of each specimen. A \( \frac{1}{4} \)-20 threaded rod was screwed into the reinforcing bar specimen, thus providing a supporting member and an electrical connection.

For the experiments where the effect of mill scale was studied, the sawed ends which had bare steel exposed were "stopped off" with Glyptal* lacquer.

For much of the work 2-in. long specimens were used. Where these were to be coated the mill scale was removed by sand- or vaporblasting. Prior to nickel or zinc coating the specimens were also acid dipped to remove residual scale.

**CONCRETED SPECIMENS**
Aside from the very early and little used concrete block cell, the concreted specimens were made using the 2-in. long reinforcing bar sections, each having a 6-in. long \( \frac{1}{4} \)-20 threaded rod screwed into them.

The cement mix used to encase the specimens had the following composition:

*General Electric Co., Schenectady, N. Y.*
Portland cement 125 grams
Washed sand (+100 mesh) 375 grams
Distilled water 65 ml

Polyethylene bottles, cut off at the shoulder so as to have a wide opening at one end, served as forms. The specimens were prepared by placing a ⅛-in. layer of cement mix on the bottom of the form, which rested on a vibrating table, setting the rod in the center of the form and then placing cement mix around the rod until the form was filled. Finally, the cement in the top was smoothed off with a spatula. The specimens were covered with several layers of damp towels overnight. By the following day the cement had hardened and the polyethylene forms were removed by slicing with a knife. The specimens were placed in a fog chamber and cured for 7 to 11 days. The resulting specimen was 1 ½ in. in diameter and 2 ½ in. high.

Specimens so made are referred to as “standard concreted specimens.”

ELECTROCHEMICAL MEASURING APPARATUS

The following paragraphs contain short descriptions of the apparatus used for the electrochemical measurements.

Reference Cells
Saturated calomel type. Beckman No. 39970, fiber-junction type. (Beckman Instruments, Fullerton, Calif.)

Potential Measurements
A standard line-operated pH meter is adequate for this purpose. Potential differences up to 1,400 mv can be read with these instruments. If it is desired to extend the range, it can be done by using a mercury cell (about 1.35 v) in the external circuit. A Leeds and Northrup model 7041 meter was used in this work. (Leeds and Northrup, Philadelphia, Pa.)

Zero-Resistance Ammeter
In measuring the current output of a laboratory corrosion cell it is desirable to know the true short-circuit current which flows. If an ammeter is used directly for this purpose, it introduces some resistance into the circuit, and the measured current is less than the short-circuit current. The so-called zero-resistance ammeter as described by Mears and Brown (34, 35, 36) overcomes this difficulty and was used to measure the true short-circuit current of the cells in this work. Essentially, it consists of a galvanometer, a dry cell, some variable resistances, and an ammeter (micro- or milliammeter, depending on the range in which the measurements are to be made). The instrument used for this work was assembled in this laboratory.

Potentiostatic Controller
For some of the polarization measurements in which potential was measured as a function of current, a potentiostatic controller was used. The Model 4100 manufactured by Anatrol, Ponca City, Okla., was used. The currents were recorded on a Bausch and Lomb V.O.M. -5 strip-chart recorder, and the potentials were measured with the pH meter previously described. The Anatrol controller scans the potential range desired automatically.

Conductivity Measurements
Conductivity measurements were made by using a model RC16B2 conductivity bridge manufactured by Industrial Instruments, Cedar Grove, N. J. This bridge utilizes a 1,000-cycle, alternating, sine wave current. In this way polarization effects are virtually absent and the measurements are less subject to error.

ESTIMATION OF TRUE SURFACE AREA OF REINFORCING BAR SPECIMENS BY AN ELECTROCHEMICAL METHOD

During the polarization study of a nickel-coated specimen it was observed that in the potential range between —0.700 v and —0.900 v (see Fig. 11) the current was quite constant. This limiting current is the result of a concentration polarization, probably involving oxygen. Because of this constant-current phenomenon, it is possible to compare the current on an unknown surface area (reinforcing bar specimen) with that of a known nickel surface area (flat polished electrode) with both electrodes in the same potential region. The ratio of the currents multiplied by the known area gives the unknown area. For a nickel-coated reinforcing bar section 1.9 cm in diameter and 5.08 cm long, the area was estimated to be 45.4 sq cm, larger than the apparent area of 36 sq cm by a factor of 1.25.

It was assumed that the uncoated iron specimens and the zinc-coated specimens had the same surface area as the nickel-coated specimen.
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