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DEPARTMENT OF TRANSPORTATION
Bureau of Materials and Physical Research

EVALUATION OF LONGITUDINAL STEEL IN ILLINOIS CRC PAVEMENTS

by

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in cooperation with
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16. Abstract

A follow-up investigation was made of several CRC pavements constructed within Illinois to determine the extent of corrosion occurring on the longitudinal reinforcement at transverse cracks. The effect of crack width, depth of reinforcement, slab thickness, type of reinforcement, infiltration of water and foreign matter, bond between concrete and steel, and D-cracking were studied to determine their influence on the progression of corrosion. The initial investigation was carried out during 1970. During the present study an analysis was made of 147 cores removed from 12 experimental pavements throughout the State for an intensive study on the behavior of a variety of CRC pavement designs.

Of the cores removed from the experimental pavements, 42.2 percent showed no evidence of active steel corrosion, 52.4 percent indicated slight pitting to moderate pitting and 5.4 percent showed advanced rusting with a marked reduction in cross-sectional area or fracture of the reinforcing steel. The findings indicate that steel corrosion has progressed with the passage of time (from 1970 to 1979) but, at this stage, its effect on the pavement performance is minimal and the steel does not appear to be a potential problem with pavements designed in accordance with the present criteria. Of the parameters investigated, crack width and depth of reinforcing steel appear to be the only significant factors influencing the progression of corrosion.

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INTRODUCTION

Continuously reinforced pavements, by nature, develop stress-relieving transverse cracks at frequent intervals. The longitudinal steel reinforcement keeps the cracks tightly closed, maintains the integrity of the structure for load transfer, and retards the entrance of water with dissolved salt or other corrosion-promoting solutes into the pavement substructure. Deicing salts, in solution, which penetrate into the pavement structure through cracks have been associated with harmful corrosion of the reinforcing steel, thereby weakening the steel and increasing probability of early pavement failure. In 1970, a study conducted by the Illinois Department of Transportation, in cooperation with the U. S. Department of Transportation, Federal Highway Administration(1), on pavements that were 4 to 7 years of age, revealed that about 49 percent of the cores that were examined had no trace of steel corrosion, 50 percent had slight-to-moderate corrosion, and only one percent were in a state of advanced corrosion. Among those that were selected for study, crack width was found to be the only parameter that was clearly associated with the observed amounts of corrosion, but tests on core samples in the laboratory showed that water was able to permeate all cracks at least to the steel depth. Some discoloration was noted at all cracks. The findings of the 1970 study were interpreted to indicate that corrosion of the longitudinal steel was not likely to be a potential problem with existent CRC pavements that were designed in accordance with modern criteria, but that a definite conclusion based on all information that was presently available would be premature, and it was recommended that a similar investigation be conducted after passage of another like time period to confirm or to revise the findings.

This report contains the results of a follow-up study which was conducted in 1979. The condition of the longitudinal reinforcement at transverse cracks was reexamined by conducting another coring program. These pavements were 13 to 16 years old at the time of the reinvestigation. The major objective of this study is to determine the extent of steel corrosion at the transverse cracks and whether this corrosion is affecting the serviceability of the CRC pavements in Illinois. A secondary objective of this study is to study the relation between crack width and the condition of the longitudinal steel with respect to corrosion at transverse cracks where surface crack-width measurements (by Whittemore gage) have been made.

This report comprises an evaluation of 147 cores removed from 12 experimental pavements constructed throughout the State between 1963 and 1966, 15 cores removed from the old Vandalia test pavement constructed in 1947 and 1948, and 18 cores removed from the experimental subbase pavements on US 36 near Springfield constructed in 1971. The 1979 findings indicate that a progression in steel corrosion since the 1970 study is evident, but the overall condition of the steel from these pavements, now 13 to 16 years old, appears to be satisfactory. No correlation was found between surface crack-width measurements (by Whittemore gage) and steel corrosion. Examinations of the crack interfaces in 1970 showed a marked discoloration plus the accumulation of soil fines in the cracks for all cores. The same is true in the 1979 study, only now the intrusion of foreign material, on the average, is greater. However, no signs of structural distress attributable to the intrusion of foreign material into the cracks were found.

STUDY DETAILS

The 1979 coring program was undertaken to obtain steel specimens to reveal the extent of corrosion that has occurred within the existing CRC pavements, and to attempt to further identify whether certain design and environmental factors associated with pavement behavior influence the progression of corrosion. The pavements investigated consisted of (1) the experimental CRC pavements, (2) the old Vandalia test pavement, and (3) the experimental subbase CRC pavements. The general location of each pavement investigated is shown in Figure 1.

Estimates of the total tonnages of salt applied per two-lane mile for these pavements are included in Table 1. These results are based on straight-line projected estimates from the 1970 study.

In 1979, a total of 150 cores were removed from the experimental pavements as compared to 151 cores in 1970. However, three steel specimens were lost during transit, leaving 147 samples for evaluation. These experimental pavements(2), constructed as part of research study IHR-36 and consisting of 12 projects located throughout the State, were constructed between 1963 and 1966 to obtain comprehensive information relative to the behavior and serviceability of CRC pavements. A listing of the test sites by location, with corresponding experimental features and number of cores removed from each section, is given in Table 2. Since the 1970 study, the 7-in. (178-mm) pavement in test site No. 10 has been overlaid and the 8-in. (203-mm) pavement with the fabric depth at 4 in. (102 mm) in test site No. 4 was removed and replaced due to a new traffic interchange with I-80; therefore, no core samples were recovered from these two pavements in 1979. However, 28 extra cores were removed at cracks where gage plugs had been installed, early in the pavement's life, to monitor change in crack width during seasonal changes. Cores were taken at these cracks

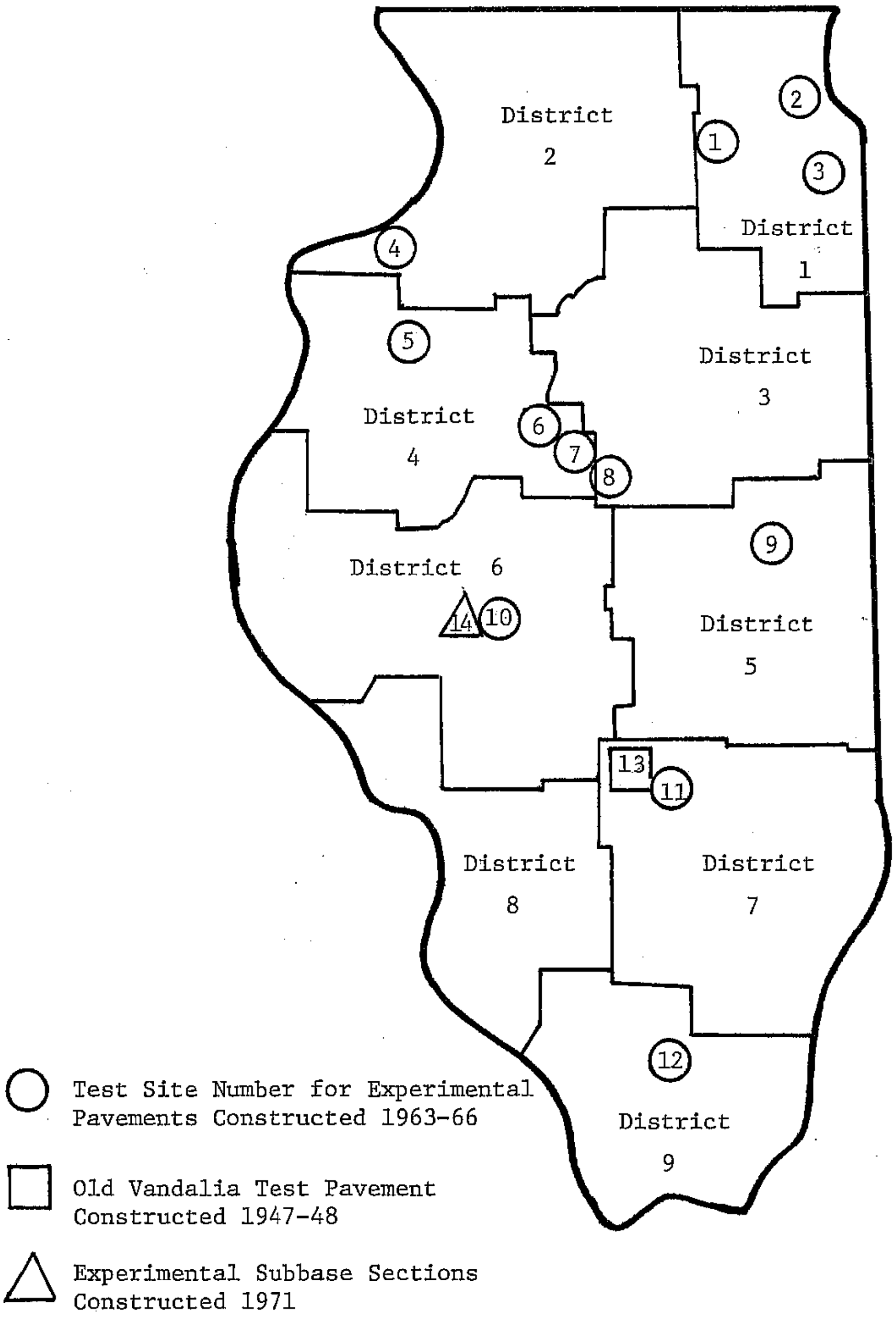


Figure 1. Location of pavements investigated

TABLE 1

ESTIMATED TONS OF SALT APPLIED TO PAVEMENTS

Test Site Number	District	Tons per 2-lane mile per year	Years Applied	Total Tons
1	1	18	15	270
2	1	72	16	1152
3	1	72	15	1080
4	2	4	15	60
5	4	10	15	150
6	4	10	14	140
7	4	10	13	130
8	3	10	13	130
9	5	8	14	112
10	6	4	13	52
11	7	7	16	112
12	9	6	14	84
13	7	7	30	210
14	6	4	8	32

TABLE 2

CORES REMOVED FROM EXPERIMENTAL PAVEMENTS
(total 147 cores)

Test Site Number	Route	Section Number	County	Year Built	Slab Thickness (in.)	Reinforcement Type	Reinforcement Depth (in.)	Number of Cores Same Crack	Number of Cores New Crack	Number of Cores At Gage	Number of Cores Total
1	FA 7	6R-1,5R	Kane	1964	6	bars	2	-	4	1	5
				1964	7	bars	2	-	4	2	6
2	FA 61	531-1	Cook	1963	8	bars	3	5	-	-	5
3	FAI 55	1314-638	Cook	1964	10	fabric	3.5	4	-	2	6
4	SBI 3	7R,7RB	Rock Island	1964	8	fabric	2	5	-	2	7
				1964	8	fabric	3	6	-	1	7
5	FAI 74	48-27	Knox	1964	7	bars	2	4	-	-	4
				1963	7	bars	3.5	3	1	1	5
				1963	7	fabric	3.5	6	-	1	7
6	FAI 74	90-16	Woodford	1965	7	bars	3	4	-	-	4
7	FAI 74	57-17	Woodford	1966	7	fabric	3	1	4	-	5
8	FAI 74	57-18	McLean	1966	7	bars	3	4	-	-	4
9	FAI 57	10-32	Champaign	1963	7	bars	3.5	5	2	3	10
				1963	8	bars	4	6	-	2	8
10	FA 196	2-1	Sangamon	1966	8	bars	2	3	1	-	4
				1966	8	bars	4	7	-	-	7
				1966	8	fabric	2	5	-	-	5
				1966	8	fabric	4	6	-	-	6
11	FAI 70	26-3,26-4	Fayette	1963	8	bars	2	4	-	3	7
				1963	8	bars	3	3	1	1	5
				1963	8	bars	4	6	1	3	10
12	FA 14	6-1	Williamson	1964	7	fabric	2	5	1	3	9
				1965	7	fabric	3.5	8	-	3	11
		TOTAL						100	19	28	147

Note: 1 inch = 25.4 mm

to study the relationship between surface crack width and the condition of the longitudinal steel with respect to corrosion at transverse cracks.

In addition to these experimental pavements, 15 cores were removed from the old Vandalia test pavement, built in 1947 and 1948, and 18 cores were removed from the experimental subbase section on US 36 near Springfield, constructed in 1971. The location and number of cores removed from these pavements are given in Table 3 and Table 4.

The variables selected to investigate the condition of the longitudinal steel are as follows:

(1) Transverse crack width - at steel level and at the pavement surface where gage plugs had been installed early in the pavement life.

(2) Depth of reinforcement - 2 in. (51 mm), 3 in. (76 mm), and mid-depth.

(3) Steel type - deformed bars and welded-wire fabric.

(4) Age - 13 to 16 years.

(5) Traffic-load applications - 0 to 24 million (18,000-lb. equivalent axle loads).

Sampling Procedure

All of the 1979 cores were taken directly over the reinforcing steel in the outer wheelpath of the traffic lane and, where possible, at the same transverse crack where the 1970 coring occurred. In those cases where it was impossible to core on the same transverse crack, an alternate similar crack was chosen. The location of the 1979 coring was adjusted to the inside or outside of the 1970 core hole, depending upon the position of the 1970 core hole, but remained within 14 in. (356 mm) to 45 in. (1143 mm) of the edge of the pavement where 90 percent of the truck wheel placements occur(3). To maintain the integrity

TABLE 3

CORES REMOVED FROM OLD VANDALIA PAVEMENT
(total 15 cores)

Test Site Number	Route	Section Number	County	Year Built	Slab Thickness (in.)	Reinforcement		Number of Cores			
						Type	Depth (in.)	Same Crack	New Crack	At Gage	Total
13	FA 12	0-2	Fayette	1947	7	bars 0.5%	3	3	-	-	3
				1947	7	bars 0.7%	3	4	-	-	4
				1948	8	bars 0.5%	3	4	-	-	4
				1948	8	bars 0.7%	3	4	-	-	4
		TOTAL						15	-	-	15

Note: 1 inch = 25.4 mm

TABLE 4

CORES REMOVED FROM THE EXPERIMENTAL SUBBASE PAVEMENTS
(total 18 cores)

Test Site Number	Route	Section Number	County	Year Built	Slab Thickness (in.)	Reinforcement		Subbase		Number of Cores			
						Type	Depth (in.)	Type	Depth (in.)	Same Crack	New Crack	At Gage	Total
14	FA 196	1	Sangamon	1971	8	bars	4	Lime	8	-	6	-	6
								BAM	4	-	6	-	6
								CAM	4	-	6	-	6
		TOTAL								-	18	-	18

Note: 1 inch = 25.4 mm

of the pavement and minimize localized distress, one longitudinal bar was left between the old and new cores in the steel bar sections, and one or two wires were skipped in the steel fabric sections. The location of the steel reinforcement was determined with the aid of a Pachometer. Crack-width measurements were taken immediately prior to coring with the Whittemore gage at cracks where gage plugs had been installed. The pavement was marked for coring, and photographs were taken of the surface width of the crack. The Bureau of Construction's coring rig cut a 4-in. (102-mm) core at each marked location. Each core was identified, labeled, and transported to the Physical Research Laboratory where core-thickness, crack-width, and steel-depth measurements were made. Each core was then opened to expose the condition of the steel reinforcement and the crack interfaces.

Corrosion Ratings

In preparing for the 1979 coring program, a considerable amount of time and effort were spent attempting to develop a corrosion-rating technique to provide more quantitative measurements of the corrosion and one that is less dependent upon the visual inspection system used during the 1970 study. Knowing that observations made by visual inspection may vary considerably from viewer to viewer, quantitative measurements were tried by attempting to measure the change in the weight of the recovered segment of reinforcing steel and by attempting to measure the variation of the diameter along the length of the corroded reinforcing steel. These methods of measurements were tried unsuccessfully on the first batch of 43 cores when they were retrieved from the pavement. Due to the variation in the lengths of the recovered reinforcing steel and the lack of a marked reduction of the cross-sectional area of the steel in those 43 cores, it became apparent that quantitative measurements were not feasible.

Therefore, even though it has its limitations, the subjective rating system based on the visual steel inspection was used. This system was developed during the planning of the 1970 coring program. The criteria used for classifying the steel reinforcement at that time was followed precisely in the 1979 program and are as follows:

Rating

1 - clear or free of rust
2 - slight rust with no appreciable reduction in cross-sectional area
3 - moderate rust with no substantial reduction in cross-sectional area
4 - heavy rust with a marked reduction in cross-sectional area

A typical sample representing each rating is shown in Figure 2. These samples are from the 1970 coring study and, after being coated with oil, have been kept in a plastic bag since that time to stop any further corrosion so they could be used as a standard for future studies. Among the four classifications, a rating of 4 is the only corrosive condition indicative of a marked reduction in the cross-sectional area of the steel, and the only rating expected to adversely affect the pavement performance. Corrosion associated with classifications 1 to 3 is considered minor, with no significant effect on the service life of the pavement.

The same rating panel, using the same rating criteria and the same rating samples, examined and rated the steel reinforcement both in 1970 and in 1979.

EXTENT OF CORROSION ON STEEL REINFORCEMENT

The following discussion covers the extent of corrosion on the steel reinforcement for each of the three types of pavements investigated, consisting of

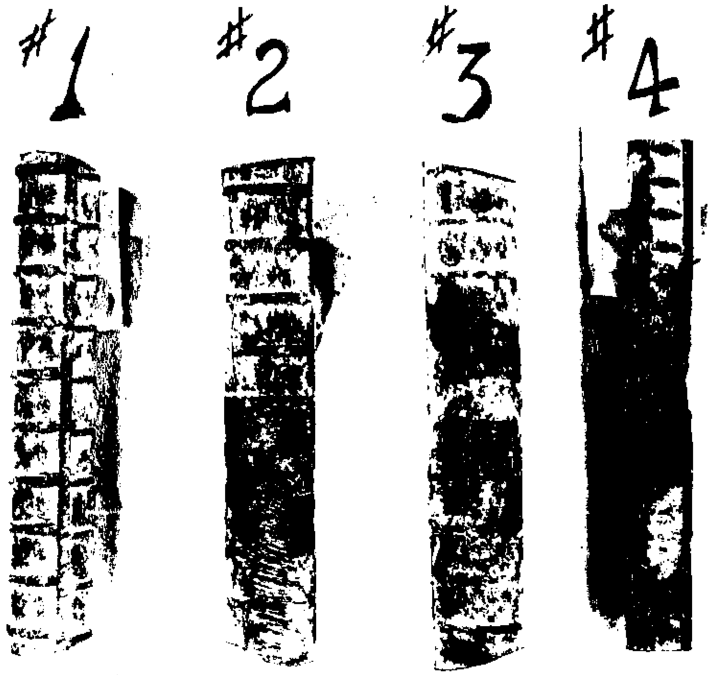


Figure 2. Typical samples representing each core rating

(1) the experimental CRC pavements, (2) the old Vandalia test pavement, and (3) the experimental subbase CRC pavement.

Experimental CRC Pavements

A comparison of the overall distribution of 1979 and 1970 cores, representing various degrees of corrosion of the reinforcement contained within the experimental CRC pavements (test sites 1 to 12) constructed between 1963 and 1966, is shown in Figure 3. At the time of the 1979 coring, the age of the experimental CRC pavements varied from 13 to 16 years, which represents from 65 to 80 percent of the normal 20-year design period before resurfacing is expected. Of the 147 steel specimens removed from the experimental pavements in 1979, 62 (42.2 percent) showed no evidence of corrosion (Rating 1), 53 (36.1 percent) indicated only slight rusting (Rating 2), 24 (16.3 percent) indicated moderate rusting (Rating 3), and 8 (5.4 percent) had evidence of advanced rusting with a marked reduction in the cross-sectional area (Rating 4). Out of these 8 specimens, 2 were fractured and 2 were severely corroded, reducing the cross-sectional area by one half. Of the 151 steel samples removed in 1970, 49 percent showed no evidence of corrosion, 40 percent had slight rusting, 10 percent indicated moderate rusting, and less than 1 percent showed advanced rusting. The progression in steel corrosion between 1970 and 1979 can be seen in this figure. As expected, the percent of specimens free of rust and having slight rusting (Ratings 1 and 2) was less in 1979 than in 1970, while the percent of specimens having moderate and advanced rusting (Ratings 3 and 4) was greater.

Of the 147 cores taken in 1979, 100 were recovered from the same transverse cracks as in 1970. The progression in steel corrosion on this one-to-one basis between 1970 and 1979 is shown in Figure 4. In 1979, 36 percent of the steel specimens were rated 1, 40 percent were rated 2, 18 percent were rated 3, and 6 percent were rated 4. In 1970, cores from these same cracks revealed

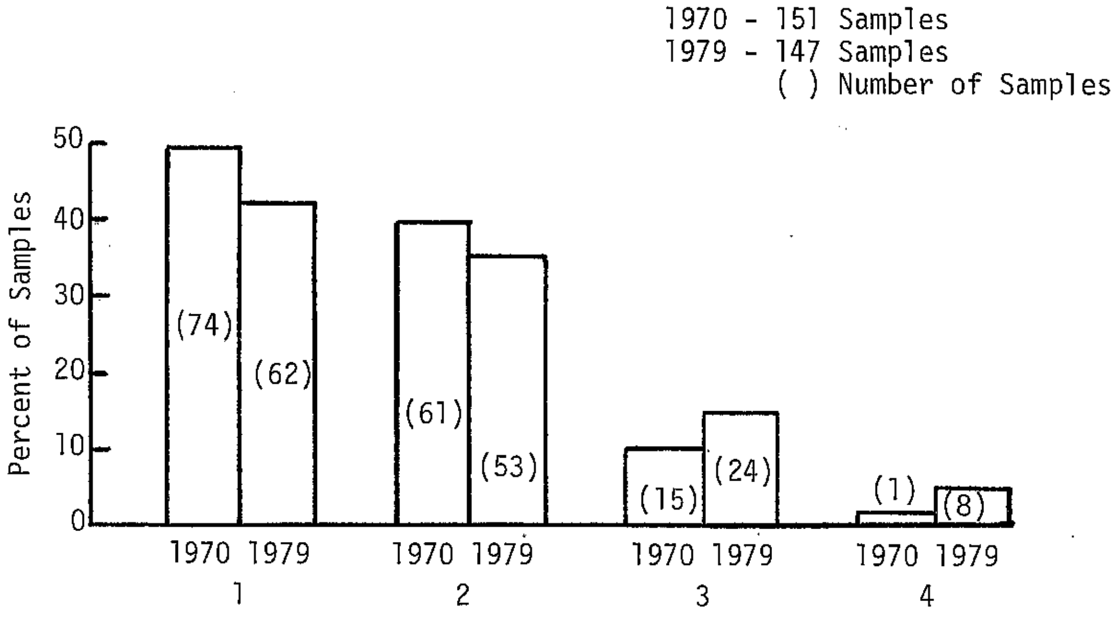


Figure 3. Distribution of steel samples versus corrosion ratings for the experimental pavements for years 1970 and 1979

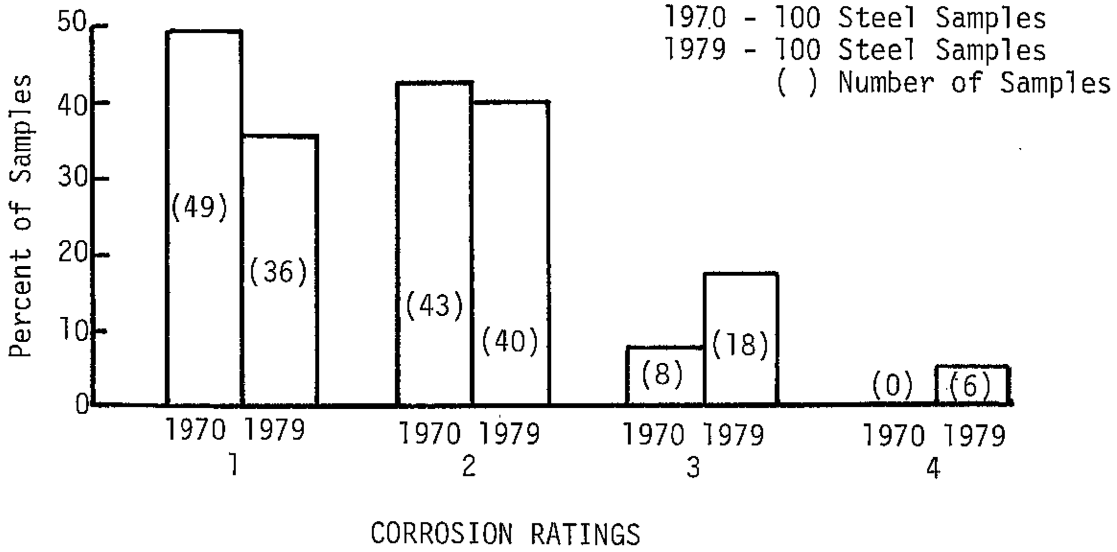


Figure 4. Distribution of steel samples versus corrosion ratings for the experimental pavements for years 1970 and 1979 where the steel samples were from the same crack

49 percent of the specimens rated 1, 43 percent rated 2, 8 percent rated 3, and no steel was rated 4. Again, the percent of specimens rated 1 and 2 was less in 1979 than in 1970, while the percent of specimens rated 3 and 4 was greater, showing about the same progression in the severity of steel corrosion as the data presented in Figure 3.

Although the steel corrosion has progressed in these experimental CRC pavements since 1970, at this stage its effect on the pavement performance is minimal.

As mentioned previously, out of 8 steel specimens rated 4, 2 were fractured and 2 were severely corroded, reducing the cross-sectional area by one half. These 4 steel segments were retrieved from the cores taken from test site 9 (FAI 57, near Champaign), where the 2 fractured bars were found in the 7-in. (178-mm) pavement and the 2 severely corroded bars were from the 8-in. (203-mm) pavement. This is the only pavement that had steel specimens with a deterioration of that magnitude. Some of the cracks in the area of the fractured steel were wide and faulted, adversely affecting the structural integrity and performance of the pavement. The average crack interval of 10 ft (3.05 m) for both the 7-in (178-mm) and 8-in. (203-mm) pavements is greater than the desired crack interval and probably overstressed the steel, contributing to the severe corrosion and fracturing of the steel. This pavement was constructed during the summer of 1963 and was not opened to traffic until the summer of 1965. During this time, as expected, the concrete gained strength but due to the absence of traffic and its ironing effect, the crack interval stayed greater than desired. The time span between the construction date and the opening to traffic is not normal and could have resulted in high tensile stresses in the steel. In addition, the penetration of salt water from ice and snow removal into the wide cracks would create an environment conducive to corrosion of the steel reinforcement.

Old Vandalia Test Pavement

The oldest CRC pavement within the State is the Vandalia test pavement (test site 13) constructed in 1947 and 1948 on US 40 west of Vandalia. This pavement served heavy two-way traffic until 1967, when the heavy traffic was diverted to a newly completed section of Interstate Route 70. Since 1967, the pavement has been serving only local traffic but still is structurally capable of serving heavy traffic. The distribution of cores by degree of corrosion found in the reinforcement within the original pavement is shown in Figure 5. Out of 15 cores taken in 1979, 13 steel specimens (87 percent) indicated slight rusting and the remaining 2 specimens (13 percent) indicated advanced rusting with a marked reduction in cross-sectional area. In 1970, from the same transverse cracks, out of 15 cores removed from the Vandalia pavement, 10 specimens (67 percent) indicated slight rusting and the remaining 5 specimens (33 percent) indicated moderate rusting. During 1979 no specimens were rated in the 3 category. One reason for this apparent discrepancy may be due to the location of the cores during the 1979 study. All steel specimens rated 2 in the 1979 study were taken approximately 38 in. (965 mm) from the outside pavement edge, while the 2 specimens rated 4 were taken approximately 21 in. (533 mm) from the outside edge, suggesting that the steel corrosion rate is greater near the edge of the pavement. Moreover, these 2 specimens rated 4 were obtained from the 7-in. (178-mm) slab having 0.5 percent longitudinal steel which is underdesigned in accordance with the present standards. The present design standards call for a longitudinal steel content of 0.6 percent. This 32-year-old pavement, based on the steel condition and its general performance, is in excellent condition.

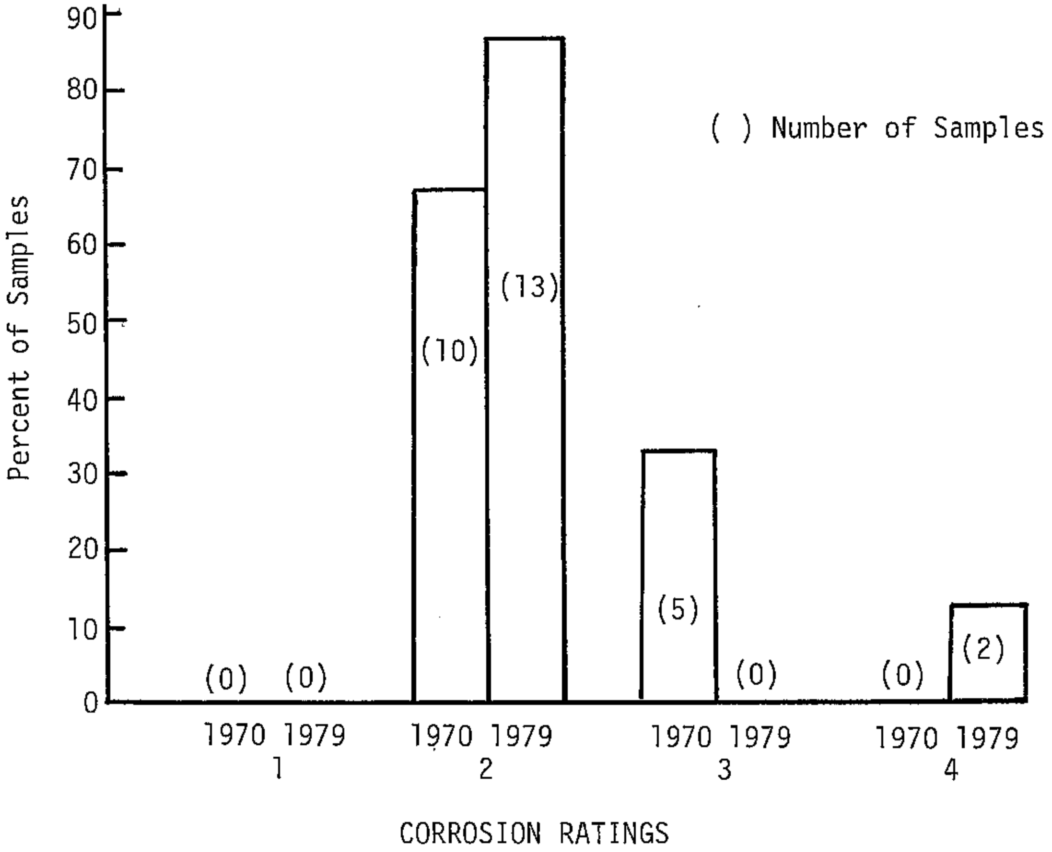


Figure 5. Distribution of steel samples versus corrosion ratings for old Vandalia pavement

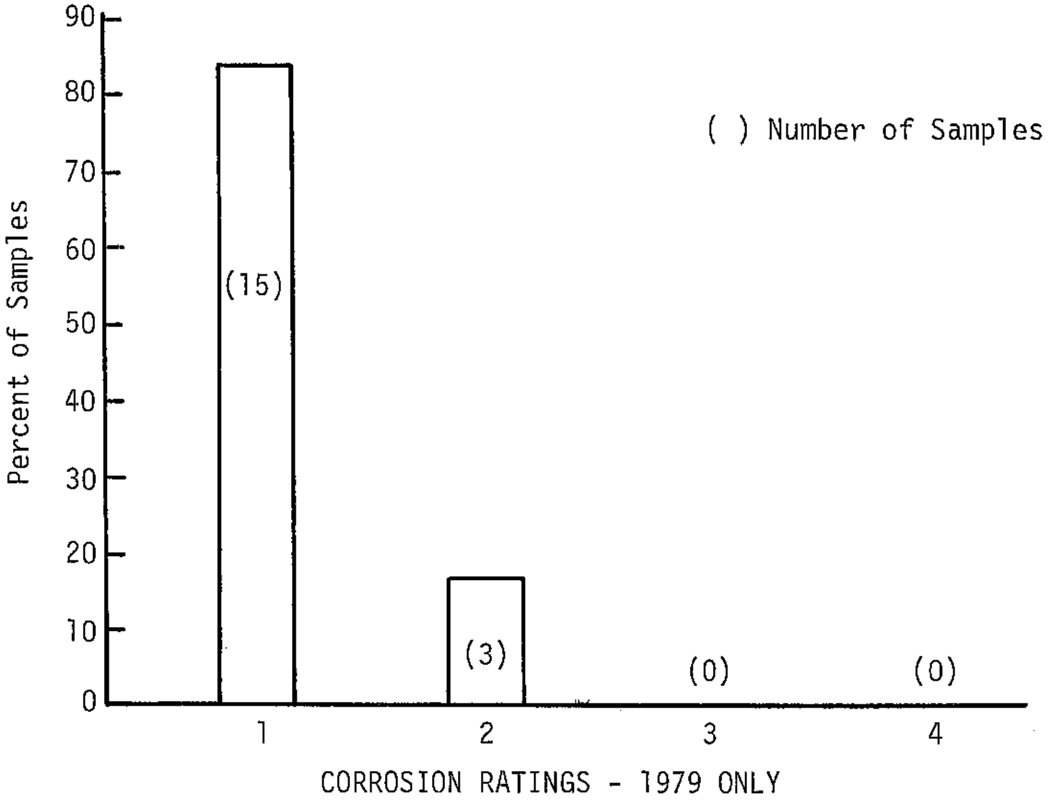


Figure 6. Distribution of steel samples versus corrosion ratings for the experimental subbase pavement

Experimental Subbase CRC Pavements

To check the condition of the reinforcing steel from the pavement constructed in accordance with modern criteria, namely, having a minimum thickness of 8 in. (203 mm), a stabilized subbase and a drainage system, 18 cores were taken from the experimental subbase section on US 36 south of Springfield and designated test site 14. This section was constructed in 1971; therefore, no cores were taken during the 1970 investigation. The distribution of cores relative to the degree of corrosion found in the reinforcement is shown in Figure 6. Out of 18 cores removed from the 8-year-old stabilized subbase section, 15 (83 percent) showed no evidence of corrosion and 3 specimens (17 percent) indicated slight rusting.

The corrosion rate is very low in comparison to the 1970 investigation when the age of the pavement on granular subbase ranged from 4 to 7 years. As expected, the stabilized subbase, having a drainage system, does not retain water containing deicing chemicals for extended periods of time as does the granular subbase constructed in trench. If corrosion continues at its present rate, and there is no reason to believe it will change, the steel corrosion at transverse cracks, which could reduce the service life of the pavement is not a critical problem for the pavements designed in accordance with the present Illinois design procedure. The present procedure, which is based on this study, calls for 4-in. (102-mm) stabilized subbase and for pipe underdrains at the inside and outside pavement edges.

ANALYSIS OF EXPERIMENTAL VARIABLES AND STEEL CORROSION

The following discussion presents an analysis of the data in relation to certain design variables and service conditions that conceivably could influence the development of steel corrosion within CRC pavements. The parameters studied in the analysis are (1) crack width, (2) depth of reinforcement, (3) type of steel reinforcement, (4) pavement age, and (5) traffic-load applications.

Crack Width

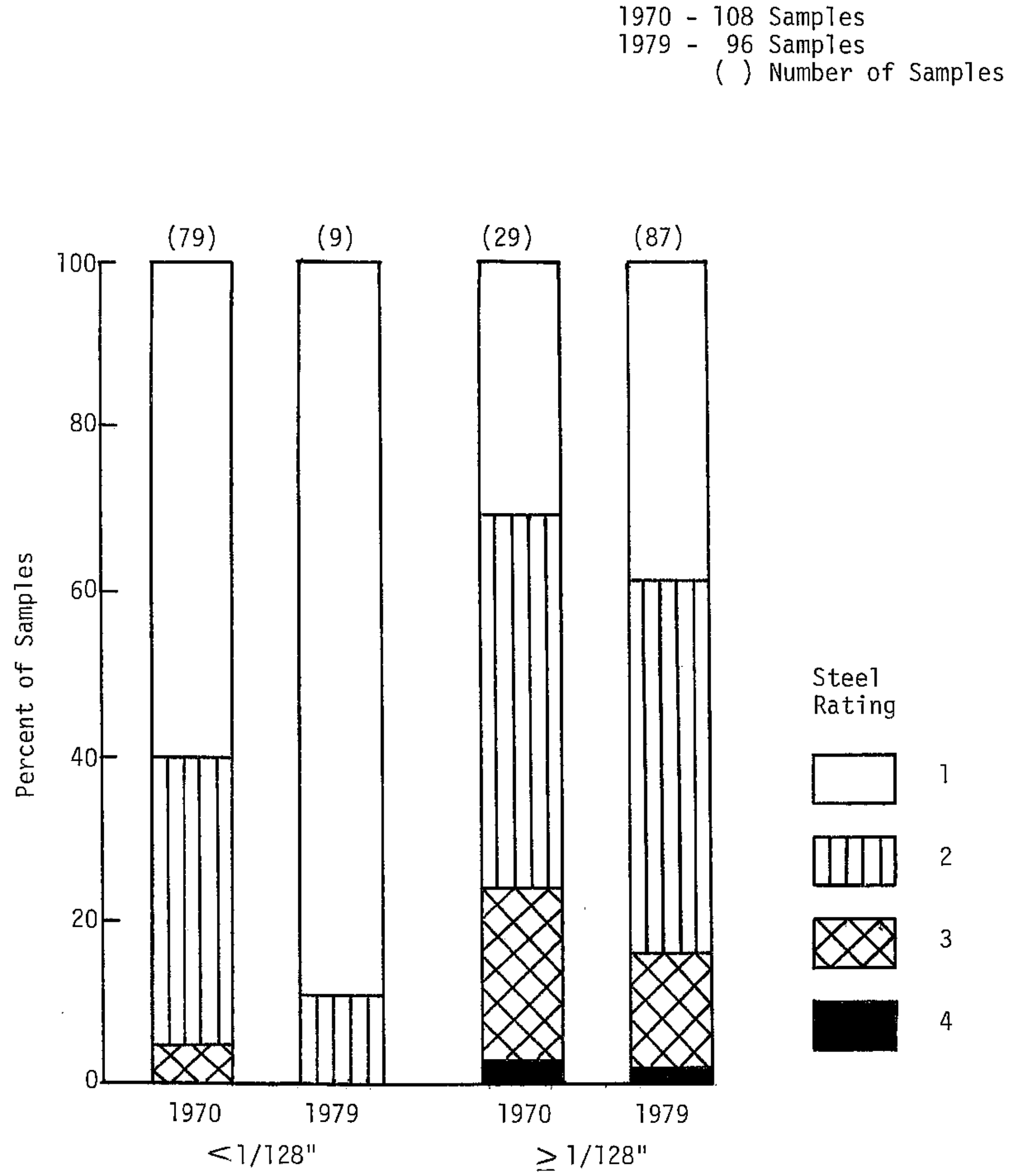
Results from the 1979 coring program substantiated the 1970 findings that a higher level of steel corrosion occurs as the crack width at the steel level becomes greater. Also, the present findings indicate that the crack width at the steel level increases with age.

As was the case in the 1970 coring program, these measurements may not represent actual crack widths at the steel level as they exist in the pavement because of the possible disturbance of the samples when they were removed from the pavement. A summary of the corrosion ratings of the steel reinforcement relative to crack widths measured at the reinforcement is shown in Figure 7.

In 1979, 96 of the cores had crack widths that could be measured at the steel level: 9 percent (73 percent in 1970) had crack widths measured at the steel level less than 1/128 in. (0.20 mm); 91 percent (27 percent in 1970) had crack widths equal to or greater than 1/128 in. (0.20 mm); and 51 cores were broken and could not be measured (43 in 1970).

From the 9 cores having crack widths less than 1/128 in. (0.20 mm), 89 percent contained steel reinforcement that was clear or free of rust. The same group also had 1 specimen (11 percent) indicating slight rusting or pitting. From this same category in 1970, 60 percent were rated 1, 35 percent were rated 2 and 5 percent were rated 3.

Of the 87 cores having crack widths equal to or greater than 1/128 in. (0.20 mm) in 1979, 39 percent had no evidence of rusting, 45 percent had slight rusting, 14 percent had moderate rusting, and 2 percent had advanced rusting. From this group in 1970, 28 percent were rated 1, 48 percent were rated 2, 21 percent were rated 3, and 3 percent were rated 4.



Note: 1 inch = 25.4 mm

Figure 7. Condition of steel reinforcement versus crack width at steel level

Of the 51 broken cores in 1979, 43 percent were rated 1, 25 percent were rated 2, 20 percent were rated 3, and 12 percent were rated 4. In 1970 there were 43 broken cores, of which 43 percent were rated 1, 45 percent were rated 2, and 12 percent were rated 3.

The above discussion and Figure 7 show that the crack width at the steel level increases with age as indicated by the number of cores with cracks that are now equal to or greater than 1/128 in. (0.20 mm). The broken cores in 1979 would, in all probability, have been in the $\geq$ 1/128-in. (0.20-mm) category if the cracks at the steel level could have been measured. These 1979 findings definitely show that a higher level of steel corrosion occurs as the crack at the steel level becomes greater, corroborating the 1970 findings.

To study the relation between surface crack width and the condition of the longitudinal steel with respect to corrosion at transverse cracks, 28 cores were removed from the experimental sections where gage plugs had been installed early in the pavement's life so that the crack width could be recorded with the Whittemore gage. These gage plugs were installed on each side of a crack in the outside lane about 8 inches from the free edge of the pavement. Previously Dhamrait and Taylor reported(4) that the actual surface crack width could not accurately be determined by this method, but the change in crack width could be determined. It was discovered during that study that the mid-summer to mid-winter change in crack width stayed about the same when the steel was placed 2 in. (51 mm) below the pavement surface, the change was small when the steel was placed at 3-in. (76-mm) depth, and the change was somewhat greater when the steel was at mid-depth. Prior to taking these 28 cores, Whittemore gage readings were taken to record the change in surface crack width that has taken place since the plugs were installed.

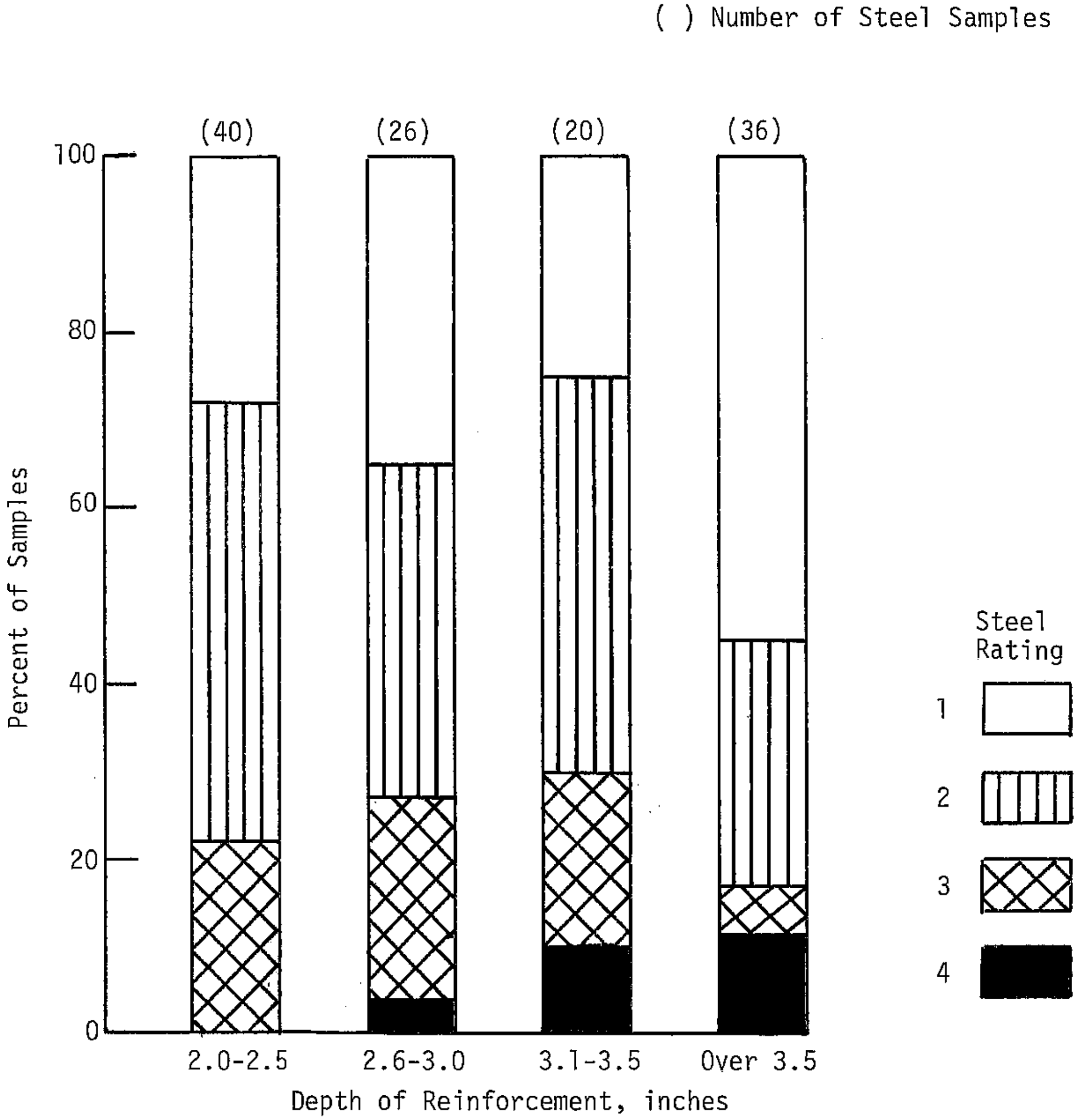
The pavements have gone through 13 to 16 yearly cycles and, as expected, the change in the crack width has increased. The data that were recorded with the Whittemore gage were further processed in an attempt to find a correlation between the surface crack width, change in the surface crack width (affected by the depth of steel, type of steel, and depth of pavement), and corrosion of the steel reinforcement, but no relation was found. This relationship may have been overshadowed by a combination of variables. For example, the cores were cut in the outside wheelpath, not between the gage plugs. Therefore, the actual crack width or the change in the crack width at the core location will be somewhat greater than at the gage plugs. Also, the effect of loading, spalling, and salting will be more severe at the core locations.

Depth of Reinforcement

In 1970, the data indicated that the potential for corrosion for depths greater than 2 in. (51 mm) remains about the same regardless of the depth of the reinforcement. However, the 1979 data point out that the amount of corrosion increases as the depth of reinforcement increases.

A graph showing the condition of the steel reinforcement relative to the depth of the reinforcement below the pavement surface is presented in Figure 8. The reinforcement depth is measured from the pavement surface to the top of the reinforcing steel (concrete cover). The measured values were taken directly from the cores and represent the actual depth, not the design depth, of the reinforcement. The core measurements were grouped in 1/2-in. (13-mm) increments of depth, beginning with a minimum of 2 in. (51 mm).

Of the 147 cores removed from the experimental pavements, 25 cores were broken to the extent that measurements could not be made. Of the remaining 122 cores, 40 had steel depths from 2.0 to 2.5 in. (51 to 64 mm), 26 were in



Note: 1 inch = 25.4 mm

Figure 8. Condition of steel reinforcement versus depth of reinforcement

the 2.6- to 3.0-in. (66- to 76-mm) range, 20 were in the 3.1- to 3.5-in. (79- to 89-mm) range, and 36 were in the over 3.5-in. (89-mm) range. Within the 2.0- to 2.5-in. (51- to 64-mm) range, 28 percent were rated 1, 50 percent were rated 2, and 22 percent were rated 3. In the 2.6- to 3.0-in. (66- to 76-mm) range, 35 percent were rated 1, 38 percent were rated 2, 23 percent were rated 3, and 4 percent were rated 4. In the 3.1- to 3.5-in. (79- to 89-mm) range, 25 percent were rated 1, 45 percent were rated 2, 20 percent were rated 3 and 10 percent were rated 4. In the over 3.5-in. (89-mm) category, 55 percent were rated 1, 28 percent were rated 2, 6 percent were rated 3, and 11 percent were rated 4.

In 1970, the data indicated that the potential for corrosion for depths greater than 2 in. (51 mm) remains about the same regardless of the depth of the reinforcement; however, the 1979 data do not agree with this finding. The number of steel samples having a rating of 4, which is expected to adversely affect pavement performance due to the marked reduction in the cross-sectional area of reinforcing steel, increases as the steel depth increases. This finding confirms and reinforces a previously reported(4) finding which states that the amount of patching for these experimental pavements increases as the depth of reinforcement increases.

Type of Reinforcement

In 1979, as in 1970, no correlation was found between the steel corrosion and type of reinforcement (bar or fabric). Figure 9 includes a graph showing the condition of the reinforcement relative to the type of reinforcement used for CRC construction. Of 84 cores removed in 1979 from the pavements reinforced with deformed bars, 58 percent were clear or free of rust, 23 percent had slight rusting, 12 percent had moderate rusting, and 7 percent had advanced

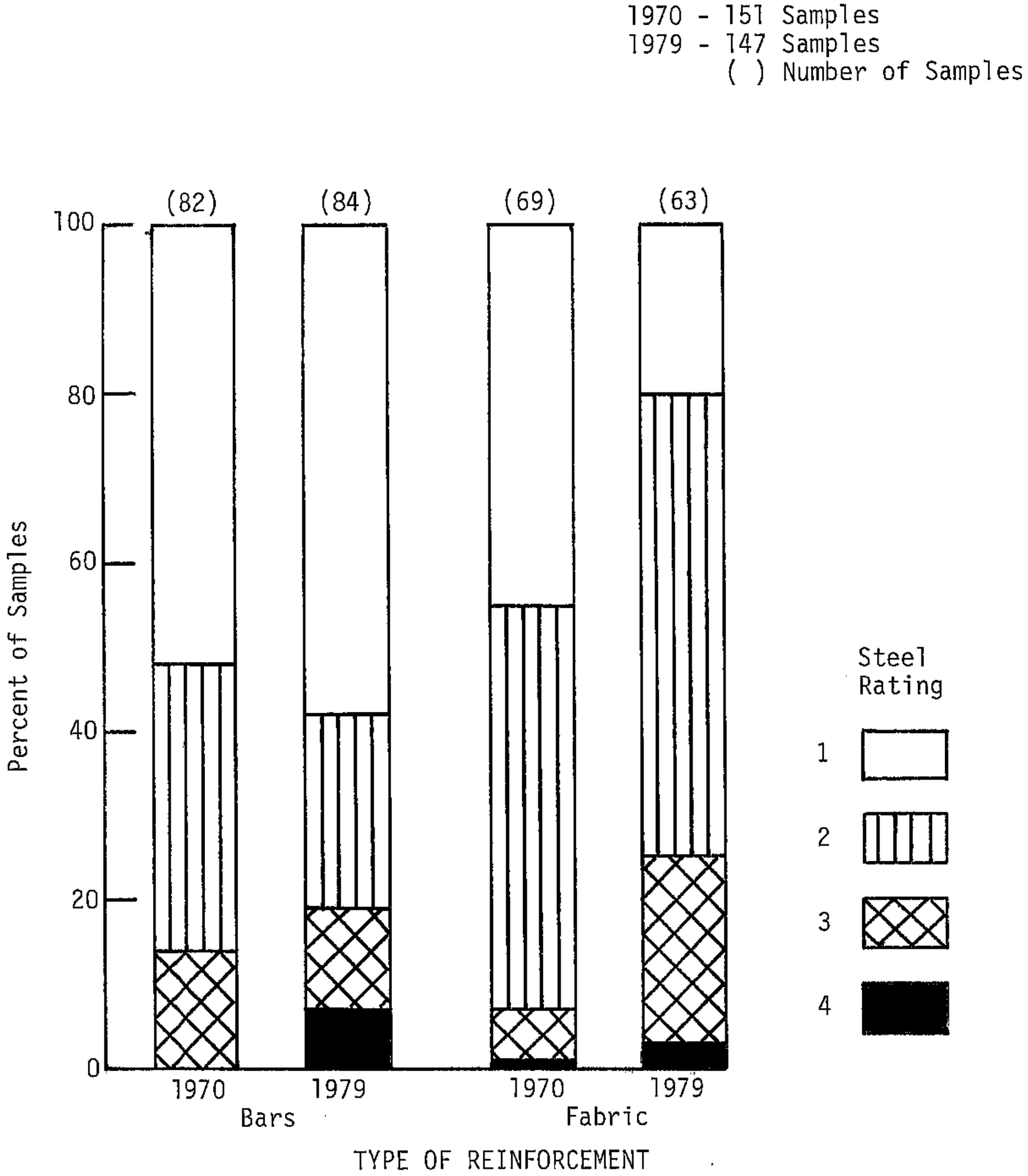


Figure 9. Condition of steel reinforcement versus type of steel reinforcement

rusting. Of the 63 cores containing welded-wire fabric removed in 1979, 13 (21 percent) were clear or free of rust, 34 (54 percent) had slight rusting, 14 (22 percent) had moderate rusting, and 2 (3 percent) had advanced rusting.

Both the steel bars and the deformed wire fabric show progressive deterioration over the years due to rusting, but no significant difference between the two was found.

Pavement Age

During the 1970 coring study, the data revealed that the relation between corrosion of the reinforcing steel and the pavement ages of 4, 5, 6, and 7 years was insignificant. The same is true in the 1979 program, where no significant correlation was found between corrosion and the pavement ages, now 13, 14, 15, and 16 years. However, the data indicate, as expected, that during the passage of time between the years of 1970 and 1979 the degree of severity of corrosion has increased.

The corrosion data with respect to age are presented in Figure 10. Of 31 cores removed from the 13-year-old pavements, 32 percent had steel specimens clear or free of rust, another 42 percent had evidence of slight rusting, 19 percent indicated moderate rusting, and 6 percent indicated advanced rusting with a marked reduction in cross-sectional area of the reinforcement. In the 14-year-old pavements, 15 cores were removed. Twenty percent had specimens rated 1, 73 percent were rated 2, 7 percent were rated 3, and no steel was found with a rating of 4. Forty-four cores were removed from pavements 15 years old. Thirty-two percent were rated 1, 39 percent were rated 2, 25 percent were rated 3, and 5 percent were rated 4. Of 57 cores removed from the 16-year-old pavements, 61 percent were rated 1, 21 percent were rated 2, 11 percent were rated 3, and 7 percent were rated 4.

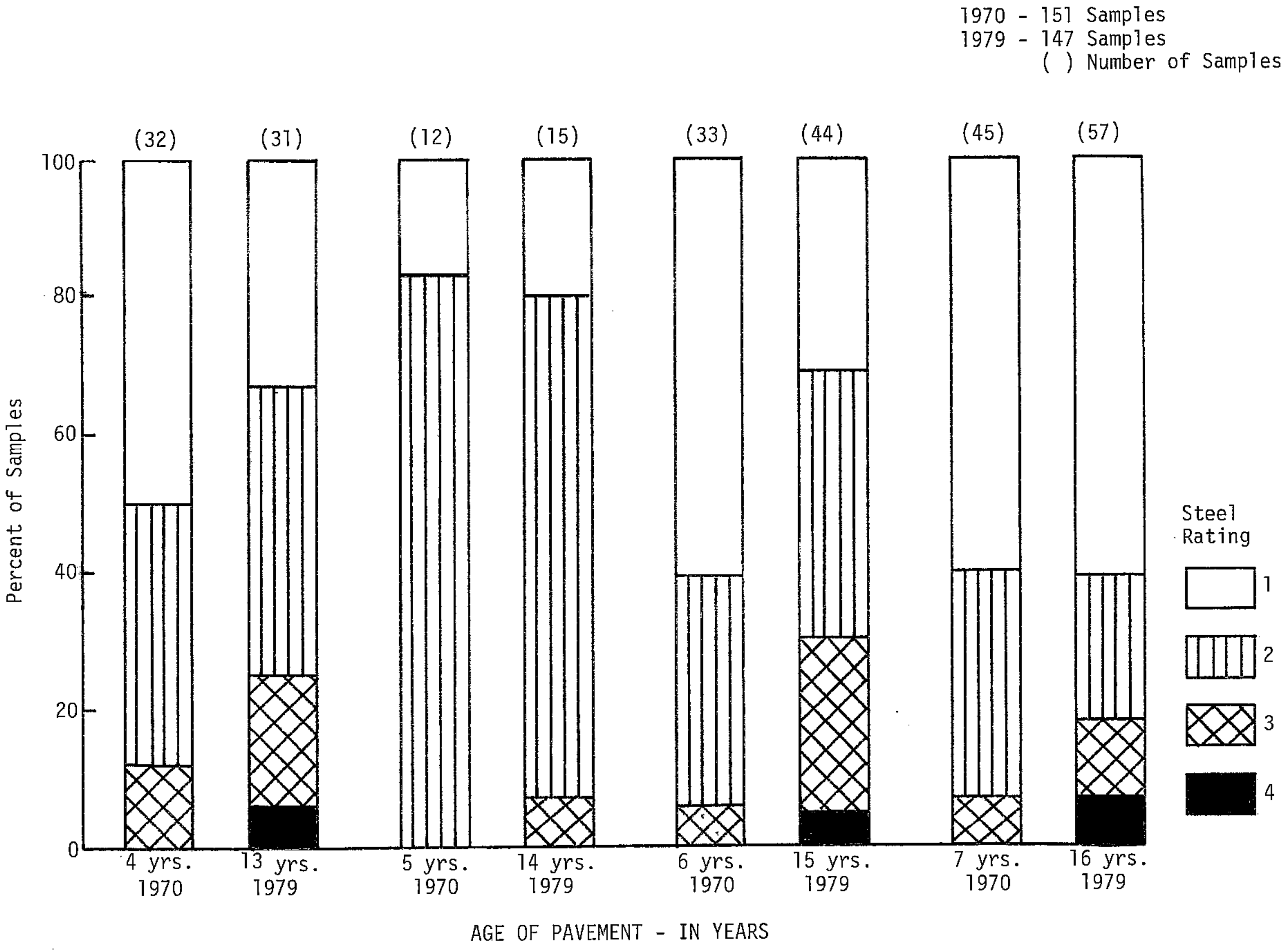


Figure 10. Condition of reinforcement versus age of pavement

Also on the graph are precentages of steel ratings taken in 1970 from the same pavements when they were 4, 5, 6, and 7 years old. As can be seen in this figure, there is no clear correlation between the corrosion of the reinforcing steel and the age of pavement. The 1979 data, when the pavement was 13, 14, 15, and 16 years old, confirm this finding. When the data of 1970 and 1979 are compared, the trend is obvious. The degree of corrosion has increased significantly during this 9-year span.

Traffic-Load Applications

In 1979, on the basis of equivalent 18,000-lb. single-axle loads, the pavements were divided into classifications of 1 to 2 million equivalent 18,000-lb. axle applications, 2 to 4 million applicatons, 4 to 6 million applications, 6 to 8 million applications, and 24 million applications. A comparison of the steel corrosion ratings relative to these traffic-load conditions is shown in Figure 11.

Of 67 cores representing 1 to 2 million axle applications, 24 percent were clear or free of rust, 51 percent showed evidence of slight rusting, 22 percent had moderate rusting, and 3 percent showed advanced rusting.

From a group of 44 cores removed from pavements exposed to 2 to 4 million load applications, 64 percent were rated 1, 20 percent were rated 2, 7 percent were rated 3, and 9 percent were rated 4.

In the 4 to 6 million axle-load group, 8 cores were removed. Sixty-two percent were rated 1, 25 percent were rated 2, and 13 percent were rated 3.

Twenty-two cores were removed from the 6 to 8 million axle-load category. Fifty percent were rated 1, 32 percent were rated 2, and 18 percent were rated 3. From the last group of 6 cores, representing 24 million axle applications, which are from test site 3 (Stevenson Expressway), 33 percent were rated 1, 17 percent were rated 2, 17 percent were rated 3, and 33 percent were rated 4.

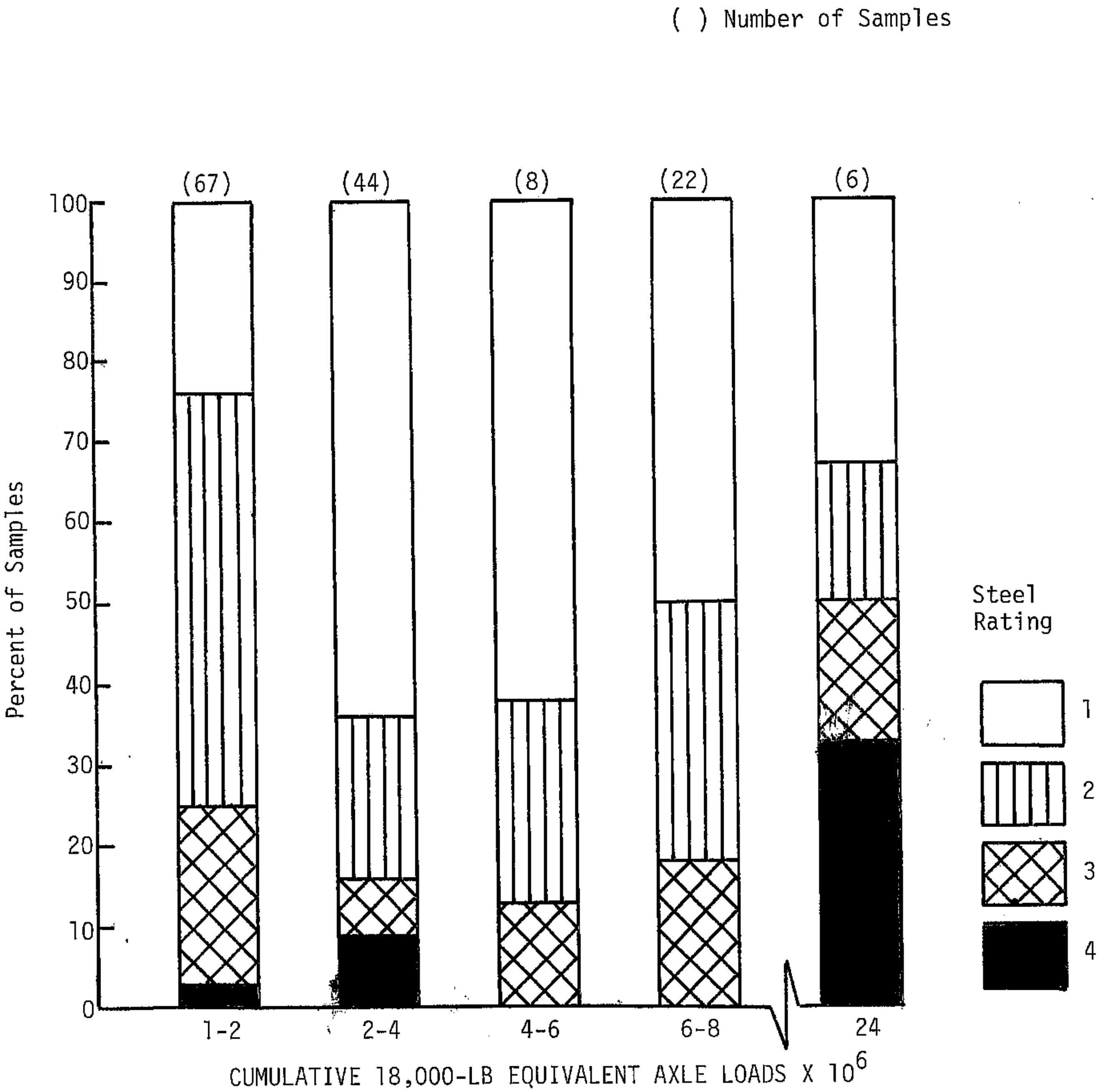


Figure 11. Condition of reinforcement versus traffic

Although Figure 11 indicates to some degree that the severity of steel corrosion increases as the volume of total load applications increases, there is no clear-cut evidence of this trend for the pavements which have received load applications between 4 to 8 million. It also can be seen that the highest percentage of corrosion (Ratings 2, 3, and 4), is from the pavements with load applications between 1 and 2 million. This nonconclusive result on the relationship between load applications and steel corrosion is similar to the 1970 study results.

INFILTRATION OF WATER AND FOREIGN MATTER

During the 1970 coring program, the crack interface of each core was examined to determine the extent of material accumulation due to progressive water infiltration and intrusion of foreign matter. Discoloration of the crack interfaces, indicative of water penetrating through the transverse cracks, was evident in all cores, with the majority of core interfaces revealing a grey or deep red stain.

The 1979 core examination of the crack interfaces revealed the same results, only now the intrusion of foreign material, on the average, is greater.

Substantiating the 1970 data, the 1979 data revealed that, although water stains and soil accumulations had penetrated all cracks to some degree, no significant sign of structural damage to the pavement or no significant relationship between the condition of the crack face and other parameters associated with this study were found.

BOND BETWEEN CONCRETE AND STEEL REINFORCEMENT

During the 1979 coring study, an attempt was made to evaluate the condition of the bond between the reinforcing steel and the concrete to determine whether the bond condition, along with steel corrosion, has had any effect on the performance of the CRC pavement. Therefore, while opening each concrete core sample to retrieve the steel reinforcement, observations and measurements were made of the steel imprint left in the core and the amount of water and rust stains in the imprint.

Of the 180 cores examined, 10 cores were too badly broken at the steel level to check the bond. D-cracking was detected in these 10 cores, which came from test sites 5, 7, and 11, and probably was instrumental in their broken condition. Sixty-two cores had clear, sharp steel imprints in the concrete, indicative of good bond, throughout the entire core sample; 69 cores had clear, sharp steel imprints, but showed water and rust stain in those imprints varying from 1/2 in. (13 mm) to 4 in. (102 mm), which could imply some reduction in the chemical bond. In 35 cores, the steel imprint was slightly less distinct and had water and rust stains varying from 1/2 in. (13 mm) to 4 in. (102 mm), which could be an indication of a lack of chemical and reduced mechanical bond. However, this condition is not believed to adversely affect the tightness of the crack and the performance of the pavement. Four cores had very slight steel imprints, along with heavy rust stains in those imprints, indicating a marked reduction in adhesion and sliding resistance. This is the only steel and concrete interface condition indicative of a marked reduction in the bond, and the only condition expected to adversely affect the pavement performance. These 4 cores from test site 9 are the same cores, previously discussed in this report, from which 2 fractured bars and 2 severely corroded bars were retrieved. The cracks at these 4 core locations were faulted near the outer pavement edge, which undoubtedly has adversely affected the pavement performance.

Also, each core was scrutinized to ascertain whether corrosion of the reinforcing steel might have caused additional cracking of the concrete, presumably showing up as radial cracking emanating from the embedded steel bar. Only 1 core showed some slight cracking, indicative of radial cracking; therefore, this type of cracking does not appear to be a problem at this time.

It has been explained earlier in this report that these pavements have served 60 to 80 percent of their designed service life and, according to present standards, they are underdesigned. Four cores (2 percent) showing a lack of bond are considered not to be a major problem and it is believed that it has not adversely affected the CRC performance in general.

D-CRACKING

In recent years D-cracking has become a major concern in Illinois. The experimental pavements incorporated into the 1979 coring program have data histories which provide a valuable documented background. Therefore, the cores from this study presented an excellent opportunity to evaluate the D-cracking process within the slab before it becomes apparent at the surface.

D-cracking is a form of concrete deterioration, appearing on the pavement surface as fine, closely spaced cracks which occur parallel and adjacent to longitudinal and transverse joints, cracks, and slab edges. The D-cracking process initiates in the lower portion of the slab. This distress is caused by stresses generated during the freezing of critically saturated coarse aggregates. The closely spaced transverse cracks, which are a design feature of CRC, unfortunately provide many paths for moisture and salt solution movement and their accumulation which are necessary for the initiation and progression of D-cracking. A pavement can reach a stage of total disintegration by the time signs of D-cracking appear on the pavement surface. D-cracking aggregates and CRC pavements are incompatible. The condition of reinforcement steel becomes a secondary contributing factor in the overall pavement performance when D-cracking appears on the pavement surface. Even though the steel may be performing satisfactorily, the pavement with D-cracking has a very serious durability problem.

In 1979, as part of another Illinois study, many pavements were rated for D-cracking. Field survey teams rated the pavement surfaces in accordance with the following definitions.

Rating	Description
None (0)	No D-crack pattern has developed.
Low (1)	The D-crack pattern is present but is less than 12 inches wide at the middle of the lane. Fanning at edges is typical.
Medium (2)	The D-crack pattern is at least 12 inches wide all the way across the lanes, or a moderate amount of spalling has developed.
High (3)	The D-crack pattern has developed over the entire area between cracks, or significant spalling or patching exists.

The numerical D-cracking rating is determined by dividing the sum of all the ratings within a construction section by the number of ratings. The cores from the 1979 study were examined to see whether D-cracking was present and, if so, whether there is any correlation between D-cracking and steel corrosion. The D-cracking ratings for most of the test sites in this coring program, along with the number and percent of cores having D-cracking, are presented in Table 5.

TABLE 5

SUMMARY OF D-CRACKING

Test Site	Number of Cores (1979)	Number of Cores Having D-Cracking	Percent of Cores Having D-Cracking	IDOT D-Cracking Rating (Surface, 1979)
1	11	7	64	No Info
2	5	1	20	No Info
3	6	0	0	No Info
4	14	0	0	0.2
5	16	16	100	1.2
6	4	3	75	0.3
7	5	5	100	0.9
8	4	4	100	0.6
9	18	3	17	1.1
10	22	5	23	0.0
11	22	13	59	0.1
12	20	0	0	0.1
13	15	0	0	No Info
14	18	8	44	0.0

The D-cracking rating for each test site is for the pavement surface only, while the D-cracking in the cores was determined by examining the entire core depth.

Out of a total of 180 cores removed from the CRC pavements during this coring program, 115 cores were retrieved in one piece, 11 in two pieces, 15 in three pieces, 11 in four pieces, 7 in five pieces, 3 in seven pieces, 4 in eight pieces, 1 in ten pieces, and 13 in more than ten pieces. Some cores got bound up in the coring bit and had to be forced out of the barrel, thus breaking the core; the 18 cores that were removed from the pavement in eight or more pieces were from test sites 5 and 7 in District 4 on Interstate 74. As can be seen in Table 5, all of the cores from these sites contained D-cracking, with surface D-cracking ratings of 1.2 and 0.9, respectively. None of the 18 steel specimens from these same cores had severe corrosion, suggesting that there is no correlation between severe steel corrosion and D-cracking in these pavements at this time. D-cracking is on the verge of becoming a very serious problem for these pavements, which undoubtedly will have an adverse effect on their performance. Also, Table 5 shows that, although test sites 10, 11, and 14 had surface D-crack ratings of 0.0, 0.1, and 0.0, respectively, some slight D-cracking was detected in the lower portion of 5 out of 32 cores from test site 10, 15 out of 24 cores from test site 11, and 8 of the 18 cores from test site 14, suggesting probable D-cracking problems in the future for these pavements.

The findings suggest that there is no correlation between D-cracking and steel corrosion, but the performance of a few CRC pavements is being affected very severely by D-cracking.

DISCUSSION AND SUMMARY

Of the 147 cores removed at transverse cracks in 1979 from the 12 experimental CRC pavements constructed between 1963 and 1966, the steel in 42.2 percent of the cores was clear and free of any rust, 36.1 percent had slight rusting, 16.3 percent indicated moderate rusting, and 5.4 percent had evidence of advanced rusting. In 1970, from these same pavements, of 151 steel samples removed, 49 percent were corrosion-free, 40 percent had slight rusting, 10 percent indicated moderate rusting, and less than 1 percent showed advanced rusting. These results indicate that steel corrosion has progressed significantly since 1970 and it is very difficult to predict the future corrosion trend, but the odds are that this trend will continue and may even accelerate. The research pavements investigated during this study are 13 to 16 years old, and some already have served more than the anticipated load applications for a normal 20-year design life. Based on these load applications, the present design would have called for thicker pavements. Thus, it is apparent that some of these pavements are underdesigned but still the overall condition of the reinforcing steel appears to be satisfactory, with the steel generally performing quite well.

The analysis of the data relative to design variables and service conditions that conceivably could influence the development of corrosion of the reinforcing steel included crack width at the steel and change in the surface crack width, depth of reinforcement, type of reinforcement, pavement age, and traffic-load applications. The results are interpreted as follows:

(1) The 1979 coring program substantiated the 1970 findings that a higher level of steel corrosion occurs as the crack width at the steel level becomes greater. Also, the present findings indicate that the crack

width at the steel increases with age. No relation was found between steel corrosion and change in crack width as measured by the Whittemore gage.

(2) The 1979 data point out that the amount of corrosion increases as the depth of the reinforcement increases. In 1970, the data indicated that the potential for corrosion for depths greater than 2 in. (51 mm) remains about the same regardless of the depth of reinforcement.

(3) In 1979, as in 1970, no correlation was found between steel corrosion and type of reinforcement (bars or fabric).

(4) The 1970 data revealed that the relation between corrosion of the reinforcing steel and the pavement ages of 4, 5, 6, and 7 years was insignificant. The same is true in the 1979 data. No significant correlation was found between corrosion and the pavement ages of 13, 14, 15, and 16 years. The 1979 data do show, as expected, that with the passage of time between the years of 1970 and 1979 the degree of severity of corrosion has increased.

(5) Although the 1979 data indicate to some degree that the severity of steel corrosion increases as the volume of total load applications increases, there is, as in the 1970 data, no clear-cut relation between steel corrosion and traffic.

Of the 15 cores removed from the old Vandalia test pavement in 1979, 87 percent of the steel indicated slight rusting and 13 percent indicated advanced rusting. In 1970, of 15 steel specimens examined, 67 percent indicated slight rusting and the remaining 33 percent were moderately corroded. None of the reinforcing steel samples were completely free of any rusting and none were found to be fractured. However, there is a progression in the steel corrosion process, with 2 bars indicating advanced rusting.

This pavement was considered of interest in this study because it already has far exceeded the normal 20-year design life and has carried, for more than 19 years, US 40 traffic which is typical of relatively heavy traffic on major rural highways in Illinois. For the last 13 years it has been serving the local traffic without any major maintenance. In addition, the design of the CRC slab is basically typical of new experimental sections and of present-day practices, the major difference being that the Vandalia pavement was constructed on the soil subgrade, whereas the experimental CRC pavements were constructed on 4-in. (102-mm) granular trench design subbase and the present-day practice calls for a 4-in. (102-mm) stabilized subbase. The results obtained from the Vandalia pavement when compared to those obtained from the new experimental pavements suggest that the progression in the corrosion process will continue but the ultimate performance of the pavement during and beyond the normal 20-year design life should not be a major problem.

To check for steel corrosion in the pavements constructed in accordance with present-day practices - constructed on a 4-in. (102-mm) stabilized subbase and having an underdrain system - 18 cores were removed from the experimental subbase section on US 36 near Springfield. These experimental pavements were constructed in 1971. Of the 18 cores removed from this 8-year-old pavement, 83 percent showed no evidence of corrosion while 17 percent indicated slight rusting. No locations were found where severe corrosion of the steel had taken place. When the results obtained from these pavements are compared to those obtained from pavement constructed on a 4-in. (102-mm) granular trench design subbase they suggest that the steel is corroding at a slower rate. Therefore, the pavements constructed in accordance with present-day practices should perform better than the granular trench design.

The examinations of the crack interfaces, in 1970, showed discoloration plus the accumulation of soil fines in the crack for all cores. The same is true in 1979, only now the intrusion of foreign material, on the average, is greater. No evidences of structural distress were found that could be attributable to the presence of foreign material in the crack and no significant relationship was found between the condition of the crack face and the condition of the steel.

An examination of the concrete cores, to check the bond between the concrete and steel reinforcement, revealed that only 2 percent showed a lack of bond, which is considered not to be a major problem and it is believed that this has not adversely affected the CRC performance in general.

The examinations of the cores revealed no correlation between D-cracking and steel corrosion, but the performance of some of the CRC pavements is being affected very severely by D-cracking.

In summary, these findings have shown that steel corrosion in Illinois pavements has progressed with the passage of time but, at this stage, its effect on the pavement performance is minimal. The condition of the steel reinforcement in these pavements (which are underdesigned according to present standards) appears to be satisfactory, considering the pavements ages (13 to 16 years) and load applications. While the study indicates that the steel corrosion will become more severe in the future, the results from the 8-year-old experimental subbase pavement suggest that the steel in the CRC pavements constructed in accordance with current Illinois design standards will corrode at a slower rate.

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