technique should be evaluated by a design group, who could optimize the repair steel density and the pattern of installation. Minor cracking can probably be injected without referral to an engineering disposition.

It is also apparent from the drill-tip performance that some change is required. The suspicions remain that the as-received tips might have been cracked or that the tips might have cracked because of the brazing operation we performed. Our preliminary review in this area has led us to an alternative tip source and a different brazing alloy. Whatever avenue is taken, the correction must be cost and performance effective.

While on the subject of the drills, we must again mention the effort needed to drill one of these holes. No judgment is yet possible on the drill durability for concretes other than our sweetened mixed-aggregate (30 percent limestone and 70 percent sand gravel) concrete, but we anticipate more difficulty in western Kansas, where our aggregates are unsweetened river sands and gravels. As a consequence, we suggest that a powered drilling system might be a desirable refinement. Let us stress, on the other hand, that the difficulties notwithstanding, the evidence we have shows that the accomplished repair is very effective.

In closing, this report is positive in all areas investigated, and we have not begun to touch the many systems involved that could definitely be improved. We know from past activities that higher bit rotation speeds reduce load requirements and increase the penetration rate. We are also certain that the bit geometrics could be improved. We do not know with certainty that we have approached or understand the maximum structural capabilities offered so far as the steel placement, types of installations, and epoxy or other bonding systems available.

ACKNOWLEDGMENTS

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Bridge-Deck Concrete-Cover Investigation in Michigan

P. W. O'Rourke and J. M. Ritchie, Testing and Research Division, Michigan Department of State Highways and Transportation

Ninety-seven concrete deck structures (282 spans) in Michigan were surveyed by using a pachometer to determine the average depth and variation of the concrete cover. Fifteen structures (36 spans) were surveyed by using the wet-depth method. It is believed that, if the clear-cover target value is increased to 7.62 cm (3.0 in) (and no attempt is made to control process variation), fewer than 3 percent of the structures will have less than 5.08 cm (2.0 in) of clear cover over more than 10 percent of their surface area. Increases in the cover specification have had no measurable effect on the mean span variation. For most structures, the distribution of measurements for individual spans is consistent with approximately 95 percent of the measurements within 1.9 cm (0.75 in) of the average value. Wet-depth measurements do not compare favorably with pachometer measurements and, in more than 50 percent of the spans, the mean difference between the two methods was greater than 0.64 cm (0.25 in). To adequately determine the depth of concrete cover, 100 measurements/span or one measurement for each 2.32 m^2 (25 ft^2), whichever is less, should be taken.

Bridge-deck deterioration from corrosion of the reinforcing steel is a serious problem in Michigan. Considerable national attention has also been directed toward determining its causes and cures. It is generally agreed that an inadequate depth of concrete cover over the steel reinforcement is a major factor. The Federal Highway Administration (FHWA) recognized the importance of this factor in 1972 and issued an instructional memorandum that directed the various state highway departments to require at least 5.08 cm (2 in) of clear concrete cover over the top mat deck reinforcement. At that time, the Michigan specification called for 5.08 ± 0.64 cm (2.00 ± 0.25 in) but, in response, that was changed to 6.35 ± 0.64 cm (2.50 ± 0.25 in). In 1975, a project was initiated to evaluate the variation in concrete cover over bridge-deck steel reinforcement and determine the level of compliance with the existing specifications for clear cover. The primary objectives of this investigation were

1. To determine the average depth and variation of concrete covers over bridge-deck steel reinforcements,
2. To determine the specification value that will ensure a prescribed minimum depth of clear concrete cover,

Table 1. Average clear cover and variation for all data according to design cover specification.

Clear-Cover Specification (cm)	No. of Structures Surveyed	No. of Spans Surveyed	Avg Clear Cover (point basis) (cm)	Avg SD (unweighted span basis) (mm)
5.08 ± 0.64	13	53	6.386	7.21
6.35 ± 0.64	78	211	6.612	6.93
7.62 ± 0.64	6	18	7.635	6.50

Note: 1 cm = 0.394 in.

3. To determine the number of measurements per span that are required to adequately determine the minimum depth of cover, and
4. To compare depth measurements made by using the pachometer (R-meter) and by using the wet-depth method and to determine whether the wet-depth method is adequate for construction control.

An interim report involving 10 structures released in December 1975 indicated that the level of compliance was still seriously deficient. As a result, the design clear-cover target was increased again—this time to 7.62 ± 0.64 cm (3.00 ± 0.25 in).

INSTRUMENTATION

Three R-meters were used to measure the concrete covers. The R-meter is an improved version of an earlier generation of pachometer. The essential modification is the introduction of a rechargeable battery pack. The R-meter is a portable, nondestructive testing device that can be used to locate and measure the depth of reinforcing steel of a known diameter. It measures the disturbance by an external magnetic source (the rebar) on a magnetic field generated at the probe. The magnitude of the disturbance is proportional to the distance from the probe and indicated at the instrument meter on a linear scale. The readings are converted to depths of clear cover through the use of a calibration curve.

ACCURACY

The R-meter used has an effective range of 0-10.8 cm (0-4 in). In general, instrument sensitivity is inversely related to depth of cover. With a modest amount of practice, measurements of depths less than 6.35 cm can be obtained with reasonable accuracy [± 0.32 cm (± 1/8 in)]. Measuring depths of cover greater than 8.89 cm (3.50 in) with consistent accuracy is difficult even for an experienced operator. A reasonable estimate of the overall accuracy in normal production conditions is approximately ± 0.64 cm. Two factors other than operator technique that affect the accuracy are the presence of magnetic aggregates and the variation in the magnetic properties of the reinforcing steel.

Magnetic Aggregate

The presence of magnetic material in the concrete affects the accuracy of the instrument. Even a small particle, if located near the surface, can cause considerable error. This is compounded by the fact that the magnetic effect varies from point to point. Although the amount of error is never known, the effect always occurs in the same direction. That is, those readings that are in error will always indicate less cover than actually exists. Therefore, results are conclusive if the data indicate that the cover is sufficient but, if the survey indicates less than minimum compliance, additional information is necessary to determine the actual amount of deficiency.

Grade and Manufacturing Process

The variation in material composition of different grades of steel has a significant effect on the magnetic properties of reinforcing bars. Also, variation within a specific grade of steel can affect calibration; differences on the order of 0.32 cm for no. 6 bars at 5.08 cm of cover are not unusual. This error increases rapidly at depths of cover greater than 7.62 cm because of the changing slope of the calibration curve. This potential source of error can be effectively eliminated, however, by calibrating the instruments against samples of the superstructure reinforcement.

DISCUSSION OF DATA

Determination of Average Depth and Variation in Concrete Cover Over Bridge-Deck Steel Reinforcement

From the summer of 1975 through the winter of 1976, 97 structures (282 spans) were surveyed by using the R-meter. The depth of the clear concrete cover was determined on a 1.52- × 1.52-m (5- × 5-ft) grid. For each span and structure, the mean or average depth of clear cover and the percentage of measurements (or area) less than a designated value were computed. These 97 structures represent three different specifications for clear concrete cover. The average depth of clear cover and the average variation (standard deviation) on a span basis were compiled according to specification (see Table 1). With the exception of those structures built to the 5.08 ± 0.64-cm specification, the results indicate excellent concurrence on an overall basis between observed average performance and design target.

As indicated by the average standard deviation, the overall variation has remained relatively constant and independent of the cover target. Despite the increased emphasis on concrete cover in the past 2 years no significant reduction in process variation has occurred.

A casual review of the data when they are grouped by span indicates good concurrence between the level of compliance and the observed range of cover depth. That is, those spans that have better than average cover also tend to have less variation. This trend emphasizes the importance of good construction control.

An inspection of the individual structure data shows considerable variation among spans, which emphasizes the need to examine each span separately. Table 2 shows that, when the span data are grouped by design clear-cover specification, 16.6 percent of the spans built to the 6.35-cm specification fail (i.e., more than 10 percent of the area has less than 5.08 cm of clear cover), whereas 22.7 percent of those built to the 5.08-cm specification fail. Thus far, only 18 spans have been surveyed that were built by using the current 7.62-cm specification; of these, none have failed. The passing and failing rates of the spans are summarized below (1 cm = 0.4 in).

Rate	Clear-Cover Specification		
	5.08 cm	6.35 cm	7.62 cm
Passing, %	77.3	83.4	100.0
Failing, %	22.7	16.6	0.0

Table 3 divides the data according to span length. There does not appear to be any significant trend. In Table 4, the data are grouped according to type of span (single or multispan, tail or midspan). Here the data show a much higher failure rate for midspans than for either single or tail spans for both the 5.08- and 6.25-cm specifications.

Determination of Necessary Specification Value to Ensure a Prescribed Minimum Depth of Cover at a Prescribed Confidence Level

An evaluation of the pachometer measurements on a span basis indicated that, regardless of the actual design cover specification, approximately 95 percent of the individual span data are within a range of 3.81 cm (1.50 in) or approximately ± 1.91 cm (±0.75 in) around the average or mean value for the span. The specific causes for this magnitude of variation are not known. However, it does represent the variation that can be expected from prevailing construction techniques and is comparable with that found in other states.

Since the study has been under way, the department has increased the cover specification from 6.25 ± 0.64 cm to 7.62 ± 0.64 cm. In addition, contractors are now required to physically tie both the top and the bottom mats to the structural steel. This was done to reduce the possibility that mat separation could be contributing to the overall variation. An evaluation of the effectiveness of this measure was made by comparing the distributions of the observed variation on a span basis for structures built before and after these changes. This comparison indicated that no significant reduction in the process variation has occurred, which suggests that either mat separation is not a problem or that the present requirements for mat tie down are not effective.

An evaluation of the effectiveness of increasing the design specification was made on the basis of the distributions of the 10th percentile cover. By using probability theory to analyze the data for the 211 spans constructed to the 6.35-cm specification, the chance of producing a deficient span was computed to be 18.7 percent. Because of the large amount of data available for spans constructed by using the 6.35-cm target, it is possible to check directly the accuracy of this estimate by comparing it with the observed failure rate. Of the 211 spans, 35 (16.6 percent) were deficient. Although

Table 2. Span areas that have less than 5.08 cm (2.0 in) of clear cover.

Percentage of Span Area That Has Less Than 5.08 cm of Clear Cover	Clear-Cover Specification					
	5.08 ± 0.64 cm		6.35 ± 0.64 cm		7.62 ± 0.64 cm	
	No.	Percent	No.	Percent	No.	Percent
0.0	26	49.0	127	60.2	17	94.4
0.1-5.0	12	22.6	40	18.8	1	5.6
5.1-10.0	3	5.7	9	4.3	0	0.0
10.1-25.0	7	13.2	20	9.5	0	0.0
25.1-50.0	3	5.7	8	3.8	0	0.0
>50.0	2	3.8	7	3.3	0	0.0
Total	53	100	211	100	18	100

Note: 1 cm = 0.394 in.

Table 3. Span areas that have less than 5.08 cm (2.0 in) of clear cover: summarized by span length and design cover specification.

Span Length (m)	No. of Spans							Passing (%)
	Percentage of Area That Has Less Than 5.08 cm of Clear Cover							
	0.0	0.1-5.0	5.1-10.0	10.1-25.0	25.1-50.0	>50.0	Total	
5.08-cm clear-cover specification								
<9.05								
9.45-15.2	9	2	1	1	1	0	14	85.7
15.5-21.3	4	4			1		9	88.9
21.7-27.4	3	2					5	100
27.8-33.5	10	1	1	4	1	1	18	66.7
33.8-39.4		2	1	1			4	75.0
>39.4		1		1		1	3	33.3
6.35-cm clear-cover specification								
<9.05	1						1	100
9.45-15.2	35	8		4	1	3	51	84.3
15.5-21.3	33	10	3	6	1		53	86.8
21.7-27.4	19	4	2	2	1	1	29	86.2
27.8-33.5	17	5	2	2	3	2	31	77.4
33.8-39.4	10	6	1	4	4	1	26	64.5
>39.4	12	7	1				20	100
7.62-cm clear-cover specification								
<9.05								
9.45-15.2	3						3	100
15.5-21.3	6						6	100
21.7-27.4								
27.8-33.5	2	1					3	100
33.8-39.4	4						4	100
>39.4	2						2	100

Note: 1 m = 3.28 ft.

Table 4. Span areas that have less than 5.08 cm (2.0 in) of clear cover: summarized by type of span and design cover specification.

	Spans													
	Percentage of Area That Has Less Than 5.08 cm of Clear Cover													
	0.0		0.1-5.0		5.1-10.0		10.1-25.0		25.1-50.0		>50.0			
Type of Span	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	Total No.	Passing (%)
5.08-cm clear-cover specification														
Single span	2	100	0	0	0	0	0	0	0	0	0	0	2	100
Multispan														
Tail	14	50	8	28.7	2	7.1	2	7.1	2	7.1	0	0	28	100
Midspan	10	43.5	4	17.4	1	4.3	5	21.8	1	4.3	2	8.7	23	65.2
6.35-cm clear-cover specification														
Single span	6	54.5	4	36.4	0	0.0	1	9.1	0	0.0	0	0.0	11	90.9
Multispan														
Tail	83	61.5	26	19.2	7	5.2	10	7.4	7	5.2	2	1.5	135	85.9
Midspan	37	56.9	11	16.9	2	3.1	9	13.9	1	1.5	5	7.7	65	76.9
7.62-cm clear-cover specification														
Single span													0	
Multispan														
Tail	11	100	0	0	0	0	0	0	0	0	0	0	11	100
Midspan	6	85.7		1	14.3	0	0	0	0	0	0	0	7	100

Note: 1 cm = 0.394 in.

slightly conservative, the predicted failure rate is in reasonable agreement with the observed frequency. Of the six structures (18 spans) thus far surveyed that were built by using the current specification (7.62 ± 0.64 cm), none were deficient. However, based on this limited experience and by using the same procedure as above, the probability of producing a deficient span can be computed to be 3.0 percent. In view of the demonstrated conservative nature of estimates computed in this manner, it is suggested that 3.0 percent is a reasonable estimate of the maximum limiting value.

If the total process variability inherent in the construction process itself continues to remain as constant as it has over the previous 2 years, then the current specification should provide adequate protection against insufficient cover.

General Comment on Process Variation

In evaluating the problem of achieving adequate clear cover, there are two basic approaches. One approach is to reduce and control the overall process variation. By using this approach, the smallest possible target value consistent with the minimum level of compliance could be determined. The alternative is to measure and accept the process variation at its existing level and adjust the target value as required to achieve the desired minimum compliance.

Although the first approach is technically possible, it would be extremely difficult. A detailed study to determine all of the parameters and their relative signficance would be required. A partial list of parameters that would have to be considered includes (a) the unpredictability of beam deflection under the dead-load effect of fresh concrete, (b) separation of the reinforcing mats, (c) concrete-placement procedure, (d) finishing techniques, and (e) limits of accuracy for level work on a surface subjected to constantly changing temperature and cloud cover.

A casual review of this list would discourage most workers. Even if a study of this magnitude were completely successful, there is no guarantee that the indicated changes would be feasible. For example, the costs of revising existing design procedures or of modifying established construction techniques would probably be prohibitive.

The second approach is clearly the preferred choice. There are three basic factors (all documented by this investigation) that recommend it over the alternative:

1. The process variability is basically constant and not likely to change.
2. The average performance is sensitive to changes in the specified target.
3. The variation is independent of the target value.

These three facts taken together suggest that the level of compliance can be effectively controlled by an appropriate adjustment of the design target.

This study has shown that, by increasing the clear-cover target value to 7.62 cm, but making no additional attempt to control the process variation, one can be reasonably confident that less than 3 percent of structures will be deficient. The economic impact of increasing the target value of 7.62 cm is minimal. The average cost of adding 1.27 cm (0.5 in) more concrete is less than 12 cents/m^2 (10 cents/yd^2) of deck area.

Determination of Number of Measurements per Span Required to Adequately Determine Minimum Depth of Cover

Another objective of this investigation was to determine an appropriate sampling frequency. All of the data were taken on a 1.52- × 1.52-m grid. This sampling frequency seemed excessive but, because of our inexperience in gathering this type of data, the decision to use it was based on an FHWA recommendation.

Sampling frequency is important. Sound judgment requires that the quantity of data be sufficient to justify the recommendation, but data collection is costly, and a reasonable balance between these two constraints is necessary. Thus, it was necessary to determine the appropriate number of measurements (N) per span such that the correct conclusion would be reached at some predetermined confidence level (the 0.05 confidence level was arbitrarily selected). Intuitively, to maintain this confidence level requires that the sample size increase as the percentage of the deck that has less than 5.08 cm of clear cover approaches the failure criterion (10 percent). Also, the minimum sampling requirement can be determined for spans that have been oversurveyed if

the number of available measurements is greater than approximately 2N. It follows that, if more than enough data have been collected, then random samples of considerably smaller size should consistently lead to the same conclusion regarding deficiency. With this in mind, 10 large spans ($N_T > 150$) were selected that had less than 5.08 cm of clear cover over 0 to 20 percent of their area. These spans were selected to cover the range between 0 and 20 percent as uniformly as possible. The first step was then to test each span to determine whether it was in fact overtested. To do this, 100 separate random samples (size $N_T/2$) were generated from the available data for each span. In turn, for each random sample, the percentage of area that had less than 5.08 cm of cover was calculated and checked against the failure criteria. If at least 95 percent of the smaller samples led to the same conclusion as was reached by using all of the data, that span was considered overtested.

The next step was to determine the minimum sample size consistent with the confidence level selected (0.05). This was accomplished by reiterating the above procedure. For each new set of 100 random samples, a smaller sample size was selected until the success rate for correctly predicting the deficiency status decreased to 95 percent. The minimum sampling frequency for each span was then plotted against the percentage of clear cover less than 5.08 cm (Figure 1). As expected, as the percentage of deck area that had less than 5.08 cm of clear cover approached 10, the sample size required increased exponentially. As shown, the point of diminishing returns occurs at approximately N = 100. This corresponds with a range of ±4 percent and indicates that, for any given span, the correct conclusion regarding deficiency made by using the 10 percent criterion is ensured at a confidence level of 0.05 or better if (a) at least 100 measurements were taken and (b) the observed percentage of area that has less than 5.08 cm of clear cover is either less than 6 or greater than 14. Because of the limited experience with the present specification (minimum of 7.62 cm of clear cover), an accurate estimate of the number of spans likely to fall within this range cannot be made at this time; however, a reasonable estimate would be approximately 3 percent. Based on this analysis, 100 measurements should be taken per span. This sampling size may be excessive for small decks; it is suggested that the 1.52- × 1.52-m grid size established by FHWA be used in those cases where the 100-size sample would result in more than 0.43 measurement/m^2 (1 measurement/25 ft^2) of deck area.

It is generally agreed that 5.08 cm of clear concrete cover is the minimum acceptable. However, the minimum acceptable level of compliance is somewhat arbitrary. In Michigan, it is at present based on the percentage of the total surface area that has less than 5.08 cm of clear cover. The department has established 10 percent as the critical value; this is the basis for the above analysis. However, FHWA has on occasion considered 40 percent to be the critical level of deficiency. For comparison, the above procedure was repeated by using the FHWA criteria (see Figure 2). As indicated, the results are similar with the following exception; the range for which the 0.05 confidence level cannot be supported increased from ±4 to ±6 percent.

Comparison of Depth Measurements Made by Using Pachometer and by Using Wet-Depth Method to Determine Whether Wet-Depth Method Is Adequate for Construction Control

A total of 15 structures (36 spans) for which both construction wet-depth measurements and pachometer readings were obtained were examined to determine how well the two methods compared. In the wet-depth method, a construction inspector pushes a calibrated rod into the freshly poured concrete immediately behind the finishing machine and records the depth to the top of the reinforcing steel. The comparison technique consisted of determining the distribution characteristics of the differences between the (a) averages for each span, (b) 40th percentile value taken from the cumulative frequency distribution of clear-cover depth for each individual span, and (c) the 10th percentile value. In all cases, the differences were determined by subtracting the pachometer readings from the wet-depth measurements. The results of this analysis are summarized in Table 5. They show that wet-depth measurements, on the average, show more depth of clear cover than do pachometer readings. Depending on the comparison criterion chosen, the mean of differences varied from 4.27 to 6.76 mm (0.168 to 0.266 in). The standard deviation for the three distributions varies from 8.58 to 9.25 mm (0.338 to 0.364 in), which indicates that, approximately 53 percent of the time, one can expect the mean difference between the two measurement methods to vary by more than ±6.4 mm

Figure 1. Relationship between percentage of deck area that has less than 5.08 cm (2.0 in) of clear concrete cover and required sampling frequency: 10 percent criterion.

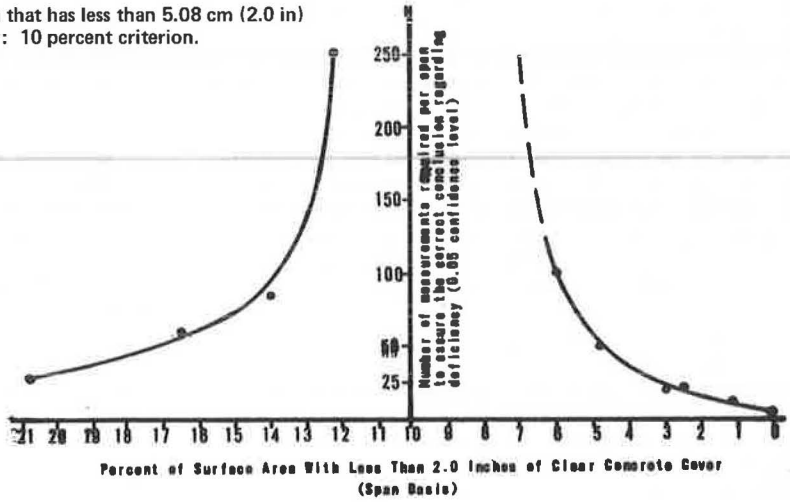

Figure 2. Relationship between percentage of deck area that has less than 5.08 cm (2.0 in) of clear concrete cover and required sampling frequency: 40 percent criterion.

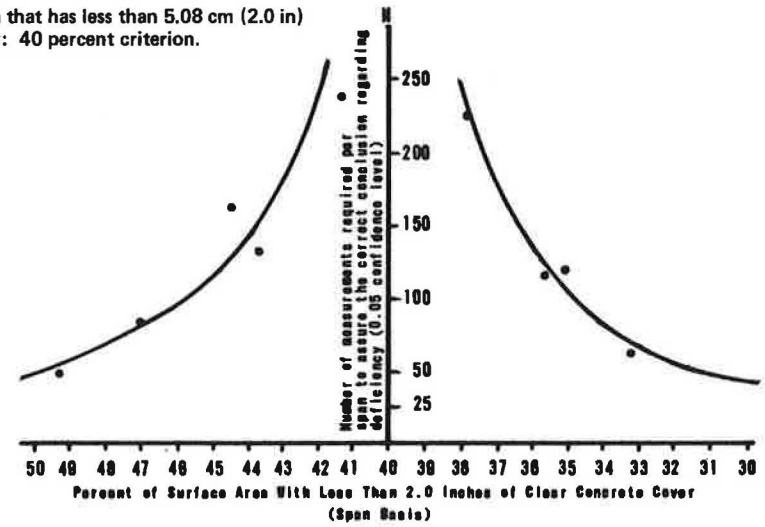

Table 5. Comparison of wet-depth measurements with pachometer readings.

Comparison Criterion	Total Number of Spans	Mean of Differences (mm)	SD of Differences (mm)	Coefficient of Variation	Range of Differences (mm)	No. of Spans Where Wet-Depth Measurements Were Greater	Remarks
Average value	36	5.51	8.84	1.60	-1.48-22.3	27	53 percent of the time, difference between methods will be greater than ±6.4 mm
40th percentile value of clear cover	36	4.27	8.58	2.01	-17.4-16.0	24	54 percent of the time, difference between methods will be greater than ±6.4 mm
10th percentile value of clear cover	38	6.76	9.25	1.37	-15.7-26.8	27	52 percent of the time, difference between methods will be greater than ±6.4 mm; 14 percent of the time, difference between methods will be greater than ±12.5 mm

Note: 1 mm = 0.0394 in.

(±0.25 in) and about 15 percent of the time to vary by more than ±12.5 mm (±0.50 in).

CONCLUSIONS

1. A specification value of 7.62 ±0.64 cm for clear concrete cover should provide adequate protection for at least 97 percent of all new construction.
2. For most structures, the distribution of measurements for individual spans is consistent with approximately 95 percent of the measurements being within a range of about 1.91 cm (±0.955 cm) of the average cover.
3. The two previous increases in the concrete-cover specification have had no measurable effect on the average variation, which has remained basically constant throughout this investigation.
4. The overall average depth of concrete cover for those structures built to either the 6.35- or the 7.62-cm cover specification agrees closely with the target value.
5. There is considerable variation among spans for the same structure, which emphasizes the need to examine spans individually. In some cases, individual spans were found to be seriously deficient, despite the fact that the data for the structure as a whole indicated substantial compliance.
6. Within a span, the distribution of cover generally appears to be random.
7. Wet-depth measurements do not compare favorably with R-meter measurements. This study indicated that, on the average, wet-depth measurements show more depth of clear cover than R-meter measurements and that more than 50 percent of the time, the mean difference will be greater than 0.64 cm.
8. At depths of clear cover of 5.1 to 7.6 cm, a properly calibrated R-meter has an accuracy of ±0.32 cm. Bar size, grade of steel, and presence of magnetic aggregates have a pronounced effect on measurements.
9. To adequately determine the depth of concrete cover, 100 measurements/span or 0.43 measurement/m^2 (whichever is less) should be taken.

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