FACTORS INFLUENCING THE PERFORMANCE OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

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A statewide condition survey of continuously reinforced concrete (CRC) pavements was conducted in Indiana in 1972 to evaluate the effects of subbase and subgrade type, the methods of paving, steel placement and steel fabrication, concrete slump, and traffic on CRC pavement performance. The measures of performance were extent of failures, parallel cracks with less than 30-in. (76-cm) crack spacing, random cracks, spalled cracks, and edge pumping. The results show that subbase type, methods of steel placement and steel fabrication, concrete slump, and traffic significantly influence CRC pavement performance. Gravel subbases showed poorer performance than crushed stone and bituminous stabilized subbases. Better performance was indicated where deformed wire fabric or loose bars were used than where tied bar mats were used. Depressed steel performed better than steel preset on chairs. The data showed little difference between performance of pavements that were slip-formed and those that were side-formed. Relative to good performance, an optimum range of concrete slump between 2.0 and 2.5 in. (5.0 to 6.5 cm) was indicated. Distress of CRC pavements is associated with traffic. Most of the pumping was observed on pavements with gravel subbases, though some pumping was also indicated where bituminous-stabilized or crushed-stone subbases were used.

•DURING the past several years use of continuously reinforced concrete pavement (CRCP) has increased considerably. The first experimental continuously reinforced concrete pavement was built in 1938 on US-40 near Stilesville, Indiana. During the next 20 years, a number of research-oriented CRCP projects were built at various locations in the United States. Experimental test sections were constructed in Illinois and New Jersey in 1947 and in California in 1949. In 1951, portions of the Fort Worth freeways in Texas were constructed with continuously reinforced concrete; other CRC pavements were built in Texas in 1955 and 1957. In addition, 2 continuously reinforced concrete projects were constructed in Pennsylvania in 1956 and 1957.

As of 1958, there were 79 miles (127 km) of equivalent 2-lane CRC pavement in the United States. Since then the use of CRC pavements in highway construction has increased; more than 10,000 miles (16 000 km) of equivalent 2-lane pavement were in use or under contract in 33 states at the end of 1971 (10).

Outside the United States, a number of countries have built CRC pavements. Notable among these are Belgium, West Germany, the Netherlands, Sweden, and Switzerland. The Great Britain Road Research Laboratory investigated the use of CRC bases under asphalt surface courses (3). Belgium built its first experimental CRC pavement in 1950 and recently decided to undertake such construction over 81 miles (130 km) of freeway (8).

One of the primary reasons for constructing this type of pavement is that CRC pavements have a better riding quality than jointed concrete pavements, and in most cases

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these pavements offer an effective means of serving heavy traffic with a minimum of interruption for routine maintenance and repairs.

Figure 1 shows the extent of CRC pavement constructed in Indiana up to the summer of 1972. The first pavement was built on an experimental basis in 1938. Several short sections of pavement were constructed in the mid-1960s. During the past several years many additional miles of CRC pavement have been built, primarily on the Interstate System. The increase in the use of CRC pavements in Indiana is shown in Figure 2.

Most of the pavements constructed in Indiana are 9 in. (23 cm) thick, although some have been constructed 7 and 8 in. (18 and 20 cm) in thickness. For the most part, non-stabilized granular subbases have been used under the pavement, although in recent years the trend has been toward the use of asphalt-treated subbases in most situations.

Various types of steel placement and construction (formed or slip-formed) have been used. The percentage of steel used has been 0.6 percent of the cross-sectional area, irrespective of the other factors of design.

STATEWIDE CONDITION SURVEY OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS IN INDIANA

To evaluate the performance of CRC pavements in Indiana, a statewide condition survey was conducted in late 1972. The field survey was a cooperative venture in which a study group from Purdue University was assisted by personnel from the Research and Training Center and the Crawfordsville District Office of the Indiana State Highway Commission. A sampling procedure was used to design the field survey, and statistical methods were used to analyze the resulting data.

STUDY DESIGN

The intent of the study design was to ensure the inclusion in the study of every CRCP contract that had been completed up to the time of the survey. A further purpose was to provide an inference space for the proposed analysis that would encompass all the factors under investigation.

Sampling Procedure

A stratified random sample of CRC pavements was used in the field survey. Stratified random sampling is a plan by which the population under consideration (in this case, all the CRCP contracts in Indiana) is divided into strata or classes according to some principle significant to the projected analysis. This is followed by sampling within each class as if it were a separate universe. The aim in stratification is to break up the population into classes that are fundamentally different in respect to the average or level of some quality characteristics (6, 7).

Such a sampling scheme is superior to a simple random sample in that the inclusion of all independent factors to be evaluated in the study is guaranteed. This vastly improves the inference space of the desired analysis.

Only one simple random sample was obtained from each stratum or class. Such a sample or unit of evaluation was designated as a field survey section. Each field survey section was a 5,000-ft (1524-m) length of pavement. The location, relative to the direction of lanes, and beginning of each section were selected from the total length of CRC pavement in each stratum by the use of random number tables. Care was taken that a randomly selected pavement length was located approximately 200 to 300 ft (60 to 90 m) away from the exact end or beginning of a construction contract.

The survey sections were stratified on the basis of the following factors: contract, method of paving, method of steel placement, method of steel fabrication, type of subbase, and type of subgrade. These factors are described in detail in the section on statistical design. Data relative to these factors were obtained from construction survey records. In addition, information pertaining to concrete slump, date of paving, and date a section was opened to traffic was also taken from construction records.

Most of the pavements were 9 in. (23 cm) thick, although several were 8 in. (20 cm) thick and 9 were 7 in. (18 cm) thick.

Figure 1. CRC pavements in Indiana in summer of 1972.

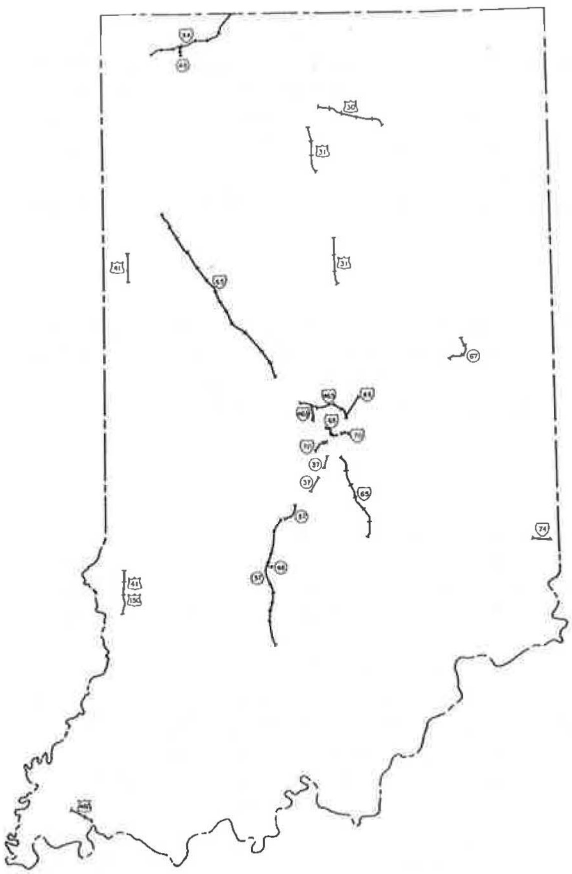
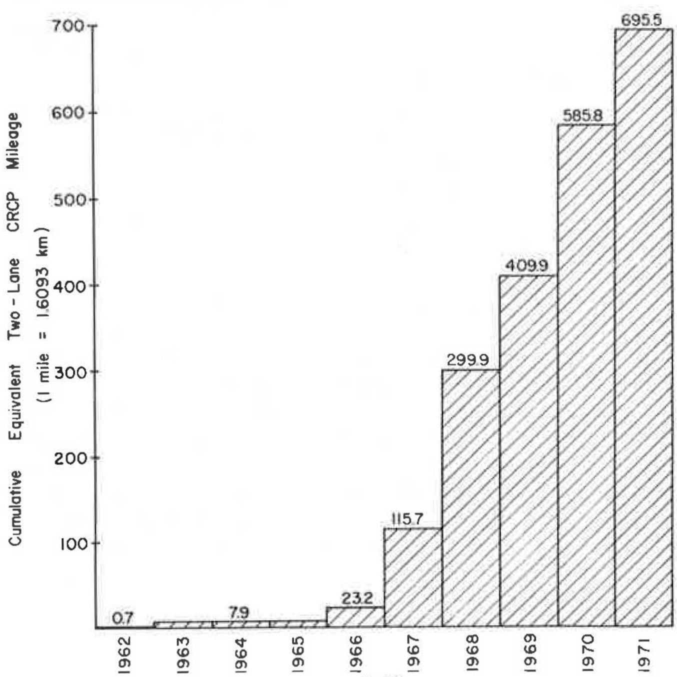


Figure 2. Use of CRCP in Indiana from 1962 to 1971.



In certain cases, more than one survey section was sampled within a particular contract. This apparent duplication resulted whenever a contract crossed more than one level of any other stratification factor. For example, if 2 subgrade types occurred over one contract, 2 sections were included in the survey. Similarly, 2 sections were surveyed if 2 different methods of steel placement were used within a particular contract. Consequently, 89 CRCP sections were used in the survey.

A provision was made in the study design so that some of the sections would be surveyed twice by different survey teams.

Statistical Design

To study the factors influencing the performance of CRC pavements, we used a $2 \times 2 \times 3 \times 4 \times 2$ factorial design with unequal subclass frequencies. A number of covariates or concomitant variables were superimposed on the factorial. The layout of the statistical design is shown in Figure 3, which also indicates the independent factors and their corresponding levels selected for this investigation.

Independent Factors

Method of Paving—This factor had 2 levels: side-formed and slip-formed.

Method of Steel Placement—The method of placing steel reinforcement was subdivided into 2 categories: preset on chairs and placed by mechanical means. The latter was usually accomplished by placing the reinforcement on top of plastic concrete and depressing it to the prescribed depth by a machine that imparts pressure and vibration. Hence, the 2 levels of this factor were labeled as "chairs" and "depressor." Concise description of methods of steel placement are given in other reports (1, 5, 13).

Method of Steel Fabrication—The 3 kinds of steel reinforcement used in CRC pavements formed the 3 levels of this factor: loose reinforcing bars, tied bar mats, and welded deformed wire fabric. The amount of longitudinal steel used was 0.6 percent of the pavement cross-sectional area irrespective of other design factors.

In case of loose bars and tied bar mats, longitudinal reinforcement consisted of No. 5 bars with a center-to-center (c. to c.) spacing of 5.5 in. (14 cm) for a 9-in. (23-cm) thick pavement and a c. to c. spacing of 6.25 in. (16 cm) for 7- and 8-in. (18- and 20-cm) thick pavements. Use of No. 4 bars with a c. to c. spacing of 4 in. (10 cm) for an 8-in. (20-cm) thick pavement and a c. to c. spacing of 4.5 in. (11.4 cm) for a 7-in. (18-cm) thick pavement was also permitted. For transverse reinforcement, No. 4 bars with c. to c. spacing of 3 ft (0.9 m) were used irrespective of pavement thickness. In some cases where steel reinforcement was mechanically placed, transverse steel was omitted. According to Indiana specifications (11), welding of intersections is not permitted on tied bar mats. Furthermore, the mats may be assembled either inside or outside the forms. The reinforcement was required to be deformed billet steel bars.

The longitudinal reinforcement in welded deformed wire fabric consisted of wires of sizes D-16.8, D-19.2, and D-21.6 at 4-in. (10-cm) c. to c. spacing for 7-in. (18-cm), 8-in. (20-cm), and 9-in. (23-cm) thick pavements respectively. For transverse reinforcement, wires of sizes D-4 to D-6 with a c. to c. spacing varying from 12 to 16 in. (30.5 to 41 cm) were used.

Type of Subbase—A variety of subbase materials have been used under CRC pavements in Indiana: gravel, air-cooled or granulated blast furnace slag, crushed stone, and plant-mixed bituminous stabilized aggregate (stone, gravel, or slag) with an asphalt content of 2.5 to 4.5 percent. Both asphalt cement and asphalt emulsions have been used as stabilizing agents. These materials constituted the 4 levels of this factor.

Type of Subgrade—Subgrades were classified into 2 types: fine-grained and granular. This information was obtained from aerial photographic strip maps and an engineering soils map of Indiana (12). The CRC pavements in Indiana traverse a variety of landforms. Of these physiographic units, ground moraines, ridge moraines, lacustrine lake-bed deposits, residual deposits, floodplains, and alluvial deposits were classified as fine-grained parent materials. Gravel terraces, eskers, glacial outwash deposits, beach ridges, and sand dunes were considered as granular parent materials.

Covariates or Concomitant Variables

Covariates or concomitant variables are used in statistical designs to increase the precision of the statistical experiment by removing potential sources of bias in the experiment. In this investigation, it was considered necessary to incorporate some property of concrete and some measure of traffic load applications, for these variables have a considerable effect on distress in concrete pavements. The 2 covariates used in the statistical design were (a) concrete slump measured in inches and obtained from construction survey records and (b) number of months since a pavement section was opened to traffic. The latter variable was used as an indirect measure of load applications.

Response or Evaluated Variables

The following measures of performance were logged by the field survey teams.

1. The term "defect" was used to define all pavement surface features indicative of a failure. The term included breakups, punch-outs, asphalt patches, and concrete patches.
2. Breakups and punch-outs were counted and also estimated in terms of area.
3. Asphalt and concrete patches were counted and also estimated in terms of area.
4. The number of spalled cracks per survey section were counted in terms of 3 qualitative categories: slightly spalled, moderately spalled, and excessively spalled.
5. Parallel cracks, with spacing less than 30 in. (76 cm), and random cracks were evaluated in terms of linear feet of longitudinal length of pavement.
6. Pumping was estimated in terms of linear feet of pavement section length that showed pumping. Pumping was identified by observing discoloration (mud marks) and wet areas on the shoulder.

Supplementary data included the following:

1. Each breakup or a patch together with its accompanying crack pattern and spalling characteristics was sketched on the survey form, and some of these defects were photographed;
2. Any dates marked on the pavement were recorded;
3. Joints (construction or expansion) were sketched and indicated by a station identification; and
4. Identification features such as bridges and interchanges were indicated by a station identification, and remarks relative to unusual soil characteristics (subgrade) were also recorded.

The primary distress variables included parallel cracks, random cracks, spalled cracks, edge pumping, and defects as noted by patching and the like.

The following response variables were used in the study:

1. Number of defects per survey section, i.e., 5,000 ft (1524 m) of pavement;
2. Number of spalled cracks per survey section;
3. Linear feet of longitudinal pavement section showing random cracks and parallel cracks, having a spacing closer than 30 in. (76 cm); and
4. Linear feet of longitudinal pavement section where edge pumping was indicated.

ANALYSIS AND RESULTS

The data obtained from the statewide CRCP condition survey were statistically analyzed by using a weighted least squares analysis of variance procedure. This procedure was necessitated because of unequal subclass cell frequencies in the data. In this situation, the different comparisons with which the sums of squares are associated become nonorthogonal and usual analysis of variance leads to biased test procedures.

The ANOVA results reported in this study were obtained by using the Least Squares and Maximum Likelihood General Purpose Program, a computer program at the Purdue University Computer Center. This program uses a general weighted least squares procedure (9) and can be used for missing value problems where cell frequencies are un-

equal and also where data are not available for certain subclasses. The program only handles main effects and 2-factor interactions, but has provisions for incorporating covariates (concomitant variables) in the analysis.

The following analysis of variance model was used:

$$Y_{ijklmp} = \mu + A_i + B_j + C_k + D_l + F_m + AB_{ij} + AC_{ik} + AD_{il}$$
$$+ AF_{im} + BC_{jk} + BD_{jl} + BF_{jm} + CD_{kl} + CF_{km} + DF_{lm}$$
$$+ \beta_1(S_{ijklmp} - \overline{S}) + \beta_2(T_{ijklmp} - \overline{T}) + \epsilon_{(ijklm)p}$$

where

Y_{ijklmp} = dependent variable, e.g., number of defects;
μ = true mean effect for the population;
A_i = true effect of method of paving (slip-formed versus side-formed);
B_j = true effect of method of steel placement (depressor versus chairs);
C_k = true effect of method of steel fabrication (bar mats versus wire fabric versus loose bars);
D_l = true effect of type of subbase (bituminous-stabilized versus crushed-stone versus slag versus gravel);
F_m = true effect of subgrade soil (granular versus fine-grained);
S_{ijklmp} = linear effect of covariate, slump (in.);
T_{ijklmp} = linear effect of covariate, number of months of traffic;
β_1, β_2 = regression coefficients;
$\overline{S}, \overline{T}$ = mean values of slump and traffic respectively; and
$\epsilon_{(ijklm)p}$ = true error, NID (o, σ^2).

The other terms denote the 2-factor interactions among the factors A, B, C, D, and F. The subscripts assume the following values:

$i = 1, 2;$
$j = 1, 2;$
$k = 1, 2, 3;$
$l = 1, 2, 3, 4;$
$m = 1, 2;$ and
$p = 0$ (missing value) or $1, 2, \ldots, n_{ijklm}$ (unequal subclass numbers).

The model does not take into consideration 3-factor and higher order interactions owing to computer program limitations. Consequently, these interaction effects are confounded with the error effect in this formulation.

A square-root transformation was applied to the data to satisfy the requirement of homogeneity of variance, a basic assumption underlying the analysis of variance procedure. The results of the Foster-Burr Q-test (4) used for testing homogeneity of variance are given in Table 1.

In the analysis of variance, interaction effects and corresponding main effects that were nonsignificant at an α-level of 0.25 were pooled with the error effect, and tests of significance were made by using the pooled error term (2).

Tables 2, 3, 4, and 5 give the results of the analysis of variance. The dependent variables used in the analysis were as follows:

1. Square root of number of defects (asphalt patches, concrete patches, and breakups) per section (Table 2);
2. Square root of number of asphalt patches and breakups per section (Table 3);
3. Square root of number of spalled cracks per section, excluding slightly spalled and excessively spalled cracks (Table 4); and
4. Length of pavement section showing random cracks plus parallel cracks with less than 30 in. (76 cm) spacing, in feet per section (Table 5).

The section length was 5,000 ft (1524 m), and the number of observations was 95.

Figure 3. Factorial design for study of factors influencing CRCP performance.

Type of Subgrade	Type of Subbase	Slipformed, Chairs, Loose Bars	Slipformed, Chairs, Bar Mats	Slipformed, Chairs, Wire Fabric	Slipformed, Depressor, Loose Bars	Slipformed, Depressor, Bar Mats	Slipformed, Depressor, Wire Fabric	Side Formed, Chairs, Loose Bars	Side Formed, Chairs, Bar Mats	Side Formed, Chairs, Wire Fabric	Side Formed, Depressor, Loose Bars	Side Formed, Depressor, Bar Mats	Side Formed, Depressor, Wire Fabric
Fine Grained	Bituminous Stabilized	9,8	8		9,8	8,8	8,8,8						
Fine Grained	Gravel	9,9,9, 8	9,9,9, 9,9,9, 9,8,8, 7,7	9,9,9, 8,8,8		9	9,9,9, 8			9,8,8, 8		8	9,9,9, 9,9,9, 8
Fine Grained	Crushed Stone	9,7,7, 7,7,7, 7		9,9,8			9,8,8, 7		9				9
Fine Grained	Slag					9,8,8, 8	9						9
Granular	Bituminous Stabilized	8			8,8	8,8							
Granular	Gravel		9	8		8	9			9		8	9,9
Granular	Crushed Stone			9			9		9				9
Granular	Slag					8,8							

Numbers in cells denote thickness of CRC pavement in inches.

Table 1. Foster-Burr test for homogeneity of variance.

Response Variable	Avg DF per Sample	Degrees of Freedom	Number of Samples	$Q_{(calculated)}$	$Q_{3,20,0.001}$	Homogeneity of Variance at $\alpha = 0.001$
Defects per section						
Number	3	3	20	0.4205	0.146	Reject
Square root	3	3	20	0.1011	0.146	Accept
Asphalt patches and breakups per section						
Number	3	3	20	0.2273	0.146	Reject
Square root	3	3	20	0.1308	0.146	Accept
Spalled cracks per section						
Number	3	3	20	0.1609	0.146	Reject
Square root	3	3	20	0.0925	0.146	Accept
L_{RC+PC} [a]	3	3	20	0.0913	0.146	Accept

[a] Length of pavement section showing random cracks plus parallel cracks with less than 30-in. (76-cm) spacing, in feet per section.

Table 2. Least squares analysis of variance of number of defects per section.

Source	DF	Sums of Squares	Mean Squares	F	$F_{0.05}$	Significant at $\alpha = 0.05$
Total (uncorrected)	95	102.756				
Main effects						
A_i	1	0.971	0.971	1.77	3.98	—
B_j	1	0.112	0.112	0.21	3.98	—
C_k	2	3.787	1.894	3.46	3.12	Yes
D_l	3	6.527	2.176	3.97	2.74	Yes
F_m	1	0.440	0.440	0.80	3.98	—
Interaction effects						
AB_{ij}	1	1.103	1.103	2.01	3.98	—
AC_{ik}	1	1.073	1.073	1.96	3.98	—
CD_{kl}	5	3.717	0.743	1.36	2.35	—
CF_{km}	2	2.529	1.265	2.31	3.12	—
Covariate effects						
S_{ijklmp}	1	3.114	3.114	5.68	3.98	Yes
T_{ijklmp}	1	1.036	1.036	1.89	3.98	—
$\epsilon_{(ijklm)p}$	75	41.117	0.548			

The extent of pavement distress was evaluated primarily in terms of number of defects. Asphalt patches and breakups were considered separately, for they manifest recent pavement distress. Concrete patches were included in only one evaluation scheme because it was not known exactly when the concrete patches were placed.

Factors Affecting Pavement Distress as Evaluated by Number of Defects per Section

The results of the analysis of variance given in Tables 2 and 3 indicate that

1. The method of steel fabrication and subbase type together with concrete slump have a significant effect on pavement distress as evaluated by the number of defects (concrete patches, asphalt patches, and breakups) observed per section;
2. The method of steel fabrication, the type of subbase, traffic, and the interaction between the methods of paving and placing steel reinforcement have a signfficant influence on pavement distress as determined by the number of asphalt patches and breakups observed per section; and
3. Irrespective of the dependent variable, subgrade type does not appear to have a significant effect on pavement distress.

Factors Affecting Pavement Cracking

A study of data given in Tables 4 and 5 indicates that

1. Spalled cracks are primarily induced by traffic; and
2. The extent of parallel cracks with a crack spacing less than 30 in. (76 cm) and random cracking observed per section of pavement are significantly influenced by traffic and the interaction between methods of paving and placing steel reinforcement.

Detailed Study of Factors Influencing Performance of CRC Pavements

Tables 6 and 7 give further elucidation of the results of analysis of variance given in Tables 2 through 5 and were developed on the basis of these results. These tables show the effect of excluding the data from 2 construction contracts. These contracts were treated separately because one of them developed distress shortly after it was opened to traffic and the other is the oldest CRCP contract (1964) included in this study.

Effect of Subgrade—The analyses indicate that subgrade parent materials had no significant effect on pavement distress or the extent of observed cracking.

Effect of Subbase—The results of data analysis show that subbase type has a major influence on pavement distress. Table 6 gives the effect of subbase on the distribution of defects per section. Bituminous-stabilized and crushed-stone subbases performed significantly better than gravel subbases. Slag subbases showed relatively poor performance. This conclusion needs a slight modification since all the defects related to slag subbases were confined to one construction contract.

Until the statewide condition survey, sections with bituminous-stabilized subbases did not show any significant distress and some sections with crushed-stone subbases showed minor distress. This conclusion should be viewed with caution as bituminous-stabilized subbases were used more recently (primarily 1972) and have not been exposed to the full range of environmental and traffic conditions. Since the time of the condition survey, severe distress has been reported on at least one contract with a bituminous-stabilized subbase.

The type and quality of subbases also have a significant influence on pavement pumping. Yoder (16) indicated that 3 basic conditions must be present to create pumping: frequent repetition of heavy loads, fine-grained material that will go into suspension with water, and free water under the pavement. The effect of subbase on pumping of CRC pavements is given in Table 8. Edge pumping was the primary mode of pavement pumping observed during the field survey, although pumping at cracks has been noted. The extent of observed pavement pumping was divided into 3 categories: no pumping; minor pumping, when pumping was indicated on less than 10 percent of the section

Table 3. Least squares analysis of variance of number of asphalt patches and breakups per section.

Source	DF	Sums of Squares	Mean Squares	F	$F_{0.05}$	Significant at $\alpha = 0.05$
Total (uncorrected)	95	73.363				
Main effects						
A_i	1	0.820	0.820	2.21	3.97	—
B_j	1	0.194	0.194	0.52	3.97	—
C_k	2	2.451	1.225	3.30	3.13	Yes
D_l	3	4.727	1.576	4.25	2.74	Yes
F_m	1	0.678	0.678	1.83	3.97	—
Interaction effects						
AB_{ij}	1	1.526	1.526	4.11	3.97	Yes
AC_{ik}	1	1.209	1.209	3.26	3.97	—
CF_{km}	2	2.013	1.007	2.71	3.13	—
Covariate effects						
S_{ijklmp}	1	1.389	1.389	3.74	3.97	—
T_{ijklmp}	1	1.647	1.647	4.44	3.97	Yes
$\epsilon_{(ijklm)p}$	80	29.670	0.371			

Table 4. Least squares analysis of variance of number of spalled cracks per section.

Source	DF	Sums of Squares	Mean Squares	F	$F_{0.05}$	Significant at $\alpha = 0.05$
Total (uncorrected)	95	147.099				
Main effects						
A_i	1	0.460	0.460	0.51	3.95	—
B_j	1	0.078	0.078	0.09	3.95	—
Interaction effects						
AB_{ij}	1	1.647	1.647	1.82	3.95	—
Covariate effects						
S_{ijklmp}	1	3.105	3.105	3.43	3.95	—
T_{ijklmp}	1	4.414	4.414	4.88	3.95	Yes
$\epsilon_{(ijklm)p}$	89	80.460	0.904			

Table 5. Least squares analysis of variance of length of pavement section showing random cracks plus parallel cracks.

Source	DF	Sums of Squares	Mean Squares	F	$F_{0.05}$	Significant at $\alpha = 0.05$
Total (uncorrected)	95	11 786 128.5				
Main effects						
A_i	1	27 013.3	27 013.3	0.33	3.98	—
B_j	1	43 741.2	43 741.2	0.53	3.98	—
C_k	2	7 983.0	3 991.5	0.05	3.12	—
D_l	3	119 550.5	39 850.2	0.48	2.74	—
F_m	1	201.1	201.1	0.002	3.98	—
Interaction effects						
AB_{ij}	1	458 089.4	458 089.4	5.51	3.98	Yes
BD_{jl}	2	239 911.7	119 955.9	1.44	3.12	—
BF_{jm}	1	198 573.4	198 573.4	2.39	3.98	—
CD_{kl}	5	838 289.3	167 657.9	2.02	2.35	—
Covariate effect						
T_{ijklmp}	1	317 479.5	317 479.5	3.82	3.98	—[a]
$\epsilon_{(ijklm)p}$	76	6 319 783.3	83 155.1			

[a]Significant at $\alpha = 0.10$.

Table 6. Effect of type of subbase on distribution of average number of defects per section.

Subbase	Number of Sections	Concrete Patches, Asphalt Patches, and Breakups	Asphalt Patches and Breakups	Concrete Patches
Gravel	46	1.42	1.08	0.34
	44[a]	0.80	0.74	0.06
Slag[b]	8	0.75	0.62	0.13
Crushed stone	20	0.15	0.15	0.00
Bituminous stabilized	15	0.00	0.00	0.00

[a]Excluding 2 construction contracts.
[b]All defects observed on 1 construction contract.

length; and major pumping, when pumping was indicated on more than 10 percent of the section length.

Data given in Table 8 show that the highest incidence of pumping occurred where gravel subbases were used; no pumping was indicated on sections with slag subbases. Minor pumping was observed on sections with crushed-stone and bituminous-stabilized subbases.

Effect of Type of Steel Reinforcement—Table 7 gives the distribution of average number of defects, average number of spalled cracks, and average length of cracking observed per pavement section for various combinations of construction factors. Conclusions are as follows:

1. Use of bar mats resulted in more defects per section than use of wire fabric or loose bars (this statement should be qualified by the fact that bar mats were used mainly in older CRCP contracts and loose bars were used more recently, primarily 1972);
2. For various combinations of methods of paving and steel placement, use of wire fabric resulted in more widespread cracking; and
3. The use of wire fabric resulted in relatively more distress in slip-formed pavement sections than in side-formed sections.

Effect of Method of Steel Placement—For various combinations of steel type and paving method, a larger number of defects per section were observed when chairs were used as a method of placement (Table 7). This relation breaks down in the case of a combination of a side-formed pavement and bar mats. Here the use of a depressor resulted in a relatively larger number of defects. More cracking was also evidenced in sections where chairs were used for placing steel reinforcement. This relation does not hold for the case of a side-formed pavement reinforced with wire fabric. In this case, use of a depressor resulted in greater amount of cracking.

Effect of Method of Paving—By itself, the method of paving has no significant effect on pavement distress (Table 3). The incidence of cracking was relatively greater in side-formed pavements than in slip-formed pavements for various combinations of steel reinforcement and method of steel placement.

Effect of Traffic—The time that a pavement has been under traffic has a significant effect on pavement distress.

Effect of Concrete Slump—Table 9 gives the effect of slump on the distribution of defects. A higher percentage of sections had defects where the concrete slump was low. The optimum value of slump relative to performance is between 2.0 and 2.5 in. (5.0 to 6.4 cm). With increase in slump, a decrease in the number of defects per section is also indicated. The effect of slump values, greater than 2.5 in. (6.4 cm), on the occurrence of defects should be carefully considered. There were only 6 sections having slump values greater than 2.5 in. (6.4 cm), and these may not be representative of the effect.

Distribution of Defects

Figure 4 shows the frequency distribution of defects observed on 89 sections, each 5,000 ft (1524 m) long, of equivalent 2- or 3-lane CRC pavement.

CONCLUSIONS

Based on a statistical analysis of data collected during a statewide survey of continuously reinforced concrete pavements in Indiana, the following conclusions are presented. The survey was statistically designed wherein each construction contract was required to be in the study. At least 1 survey section 5,000 ft (1524 m) in length was sampled from each contract. In some cases, more than one 5,000-ft (1524-m) section was observed within a construction contract because of the stratification of factors used in the statistical study.

The results of the statewide survey have given some definite indications relative to causes of distress in CRC pavements as will be pointed out below. However, several questions remain unanswered concerning the reasons for distress on certain CRCP sections in the state. In view of this, a continuing field and laboratory study of CRC pavements is currently in progress at Purdue University.

Table 7. Effect of method of construction on distribution of average number of defects and spalled cracks and average length of cracking.

Paving	Number of Sections	Concrete Patches, Asphalt Patches, and Breakups	Asphalt Patches and Breakups	Length of Cracking[a] (ft)	Spalled Cracks	Years of Traffic
Slip-formed						
Loose bars						
Depressor	4	0.0	0.0	191.5	0.25	1.04
Chairs	13[b]	0.15	0.15	464.2	0.77	0.61
	14	1.5	0.64	478.8	1.14	0.63
Wire fabric						
Depressor	14	0.53	0.53	308.3	0.43	0.54
Chairs	11	0.64	0.55	596.8	3.82	1.62
Bar mats						
Depressor	12	0.67	0.58	191.1	0.92	0.41
Chairs	13	1.08	1.0	543.5	2.89	2.21
Side-formed						
Wire fabric						
Depressor	12	0.08	0.08	669.4	2.46	1.97
Chairs	4[c]	0.25	0.25	383.5	2.75	1.62
	5	2.4	2.2	508.0	6.40	2.92
Bar mats						
Depressor	2	1.0	1.0	412.0	0.00	0.25
Chairs	2	0.50	0.50	866.0	0.67	3.25

[a] Longitudinal pavement length showing parallel cracks less than 30-in. (76-cm) spacing plus longitudinal pavement length showing random cracking.
[b] Exluding the contract that showed immediate distress.
[c] Exluding the oldest CRCP contract.

Table 8. Effect of subbase type on amount of pumping in CRCP sections.

Subbase	Number of Sections	No Pumping		Minor Pumping		Major Pumping	
		Percent	Number	Percent	Number	Percent	Number
Gravel	46	56.5	26	34.7	16	8.8	4
Crushed stone	20	90.0	18	10.0	2	-	-
Bituminous stabilized	15	93.3	14	6.7	1	-	-
Slag	8	100.0	8	-	-	-	-

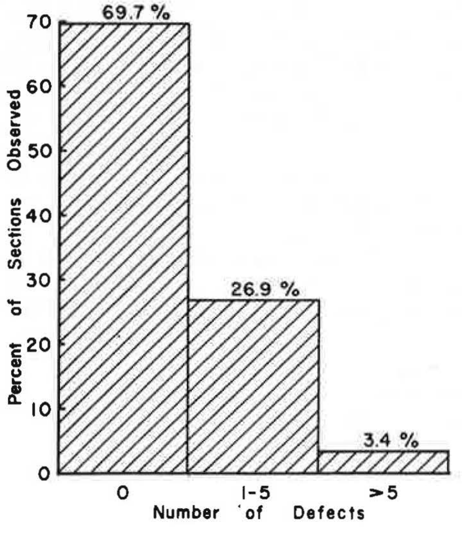
Table 9. Effect of slump on distribution of defects among sections.

Slump (in.)	Number of Section Surveyed	Sections With No Defects	Sections With Defects		
			Number	Percent	Number per Section[a]
1.0-1.5	31	17	14	42.2	2.9
1.5-2.0	39	29	10	25.6	3.2
2.0-2.5	13	11	2	15.4	1.0
2.5-3.0	4	3	1	25.0	1.0
>3.0	2	2	0	0.0	0.0

Note: 1 in. = 2.5 cm.

[a] Only section with defects considered.

Figure 4. Frequency distribution of defects observed in the statewide CRCP survey.



The following conclusions pertain to the effect of various factors influencing the performance of CRC pavements in Indiana.

1. Subbase type was found to be a significant contributor to the performance of CRC pavements; gravel subbases showed the poorest performance. Crushed stone and slag subbases have, in general, shown good performance, and until the survey the bituminous-stabilized subbases showed little or no distress. However, since the survey was conducted, some breakup has been encountered on at least one bituminous-stabilized subbase.
2. Depressed steel performed significantly better than preset steel used on chairs.
3. All other factors being constant, loose bars and welded wire fabric showed good performance. Bar mats showed the poorest performance, but this type of steel was used mainly on some of the earlier projects and, thus, these pavements have been exposed to a wider range of environmental and traffic conditions.
4. Concrete slump has a significant effect on pavement performance; the optimum slump range was between 2.0 and 2.5 in. (5.0 to 6.4 cm). Slump values of 1.5 in. (3.8 cm) and greater have shown good results.
5. Pavements that were side-formed performed the same as those that were slip-formed.
6. Much of the distress takes place during the cold months of the year, suggesting that extreme temperature drops have a major effect on performance.
7. Distress of CRC pavements is associated with traffic which apparently is on the increase in Indiana.
8. The primary mode of pumping of CRC pavements is edge pumping. The results of the condition survey indicate that pavements with gravel subbases are more susceptible to pumping. Pavements with crushed-stone and bituminous-stabilized subbases have shown some indication of pumping; pavements with slag subbases have not pumped.
9. Subgrade parent material type (granular or fine-grained) was not a significant contributor to performance of CRC pavements. This refers to type of subgrade and not to other factors such as degree of compaction.

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