FACTORS INFLUENCING THE PERFORMANCE OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

DECEMBER 1973 - NUMBER 30

BY

ASIF FAIZ
E. J. YODER

JHRP

JOINT HIGHWAY RESEARCH PROJECT
PURDUE UNIVERSITY AND
INDIANA STATE HIGHWAY COMMISSION

Technical Paper

FACTORS INFLUENCING THE PERFORMANCE OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

TO: J. F. McLaughlin, Director
Joint Highway Research Project

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

December 13, 1973

Project: C-36-52J

File: 6-20-10

The attached Technical Paper "Factors Influencing the Performance of Continuously Reinforced Concrete Pavements" has been prepared by Messrs Asif Faiz and E. J. Yoder of our staff. They plan to present it to the 1974 Annual Highway Research Board meeting and to then offer it for publication.

The paper reports a portion of the research being performed by the Joint Highway Research Project on reinforced concrete pavement deterioration. The paper include results of analysis of a statewide condition survey and an evaluation of the effects of subbase and subgrade type, the methods of paving, steel placement and steel fabrication, concrete slump and traffic on performance.

The paper is submitted for information and for approval of publication.

Respectfully submitted,

Harold L. Michael

Harold L. Michael
Associate Director

HLM:mw

cc: W. L. Dolch
R. L. Eskew
G. D. Gibson
W. H. Goetz
M. J. Gutzwiller
G. K. Hallock
R. H. Harrell
M. L. Hayes
C. W. Lovell
G. W. Marks
R. D. Miles
G. T. Satterly
C. F. Scholer
M. B. Scott
J. A. Spooner
N. W. Steinkamp
H. R. J. Walsh
E. J. Yoder

PREPRINT
-NOT FOR PUBLICATION-

Technical Paper

FACTORS INFLUENCING THE PERFORMANCE OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

by

Asif Faiz
Graduate Instructor

and

E. J. Yoder
Professor of Highway Engineering

Joint Highway Research Project
Project: C-36-52J
File: 6-20-10

A paper submitted to the Highway Research Board for presentation at the 53rd Annual Meeting, Washington, D.C., January 1974. Research reported was sponsored by the Indiana State Highway Commission

Purdue University
Lafayette, Indiana
December 13, 1973

ABSTRACT

FACTORS INFLUENCING THE PERFORMANCE OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

by

Asif Faiz and Eldon J. Yoder

A statewide condition survey of continuously reinforced concrete pavements was conducted in Indiana in 1972. The survey was statistically designed and the resulting data were analyzed by using a weighted least squares analysis of variance procedure. The results of the survey were used 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 measure of performance was extent of failures, parallel cracks with less than 30 in. (76 cm) crack spacing, random cracks, spalled cracks and edge pumping.

The results of the statistical analysis show that subbase type, the 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 as compared with the use of tied bar mats. Depressed steel resulted in superior performance than using steel preset on chairs. The data showed little difference between performance of pavements that were slipformed as compared to those which were side formed. Relative to good performance, an optimum range of concrete slump between 2.0 to 2.5 in. (5.0 to 6.5 cm) was indicated. It was further noted that 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.

INTRODUCTION

During the past several years use of continuously reinforced concrete pavements (CRCP) has increased considerably. It is of interest to note that the first experimental continuously reinforced concrete pavement was built in 1938 on US 40 near Stilesville, Indiana. Over the next 20 years, a number of research oriented CRCP projects were built at various locations in the United States. Illinois and New Jersey constructed experimental test sections in 1947. Two years later California built a similar project. In 1951, portions of the Fort Worth freeways in Texas were constructed with continuously reinforced concrete. This was followed by other CRC pavements in Texas in 1955 and 1957. In addition, Pennsylvania constructed two continuously reinforced concrete projects in 1956 and 1957.

As of 1958, there were 79 miles (127 km) of equivalent two-lane CRC pavement in the United States. Since then the use of CRC pavements in highway construction has been on the increase with the result that more than 10,000 miles (16000 km) of equivalent two-lane pavement were in use or under contract in thirty-three states at the end of 1971 (10).

Outside the United States, a number of countries have built CRC pavements. Notable among these are Belguim, West Germany, the Netherlands, Sweden and Switzerland. The Road Research Laboratory (U.K.) has investigated the use of CRC bases under asphalt surface courses (3). Belguim built its first experimental CRC pavement in 1950 and has recently decided to undertake such construction over a total of 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 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 continuously reinforced concrete pavement constructed in Indiana up to the summer of 1972. The first pavement, as was mentioned previously, was built on an experimental basis in 1938. Several short sections of pavement were constructed in the mid-60's. During the past several years many additional miles of continuously reinforced 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 nine inches (23 cm) thick although some have been constructed seven (18 cm) and eight inches (20 cm) in thickness. For the most part, nonstabilized granular subbases have been used under the pavement, although in recent years the trend has been towards the use of asphalt-treated subbases in most situations.

Various types of steel placement and construction (formed or slipformed) 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 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

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

Sampling Procedure

In order to attain the above objectives, 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 signficant 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 the sense 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 5000 feet (1524 m) length of pavement. The location, relative to the direction of lanes, and beginning of each section was selected from the total length of CRC pavement, falling under each stratum, by the use of random number tables. Care was taken that a randomly selected pavement length was located approximately 200 - 300 feet (60 - 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:

1. Contract
2. Method of Paving
3. Method of Steel Placement
4. Method of Steel Fabrication
5. Type of Subbase
6. Subgrade Type

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.

It is to be noted that most of the pavements were 9 inches (23 cm) thick, although several were 8 inches (20 cm) thick and nine of the sections had a thickness of 7 inches (18 cm).

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 two subgrade types occurred over one contract, two sections were included in the survey. Similarly, two sections were surveyed if two different methods of steel placement were used within a particular contract. Consequently, a total of 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

In order to study the factors influencing the performance of CRC pavements, a 2x2x3x4x2 factorial design with unequal subclass frequencies was used. A number of covariates or concomitant variables were superimposed on the factorial. The layout of the statistical design is shown in Table 1, which also indicates the independent factors and their corresponding levels selected for this investigation.

Independent Factors

1. Method of Paving. This factor had two levels;
    a. Side Formed
    b. Slipformed
2. Method of Steel Placement. The method of placing steel reinforcement was subdivided into two categories:
    a. Pre-set on chairs.

TABLE I FACTORIAL DESIGN FOR STUDY OF FACTORS INFLUENCING CRCP PERFORMANCE

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

Numbers in cells denote thickness of CRC pavement in inches.

b. Placed by mechanical means. This was usually accomplished by placing the reinforcement on top of plastic concrete and depressing it to the prescribed depth by a machine which imparts pressure and vibration.

Hence, the two levels of this factor were labeled as "chairs" and "depressor". Concise description of methods of steel placement are given in references (1), (5), and (13).

3. Method of Steel Fabrication. The three kinds of steel reinforcement used in CRC pavements formed the three levels of this factor. These were:

a. Loose Reinforcing Bars

b. Tied Bar Mats

c. 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 c/c spacing of 5.5 in. (14 cm) for a 9 in. (23 cm) thick pavement and a c/c spacing of 6.25 in. (16 cm) for 7 in. (18 cm) and 8 in. (20 cm) thick pavements. Use of No. 4 bars, with a c/c spacing of 4 in. (10 cm) for an 8 in. (20 cm) thick pavement and a c/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 at 3 feet (0.9 m) c/c spacing were used irrespective of pavement thickness. In some cases where steel reinforcement was mechancially 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/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/c spacing varying from 12 in. (30.5 cm) to 16 in. (41 cm) were used.

4. Type of Subbase. A variety of subbase materials have been used under CRC pavements in Indiana. These are:
   a. Gravel
   b. Air cooled or granulated blast furnace slag
   c. Crushed stone
   d. 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.

   The above materials constituted the four levels of this factor.
5. Type of Subgrade. Subgrades were classified into two types namely:
   a. Fine grained, and
   b. 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, flood plains 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 as these variables have a considerable effect on distress in concrete pavements. The two covariates used in the statistical design were:

a. Concrete slump measured in inches. This information was obtained from construction survey records.

b. Number of months since a pavement section was opened to traffic. This variable was used as an indirect measure of load applications.

Response or Evaluated Variables

Table 2 shows a listing of features that were logged by the field survey teams. The primary distress variables included

TABLE 2. DATA OBTAINED DURING STATEWIDE CONDITION SURVEY OF CRC PAVEMENTS

Measures of Performance:

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

Supplementary Data:

1. Each breakup or a patch together with its accompanying crack pattern and spalling characteristics was sketched on the survey form. 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.
4. Identification features such as bridges, interchanges, etc. were indicated by a station identification. Remarks relative to unusual soil characteristics (subgrade) were also recorded.

parallel cracks, random cracks, spalled cracks, edge pumping, and defects as noted by patching etc.

The following response variables were used in the study:

a. Number of defects per survey section i.e. 5000 ft. (1524 m) length of pavement.

b. Number of spalled cracks per survey section.

c. Linear feet of longitudinal pavement section showing random cracks and parallel cracks, having a spacing closer than 30 inches (76 cm).

d. Linear feet of longitudinal pavement section where edge pumping was indicated.

Defect is a generic term used in this study to define all pavement surface features indicative of a failure. The term includes severely distressed locations such as breakups and punchouts or those locations that had been previously patched with asphalt or portland cement concrete.

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 sub-class cell frequencies in the data. In this situation, the different comparisons with which the sums of squares are associated become non-orthogonal and usual analysis of variance leads to biased test procedures.

The ANOVA results reported in this study were obtained by using LSMLGP (Least Squares and Maximum Likelihood General Purpose Program), a computer program at the Purdue University Computer

Center. This program utilizes a general weighted least squares procedure (9) and can be used for missing value problems, where cell frequencies are unequal and, also where data are not available for certain subclasses. The program only handles main effects and two-factor interactions, but has provisions for incorporating covariates (concomitant variables) in the analysis.

To study the effect of factors influencing the performance of CRC pavements, the following analysis of variance model was used.

$$
\begin{aligned}
Y_{ijk\ell mp} = {} & \mu + A_i + B_j + C_k + D_\ell + F_m + AB_{ij} + AC_{ik} + AD_{i\ell} \\
& + AF_{im} + BC_{jk} + BD_{j\ell} + BF_{jm} + CD_{k\ell} + CF_{km} + DF_{\ell m} \\
& + \beta_1(S_{ijk\ell mp} - \bar{S}) + \beta_2(T_{ijk\ell mp} - \bar{T}) + \varepsilon_{(ijk\ell m)p}
\end{aligned}
$$

where

$Y_{ijk\ell mp}$ = dependent variable, e.g., No. of defects,

μ = true mean effect for the population,

A_i = true effect of method of paving (slipformed vs. sideformed),

B_j = true effect of method of steel placement (depressor vs. chairs),

C_k = true effect of method of steel fabrication, (bar mats vs. wire fabric vs. loose bars),

D_ℓ = true effect of type of subbase (bituminous stabilized vs. crushed stone vs. slag vs. gravel),

F_m = true effect of subgrade soil (granular vs. fine-grained),

$S_{ijk\ell mp}$ = linear effect of covariate, slump (in),

$T_{ijk\ell mp}$ = linear effect of covariate, number of months of traffic,

β_1, β_2 = regression coefficients

$\bar{S}$, $\bar{T}$ = mean values of slump and traffic respectively,

$\varepsilon_{(ijk\ell m)p}$ = true error, NID(o, σ^2).

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

$i = 1,2$

$j = 1,2$

$k = 1,2,3$

$\ell = 1,2,3,4$

$m = 1,2$

$p = 0$ (missing value), or
$1,2....n_{ijk\ell m}$ (unequal sub-class 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.

In analyzing some of the measured variables, 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 shown in Table 3.

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

Tables 4 through 7 summarize the results of analysis of variance. The dependent variables used in the analysis were:

TABLE 3: FOSTER-BURR TEST FOR HOMOGENEITY OF VARIANCE

Response Variable	Average DF Per Sample	Degrees of Freedom	No. of Samples	Q (calculated)	$Q_{3,20,0.001}$	Homogeneity of Variance at $\alpha = 0.001$
1. No. of Defects per Section	3	3	20	.4205	.146	REJECT
2. Square Root of No. of Defects per Section	3	3	20	.1011	.146	ACCEPT
3. No. of Asphalt Patches and Breakups per Section	3	3	20	.2273	.146	REJECT
4. Square Root of No. of Asphalt Patches and Breakups per Section	3	3	20	.1308	.146	ACCEPT
5. No. of Spalled Cracks per Section	3	3	20	.1609	.146	REJECT
6. Square Root of No. of Spalled Cracks per Section	3	3	20	.0925	.146	ACCEPT
7. L_{RC+PC} (ft. per section)	3	3	20	.0913	.146	ACCEPT

L_{RC+PC} = Length of Pavement Section showing random cracks plus parallel cracks with less than 30 in. (76 cm) spacing, in feet per section.

1. Square root of number of defects (asphalt patches, concrete patches and breakups) per section, . (Table 4)
2. Square root of number of asphalt patches and breakups per section, ... (Table 5)
3. Square root of number of spalled cracks per section, ... (Table 6)
4. Length of pavement section showing random cracks plus parallel cracks with less than 30 in. (76 cm) spacing, in feet per section . . . . (Table 7)

The above variables are defined in Table 2. The extent of pavement distress was evaluated primarily in terms of number of defects. Asphalt patches and breakups were considered separately as these manifest recent pavement distress. Concrete patches were included in only one evaluation scheme, since it was not known exactly when the concrete patches were placed.

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

It is indicated by the results of the analysis of variance shown in Tables 4 and 5 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 placement of steel reinforcement have a significant influence on pavement distress as determined by the number

TABLE 4. LEAST SQUARES ANALYSIS OF VARIANCE
(Number of Defects Per Section)

Source	DF	Sums of Squares	Mean Squares	F	$F_{.05}$	Significance
Total(uncorrected)	95	102.756				
<u>Main Effects</u>:						
Paving (A_i)	1	0.971	0.971	1.79	3.97	-
Steel (C_k)	2	3.787	1.894	3.50	3.13	S
Subbase (D_ℓ)	3	6.527	2.176	4.02	2.74	S
<u>Interaction Effects</u>:						
Paving x Placement (AB_{ij})	1	1.103	1.103	2.04	3.97	-
Paving x Steel (AC_{ik})	1	1.073	1.073	1.98	3.97	-
Steel x Subbase ($CD_{k\ell}$)	5	3.717	0.743	1.37	2.35	-
Steel x Subgrade (CF_{km})	2	2.529	1.265	2.34	3.13	-
<u>Covariate Effects</u>:						
*Slump, Linear Effect ($S_{ijk\ell mp}$)	1	3.114	3.114	5.75	3.97	S
**Traffic, Linear Effect ($S_{ijk\ell mp}$)	1	1.036	1.036	1.91	3.97	-
Error (Pooled), $\varepsilon_{(ijk\ell m)p}$	77	41.669	0.541			

Dependent Variable Y = Square Root of Number of Defects Per Section

Defect = A Breakup, an Asphalt Patch or a Concrete Patch

Section Length = 5000 ft. (1524 m)

Number of Observations = 95

Level of Significance = α = .05

S = Significant

*Slump in inches

**Traffic in months

TABLE 5. LEAST SQUARES ANALYSIS OF VARIANCE

(Number of Asphalt Patches and Breakups Per Section)

Source	DF	Sums of Squares	Mean Squares	F	$F_{.05}$	Significance
Total (uncorrected)	95	73.363				
<u>Main Effects</u>:						
Paving (A_i)	1	0.820	0.820	2.22	3.97	-
Steel (C_k)	2	2.451	1.225	3.32	3.13	S
Subbase (D_ℓ)	3	4.727	1.576	4.27	2.74	S
Subgrade (F_m)	1	0.678	0.678	1.84	3.97	-
<u>Interaction Effects</u>:						
Paving x Placement (AB_{ij})	1	1.526	1.526	4.14	3.97	S
Paving x Steel (AC_{ik})	1	1.209	1.209	3.28	3.97	-
Steel x Subgrade (CF_{km})	2	2.013	1.007	2.73	3.13	-
<u>Covariate Effects</u>:						
*Slump, Linear Effect ($S_{ijk\ell mp}$)	1	1.389	1.389	3.77	3.97	-
**Traffic, Linear Effect ($T_{ijk\ell mp}$)	1	1.647	1.647	4.47	3.97	S
Error (Pooled), $\epsilon_{(ijk\ell m)p}$	81	29.864	0.369			

Dependent Variable Y = Square Root of Number of Asphalt Patches and Breakups per Section

Section Length = 5000 ft. (1524 m)

Number of Observations = 95

Level of Significance = α = .05

S = Significant

*Slump in inches

**Traffic in months

TABLE 6. LEAST SQUARES ANALYSIS OF VARIANCE
(Number of Spalled Cracks Per Section)

Source	DF	Sums of Squares	Mean Squares	F	$F_{.05}$	Significance
Total (uncorrected)	95	147.099				
<u>Interaction Effect</u>:						
Paving x Placement (AB_{ij})	1	1.647	1.647	1.85	3.95	-
<u>Covariate Effects</u>:						
*Slump, Linear Effect ($S_{ijk\ell mp}$)	1	3.105	3.105	3.49	3.95	-
**Traffic, Linear Effect ($T_{ijk\ell mp}$)	1	4.414	4.414	4.96	3.95	S
Error (Pooled), $\varepsilon_{(ijk\ell m)p}$	91	80.998	0.890			

Dependent Variable Y = Square Root of Number of Spalled Cracks Per Section (Excluding slightly spalled and excessively spalled cracks)

Section Length = 5000 ft. (1524 m)

Number of Observations = 95

Level of Significance = α = .05

S = Significant

*Slump in inches

**Traffic in months

TABLE 7. LEAST SQUARES ANALYSIS OF VARIANCE

(Length of Pavement Section Showing Random Cracks Plus Parallel Cracks)

Source	DF	Sums of Squares	Mean Squares	F	$F_{.05}$	Significance
Total (uncorrected)	95	11786128.5				
<u>Interaction Effects</u>:						
Paving x Placement (AB_{ij})	1	458089.4	458089.4	5.90	3.96	S
Placement x Subbase ($BD_{j\ell}$)	2	239911.7	119955.9	1.55	3.12	-
Placement x Subgrade (BF_{jm})	1	198573.4	198573.4	2.56	3.96	-
Steel x Subbase ($CD_{k\ell}$)	5	838289.3	167657.9	2.16	2.34	-
<u>Covariate Effect</u>:						
*Traffic, Linear Effect ($T_{ijk\ell mp}$)	1	317479.5	317479.5	4.09	3.96	S
Error (Pooled), $\varepsilon_{(ijk\ell m)p}$	84	6518272.4	77598.5			

Dependent Variable Y = Length of Pavement Section Showing Random Cracks Plus Parallel Cracks with Spacing Less Than 30 in. (76 cm), in Feet Per Section.

Section Length = 5000 ft. (1524 m)

Number of Observations = 95

Level of Significance = α = .05

S = Significant

*Traffic in months

of asphalt patches and breakups observed per section.

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 tables 6 and 7 indicates that:

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

Detailed Study of Factors Influencing Performance of CRC Pavements

Tables 8 and 9 further elucidate the results of analysis of variance shown in Tables 4 through 7 and were developed on the basis of these results. In these tables, two separate columns are provided to show the effect of excluding the data from two construction contracts. These contracts were treated separately because one of them developed distress shortly after it was opened to traffic, while the other is the oldest CRCP contract (1964) included in this study.

1. Effect of Subgrade. The analyses indicate that subgrade parent material had no significant effect on pavement distress or the extent of observed cracking.
2. Effect of Subbase. The results of data analysis show that subbase type has a major influence on pavement

TABLE 8. EFFECT OF TYPE OF SUBBASE ON THE DISTRIBUTION OF DEFECTS PER SECTION

	Type of Subbase				
	Gravel		Slag**	Crushed Stone	Bituminous Stabilized
Average No. of Defects (Concrete Patches, Asphalt Patches and Breakups) per Section.	1.42 (46)	0.80* (44)	0.75 (8)	0.15 (20)	0.00 (15)
Average No. of Asphalt Patches and Breakups per Section.	1.08 (46)	0.74* (44)	0.62 (8)	0.15 (20)	0.00 (15)
Average No. of Concrete Patches per Section.	0.34 (46)	0.06* (44)	0.13 (8)	0.00 (20)	0.00 (15)

*Excluding two construction contracts.

**All defects were observed on just one construction contract.

Numbers in Parentheses are Number of Sections Included in the Average.

TABLE 9 EFFECT OF METHOD OF CONSTRUCTION ON DISTRIBUTION OF DEFECTS, SPALLED CRACKS AND LENGTH OF CRACKING

Type of Paving	Slipformed							Side Formed				
Method of Steel Fabrication	LB			WF		BM		WF			BM	
Method of Steel Placement	Dp	Ch		Dp	Ch	Dp	Ch	Dp	Ch		Dp	Ch
Ave. No. of Defect (Concrete Patches, Asphalt Patches and Breakups) per Section	0.0 (4)	0.15* (13)	1.5 (14)	0.53 (14)	0.64 (11)	0.67 (12)	1.08 (13)	0.08 (12)	0.25** (4)	2.4 (5)	1.0 (2)	0.50 (2)
Ave. No. of Asphalt Patches and Breakups per Section	0.0 (4)	0.15* (13)	0.64 (14)	0.53 (14)	0.55 (11)	0.58 (12)	1.0 (13)	0.08 (12)	0.25** (4)	2.2 (5)	1.0 (2)	0.50 (2)
†Ave. Length of Cracking per Section in feet	191.5 (4)	464.2* (13)	478.8 (14)	308.3 (14)	596.8 (11)	191.1 (12)	543.5 (13)	669.4 (12)	383.5** (4)	508.0 (5)	412.0 (2)	866.0 (2)
Ave. No. of Spalled Cracks per Section	0.25 (4)	0.77* (13)	1.14 (14)	0.43 (14)	3.82 (11)	0.92 (12)	2.89 (13)	2.46 (12)	2.75** (4)	6.40 (5)	0.00 (2)	0.67 (2)
Ave. No. of Years of Traffic per Section	1.04 (4)	0.61* (13)	0.63 (14)	0.54 (14)	1.62 (11)	0.41 (12)	2.21 (13)	1.97 (12)	1.62** (4)	2.92 (5)	0.25 (2)	3.25 (2)

* Excluding the contract that showed immediate distress.

** Excluding the oldest CRCP contract.

† Longitudinal Pavement Length Showing Parallel Cracks Less than 30" (76 cm.) Spacing, Plus Longitudinal Pavement Length Showing Random Cracking

Numbers in Parentheses are number of sections included in the average

Method of Steel Fabrication

LB: Loose Bars
WF: Wire Fabric
BM: Bar Mats

Method of Steel Placement

Dp: Depressor
Ch: Chairs

distress. Table 8 shows the effect of subbase on the distribution of defects per section. It is indicated that the use of bituminous stabilized and crushed stone subbases resulted in significantly better performance than the use of gravel subbases. It is further indicated that 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.

Up to the time of the statewide condition survey, sections with bituminous stabilized subbases did not show any significant distress while 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 three basic conditions must be present to create pumping. These are (a) frequent repetition of heavy loads (b) fine-grained material that will go into suspension with water and (c) free water under the pavement. The effect of subbase on pumping of CRC pavements is shown in Table 10. It may be noted that 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 three categories namely:

TABLE 10: EFFECT OF SUBBASE TYPE ON CRC PAVEMENT PUMPING

Type of Subbase	Percentage of Survey Sections Showing		
	No Pumping	Minor Pumping*	Major Pumping**
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)	--- ---	--- ---

Numbers in Parenthesis are Number of Field Survey Sections Falling in the Category indicated.

*Pumping indicated on less than 10 percent of the section length.

**Pumping indicated on more than 10 percent of the section length.

a) No pumping observed on the survey section.

b) Minor pumping, when pumping was indicated on less than 10 percent of the section length.

c) Major pumping, when pumping was indicated on more than 10 percent of the section length.

Table 10 shows that the highest incidence of pumping occured where gravel subbases were used while no pumping was indicated on sections with slag subbases. Minor pumping was observed on sections with crushed stone and bituminous stabilized subbases.

3. Effect of Type of Steel Reinforcement. Table 9 indicates 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.

From the results presented in this table, it may be concluded:

a) That use of bar mats resulted in more defects per section than the use of wire fabric or loose bars. This statement should be qualified by the fact that use of bar mats was confined mainly to older CRCP contracts while the use of loose bars is more recent (primarily 1972).

b) For various combinations of methods of paving and steel placement, use of wire fabric resulted in more widespread cracking.

c) The use of wire fabric resulted in relatively more distress in slipformed pavement sections than in side formed sections.

4. Effect of Method of Steel Placement. For various combinations of steel type and paving method, it would be noticed in Table 9 that a larger number of defects per section were observed where chairs were used as a method of placement. This relationship breaks down in one case where a combination of a side formed pavement with bar mats was used. 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 relationship does not hold for the case where a side formed pavement, reinforced with wire fabric was used. In this case, use of a depressor resulted in greater amount of cracking.
5. Effect of Method of Paving. Table 5 shows that, by itself, the method of paving has no significant effect on pavement distress. Relative to pavement cracking, it is indicated that the incidence of cracking was relatively greater in side formed pavements as opposed to slipformed pavements for various combinations of steel reinforcement and method of steel placement.
6. Effect of Traffic. The time that a pavement has been under traffic has a significant effect on pavement distress.
7. Effect of Concrete Slump. Table 11 indicates the effect of slump on distribution of defects, where defects are defined as the number of concrete patches, asphalt

TABLE 11. EFFECT OF SLUMP ON DISTRIBUTION OF DEFECTS

Slump	Number of Section Surveyed	Number of Sections With No Defects	Number of Sections With Defects	Percent Sections With Defects	Number of Defects Per Section*
1.0-1.5 in. (2.5-3.8 cm)	31	17	14	42.2	2.9
1.5-2.0 in. (3.8-5.0 cm)	39	29	10	25.6	3.2
2.0-2.5 in. (5.0-6.4 cm)	13	11	2	15.4	1.0
2.5-3.0 in. (6.4-7.6 cm)	4	3	1	25.0	1.0
>3.0 in. (7.6 cm)	2	2	0	0.0	0.0

*Only Considering Section With Defects

patches, and breakups per section. It may be concluded from Table 11 that a higher percentage of sections had defects where the concrete slump was low. From this table, it further appears that the optimum value of slump relative to performance is between 2.0-2.5 inches (5.0-6.4 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 inches (6.4 cm), on the occurrence of defects should be carefully considered. There were only six sections having slump values greater than 2.5 inches (6.4 cm) and these may not be representative of the effect.

Distribution of Defects

Figure 3 shows the frequency distribution of defects observed in the statewide CRCP survey where defects are defined as the number of concrete patches, asphalt patches and breakups. This distribution shows that:

1. 69.7% of CRCP sections surveyed did not show any defects.
2. 26.9% of CRCP sections had from one to five defects per section.
3. 3.4% of CRCP sections had more than five defects per section.

This information was based on 89 sections, each 5,000 ft. (1524 m) long, of equivalent two-lane or three-lane CRC pavement.

CONCLUSIONS

Based upon a statistical analysis of data collected during a statewide survey of continuously reinforced concrete pavements in Indiana the following conclusions are presented. It should be kept in mind that the survey was statistically designed wherein each construction contract was required to be in the study. At least one survey section 5000 ft. (1524 m) in length was sampled from each contract. In some cases, more than one 5,000 ft. (1524 m) section were 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.

Significant Factors Affecting Performance

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

1. Subbase Type. Subbase type was found to be a significant contributor to the performance of CRC pavements, with gravel subbases showing the poorest performance. Crushed stone and slag subbases have, in general, shown good performance and up to the time of 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. Method of Steel Placement. Depressed steel was shown to have significantly better performance than preset steel used on chairs.
3. Steel Fabrication. All other factors being constant, (type of subbase, method of construction, etc.), loose bars and welded wire fabric have shown good performance. Bar mats showed the poorest performance, but as was pointed out earlier, 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. Concrete slump has a significant effect on pavement performance with an optimum slump range between 2.0 to 2.5 inches (5.0-6.4 cm). Slump values of 1.5 inches (3.8 cm) and greater have shown good results.
5. Method of Paving. The data showed little difference between performance of pavements that were constructed using side forms compared to those which were slipformed.
6. Temperature. It has been observed that 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. Traffic. Distress of CRC pavements is associated with traffic and apparently is on the increase in Indiana.
8. Pumping. The primary mode of pumping of CRC pavements has been observed to be edge pumping. The results of the condition survey indicate that pavements with gravel subbases are more susceptible to pumping. Pavements with crushed stone and bitumunous stabilized subbases have shown some indication of pumping while pavements with slag subbases have not pumped.
9. Subgrade. The results have suggested that subgrade parent material type (granular or fine-grained) was not a significant contributor to performance of CRC pavements. This refers to <u>type</u> of subgrade and not degree of compaction etc.

REFERENCES

1. Aaron, H., "Continuously Reinforced Concrete Pavements - United States Practice". 1st European Symposium on Concrete Pavements, Paris, July 1969, Vol. 2, pp. 127-140.
2. Anderson, V. L., and McLean, R. A., "A Realistic Approach to Designing Experiments". Unpublished Course Notes, Department of Statistics, Purdue University, 1972.
3. Burks, E., "Continuously Reinforced Paving as a Base for Asphalt Running Surface". 1st European Symposium on Concrete Pavements, Paris, July 1969, Vol. 2, pp. 141-150.
4. Burr, I. W., and Foster, L. A., "A Test for Equality of Variances", Department of Statistics, Purdue University Mimeograph Series No. 282, April 1972.
5. Continuously Reinforced Pavement Group, "Design and Construction - Continuously Reinforced Concrete Pavement". Chicago 1968, pp. 48-58.
6. Dames, T. A., "The Urban Planning Process", Joint Highway Research Project, Purdue University, Research Report No. 22, July 1972, pp. 92-100.
7. Deming, W. E., "Some Theory of Sampling". Dover Publications Inc., New York, 1950, pp. 213-214.
8. Doyen, A., Hofmann, M., and Van Ael, P., "Pavements of Continuous Reinforced Concrete in Belguim". 1st European Symposium on Concrete Pavements, Paris, July 1969, Vol. 2, pp. 162-163.
9. Harvey, W. R., "Least-Squares Analysis of Data with Unequal Subclass Frequencies". USDA, Agriculture Research Service, ARS 20-8, 1960.

10. Highway Research Board, "Continuously Reinforced Concrete Pavements", NCHRP Synthesis of Highway Practice No. 16, 1973 pp. 2-3.

11. Indiana State Highway Commission, "Standard Specifications", 1971, pp. 483-485.

12. Joint Highway Research Project, "Engineering Soil Parent Material Areas of Indiana". Revised Edition of 1943 Map of Bulletin No. 87, Purdue University, 1950.

13. Olateju, O. T., "Techniques in Slipform Paving and Continuously Reinforced Concrete Pavement Construction". Joint Highway Research Project, Purdue University, Research Report No. 6, March 1971.

14. Yoder, E. J., and Faiz, A., "Statewide Condition Survey of Continuously Reinforced Concrete Pavements in Indiana". Purdue University, February 1973, (Unpublished).

15. Yoder, E. J., and Faiz, A., "Design and Performance of Continuously Reinforced Concrete Pavements", Paper presented at Annual Road School, Purdue University, March 1973 (to be published).

16. Yoder, E. J., "Pumping of Highway and Airfield Pavements" HRB Proceedings, Vol. 36, 1957, p. 388.

APPENDIX - FIGURES

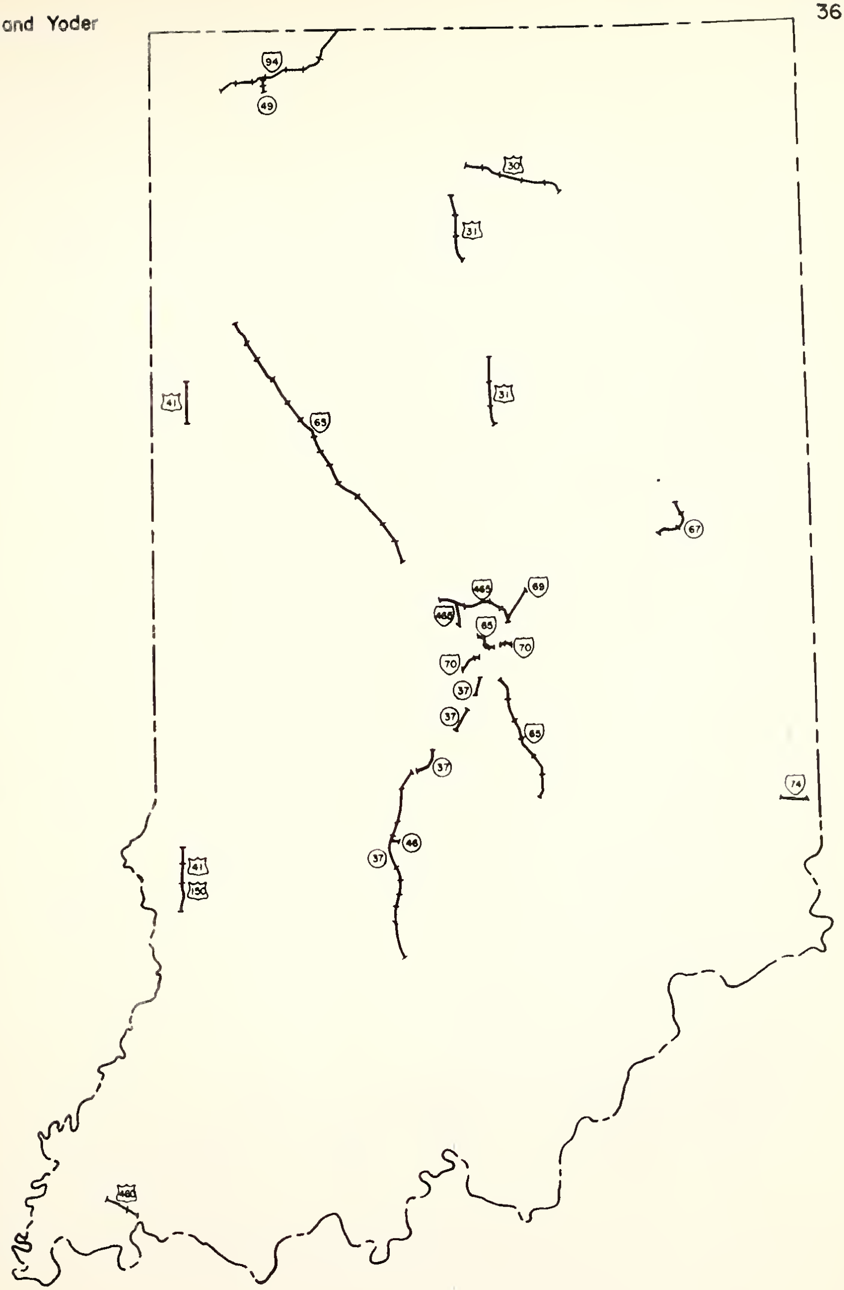

FIG. I CRC PAVEMENTS IN INDIANA
SUMMER 1972

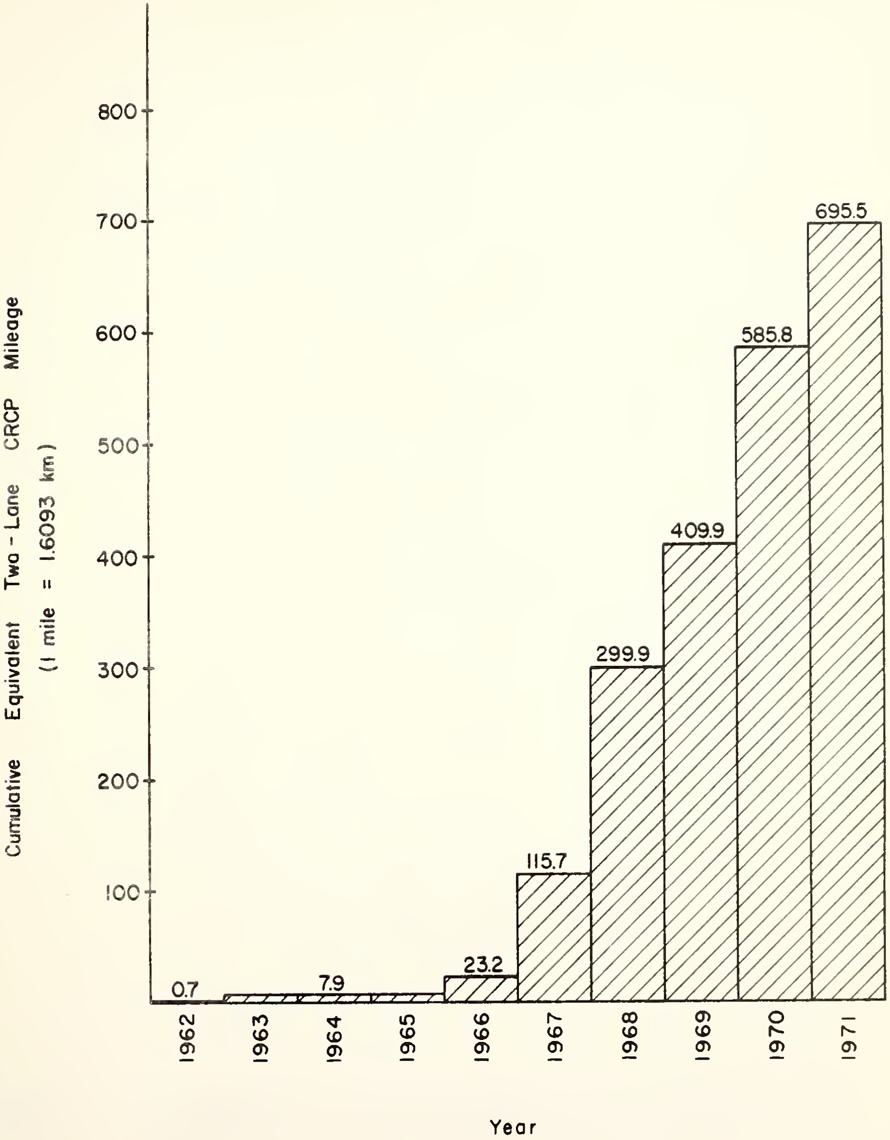

FIG. 2 USE OF CRCP IN INDIANA BY YEARS

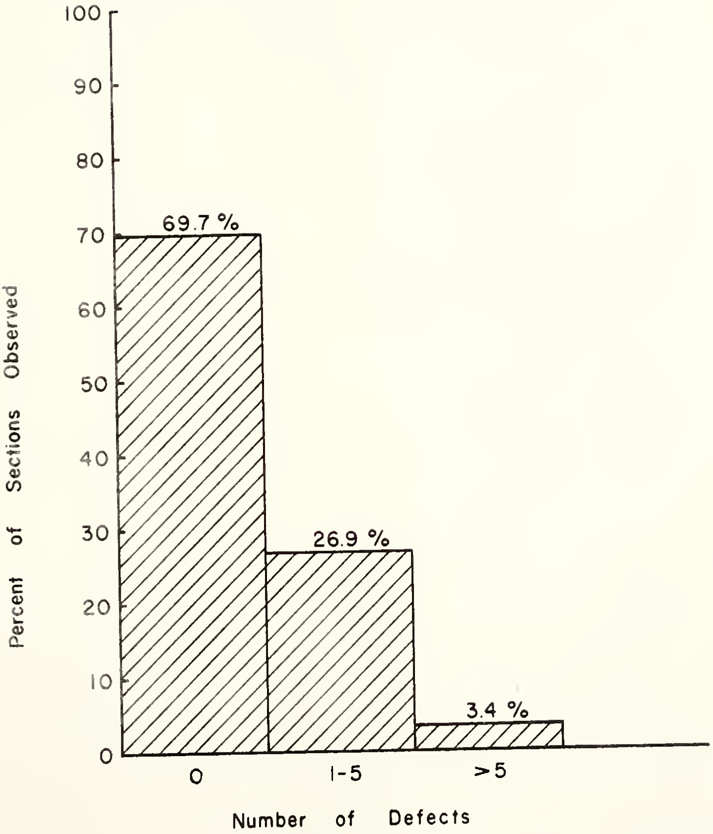

FIG. 3 FREQUENCY DISTRIBUTION OF DEFECTS OBSERVED IN THE STATEWIDE CRCP SURVEY