Development and Application of Randomness Index for Continuously Reinforced Concrete Pavement

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Transverse cracks in continuously reinforced concrete (CRC) pavements have various shapes in the field. The randomness of a crack increases the probability of the formation of secondary cracks and consequently increases the possibility of punchouts and Y-cracks, which are the major form of distress in CRC pavements. If the factors affecting the randomness of cracks can be identified and controlled, the pavement life will be increased. So far insufficient attention has been given to the shapes of cracks in concrete pavement design and construction. As a first step toward the study of randomness, a methodology for objectively quantifying the degree of randomness of the crack was developed. The concept for a randomness index, to be used as a tool to represent the degree of randomness, is introduced. The technique used in the derivation of present serviceability index (PSI) was used in developing the randomness index. An example of the application of the randomness index to an experimental study is also presented. It was found from the experimental study that the construction season, coarse aggregate type, and time of crack occurrence significantly affect the randomness of cracks.

Cracks in continuously reinforced concrete (CRC) pavements have various shapes; some of them are fairly straight, and some are winding. Cracks that meander increase the possibility of secondary cracks, which result in punchouts—the major form of distress of CRC pavements. Pavements will perform differently in the long term if there is a big difference in the shapes of their cracks, even though other conditions are the same (see Figure 1). Therefore, the engineer should try to avoid excessively random cracks at the design stage.

The first step in the randomness study was development of a methodology to objectively quantify the degree of randomness of cracks. Using this methodology, the factors influencing the randomness of cracks can be identified. If these factors can be controlled, the randomness of cracks and the resulting distress can be minimized, which should lead to longer pavement life.

The concept of a randomness index (RI) is introduced in the following paragraphs. The technique used in developing the RI is exactly the same as that used in the derivation of the present serviceability index (PSI) (*1*), which has been widely used since the AASHO Road Test. In this technique, subjective ratings of each crack were made by a group of panel members, and a mathematical model was developed by correlating the average rating with several measurable characteristics of the crack so that the rating of any crack can be predicted in the future without any further rating. This prediction is accomplished by inserting the physically measured values into the model. The variables in the model include the length of the crack and the number of concrete blocks formed by cracks, joints, or a pavement edge.

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DEVELOPMENT OF RI

Definitions

A randomness rating (RR) is the mean of the individual randomness ratings made by the panel members. An individual randomness rating is a subjective rating of the randomness of a specific crack by an individual rater.

The RI is a mathematical model for predicting the RR using certain physical measurements of the crack.

Randomness Rating

The randomness of 51 cracks was rated subjectively by a panel of 12 persons (8 from the Center for Transportation Research at The University of Texas at Austin and 4 from the Texas State Department of Highways and Public Transportation) working in the pavement area.

A wide range of cracks, in terms of randomness, was selected for rating from CRC pavements in Houston; some selected cracks were meandering, some fairly straight, and some in between. Some cracks were connected with one or more secondary cracks (i.e., Y-cracks).

Slides of the selected cracks were shown to the raters. The rating scale they used was exactly the same as that used by the panel members of the present serviceability rating (*1*). The scale was as follows:

- 5.0: very good (almost straight cracks),
- 4.0: good,
- 3.0: fair,
- 2.0: poor, and
- 1.0: very poor (very meandering).

The rater was instructed to exclude from consideration all features not related to the shape of the crack itself, such as width of the crack and spalling. Ratings were recorded to the nearest tenth. The acceptability of each crack in terms of the

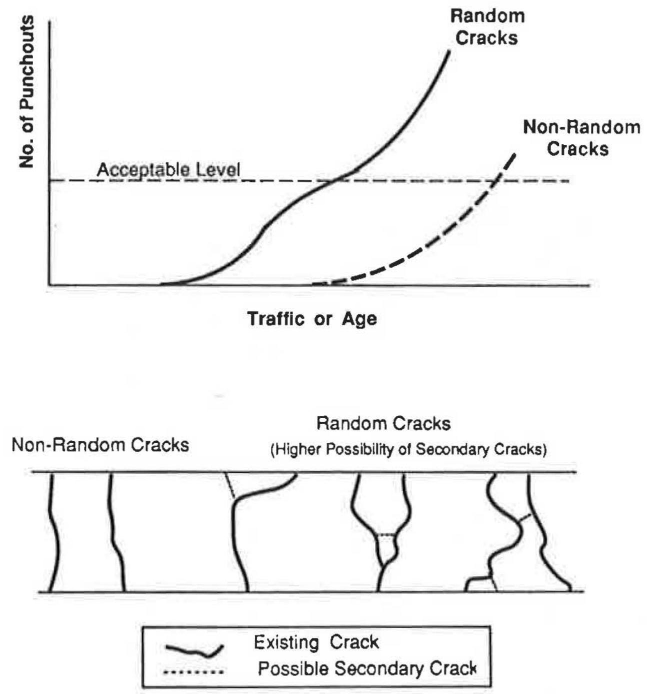

FIGURE 1 Effect of shape of cracks on pavement performance.

shape of the crack was also judged. Raters were told to decide the acceptability by asking themselves, "If I were a pavement designer, would I want to design to avoid this kind of crack in the future?" The form used in the panel rating is shown in Figure 2.

Results of Randomness Rating

The RR value of each crack (the average of the 12 individual ratings) is given in the second column of Table 1. The mean of RRs of the 51 cracks rated was 3.6. The standard deviation of ratings among raters for each crack is given in the third column of the table. The average of the standard deviation was 0.5.

The fourth column of Table 1 represents the panel responses to the acceptability question. For a particular crack, the table shows what percent of the panel judged the shape of the crack to be acceptable. The remaining percent of the panel considered it unacceptable. Figure 3 shows the relationship between acceptability and the corresponding RR values. The curve in Figure 3 indicates that the 50th percentile for acceptability occurs when the RR is about 2.5.

Derivation of Randomness Index

A mathematical model of RI is derived by correlating the RR with objectively measured values taken from the correspond-

RATER ________________

CRACK ID	RATING	ACCEPTABLE?
B113		YES NO
B199		YES NO
C5		YES NO
A43		YES NO
A16		YES NO
B75		YES NO
B165		YES NO
C151		YES NO
A13		YES NO
D170		YES NO
D167		YES NO
D17		YES NO
D139		YES NO
B128		YES NO
A7		YES NO
D16		YES NO
A24		YES NO
A9		YES NO
B14		YES NO
D20		YES NO
D13		YES NO
B18		YES NO
C14		YES NO
F16		YES NO
D5		YES NO
G4		YES NO
F5		YES NO
E15		YES NO

CRACK ID	RATING	ACCEPTABLE?
B10		YES NO
C61		YES NO
H5		YES NO
H17		YES NO
E13		YES NO
B6		YES NO
E5		YES NO
G9		YES NO
E7		YES NO
H4		YES NO
E17		YES NO
G21		YES NO
E10		YES NO
C8		YES NO
D19		YES NO
B15		YES NO
D10		YES NO
A22		YES NO
B4		YES NO
A70		YES NO
A128		YES NO
A143		YES NO
B35		YES NO
		YES NO
		YES NO
		YES NO
		YES NO
		YES NO

FIGURE 2 Individual randomness rating form.

TABLE 1 SUMMARY OF THE DEVELOPMENT OF THE RI

Crack ID	RR	Std. dev of RR among raters	Percent acceptability	R (percent)	N	RI	Residual
B113	2.0	0.6	0	9.4	2	1.7	0.3
B199	2.4	0.6	42	8.7	1	2.1	0.3
C5	3.3	0.9	83	6.9	0	3.2	0.1
A43	3.6	0.7	100	6.5	0	3.2	0.3
A16	3.3	0.8	100	5.8	0	3.3	0.0
B75	2.3	0.4	17	5.8	2	1.9	0.4
B165	3.5	0.8	92	5.8	0	3.3	0.2
C151	2.4	0.7	25	5.1	1	2.4	0.0
A13	3.2	0.8	100	5.0	0	3.4	-0.2
D170	4.2	0.4	100	4.7	0	3.5	0.7
D167	1.8	0.6	0	4.7	2	2.0	-0.2
D17	3.3	0.7	100	4.7	0	3.5	-0.1
D139	3.5	0.6	100	4.7	0	3.5	0.1
B128	3.6	0.5	100	4.3	0	3.5	0.0
A7	3.4	0.7	92	4.3	0	3.5	-0.1
D16	3.5	0.7	100	4.0	0	3.6	-0.1
A24	3.8	0.5	100	3.6	0	3.7	0.1
A9	4.0	0.5	100	3.6	0	3.7	0.3
B14	4.0	0.5	100	3.6	0	3.7	0.4
D20	3.8	0.5	100	3.2	0	3.8	0.1
D13	3.9	0.5	100	3.2	0	3.8	0.2
B18	3.7	0.5	100	2.9	0	3.8	-0.1
C14	3.5	0.5	92	2.9	0	3.8	-0.3
F16	3.9	0.4	100	2.9	0	3.8	0.1
D5	3.7	0.6	100	2.5	0	3.9	-0.2
G4	4.2	0.4	100	2.5	0	3.9	0.2
F5	4.3	0.3	100	2.5	0	3.9	0.4
E15	4.4	0.3	100	2.2	0	4.0	0.3
B10	4.0	0.5	100	2.2	0	4.0	0.0
C61	4.3	0.2	100	2.2	0	4.0	0.2
H5	3.8	0.3	100	1.8	0	4.2	-0.4
H17	4.1	0.4	100	1.8	0	4.2	-0.1
E13	4.2	0.3	100	1.8	0	4.2	0.0
B6	4.1	0.3	100	1.4	0	4.4	-0.2
E5	4.1	0.4	100	1.4	0	4.4	-0.2
G9	4.6	0.4	100	1.1	0	4.5	0.1
E7	4.7	0.2	100	0.4	0	5.0	-0.3
H4	4.4	0.4	100	1.1	0	4.5	-0.1
E17	4.6	0.2	100	1.4	0	4.4	0.3
G21	4.0	0.3	100	2.2	0	4.0	-0.1
E10	3.9	0.3	100	2.2	0	4.0	-0.1
C8	3.8	0.3	100	3.6	0	3.7	0.1
D19	3.8	0.3	100	3.6	0	3.7	0.1
B15	3.5	0.6	100	4.3	0	3.5	-0.1
D10	3.3	0.6	100	4.7	0	3.5	-0.2
A22	3.3	0.5	100	5.8	0	3.3	-0.1
B4	3.2	0.6	90	5.8	0	3.3	-0.2
A70	2.8	0.7	100	6.5	0	3.2	-0.4
A128	2.0	0.6	0	6.9	1	2.2	-0.2
A143	2.9	0.7	100	8.3	0	3.1	-0.2
B35	1.2	0.6	0	13.8	2	1.6	-0.3
Mean	3.6	0.5				3.5	0.0

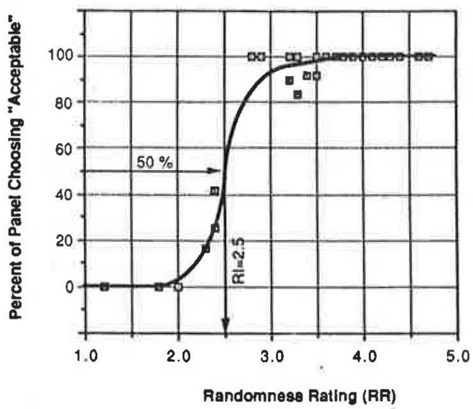

FIGURE 3 Relationship between acceptability and corresponding RR.

ing cracks. The RI model can be used to obtain an estimate of the RR for any crack without the need for any further rating. The RR of a crack is represented by the following:

$$RR = RI + E \tag{1}$$

where E is the residual not explained by the mathematical model.

Measured variables include the length of the crack in a lane (L), the lane width (W), and the number of concrete blocks (N) that are associated with the crack and enclosed by secondary cracks, the pavement edge, or joints (see Figure 4). These characteristics are selected because they are simple to measure and because the effects of secondary cracks, such as Y-cracks or punchouts, are reflected by the number of separated concrete blocks (N). The length of the crack was measured using the edge of a roller-tape (see Figure 5). The measurements were performed along the path of the crack, through the longest path when a secondary crack existed (see Figure 4). The number and shape of secondary cracks determine the number of concrete blocks enclosed by cracks. Randomness (R) is represented by the difference between the

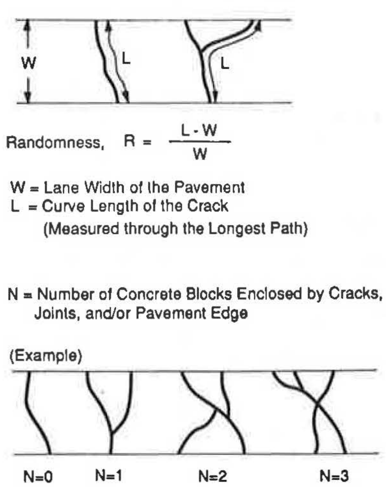

FIGURE 4 *R* and *N* in the RI model.

FIGURE 5 Measurement of crack length using edge of roller-tape.

length of the crack and the lane width, divided by the lane width, as follows:

$$R = \frac{L - W}{W} \times 100 \qquad \text{in percent} \tag{2}$$

where

R = randomness,
L = curve length of the crack, and
W = lane width.

The R and N values for the rated cracks are given in the fifth and sixth columns of Table 1.

Using the general linear model procedure in the Statistical Analysis System (SAS), a mathematical model for the RI, which is a function of R and N, was developed:

$$RI = \frac{5.463}{(R + 1)^{0.259}(N + 1)^{0.510}} \tag{3}$$

The R^2 value of this model is 0.9, indicating that 90 percent of variability of RR is explained by the model. Both variables, R and N, are significant, even at the 0.0001 level. The correlation between RI and RR is shown in Figure 6. Figure 7

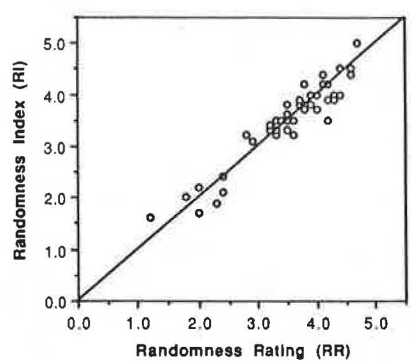

FIGURE 6 Correlation between RI and RR.

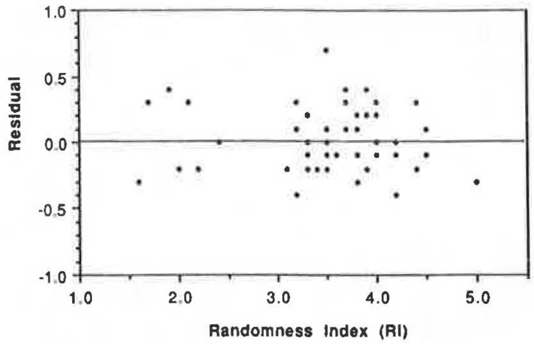

FIGURE 7 Plot of randomly scattered residuals of the RI model.

shows the random scattering of the residuals of the model, indicating that the model fits the data well. The range of the resulting RI values is from 0 to 5.46. The maximum RI value occurs when the crack is a straight line ($R = 0$) without any secondary crack ($N = 0$). In practice, there is no perfectly straight crack in concrete. Therefore, most of the cracks have an RI of less than 5.0. Figures 8–11 show cracks with RI values of 4.8, 3.2, 2.3, and 1.8, respectively.

FIGURE 8 Crack with RI value of 4.8 (R = 0.7 percent and N = 0).

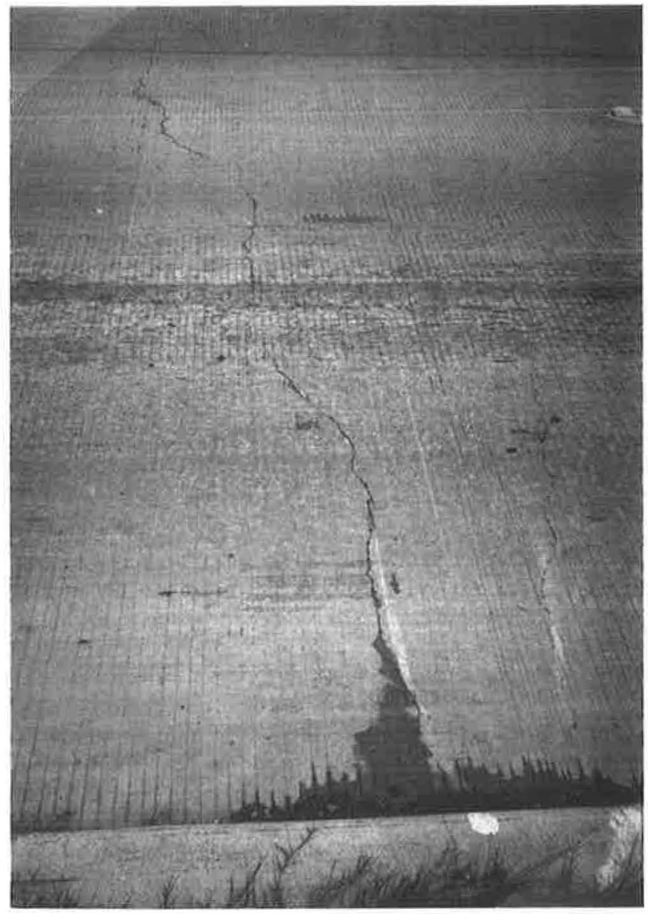

FIGURE 9 Crack with RI value of 3.2 (R = 6.6 percent and N = 0).

EXAMPLE APPLICATION

The RI developed in the previous sections is applied to the transverse cracks of several experimental test sections. The objective of this experiment is to find the significant factors affecting the randomness of cracks in CRC pavements.

The experiment test sections consisted of four CRC pavement projects constructed in Houston, Texas, in 1989 and 1990. One project was constructed in the summer (with a maximum air temperature of approximately 95°F) and the other three projects were constructed in the winter (with a maximum air temperature of approximately 60°F to 75°F). Each project included two types of coarse aggregate (siliceous river gravel and limestone) and four different amounts of longitudinal steel. The length of each project was 1,840 ft. More details on the test sections are provided by Suh (*2*).

The lengths of transverse cracks in a traffic lane (L) and the corresponding lane widths (W) were measured and the separated concrete blocks (N) were counted for the 220 randomly selected cracks from the experimental CRC pavements. The RI value for each crack was calculated using Equations 2 and 3.

Calculated RI values are plotted by projects and coarse aggregate types in Figure 12. The marks on the tops of the

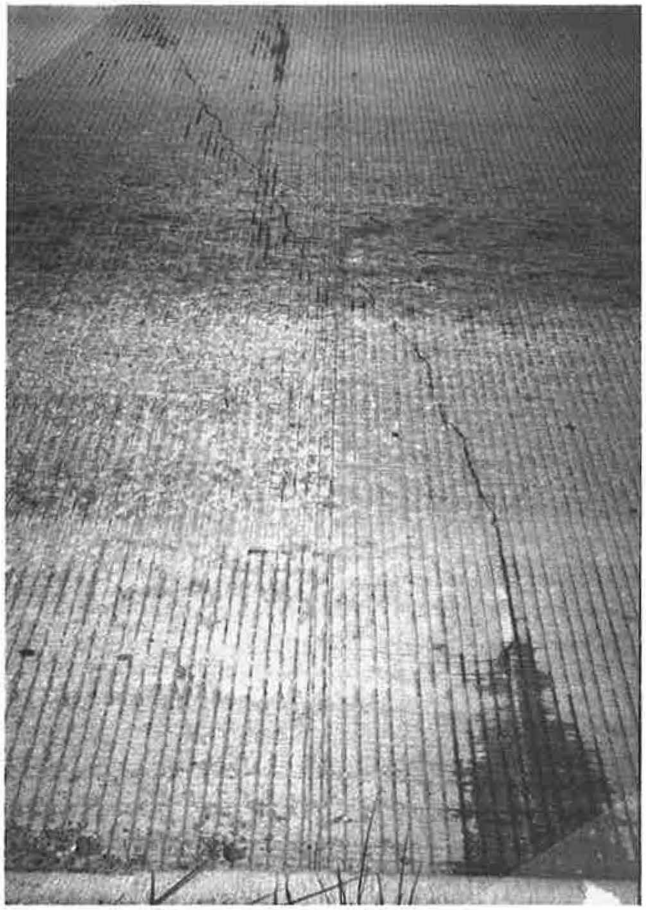

FIGURE 10 Crack with RI value of 2.3 (R = 5.8 percent and N = 1).

FIGURE 11 Crack with RI value of 1.8 (R = 7.3 percent and N = 2).

columns represent the standard deviations of each category. Because variations in RIs among different steel designs were small, this variable is not included in the plot for simplification. Figure 12 shows that summer construction (Project 1) resulted in lower RI values (cracks are more random) with greater standard deviations than winter construction (Projects 2–4). Figure 12 also shows that concrete with limestone aggregates has higher values of RI than does concrete with siliceous river gravel.

The general linear model procedure in SAS was used to see if these differences are statistically significant. Variables considered were project, coarse aggregate type, amount of longitudinal steel, time of crack occurrence, and two factor interactions of these factors. Three or more factor interactions were ignored. Time of crack occurrence was included in the analysis because the early-age cracks have a higher tendency to meander.

It was found from the statistical analysis that the significant factors at the 0.05 significance level are project, coarse aggregate type, and time of crack occurrence. As expected, the effect of the amount of longitudinal steel was not a significant factor in the randomness of cracks. The interaction between project and coarse aggregate type was also significant at the 0.05 level. The other two factor interactions were not significant.

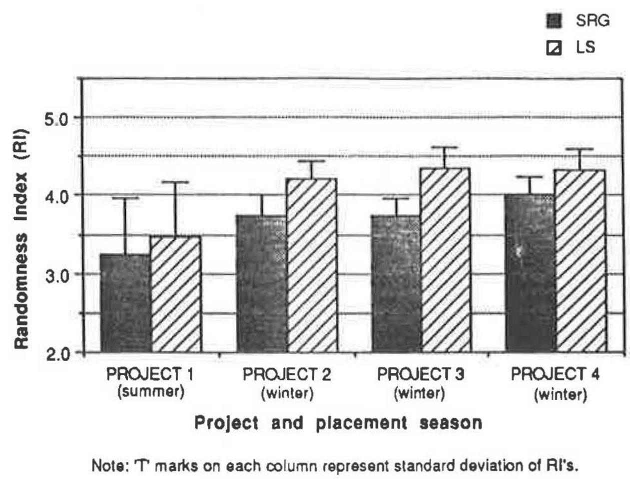

FIGURE 12 Average RI values for each project and coarse aggregate type.

The effect of time of crack occurrence obtained from the statistical analysis is shown Figure 13. The cracks occurring during the first night of construction exhibited much more randomness (had a much lower RI value) than cracks that occurred later. This finding might be because of the soft and heterogeneous state of concrete at the early ages. To keep

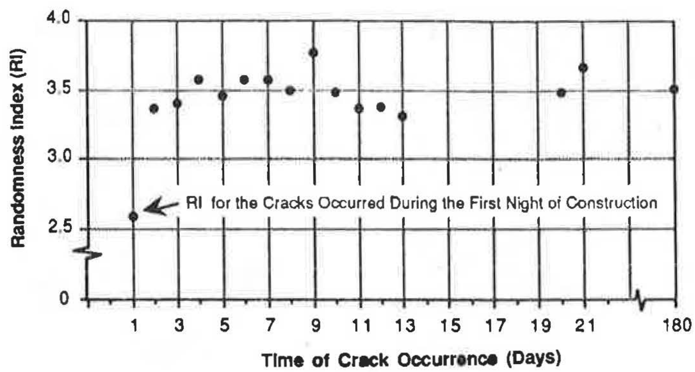

FIGURE 13 Effect of time of crack occurrence on randomness of crack.

the cracks from meandering excessively, the cracks occurring during the first night of construction should be avoided by proper construction and curing.

The experiments show that early-age cracks are more prevalent in summer construction than in winter construction. The higher tendency for early-age cracks, and consequently more meandering cracks, for summer construction might be due to the large temperature differential resulting from the rapid temperature increase (from fast hydration of the cement caused by the high ambient and fresh concrete temperatures) and consequent cooling during the first night after construction (*2*). Because the temperature differential for winter construction was small during the first 24 hr because of the slow hydration of cement, few cracks were observed during that time.

The reason for a tendency toward higher meandering of cracks in concrete with siliceous river gravel than in that with limestone is not clear. However, possible reasons could be less bond with cement mortar, less strain capacity, higher thermal coefficient, and so on.

CONCLUSIONS

An RI for objectively quantifying the randomness of cracks in terms of their shapes has been developed. The technique used was the same as that used in the derivation of PSI in the AASHO Road Test. Subjective ratings of each crack were made by a group of panel members, and a mathematical model was developed by correlating the average rating with several measurable characteristics of the crack. The measured variables needed for the model include the length of the crack, the lane width, and the number of concrete blocks enclosed by cracks, joints, or a pavement edge.

The concept of RI can be used in identifying the factors affecting the randomness of cracks and in quantifying the effects. The reliability of concrete pavements can be increased by controlling these factors.

It was found in an example application using the RI that construction season, coarse aggregate type, and time of crack occurrence are significant factors influencing the randomness of cracks. To minimize random cracking, cool weather construction with the use of limestone aggregate, rather than siliceous river gravel aggregate, is recommended.

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