Structural Distress Mechanisms in Continuously Reinforced Concrete Pavement

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A study of distress types and mechanisms in continuously reinforced concrete pavement in Illinois is reported. The major purpose of the study was to determine types and amounts of distress so that improved maintenance and design procedures could be developed. The approximately 1979 km (1230 miles) of Interstate highway surveyed consisted of 18- to 25-cm (7- to 10-in) slabs over granular and stabilized subbases. Edge punchouts, steel ruptures, D-cracking, blowups, joint failures, lug rotation, longitudinal cracking, construction-related distress, pumping, and shoulder deterioration were found. Since the edge punchout is the major structural distress, its mechanism was studied in depth. Heavy truck loads, excess free moisture, deicing salts, construction practice, and poor aggregate quality in the slab are the major causes of distress. Slab thickness and foundation support have a very significant effect on the development of structural distress. D-cracking is causing severe deterioration on several projects. Overall, the performance of the thicker [23- to 25-cm (9- to 10-in)] slabs has been excellent under heavy truck traffic, but a number of thinner [18- to 20-cm (7- to 8-in)] sections have performed poorly and are showing an accelerated rate of distress development over time. The amount of distress that is expected to occur in the future indicates a need for more efficient and durable ways of maintaining continuously reinforced concrete pavement and for revised design procedures.

A study of the occurrence of edge punchouts in continuously reinforced concrete pavement (CRCP) in Illinois has been conducted. The purpose of the study was to determine the amount of this type of distress and the specific mechanism that causes it. This study represents part of the first phase of an overall effort aimed at the development of optimal maintenance procedures for CRCP. A comprehensive study of all types of distress in CRCP is provided elsewhere (1).

The state of Illinois has constructed 3226 equivalent two-lane km (2000 two-lane miles) of CRCP on the Interstate highway system. A detailed condition survey was conducted on 1979 km (1230 miles), or 132 projects. These projects range in age from 5 to 15 years. Slab thickness ranges from 18 to 25 cm (7 to 10 in). The subbases were initially granular but since about 1965 have been stabilized with asphalt or cement. Both deformed rebar and welded wire fabric have been used as reinforcement. Many of the projects that are located on heavily traveled routes are approaching or have exceeded their design traffic and are showing significant distress at an increasing rate.

DESCRIPTION OF EDGE PUNCHOUTS

Edge punchouts, the major structural distress found in CRCP, occur when a portion of the concrete slab near the outside edge of the truck lane between two closely spaced transverse cracks breaks off and subsequently punches downward. Edge punchouts have only occurred along the outer edge of the truck lane. A type of punchout that occurs in the center of the lane is caused by other factors (generally lack of consolidation) and should not be confused with edge punchouts, which are caused primarily by traffic load and loss of support.

An edge punchout is first characterized by a loss of aggregate interlock at one or two cracks that are usually spaced less than 122 cm (48 in) apart. The crack or cracks begin to fault and spall slightly, and this causes the portion of the slab between the closely spaced cracks to act essentially as a cantilever beam. As heavy truck loads continue, a short, longitudinal crack forms between the two transverse cracks about 61-152 cm (24-60 in) from the pavement edge. Eventually, the transverse cracks break down further, the steel ruptures, and the pieces of concrete punch downward into the subbase and subgrade, causing a very serious traffic hazard. There is generally evidence of pumping and settlement—and sometimes extensive pumping—near edge punchouts. If it is not repaired, the distressed area will expand in size to adjacent transverse cracks and become quite large.

FIELD RESULTS

Edge punchouts per kilometer versus total accumulated 80-kN [18 000-lb (18-kip)] equivalent single-axle loads (ESALs) in the outside truck lane are plotted for all 18- to 25-cm (7- to 10-in) projects in Figures 1-3. This value was computed for each project by adding the number of observed edge punchouts plus those previously patched in the truck lane of the project and dividing by the length of the project.

All CRCP slab thicknesses show an increase in punchouts per kilometer as traffic loads accumulate. For any given traffic level, the thicker the CRCP slab is, the fewer the edge punchouts that occur. Figure 4 shows a comparative plotting of the mean curves for each CRCP thickness. These curves should be considered overall averages only since there is a large scatter in the data about each curve. In addition to the relation between the thickness of the CRCP slab and the number of edge punchouts, the data show that the amount of distress increases curvilinearly with repeated traffic loadings.

The relative performance of each CRCP thickness with respect to the total number of 80-kN ESAL applications can also be plotted as shown in Figure 5. This figure shows 80-kN ESALs (in the truck lane) versus the cumulative percentage of projects that have more than 0 punchouts/km. More than 70 percent of all 18-cm (7-in) thick projects have some punchouts after 4 million 80-kN ESALs. After 8 million, almost 70 percent of all 20-cm (8-in) thick projects have some punchouts, whereas only 45 percent of 23-cm (9-in) thick projects show punchouts. After as many as 10 million or more 80-kN ESALs, 0 percent of the 25-cm (10-in) thick projects show edge punchouts.

Another distribution shows that almost 70 percent of the 20-cm-thick projects show punchouts after 8

Figure 1. Traffic loadings versus edge punchouts for 18-cm-thick CRCP.

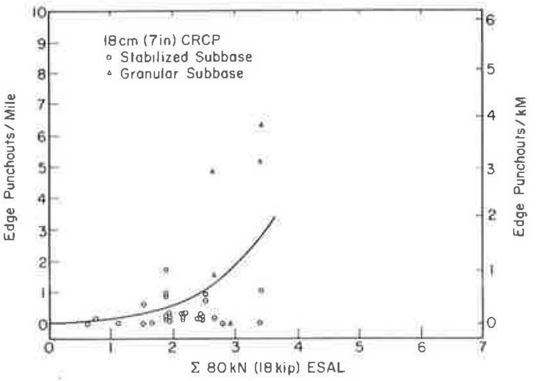


Figure 2. Traffic loadings versus edge punchouts for 20-cm-thick CRCP.

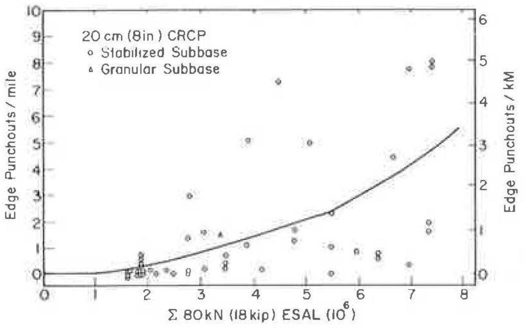


Figure 3. Traffic loadings versus edge punchouts for 25- and 23-cm-thick CRCP.

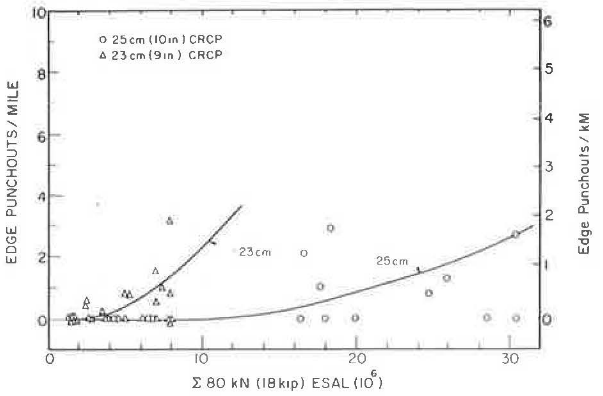


Figure 4. Traffic loadings versus mean edge punchouts for 18-, 20-, 23-, and 25-cm-thick CRCP.

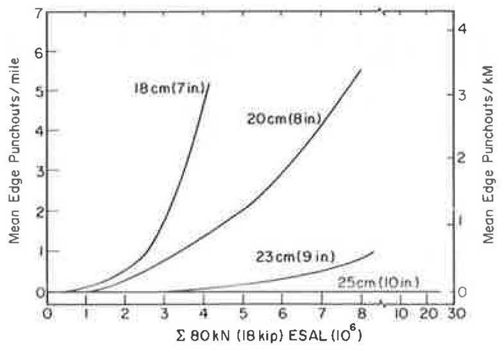
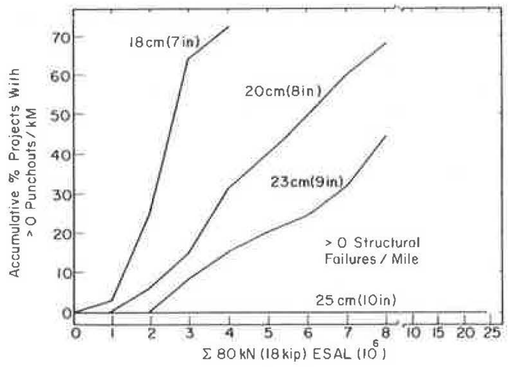


Figure 5. Relative performance of each CRCP thickness with > 0 edge punchouts.



million 80-kN ESALs, 38 percent show more than 0.6 punchout/km (1 punchout/mile), 21 percent more than 1.2 punchouts/km (2 punchouts/mile), and 9 percent more than 3.7 punchouts/km (6 punchouts/mile). The proportion of projects that show punchouts increases with accumulated traffic loadings.

STRESS ANALYSIS

A stress analysis was conducted by using a finite-element computer program developed and validated at the University of Illinois (2). The program is capable of determining stresses and deflections in CRCP that has full support or that shows a loss of subgrade support attributable to pumping. Parameters such as slab thickness, subgrade support, transverse crack spacing and load-transfer efficiency, and the lateral position of load were studied. The program output gives stresses at the top and bottom of the slab and the deflection of each node as they correspond to a grid system determined by the user.

The critical stress that causes edge punchouts occurs when the wheel of a truck is located near the slab edge. Figure 6 shows a high tensile stress occurring at the top of the slab at a distance T from the edge of the pavement. This stress is highly dependent on the amount of load transfer across the transverse cracks. It would occur when there is no such load or moment transfer. This would be representative of the slab only after the transverse cracks have opened up and aggregate interlock is lost and some of the reinforcement has ruptured. This effect is shown in Figure 6, where the maximum transverse stress is computed over a range of crack spacing for full and zero load transfer across the transverse cracks. The transverse stress becomes considerably greater as crack spacing shortens and load transfer is lost.

Critical tensile stress depends on several pavement and load variables and on the distance T, which is also variable. Results show that, as the outside wheel load is moved inward from the edge of the pavement just 30 cm (12 in), not only does the critical stress decrease by 50 percent but also the maximum stress moves from 91 to 122 cm (36 to 48 in) from the slab edge.

Figure 7 shows that slab thickness has a very significant effect on critical stresses as the maximum tensile stress increases by 76 percent, from 1758 kPa (255 lbf/in^2) for a 25-cm (10-in) slab to 3096 kPa (449 lbf/in^2) for an 18-cm (7-in) slab. Note that the location of the maximum stress is 91 cm (36 in) from the slab edge. The relative effect of slab thickness on edge

Figure 6. Effect of load transfer across transverse cracks and crack spacing on critical transverse tensile stress in CRCP slab.

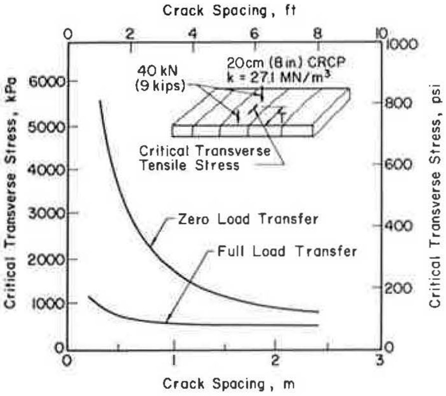
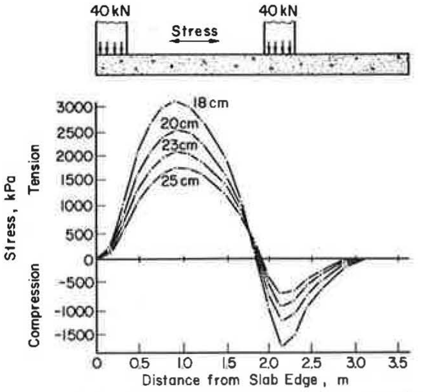
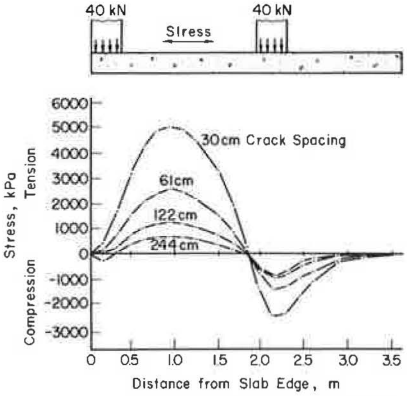


Figure 7. Effect of slab thickness on maximum tensile stress.



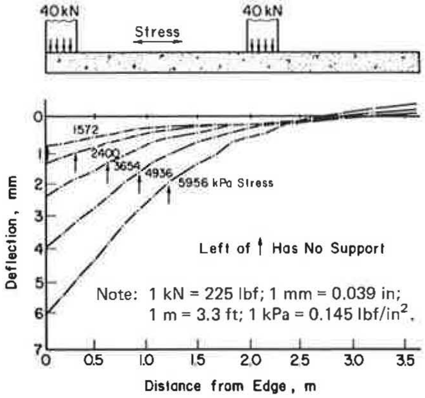
Note: 1 kN = 225 lbf; 1 kPa = 0.145 lbf/in^2;
1 cm = 0.39 in; 1 m = 3.3 ft.

Figure 8. Effect of crack spacing on maximum tensile stress with zero load transfer across transverse cracks.



Note: 1 kN = 225 lbf; 1 kPa = 0.145 lbf/in^2;
1 cm = 0.39 in; 1 m = 3.3 ft.

Figure 9. Effect of erodibility on maximum tensile stress and its distance from slab edge.



Note: 1 kN = 225 lbf; 1 mm = 0.039 in;
1 m = 3.3 ft; 1 kPa = 0.145 lbf/in^2.

punchouts is shown in Figure 4. Thus, increased slab thickness has a considerable effect on reducing critical stress, which in turn results in a reduction of edge punchouts.

As Figure 8 shows, crack spacing has the most dramatic effect on stress. For a 20-cm (8-in) thick slab over a foundation k-value of 54.2 N/cm^3 (200 lbf/in^3), the maximum tensile stress increases from 731 kPa (106 lbf/in^2) at a crack spacing of 244 cm (96 in) to 5069 kPa (735 lbf/in^2) at a crack spacing of 30 cm (12 in). This is important because many edge punchouts occur in areas where there is "cluster cracking"—the formation of several cracks at an average spacing of about 30-61 cm (12-24 in). Again, note that the maximum stress occurs 91 cm (36 in) from the slab edge.

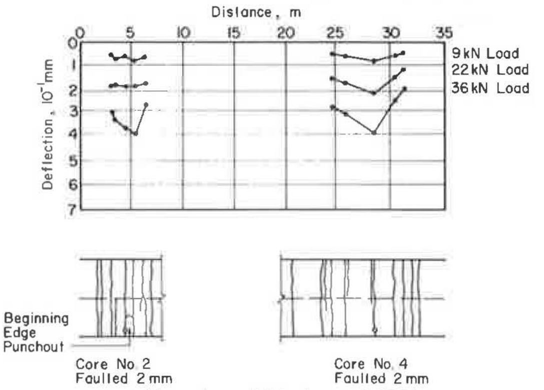
The majority of edge punchouts have occurred between cracks spaced 30-91 cm apart, and the short, longitudinal crack has usually occurred 61-152 cm (24-60 in) from the slab edge. In most cases in which the longitudinal crack has formed at greater distances from the edge—i.e., 152 cm—there had been extensive pumping, which indicated loss of support (see Figure 9). Very seldom has an edge punchout occurred where cracks were spaced 122 cm (48 in) or more apart or where a longitudinal crack was less than 61 cm or more than 152 cm from the slab edge. This is illustrative of the fact that the tensile stress under the inner wheel is much less than that under the outer wheel near the slab edge.

Changing the k-value from 13.5 N/cm^3 (50 lbf/in^3), which is typical of a fine-grained, saturated soil subgrade, to 135.5 N/cm^3 (500 lbf/in^3), which is typical of a stabilized subbase over a granular subgrade, decreases the transverse stress by 34 percent. Figure 9 shows the effect of loss of subgrade support along the slab edge. As the loss of support increases, in addition to the increase in deflections and the movement of the point of maximum stress inward from the pavement edge, the stresses increase dramatically [52 percent for a 30-cm (12-in) loss of support].

Field observations and past experience have indicated that a granular subbase has a high tendency to pump under moisture and load conditions in Illinois. This pumping causes a loss of support along the edge, increased stresses, and higher potential for edge punchouts. The results shown in Figure 1 indicate that the only sections of 18-cm (7-in) thick CRCP that had more than 1.2 punchouts/km (2 punchouts/mile) were those sections with a granular subbase that pumped. Sections constructed with a stabilized subbase contained fewer edge punchouts.

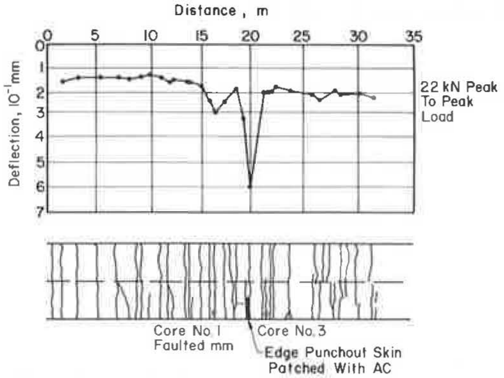
The effect of a good foundation support can be seen by observing the performance of a project on I-70 that was constructed in 1967. The westbound lane was constructed by placing the CRCP slab over an old jointed reinforced concrete slab that was overlayed with asphalt concrete. No edge punchouts have occurred in this lane. The eastbound lane was constructed with a typical stabilized subbase over a new alignment. Almost 3 punchouts/km (5 punchouts/mile) have occurred in the eastbound lane. Traffic was heavy in both directions

Figure 10. Crack pattern and deflections at cores 2 and 4.



Note: 1 m = 3.3 ft; 1 mm = 0.039 in;
1 kN = 225 lbf.

Figure 11. Crack pattern and deflections at cores 1 and 3.



Note: 1 m = 3.3 ft; 1 mm = 0.039 in;
1 kN = 225 lbf.

and approximately equivalent (6.7 million 80-kN ESALs). The effect of the underlying portland cement concrete (PCC) slab in providing increased support is evident. In addition, local maintenance personnel indicated that, on several projects that had an above-average number of punchouts, the stabilized subbase had deteriorated and loss of support was a major cause.

STUDY OF DEFLECTIONS AND CORES

One project on I-57 has experienced many edge punchouts. It was believed that studying deflections and core samples might help in determining the causes. A vibratory deflection device (road rater) owned by the Illinois Department of Transportation that can apply up to 35.5 kN (8000-lbf) peak-to-peak vibratory load was used. Deflections were taken continuously over a 61-m (200-ft) section and at four other sections within a test area of 198 m (650 ft). Core samples were taken at four locations that corresponded with certain of the areas of deflection measurement. The cores were taken approximately 30 cm (12 in) from the slab edge in an attempt to sample the second reinforcing bar. Figures 10 and 11 show the CRCP crack pattern and deflections and the locations of the cores taken.

Core 1 was taken at what appeared to be a typical tight crack. It was noticed that this crack had twice the deflection of the immediately adjacent cracks. On further examination, it was found that the crack had faulted approximately 1 mm (0.04 in), and it was decided to take a core sample. The rebar was corroded nearly all the way through, and considerable concrete was missing around the bar (thus only minimal aggregate interlock was present).

Core 2 was taken at a crack that typified the beginning stages of an edge punchout. The crack had faulted 2 mm (0.08 in), and the deflection was high at the punchout. A short, longitudinal crack had formed approximately 152 cm (60 in) from the edge, and the transverse crack spacing was 63 cm (25 in). Again, there was extensive rebar corrosion and concrete deterioration in the core.

Core 3 was taken over a very tight crack. It was believed that there would be no corrosion or deterioration. The crack became microscopic just below the surface of the slab, and the core had to be broken apart to observe the steel that was not corroded. The deflection at this crack was similar to that at other tight cracks.

Core 4 was taken over a crack that had spalled considerably but had not yet opened extensively. Results showed that the rebar had ruptured and there was a void in the concrete around the rebar as in cores 1 and 2. The rebar was necked down on both ends as a result of corrosion.

These results and other observations made during patching operations indicate that, when a crack shows any faulting at all [i.e., as little as 1 mm (0.04 in)], it is reasonable to assume either that corrosion has been significant enough to reduce the cross-sectional area of steel or that there has been a considerable loss of aggregate interlock. Deflections were markedly greater at each of the three locations that had faulted than they were at immediately adacent cracks where there was no faulting. The high deflections are also an indication of a void under the slab. Water was introduced into core holes 1, 2, and 4 for 10 min by means of a hose connected to a water barrel. The water never filled up the holes. Thus, there must have been extensive voids at these locations. The cement-aggregate-mixture (CAM) subbase could not be cored at any of the four holes (it disintegrated during coring).

It is believed that deflections can be used to locate areas that may be in early stages of distress. For future study, however, it should be noted that the magnitude of load needed to get adequate information is relatively high. As Figure 10 shows, a vibratory load of 8.9 kN (2000 lbf) does not adequately produce deflections that will indicate the true loss of support. Thus, it is recommended that peak-to-peak loads of 22.2 kN (5000 lbf) or more be used so that distressed areas can be located.

MECHANISM OF EDGE PUNCHOUTS

The development of the typical edge punchout in CRCP is a complex phenomenon that may have more than one basic cause. The following analysis is based on field observations of many edge punchouts and the information given above.

A localized loss of support beneath the slab that results in relatively high deflection is the primary causative factor in edge punchouts. Deflections measured near the point of initiation of a punchout were invariably much higher than those in the adjoining CRCP. Loss of support had occurred in several ways, including accumulation of free moisture in a "soft" localized subgrade area, localized disintegration of a stabilized subbase course, and localized pumping of a stabilized or granular subbase course. High deflection will result in increased stress in the reinforcement under-load and also greater vertical shear that must be carried across a transverse crack. Experimental studies have shown that the wider the crack is the sooner the aggregate interlock will break down across the crack under repeated loadings (3). Other factors in addition to high localized deflections may cause a widening of the crack, including high tensile stress in the steel at the crack as a result of drying shrinkage or cold temperatures (4). An inadequate overlap of the reinforcing steel may prevent the transfer of all of the stress from one bar to another, allowing the bars to pull apart and resulting in an open crack. A loss of bond between the steel and the concrete in the vicinity of a crack would allow the stresses and strains in the steel to be applied over a longer length and result in greater crack width. The latter two causes have been verified in a report by Lepper and Kim (5).

Once a transverse crack has opened up somewhat, repeated heavy traffic loads may eventually break down the aggregate interlock (6, 7). In a study conducted by Colley and Humphrey (3), the load-transfer capabilities of aggregate-interlock systems for certain variables—including width of crack opening, thickness of concrete slab, magnitude of load, foundation support, and type of aggregate—were investigated. For a 23-cm (9-in) slab over 15 cm (6 in) of gravel base when the crack opening is 2 mm (0.065 in), the effectiveness of load transfer is reduced to 25 percent after only 400 000 load cycles. A more rapid deterioration occurs for an 18-cm (7-in) pavement.

As the aggregate interlock continues to break down, slight faulting and spalling of the crack appear near the slab edge. Continued traffic loadings reduce aggregate interlock even more, increasing both deflections and the critical transverse tensile stress at the top of the slab. The reinforcing steel, of course, resists the crack opening and faulting. But as aggregate interlock is lost, more and more of the vertical shear is transferred to the reinforcement, which eventually may rupture.

Corrosion may also have an effect. Whenever crack width becomes great enough to admit moisture, corrosion of the reinforcement may begin. Results obtained from National Cooperative Highway Research Program (NCHRP) Project 1-15 (4) indicate that crack width need not be very great since cracks with an opening as small as 0.6 mm (0.023 in) allowed enough moisture to reach the reinforcement to cause "minor" corrosion. The NCHRP report also shows that cracks wider than about 0.6 mm allowed rapid infiltration of surface water and caused "heavy" corrosion of the reinforcement. Corrosion was found at many distress areas where the reinforcing bars were necked down across a wide transverse crack. Observation and discussion with various maintenance personnel also indicated that corrosion of rebars at failed areas was common in some areas. However, the performance of CRCP in areas where no deicing salt is used indicates that edge punchouts occur even without corrosion. Thus, corrosion is believed to have an effect only after a crack has opened. The corrosion that does occur has two effects: It reduces the cross-sectional area of steel reinforcement, and its expansive forces fracture the concrete surrounding the steel and cause it to spall. Thus, as cores 1, 2, and 4 show, there is a void around the steel.

Then, because of increasing transverse tensile stresses and accumulated fatigue damage, a longitudinal crack eventually forms between the two transverse cracks. Under additional traffic loading, the aggregate interlock wears away completely, the steel begins to rupture at the outer bar near the slab edge, and the outside portion of the slab begins to depress into the subbase. Once the block of concrete begins to punch downward, pumping accelerates so that more and more support is lost under the slab, and fatigue may cause more longitudinal cracking, faulting, and spalling. The area eventually expands so much that a large patch is required. It is noted that, because fatigue, corrosion, loss of aggregate interlock, and pumping all increase with time and traffic, the occurrence of edge punchouts also accelerates with age and traffic.

EFFECTS OF DRAINAGE ON DISTRESS

One of the major factors that contributes to several types of distress is free moisture within the CRCP structure. Several recent studies have concluded that free water, largely in the form of surface infiltration of precipitation, is a primary causative or accelerating factor in many structural distresses (8-10). Most of the CRCPs surveyed had a "bathtub" cross section in which stabilized subbase and shoulders completely encased the CRCP slab. In addition, the slab-shoulder longitudinal joint is nearly always wide open and unsealed so that most precipitation that falls on the traffic lane can readily infiltrate the joint. The free water that infiltrates this joint does not have a flow path by which to escape and thus becomes entrapped. Many examples have been seen in which, at a low point in the profile, water "bleeds" out of the longitudinal joint and can be seen standing in the joint for several days after a rainstorm. This free water can thus saturate both the concrete and the subbase for long periods of time during the year. Some of the older designs used a granular subbase. The basic moisture-flow pattern of the bathtub design, however, is not changed since dense-graded gravel is essentially as impervious as the stabilized subbase.

One of the major results of this free water surrounding the CRCP slab is pumping. A heavy wheel puts high pressure on the free water beneath the slab, which causes the water to move violently in any available direction. This water thrust under high pressure, repeated over many truck loads, eventually leads to disintegration of the subbase and shoulder. This phenomenon of water pumping from the longitudinal joint has been observed several times after rainstorms on various projects. Pumping of fine soil has been observed on the shoulder surface of CRCP with stabilized subbase. CRCP with granular subbase has shown much greater pumping, however. A major result of pumping is a loss of support under the pavement edge. This loss of support causes high stresses and deflections, both of which lead to accelerated occurrence of punchouts. Recognizing this problem, the Illinois Department of Transportation (DOT) has installed in some sections longitudinal edge drains that, according to local maintenance personnel and the limited data given in Table 1, have generally had a beneficial effect. These drains have decreased the number of punchouts by an average of 24 percent for these projects.

TRAFFIC LOADINGS

Most of the Interstate highways in Illinois that are included in this study are very heavily trafficked truck routes. A comparison of this traffic with that on routes in other states shows that these Illinois routes carry as much heavy truck traffic as most states or more (11). The volume and weight of truck traffic have increased sharply during the 1960s and 1970s (1). The amount of overloadings is also believed to be large.

Table 1. Effect of longitudinal edge subdrains on distress in Illinois CRCP.

Highway	Subdrains	Number of Projects	Age (years)		Mean Punchouts per Kilometer
			Projects	Subdrains	
I-57	With	5	8	7	1.1
	Without	3	9		1.6
I-74	With	1	11	11	1.0
	Without	1	11		1.3
I-80	With	1	9	2	1.6
	Without	1	9		2.1

Note: 1 km = 0.62 mile.

Data were obtained from enforcement weight tickets for a few months on the freeway system in Chicago during 1975. Single-axle weights ranged up to 169 kN (38 000 lbf), and tandem-axle weights ranged up to 249 kN (56 000 lbf) (1).

Truck-traffic volume and weight can be expressed in 80-kN (18 000-lb) ESALs. The total accumulated 80-kN ESALs for each project range from less than 1 million to 30 million on the Stevenson Expressway in Chicago. The following table gives the range in traffic loadings at various Illinois locations:

Location	Total 80-kN ESALs on Heaviest-Traveled Truck Lane (000 000s)	Age (years)	80-kN ESALs per Year (000 000s)
I-94 Chicago	16.6	6	2.8
I-55 Chicago	30.0	15	2.0
I-57 Champaign	2.6	8	0.3
I-80 Joliet	8.0	8	0.9
I-70 Vandalia	6.0	10	0.6
I-57 Mt. Vernon	2.9	10	0.3
I-74 North Peoria	2.2	7	0.3
I-70 Marshall	3.5	6	0.6

The design 80-kN ESAL for each slab thickness, assuming typical foundation conditions, is as follows (1 cm = 0.39 in):

Slab Thickness (cm)	Design 80-kN ESAL (000 000s)
18	2.1
20	4.8
23	10.0
25	20.5

The 18-cm (7-in) CRCP is no longer constructed by the Illinois DOT.

Assuming these design limits with actual accumulated traffic, 46 percent of the kilometers of CRCP has surpassed its design traffic limits even though the mean age is only nine years. After 100 percent design traffic life was reached, the serviceability index should have dropped to 2.5. However, because permanent patching restores rideability almost to the original smoothness, the projects are well above this serviceability level. The use of the serviceability-performance approach to design is questionable because extensive patching could keep a CRCP above the 2.5 almost indefinitely. However, maintenance cost and lane downtime would become very high. Discussions with maintenance engineers show that, whenever projects require more than 1.8 patches/km (3 patches/mile), keeping up with the necessary repairs becomes very difficult and lane closures become excessive. A more rational design approach would be to design the CRCP for an acceptable number of edge punchouts that could be determined from economic and other studies. The data obtained in this study could be used to develop updated design procedures.

CONCLUSIONS

1. The edge punchout occurs between two closely spaced transverse cracks near the edge of the travel lane and is the result of a combination of factors. The mechanism of development was analyzed by using a finite-element structural computer program. The location of critical stress, which was found at the top of the slab and transverse across the slab, should be used to design against the punchout. Critical stress was affected mostly by transverse crack spacing and load transfer, slab thickness, and loss of support along the slab edge (from pumping) in addition to repeated truck loadings. These results were generally verified through numerous field observations. The occurrence of edge punchouts by thickness of slab was approximately as follows (1 cm = 0.39 in):

Slab Thickness (cm)	CRCP with Edge Punchouts (%)
18	72
20	64
23	44
25	40

The thicker slabs had much heavier truck traffic.

2. The rate of occurrence of edge punchouts in CRCP is highly dependent on traffic loadings. As loads accumulate, the number of edge punchouts increases at an increasing rate (see Figure 4). In the Illinois projects truck traffic has been much heavier than expected, and many projects (46 percent) are approaching or have exceeded their design traffic life long before reaching their normal 20-year age (the mean age is 9 years).

3. The placement of edge subdrains has reduced the rate of occurrence of distress by about 24 percent on a few available comparative projects (Table 1).

4. The structural design of CRCP needs revision. The use of the serviceability-performance concept is believed not to be valid since continuous patching can keep the pavement in operation almost indefinitely although at a very high maintenance cost and considerable lane downtime. Design should be based on prediction of the occurrence of an acceptable amount of structural distress.

5. The repair of distress in CRCP is a very difficult, time-consuming, and expensive operation and has become a major concern in several districts where 18- and 20-cm (7- and 8-in) thick CRCP carries heavy truck traffic. Thus, there is a great need for less costly and more durable procedures for maintaining CRCP. Research is currently under way at the University of Illinois, and many experimental patches have been placed (12).

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Response and Distress Models for Pavement Studies

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Results of a detailed study to select mathematical and other models for the prediction of significant distress for flexible, composite, and rigid pavements are presented. Rigid pavements were subdivided for study into nonreinforced jointed concrete pavements (JCP), jointed reinforced concrete pavements (JRCP), and continuously reinforced concrete pavements (CRCP). The models selected are to be used in establishing optimal material properties for zero-maintenance pavements. The published results of field surveys and other experience were used to identify, for each type of pavement, distresses that cause considerable maintenance or loss of serviceability. Material properties that influence the occurrence of significant distresses were then identified, and theoretical or empirical models were selected to predict these distresses by using material properties and other engineering parameters. The distresses found to be most significant for these studies were (a) fatigue cracking for all types of pavement, (b) rutting and reduced skid resistance for flexible and composite pavements, (c) reflection cracking for composite pavements, (d) low-temperature cracking for flexible pavements, (e) spalling for all rigid pavements, (f) faulting for JCP and JRCP, (g) low-temperature and shrinkage cracking for JRCP and CRCP, and (h) punchouts and steel rupture for CRCP. The models considered, the context in which they are to be used, their attributes and limitations, and those finally selected for the study of specific distress for specific pavement types are briefly described.

The Federal Highway Administration (FHWA) research project on Material Property Requirements for Zero-Maintenance Pavements has as its goal the identification of material properties that will provide optimal performance in flexible, rigid, or composite premium or zero-maintenance pavements. This goal is to be accomplished through a combination of empirical and theoretical studies. The published results of field surveys, notably those of Darter and Barenberg (1) and McCullough and others (2), and other experience were used to identify, for each type of pavement, distresses that cause significant loss of serviceability or require significant maintenance. Material properties that influence the occurrence of significant distress were then identified, and theoretical or empirical models were selected to predict these distresses by using material properties and other engineering parameters. A detailed account of these studies appears elsewhere (3).

This paper reports the results of studies of contemporary mathematical models to select those most capable of predicting the distresses of interest in terms of the significant material properties. It includes identification and brief descriptions of the distress models considered and tabular identification of the significant distresses by (a) pavement type, (b) the material properties considered to affect the occurrence of each distress, and (c) the distress model selected to predict each distress.

MODELS OF PAVEMENT RESPONSE AND DISTRESS

There are many models of pavement response that predict stresses and strains in a pavement structure. They all assume linear elasticity, and most fall into two categories: those that basically analyze an elastic plate sup-