EFFECT OF TRANSVERSE STEEL IN CONTINUOUSLY REINFORCED CONCRETE PAVEMENT

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Continuously reinforced concrete pavements are reinforced in the transverse direction for several reasons based on practice, judgment, and some theory. Since 1966 some pavements of this type have been constructed without transverse reinforcement with an economic advantage. This paper presents an evaluation of transverse steel in continuously reinforced pavements and considers the probability that the pavement will experience longitudinal cracking. The analysis also considers potential monetary saving by omitting transverse steel and the probabilities that pavement will last its design life with and without transverse steel, assuming that it will experience longitudinal cracking.

During the past couple of years, there has been considerable discussion among people in the concrete paving industry concerning the need for transverse steel in pavements. Opinions range from complete elimination of the transverse steel to provision of a heavy mat approaching 0.1 percent of cross-sectional area. Obviously, each point of view has merit because an initial monetary savings may be realized if the transverse steel is omitted. Balanced against this must be the consideration of possible loss of pavement performance and monetary investment if the steel is serving a useful function.

The objectives of this paper are to study the rationale and economic feasibility of using transverse steel in concrete pavements. This rationale is considered in terms of both design and construction and is evaluated in terms of field performance. Performance reliability is then used to establish economic criteria for transverse steel and considers both the initial investment and the long-term service.

Reinforcement design for rigid pavements is based on the fact that it is impossible to prevent the formation of cracks; therefore, it is necessary to control the opening of such cracks so that the original load-carrying capacity of the pavement is preserved. If cracks are permitted to open excessively, contact between the faces of the crack is lost with a corresponding loss in shearing resistance. With continued application of wheel loads, progressive breakage and distress occurs in the pavement, resulting in a serviceability loss. With these conditions, the pavement does not attain its design life; thus, a monetary loss results for travelers. Reinforcing steel may be used in the pavement to control crack movements due to temperature and to provide load transfer across cracks or joints.

This paper is concerned only with the control of volume change movements. Therefore, if this limitation in scope is considered, the function of the transverse steel reinforcement is to hold interlocking faces of a crack in tight contact and to provide load transfer. It is only necessary to furnish sufficient steel to resist the forces tending to

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open the crack. When longitudinal cracks occur in continuously reinforced concrete pavement (CRCP), the tensile stresses that were present to crack the concrete are transferred to the transverse steel reinforcement.

Most of the continuously reinforced pavements built in this country have been built by using some transverse steel. This paper examines rigid pavement theories in literature to note any theoretical basis for transverse steel in rigid pavement. It also documents current practices for the design of transverse steel in continuously reinforced pavement. Also, sources of longitudinal cracking are discussed; and, finally, the effect of longitudinal cracking on pavement life is covered in detail in a probability analysis.

RIGID PAVEMENT DESIGN THEORIES

There are a number of rigid pavement design theories available in the literature such as those of Westergaard (1), Portland Cement Association (2), Bradbury (3), Teller and Sutherland (4), Spangler (5), and Kelly (6). An examination of these contributions reveals that they pertain primarily to wheel load stresses; thus, they provide very little theoretical basis for the design of transverse steel in rigid pavements and in continuously reinforced pavements in particular. Consequently, the principles of design for longitudinal steel in jointed concrete pavements (JCP) were applied to the design of transverse steel.

Design of Longitudinal Steel for Jointed Pavements

With the advent of using reinforcing steel in concrete pavements, the "subgrade drag" theory was developed for designing the amount of longitudinal steel in jointed concrete pavements (7). The principle of this design theory is to provide sufficient steel in the pavement to drag the slab over the subgrade if a crack occurs at the center of the slab. The general form of the equation is as follows:

$$P_S = \frac{100LF}{2f_S} \tag{1}$$

where

P_S = percentage of steel;
L = length of slab panels between joints;
F = friction factor; and
f_S = allowable working stress in steel.

Design of Transverse Steel

The earlier concrete pavements were narrow, i.e., 18 to 22 ft wide; thus, evaluation of the steel requirements for the centerline longitudinal joint was provided primarily by experience. During the postwar years, as traffic volumes increased, pavement slab widths of 24 to 60 ft became a common practice. These excessive widths along with distress experienced with longitudinal cracking focused on the need for considering transverse steel design. At the present time, most of the design methods for transverse reinforcement in JCP and CRCP have been based on the conventional subgrade grade drag theory expressed in Eq. 1 (8, 9, 10, 11, 12). In lieu of using the length of the jointed slab in Eq. 1, the width of the CRCP is used as follows:

$$P_{TS} = \frac{100WF}{2f_S} \tag{2}$$

where

P_{TS} = required steel percentage;
W = width of CRCP in ft;

F = friction factor of subbase; and
f_s = allowable working stress in steel in psi.

Thus Eq. 2 has been used to compute the percentage of transverse steel.

Comments on Existing Theories

Although Eqs. 1 and 2 are currently used in design, these mathematical models are only crude simulations of the complex phenomena of cracking and slab movement. Recent studies of crack width fluctuations in reinforced concrete pavements have indicated that in any design equation (13, 14, 15) consideration should be given to variables such as those related to concrete, including strength, thermal coefficient, modulus of elasticity, temperature, temperature change, moisture variations, and steel, including strength, percentage, spacing, load properties, and diameter.

Unfortunately, these concepts cannot be included at the present time; therefore, Eq. 2 must be relied on as the primary design method for the transverse steel. The answers from this approach are probably conservative in most instances.

CURRENT PRACTICES

As of September 1969, 29 states had built some continuously reinforced concrete pavements. The total of equivalent 2-lane miles built by these 29 states, or under contract at that time, was 7,020.3 miles (16). In 1969, the states using CRCP were surveyed as to their design and construction practices (17). This survey showed that 7 out of 25 states permitted contractors to omit the transverse steel with CRCP. The specific practices for CRCP are somewhat dependent on which general construction practices are permitted for concrete pavements.

A design method for transverse steel was discussed, but on the basis of the survey information some states are not requiring its use. Therefore, in order to develop decision criteria as to the proper design approach, it is necessary to consider the rationale for using transverse steel as well as that for deleting it from the pavement.

Rationale for Use of Transverse Steel

Transverse steel has been used in CRCP for reasons pertaining to construction as well as to design. The design criteria that require sufficient steel to retain the load transfer across a crack were discussed previously. Because it is impossible to predict the exact location of longitudinal cracking, designers generally provide for some degree of reinforcement across the entire width. In order to evaluate the merits of this criterion, it is necessary to understand the causes of longitudinal cracking and its possible detriment to satisfactory performance. A very important reason for using transverse steel is that it serves as an aid in construction. The positioning of the longitudinal reinforcing in CRCP and its retainment during construction may be quite difficult if the bars are not tied together to form a bar mat. If the vertical positioning of the longitudinal bars is not adequately controlled, problems with corrosion may result if steel is too near the surface. Second, the transverse bars are used to set the bar mats on chairs to the desired height in the pavement. The third reason for having transverse steel for construction purposes is to keep the bar mat adequately supported so that concrete dumped on the bar mat will not shift longitudinal steel out of the proper vertical or horizontal position. Thus, in some cases the transverse steel can serve as a convenience in construction, although in recent years many new equipment and construction technique developments have reduced the importance of this consideration.

Rationale for Deletion of Transverse Steel

There have been several reasons cited for the omission of transverse steel in CRCP. The first and foremost reason is first-cost economics, and the second is engineering design judgment (18, 19). It has been shown by the Iowa State Highway Commission and the Iowa Concrete Paving Association that the omission of transverse steel can reduce the initial cost per square yard of CRCP by approximately 10 percent. The approximate total initial cost differential per square yard by the omission of the transverse steel is 50 cents, 20 cents for material cost, and approximately 30 cents for labor cost (18, 19). The data for developing these cost comparisons are somewhat limited. Contrary to this, when the Virginia Department of Highways allowed the omission of transverse steel, no significant cost reduction was apparent in the bid prices.

In a methods and time study (20) it was found that for a 2-lane, 24-ft CRCP with longitudinal and transverse steel and form type of construction, 8.16 man-hours were required to place, tie steel, and set on chairs for paving per 100 ft of pavement length. For a range of wage rates such as $2.50 to $4.00, the cost per square yard for total steel placement would range from 9 to 12 cents per square yard. These costs are not in agreement with approximate cost savings reported by Knutson (18).

After the reasons for using or deleting transverse steel are examined, it is evident that each of the approaches has merit. The deciding issue may be reduced to a consideration of the probability of longitudinal cracking and what effects the presence of such cracks might have in terms of service life. With this information, the engineer may decide between (a) an initial saving of construction funds by omitting transverse steel on the basis that the probability of longitudinal cracking is small, or (b) investing in transverse steel to ensure the desired performance life if the environmental conditions are such that longitudinal cracking is probable.

CAUSES OF LONGITUDINAL CRACKING

There are several items that might be considered as potential causes of longitudinal cracking in CRCP. These items include expansive clay foundations; differential loss of support; consolidation, natural soil, or granular material; and transverse volume changes due to temperature change or shrinkage. Expansive soils have resulted in much damage to rigid pavements in certain areas in Texas. The distress occurs because of an upward pressure exerted on the pavement due to deep soil movements. Excessive moments are induced in the slab; thus, both longitudinal and transverse cracking occur. CRCP is believed to perform best on swelling clay subgrades because the ribbon of concrete is made discrete by the transverse volume change cracks so that it can easily take on the longitudinal profile as well as the transverse profile of the foundation or subgrade.

Differential loss of support and consolidation are also potential causes for longitudinal cracking. In this case, a void is created beneath the slab, and an excessive stress condition results with wheel load passage. Thus longitudinal cracking occurs as the pavement relieves the excessive stress condition. Conditions may exist in the pavement such that the transverse volume changes of the concrete produce longitudinal cracking. Improper placement of longitudinal joints, exceptionally wide pavements, high friction subbase, concrete with a high thermal coefficient or all of these may give stress conditions that result in longitudinal cracking.

An example of a typical longitudinal crack in a CRCP is shown in Figure 1. It has been hypothesized by the Texas Highway Department that this crack occurred due to movement deep in the subgrade. Figure 2 shows a close-up view of the same longitudinal crack at its intersection with a transverse crack. There were numerous other longitudinal cracks in the same project where these photographs were made. Figures 3 and 4 show longitudinal cracks that have not yet progressed to the state of distress shown in Figure 1.

Deflection and radius of curvature data obtained in the longitudinally cracked areas shown in Figures 1, 2, 3, and 4 were compared with similar data from adjacent but uncracked areas of the same project (21). An analysis of variance, made on the data, showed no significant difference in either the deflection or the radius of curvature at the 5 percent significance level. This indicates that the transverse steel is serving its purpose in holding the pavement intact transversely and that the cracks are having no adverse effect on the behavior of the pavement.

Many times JCP without centerline longitudinal joints experience severe longitudinal cracking. These longitudinal cracks often meander and take the path of least resistance. In plain concrete pavements with no transverse reinforcement these cracks tend to open up; thus, the load transfer provided by aggregate interlock is lost. This same

Figure 1. Longitudinal crack in CRCP.

Figure 2. Close-up view of longitudinal crack.

Figure 3. Longitudinal cracking with no spalling.

Figure 4. Longitudinal cracking with minor spalling.

situation would occur in CRCP without transverse steel if the longitudinal joints designed into the pavements do not perform as anticipated.

EFFECT OF LONGITUDINAL CRACKING ON PAVEMENT LIFE

Several possible causes of longitudinal cracking have previously been enumerated. The question remains, What effect does the cracking have on pavement life? If longitudinal cracking has no effect on pavement life, then the decision to omit the transverse steel is a good one because it reduces cost. On the other hand, a possible reduction in performance life due to longitudinal cracking may more than justify the cost of transverse steel.

The answer to this question is a complex one and can be answered ultimately by comparative experience. Perhaps a reasonable answer can be obtained by applying the field experience acquired with transverse cracking. Performance studies of transverse cracks and joints have shown that the life is a direct function of the degree of load transfer (22, 23). Figure 5 shows a slab deflection pattern for several degrees of load transfer. The zero load transfer pattern represents the most detrimental stress condition; hence, it results in the shortest life, whereas the full load transfer condition results in the longest life.

The purpose of using transverse steel is to minimize the opening of any longitudinal crack in order to provide the full load transfer condition shown in Figure 5. These concepts have primarily been thought of in terms of transverse cracks, but the same principles are applicable to longitudinal cracks and joints. Hence, an excessive opening of longitudinal cracks can also increase stresses and reduce pavement life. The extent of the pavement life reduction due to longitudinal cracking will depend on the location of the cracks with respect to the wheelpath as well as the crack width.

The design decision on whether to use transverse steel should be based on costs and probabilities of success and failure of the various designs. Figure 6 shows a diagram of the design decision that includes the parameters covered in this report.

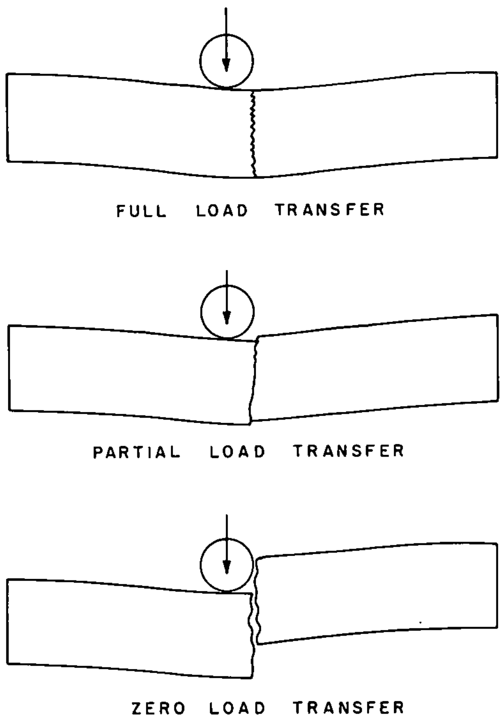

Figure 5. Slab deflection and load transfer.

Field Observations of Performance With Longitudinal Cracking

Much of the longitudinal cracking in concrete pavement observed by the authors has been on pavements that were ailing from other distress mechanisms. However, there are some pavements that have experienced longitudinal cracking for such reasons as have been cited previously.

In several cases with plain concrete, i.e., no reinforcing steel, considerable deterioration was experienced in the vicinity of the cracks. This is to be expected because the cracks opened widely, with a resulting loss of load transfer. The longitudinal cracks for these pavements meandered between the centerline and the wheelpath. The resulting damage was approximately proportional to the distance of the crack from the wheel part and was worst in the wheelpath. This particular example is an excellent illustration of the influence of load transfer and wheel load repetitions on pavement performance.

All of the CRCP on which longitudinal cracking has been observed has contained about one-tenth of a percent transverse steel reinforcement. The longitudinal cracking and crack widths observed appear much the same as the transverse cracking. However, if mechanisms are present to create longitudinal cracking in CRCP, it should be expected that further distress will occur such as that shown in Figure 2 where severe spalling has occurred along a longitudinal crack in a pavement where transverse steel was present. It is probable that, had the transverse steel not been present, the longitudinal cracks would have been wider and distress more severe than that shown in Figure 2.

Thus, extra maintenance can be anticipated when longitudinal cracks become excessively wide. The pavement shown in Figure 1 is a case where longitudinal cracking was so severe that maintenance was required as shown in Figure 7. Only time will tell how much more maintenance will be required and to what degree the distress shown in these figures will be propagated. Ultimately the performance life of this pavement will be reduced by these failures.

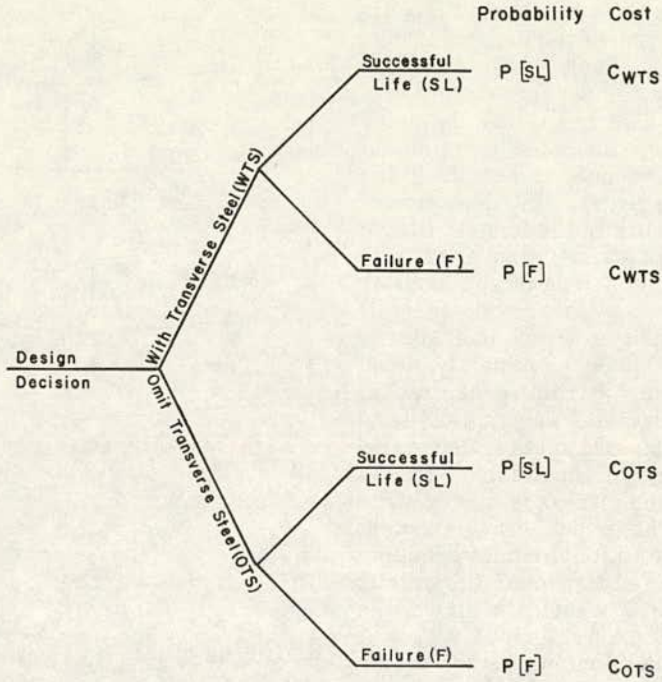

Figure 6. Design decision considerations with respect to transverse steel.

An important question arises at this point: Does the presence of a distressed longitudinal crack really create a detrimental situation? It has been shown in a previous study (24), where spalling was experienced with transverse cracks, that failure of only 2 to 5 percent of the surface area of an entire paving project causes engineers and users to consider the section of roadway a total failure. The extra distress due to longitudinal cracking described can significantly affect public reaction and result in premature overlay of the pavement.

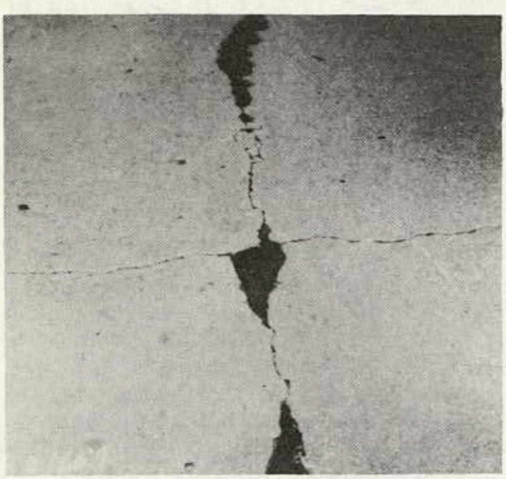

Figure 7. Maintenance on longitudinal crack.

Probability That a Crack Will Occur

What are the chances that any continuously reinforced concrete paving project might experience longitudinal cracking? In a recent nationwide survey of rigid pavements by the Federal Highway Administration (25), it was shown that, of 17 continuously reinforced concrete paving projects surveyed throughout the United States and built from about 1964 to 1966, 3 projects were reported to have experienced longitudinal cracking. Based on this small sample from a nationwide survey, the probability that a pavement would experience longitudinal cracking would thus be 0.2. The true probability of cracking probably ranges from 10 to 30 percent and probably would increase as the pavement width increased and as other detrimental factors become involved. Thus for urban sections the probability would be slightly higher because pavements of 3 to 5 lanes are commonly used.

Analysis of Longitudinal Cracking

In systems engineering terminology (26, 27, 28) the probability of failure is thought to be a function of the probability of cracking, materials properties, environmental variables, load variables, construction variables, and structural design variables. A complex mathematical function would be required to define the probability of failure in terms of all of these variables. To arrive at a practical analysis, the probability of failure in this paper is being calculated through the transformation of all these variables into the wear-out function involving present serviceability index and pavement life (26, 29).

This probability of failure will be developed by evaluating a typical CRCP design (12, 30, 31, 32). This typical CRCP design consists of an 8-in. slab, 24 ft wide, with a supporting subgrade k-value equal to 100 pci. The structural model used to evaluate this pavement is an analytical method developed by Hudson, Stelzer, and others (33, 34, 35). This particular analytical method makes possible analyses of the following 3 pavement conditions so that the probability of failure can be determined: a pavement expected to last its normal design life; a longitudinally cracked pavement that contains transverse steel; and a longitudinally cracked pavement that does not contain transverse steel.

These conditions basically simulate the 3 load transfer conditions shown in Figure 5. For each of these 3 pavements, the deflection and maximum stress for an applied load of 12,000 lb can be evaluated. By knowing the concrete flexural strength together with the maximum stress, one can predict the life of each of the 3 pavements by using a relationship of performance, concrete strength, and stress developed from AASHO Road Test data (36).

For the 3 conditions of the given pavement design, the maximum stress was determined. The maximum stress was 311 psi for the case with no longitudinal cracking and a 12,000-lb load. Based on the assumption that the concrete flexural strength is 690 psi, which was the strength of the concrete at the AASHO Road Test (37), the following relationship developed from AASHO Road Test information for load applications, concrete strength, and stress was used to determine the total number of load applications:

$$\log W = 5.789 + 3.42 \log \left(\frac{S_c}{\sigma}\right) \tag{3}$$

The total number of load applications that the 8-in. CRCP can carry to a terminal serviceability index of 2.5 is 9,360,000 load applications for the condition of no cracking, i.e.,

$$W_{nc} = 9,360,000$$

The pavement life is next determined for the condition where a pavement has transverse steel and experiences longitudinal cracking. Longitudinal cracking was modeled by a 40 percent stiffness reduction based on differences in deflections actually measured on real pavements (23). For this continuity condition or cracking pattern with transverse steel, a maximum stress was determined as 323 psi. This value was used with a concrete strength of 690 psi to determine the number of load applications:

$$W_{cs} = 8,190,000$$

For the third condition, a pavement that has no transverse steel and experiences longitudinal cracking, the longitudinal crack with no mechanical load transfer was

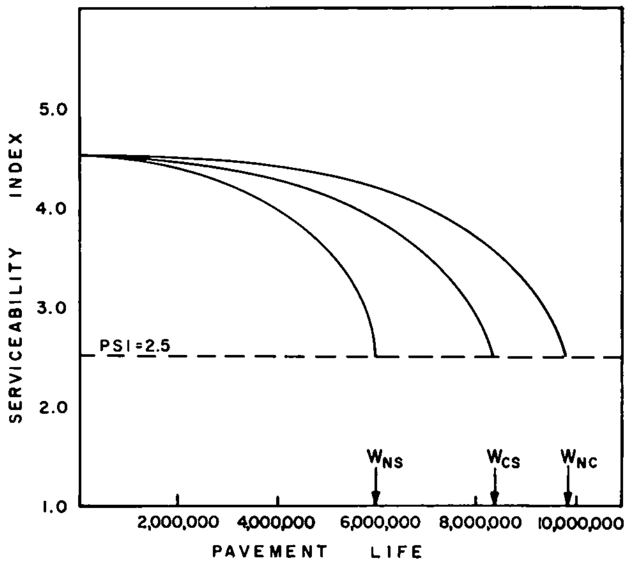

Figure 8. Comparison of pavement life for 3 pavement conditions.

simulated by a hinge, i.e., zero bending stiffness. The stress was calculated to be 355 psi. If the performance equation and 690-psi strength concrete are used, the number of load applications that the cracked pavement with no transverse steel can sustain is

$$W_{cns} = 5,950,000$$

Figure 8 shows a comparison of the 3 pavement conditions. The relation of serviceability to pavement life is shown for the design life and for the actual life of longitudinally cracked pavement with and without transverse steel.

Expected Cost-Performance Analysis

In the following analysis 2 fundamental assumptions are as follows: (a) The probability of crack occurrence is independent of the fatigue life; and (b) the probability of longitudinal crack occurrence is independent of the presence or absence of transverse reinforcement.

The expected pavement cost per square yard per unit life of a pavement is

$$C/W = \text{cost per sq yd} \div \text{life of the pavement}$$

Thus, the expected cost per sq yd per unit life of pavement is

$$E(C/W) = \sum_{i=1}^{n} \left(\frac{C}{W_i}\right) P_i \tag{4}$$

where

C = cost per sq yd of pavement;
W_i = pavement life with pavement condition i;
P_i = probability of occurrence of pavement condition i; and

$$\sum_{i=1}^{n} P_i = 1.00.$$

If we assume, for the purposes of analysis, that only 4 pavement conditions exist, i.e., pavements with and without transverse steel and pavements with and without longitudinal cracks, the expected cost per unit of life is

$$E(C/W)_s = \left(\frac{C_s}{W_{nc}}\right)(1 - P_c) + \left(\frac{C_s}{W_{cs}}\right)P_c \tag{5}$$

with transverse steel, and

$$E(C/W)_{ns} = \left(\frac{C_{ns}}{W_{nc}}\right)(1 - P_c) + \left(\frac{C_{ns}}{W_{cns}}\right)P_c \tag{6}$$

without transverse steel, where

C_s = cost per sq yd with transverse steel;
C_{ns} = cost per sq yd without transverse steel;
W_{nc} = life of pavement without longitudinal cracks and with and without transverse steel in millions of load applications;
W_{cs} = life of pavement with longitudinal cracks and with transverse steel in millions of load applications;
W_{cns} = life of pavement with longitudinal cracks and without transverse steel in millions of load applications; and
P_c = probability of occurrence of longitudinal cracking in CRCP.

Equations 5 and 6 are generalized models where the expected cost per million load applications is related to cost, pavement life with no cracking, pavement life with longitudinal cracking, and the probability of longitudinal cracking. By subtracting Eq. 5 from Eq. 6, a relationship can be obtained for the difference in cost per million load applications between CRCP without and with transverse reinforcement. This difference will be referred to as the performance cost differential.

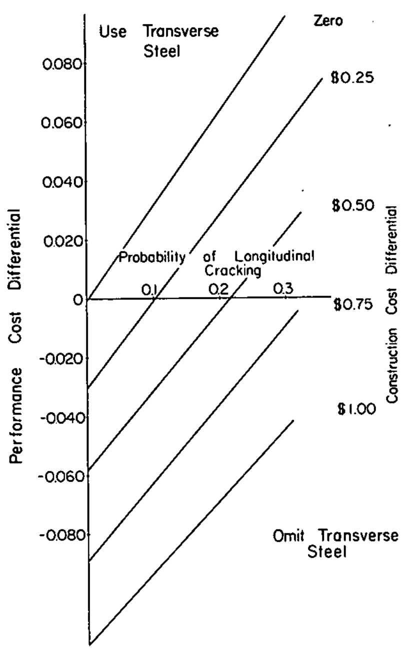

Figure 9. Relation of probability of longitudinal cracking and construction cost differential.

The relationship of probability of longitudinal cracking, initial construction cost differential, and performance cost differential is related by Eq. 7.

$$E(C/W)_{ns} - E(C/W)_s = \frac{C_{ns}}{W_{nc}}(1 - P_c) + \frac{C_{ns}}{W_{cns}}P_c - \frac{C_s}{W_{nc}}(1 - P_c) + \frac{C_s}{W_{cs}}P_c \tag{7}$$

where

$E(C/W)_{ns} - E(C/W)_s$ = performance cost differential;
C_s = \$6.00;
W_{nc} = \$9.36;
W_{cns} = \$5.95; and
W_{cs} = \$8.19.

Figure 9 shows a family of straight lines relating probability of longitudinal cracking and performance cost differential for various differences in initial construction cost based on Eq. 7. For all combinations of probability of longitudinal cracking and initial construction cost differentials above the horizontal axis, a designer should specify the use of transverse steel. For combinations beneath the horizontal axis, the transverse steel may be omitted. Thus, if a positive performance cost differential is determined, transverse steel is required; if the differential is negative, steel is not required.

SUMMARY

The development of new construction techniques for the placement of CRCP has led to questioning the purpose of transverse steel. The original purpose was based on both construction and design reasons. The recent developments in construction technique have eliminated the need from a construction standpoint, but the design criteria are still applicable. Basically, the transverse steel is used to ensure adequate load transfer across random longitudinal cracks that might occur in the pavement. Performance studies have shown that inadequate load transfer across a crack or joint can cause a pronounced reduction of service life. In essence, the principle of providing adequate load transfer across transverse cracks also applies to the longitudinal cracks. The primary difference is that the design conditions are not as critical; hence, the required amount of steel is considerably reduced.

Basically, the engineer's decision on use of transverse steel is one of the following: (a) eliminate the steel to obtain a reduced initial construction cost and gamble that longitudinal cracking will not occur to an extent that it reduces service life; or (b) use the transverse steel and ensure that if longitudinal cracking occurs the service life is not severely reduced from the expected design life. A number of possible causes for random longitudinal cracking were presented in the text. These include temperature changes, improper joints, deep earth movements, differential subbase compaction, and others. As the pavement width increases, the probability of longitudinal cracking and reduced performance increases.

A cost-performance analysis has been presented that shows when, and when not, to use transverse steel based on the probability of longitudinal cracking and the difference in initial construction cost. Thus, the designer can determine whether to use transverse steel based on the expected difference in initial construction cost and the probability of longitudinal cracking. Certainly the probability of longitudinal cracking would be low for pavements on good subgrades. However, for pavements wider than 2 lanes and on subgrades that have a potential to swell, the probability of longitudinal cracking would be higher. The probability of longitudinal cracking developed here is reasonable for pavements with expectant subgrade problems.

The difference in initial construction cost may be quite difficult to establish. The material cost is simple, but the reduced labor cost is dependent on too many factors to be established very easily.

On the basis of this limited study the following conclusions are offered:

1. The transverse steel in the pavement serves the design function of ensuring adequate load transfer across longitudinal cracks; thus, it ensures long-term performance.
2. With low probabilities of longitudinal cracking and available initial construction cost reductions, the transverse steel may be omitted; however, the basis for this decision needs to be studied further before a decision can be made to omit transverse steel from all pavements.

The general area of pavement reinforcement is in need of research. A survey of longitudinal cracking in all CRCP paving projects in the United States could provide data for probability of longitudinal cracking. Economic studies on labor savings are also needed to establish more accurate data.

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