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Research Methods

Report

on

THE SIGNIFICANCE OF TRANSVERSE CRACKS IN CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

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Outline of Report on THE SIGNIFICANCE OF TRANSVERSE CRACKS IN CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS for Oral Presentation

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THE SIGNIFICANCE OF TRANSVERSE CRACKS IN CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

by A Crabtree

1. SYNOPSIS

The purpose of this report is to provide a brief background for further study into the significance of transverse cracks in continuously reinforced concrete pavements. This presentation provides a chronological review of past research culminating with present experiments by the Pennsylvania Department of Highways. The theory of transverse cracks is stated to be the key to design of continuously reinforced concrete highways. Apartial review of the variables involved is made in order to indicate the difficulties of model studies and the difficulties of comparison of full size test sections in different locations. A review is made of the conventional pavement design formulas for transition to a comparison of recent formulas pertaining to continuous pavement. Conclusions are provided and the possibilities for future research are stated.

2. INTRODUCTION

2.1 Purpose and scope in detail. Within this report an attempt is made, by way of a brief review of certain developed formulas, to indicate that transverse cracks are the key to the design of continuous or jointless pavement. For each of the formulas selected, references for complete derivation and further discussions of theory are provided. These selected formulas show that from the earliest consideration of concrete pavement as a structure subject to external loads, engineers approached the problem of pavement design utilizing the conditions occuring at either a formed or natural crack. Formulas for conventional pavement are based on design of critical sections adjacent to a formed crack; whereas, current theories regarding jointless pavement provide design formulas concerning action of the pavement at a "natural" crack.

2.2 Historical background. It is interesting to note that the first construction of jointless pavement occured about the same time that D. A. Abrams proved that the strength of concrete is related to the water-cement ratio. (1918-20) Of course the value of concrete itself was recognized at an early date until today MORE CONCRETE IS USED IN CONSTRUCTION THAN ALL OTHER MATERIALS COMBINED; yet, this major structural item is so completely governed by such a vastness of variables as to defy direct solution in most cases. This situation extends to jointless pavement and the only research data available has been obtained by the observation of full scale field structures. So, when compared to steel, concrete is a "dirty" material which requires the pains taking means of "try, try, try again" before the silver platter of formula can be guarantied to the profession of engineering.

2.3 In regard to jointless pavement, a start in the direction of research was made by Indiana in 1938. No further research was attempted until 1947 when Illinois and New Jersey realized the importance of a maintenance free pavement. By 1951, Texas was also convinced and, therefore, selected this construction method for a section of the Fort Worth Freeway as insurance against maintenance troubles. (Table 1, SECTION 9 contains a summary of research items considered)

2.4 Test Program in Pennsylvania. In 1956 Pennsylvania, co-operating with the Bureau of Public Roads and the American Iron and Steel Institute, constructed a section of jointless pavement at York, Penn. and in 1957 another section was constructed near Hamburg, Penn. (Highlights of these projects are available on a Fritz Laboratory Poster)

Of mentionable interest and directly effecting Fritz Laboratory, is the fact that publicity can be a most vital factor in the continuence of any research. For instance, no failures have occured on the York project but, even without traffic load, five major failures have developed at the Hamburg site. This was of understandable concern to the 15 or more dignitaries who visited the site and with the cracks at hand could reach no conclusion or explanation. Such failures, to understate, were significant to continuation of the research program especially since the Hamburg pavement was due to be open to the public in the next few days. This project was also highly publicized on the site as well as in many construction magazines including an important feature in Engineering News Record. Fortunately for future research, investigation by core boring a few days later revealed that in every case the unpredicted cracks were due to complete lack of reinforcement. This deficency is attributed to careless construction and poor inspection and not to theory or specifications.

3. DESCRIPTION OF TESTS.

The Pennsylvania tests are similar to past projects of other highway departments, except that the Pennsylvania projects will be accurately observed with the advantage of contract strain gaging under the research supervision of Ivan J. Taylor of Fritz Engineering Laboratory. A notable feature of the test section is the simulated crack as induced or partly formed by a thin corrugated (to preserve aggregate interlock) plate. Strains are measured at the crack and on each side by the installation of waterproofed SR-4 gages on the reinforcing and within the concrete prior to pouring. Internal and external temperatures are also recorded. (A sketch of the gaged section is contained on Figure 1, SECTION 9). The pavement sections at York and Hamburg will be observed for the next ten years.

4. THEORECTICAL ANALYSIS.

4.1 Assumptions and limitations. The theory of transverse cracks is the key to continuous pavements. Actually with the vast extent of variables involved, it is significant that any single item can be pointed to at all. Of course official acceptance of recent formulas and proposals for design methods and later reduction into codes will not occur until more test sections are studied and more of the side issues can be fully explained. However, the general theory may be simplified as follows: Concrete expands and contracts with changes in temperature. If we keep the resulting cracks to a small magnitude but frequent in occurance, we have satisfied temperature requirements while providing the advantages of a smooth highway, free of expensive joints, without the danger of joint or crack pumping action.

Assuming knowledge of conventional pavement, a successful highway depends on an adequate subgrade and a proper wearing surface. To arrive at any formula for jointless pavement we should attempt to name all variables and to understand to some degree their relation to each other. What are some of these variables? A partial list of items influencing initial thoughts toward a final design formula are outlined below:

VARIABLES

- TEMPERATURE
  - daily
  - seasonal
  - pouring
  - setting
- SUBGRADE
  - compaction
  - moisture
  - type
- STEEL
  - quanity
  - type
  - bond
- LOADS
  - weight
  - speed
  - impact
  - frequency
  - distribution

The above list of items could be readily expanded and, by a glance at the number of variables that could be involved, any model study would be questionable. Even comparisonof full scale pavements in separate locations would be extremely difficult. However, the advantages to be gained has provided the highway research engineer with the necessary patience for long time studies. (It would seem that the time required for such solutions could be said to be a function of the quantity of variables involved).

Bond is an important variable to jointless concrete pavement; and researchers in pre-stressed concrete, knowing of the importance of bond to their field, after years of study have apparently only approached an understanding of this item. Today they must lean to ''rule of thumb'' tempered by rules derived from observed action. The subject of bond is further discussed in a later section of this report.

With all this seemingly lack of knowledge, concrete pavements have been successfully designed and constructed, if success is not judged on a strict economic basis. Fortunately, the nicks in the hard shell of concrete variables are continuing and are becoming progressively larger in order that pavement thickness may be reduced to an economical minimum. Progress can be proved by review of Westergaard's formulas which have been highly respected for many years. In fact for todays maximum loads, ten inches of thickness is accepted as a usual requirement for conventional pavement if consistant with Westergaard's radius of pressure theory; but jointless pavement designers look forward to slabs of seven inches or even less.

4.2 Development. With the remainder of this report, the references provided, and a wealthy sponsor, establishment of an ultimate design formula or procedure may be possible. For a better understanding of the significance of transverse cracks, certain formulas and theories of highway engineers have been selected and are discussed below in the order in which the were developed.

Clifford Older of Illinois is considered to be the first engineer to design conventional concrete pavements on the basis that they could be analyzed as a structure to resist certain loads. His theory considered that the critical section for design occured at formed load transfer joints or cracks and also provided for thinner sections away from joints or edges. Older's edge depth formula:

$$d_e = \sqrt{\frac{W}{\sigma_c}} + 2\left[\sqrt{\frac{2W}{\sigma_c}} - \sqrt{\frac{1.33W}{\sigma_c}}\right]$$

W = load σ_c = concrete stress

It is significant to note that the earliest formula for conventional pavement considered load transfer by the steel across a formed crack. In continuous pavement steel continues to transfer load but the transfer is made across a natural crack at the same time providing a dual purpose of keeping the crack small in a longitudinal direction.

H. M. Westergaard made stress studies at three critical points within conventional pavement. His theory is based on a radius of relative stiffness between the slab and the subgrade. Westergaard's stiffness radius formula:

$$\ell = \sqrt{\frac{E_c d^3}{12(1-\mu^2)k}}$$

E_c = modulus of elasticity d = depth
μ = poissons ratio k = modulus of subgrade reaction

The significance of this approach is that the most critical section occurs a point adjacent to the edge of a formed crack.

The next step in understanding and in transition from conventional pavement to continuous pavement design would be to analyze the similarities of past research as made by Indiana, Illinois, New Jersey, California, Texas, and Pennsylvania. The results common to all states are as follows:

1. Resistance to pumping action and hence pumping failure is a function of crack width.
2. Crack interval and crack width is dependent on the amount of steel.
3. Temperature influence is of much greater importance than previously considered.

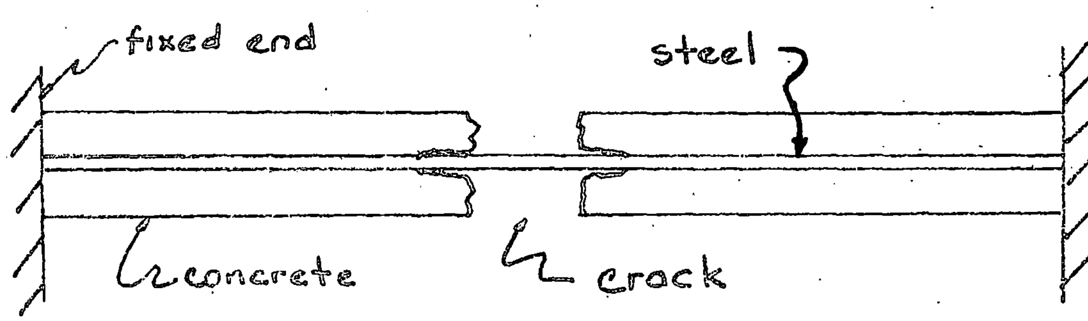
The above conclusions are inline or vise versa with B. F. Fribergs temperature crack theory which assumes a fully restrained slab without consideration of wheel loads.

Friberg's percent steel formula:

$$\rho = \frac{E_c}{\frac{\sigma}{et} - E_s}$$

E_c = concrete modulus of elasticity; E_s = steel modulus of elasticity; σ = steel stress; e = coef. of expansion t = temperature change

A sketch of the theorectical slab with a magnified crack is provided below and is applicable to the theories of Friberg and Yerlici:



Next in chronological consideration, is Prof. William Zuk who provides a theory that the pavement is subject to concentrated loads and may be treated as a beam on an elastic foundation but without consideration of torsion or temperature.

Zuk's pavement thickness formula:

$$t = \left[\frac{4.526\, E_c\, p^4}{(f_t)^4\, b^3\, (K_1 + K_2 + K_3)}\right]^{1/5}$$

b = crack interval p = % steel
K_1 = elastic subgrade modulus
K_2 = " restraining modulus of adjacent sec.
K_3 = aggregate interlock modulus
E_c = concrete modulus of elasticity

In general agreement with Friberg but with an approach based on limiting the crack width to a small magnitude for continuity is the soon to be published Lehigh formula of Yerlici and Eney.

Yerlici's formula for percent steel:

$$p = \frac{f_t}{f_s - \alpha_s T E_s}$$

f_s = allowable tensile stress of steel
α_s = thermal coef. of expansion
E_s = modulus of elasticity for steel
T = maximum temperature change

The method of design soon to be published by Yerlici and Eney is considered to be of considerable importance since it is based directly on the theory of continuous pavement, is simple in derivation and adaptation and therefore most likely to be accepted by the highway engineering profession. It is the first simple and direct procedure for design of continuous pavement and its importance can not be over emphasized.

Y. J. Shieh of Lehigh has proposed a rigorous mathmatical analysis beyond the attemps of Prof. Zuk. This involved an analysis of a section between cracks as a plate on an elastic foundation. As a practical reduction to the work involved, Shieh suggests considering the entire pavement as an infinite or semi-infinite orthotropic plate on an elastic foundation by application of the methods employed within the theory of plates and shells. Details for solution remain.

4.3 Consideration of Bond. Before concluding this report or before summarizing the work of the engineers discussed in this report, a few statements should be made on the importance of bond to pavement design. The crack of consideration in all of the above formulas could not occur without loss of bond between the conrete and steel. The bond loss is not only within the crack width but continues for a variable distance and in an uncertain variation into the concrete adjacent to the crack. Conventional pavement designers did not consider beam or plate action and hence had no concern or knowledge of bonds importance. Friberg assumed full bond except at the crack. Zuk assumes bond concentrated at the first transverse rod. Yerlici's approach is an improvement but still incomplete since he implies that the user of his formula should select an unbonded length beyond the crack and this length must then be incorporated into the the design formula. Details of Shieh's method remain to be developed.

In personal consideration of this item no futher conclusion could be reached without extending the scope of this report. However, thereis no hesitation in stating that more detailed study should be given to the extent to which bond should be considered beyond the results of pavement designers to date. It is interesting to note that the state of Virginia plans future studies and tests under the direction of Prof. Zuk which will include additional consideration of bond. But even without field tests, current literature includes a wealth of material both American and foriegn which may provide further clues to the treatment of this factor for jointless pavement. Of especial consideration would be the influence of bond as reported in Rene Walther's Ultimate Strength of Conventional and Pre-Stressed Concrete as well as Ueber die Beanspruchung der Schbarmierung von Eisenbetonbalken which remains for personal translation at a more opportune time. Local resources would be the information within the pre-stressed concrete research files of G. A. Dinsmore and P. L. Deutsch. Additionally, Contribution a l'etude de l'adherence des fers d'armature au beton which extensively considers bond under many pull out conditions and includes a fascinating idea and report on the installation of strain gages within the steel bar by removal of the bars interior without effecting the results of the test on bond.

5. DISCUSSION OF THEORIES

The theories developed by engineers independently concerned with highways seem to establish a trend which can be progressively and roughly outlined as follows:

Older: Concrete pavement as an engineering structure subject to traffic loads with reduction in section permitted beyond the formed crack or edge.

Westergaard: Most critical section occurs adjacent to formed crack when pavement is subject to traffic loads.

Friberg: Continuous pavement may be considered as a fully restrained slab and reinforced on the basis of conditions occuring at a naturally or temperature cracked section.

Zuk: Continuous pavement subject to wheel loads may be considered as a beam between cracks supported by an elastic foundation. Torsion nor temperature considered.

Yerlici: Pavement considered as a fully restrained slab subject to temperature change which may be reinforced to provide a limiting crack width.

Shieh: To consider slab as anistropic plate on an elastic foundation or as an infinite or semi-infinite orthotropic plate strip on an elastic foundation.

The six methods above may be devided into three separate classes as follows:

1. Conventional pavements (Older and Westergaard) which do not take temperature into consideration and only analyze on the basis of local stiffness.

2. Beam or plate action (Zuk and Shieh) which do not provide for the influence of temperature as proved by current research.

3. Temperature formulas (Friberg and Yerlici) which do not mathmatically account for wheel loadings and inherent stiffness.

These theories and research into the subject of jointless pavement indicate that we are dealing with a continuous, cracked, reinforced concrete slab subject to dynamic loads and resting on soil of non-uniform resistance. It is also true that the magnitudes of crack spacing, impact, modulus of elasticity, moment of inertia, and foundation modulus are not reliable factors. However, any of the above theories is an aid to at least a qualitative understanding of pavement behavior and would provide an approximate answer to the problem of pavement design.

6. SUMMARY AND CONCLUSIONS

In final review of this subject and the three classes of design formulas covered in this report, the statement can be made that none of the approaches to date can be considered as a final answer. Therefore, further research is needed and in a direction which would effectively combine the temperature influence (Yerlici) with plate action (Shieh) and with the not yet considered dynamic action of loads.

With personal license, the trend of development reported in SECTION 5 may be extended to include future developments which would be Reduction of thickness based on consideration of temperature and limited by observation of traffic requirements as provided by field research. Such reduction will reach the point whereby external wheel loads will be of equal importance or necessity for consideration. The mathmatical possibility exists for analysis as an anistropic plate on an elastic foundation in combination with reinforcement for temperature requirements in order to provide a limited crack width.

Other challenges are such refinements as (1) location of reinforcement within the slab for the most effective thickness and with continuous cycles of temperature; (2) minimization of subgrade preparation; (3) most economical combination when both (1) and (2) are considered toge ther. Most important and eventually, engineers must reduce mathmatical theories providing an economical design into usable computer, tabular, or formula methods for ready consumption by highway engineers.

The guiding hand of Federal funds will be responsible for more research and current allocations to highway departments require that a certain percentage must be spent on research. As a result Virginia under Prof. Zuk will study slabs restrained by anchor keys or lugs as well as the influence of bond by maintaining constant steel area while varying perimeter. The state of Maryland has also approached Lehigh to measure strains in experimental sections. North Carolina has initiated plans for experimentation on continuous highways. The Highway Research Board, an organization of interested parties, continues to be a sounding board and Zuk's theory will soon be discussed at a meeting in Washington. This meeting will be attended by Taylor, Yerlici, and Shieh of Lehigh University.

Future proposals for tests at Fritz Lab may consist of the testing and development of indoor slabs inorder to verify the optimum width theory, or verification of Shieh's concept of an orthotropic plate on an elastic foundation. Small, but perhaps significant, tests could indicate the influence of bond on crack width. Difficult and expensive tests would consist of laboratory simulation of temperature and dynamic conditions in order to measure appropriate influences.

A storehouse of possibilities exist upon the application of computers to the mathmatical concepts of Zuk and Shieh. Especially since the final and required cases, curves, and tables that must be established for all concrete strengths, subgrades, and steel variables.

(Final note: The formula and systems reported herein should not be utilized without reference to more complete details and dicussions as may be obtained by referenced to those articles contained in SECTION 8)

SECTION 7

Acknowledgements

This report has been prepared for the dual purpose of CE 400 Research Methods course requirements and as a partial summary of Fritz Engineering Laboratory research in continuously reinforced concrete pavements.

Prof. W. J. Eney is the Director of Fritz Laboratory and serves as a consultant on this project. The project is under the direction and supervision of Mr. I. J. Taylor. Directly assigned for research assistance on this project are Prof. V. Yerlici and Mr. Y. J. Shieh.

The advice of Prof. V. Yerlici and Mr. Y. J. Shieh proved beneficial in completion of this report.

The author is not assigned to this project but has been permitted access to all research files and to attend all weekly conferences during 1957. The privilege of this association has been of considerable influence to the authors knowledge of research methods. For this reason, acknowledgement and sincere thanks must be extended to Prof. Eney and Mr. Taylor.

SECTION 8

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SECTION 9

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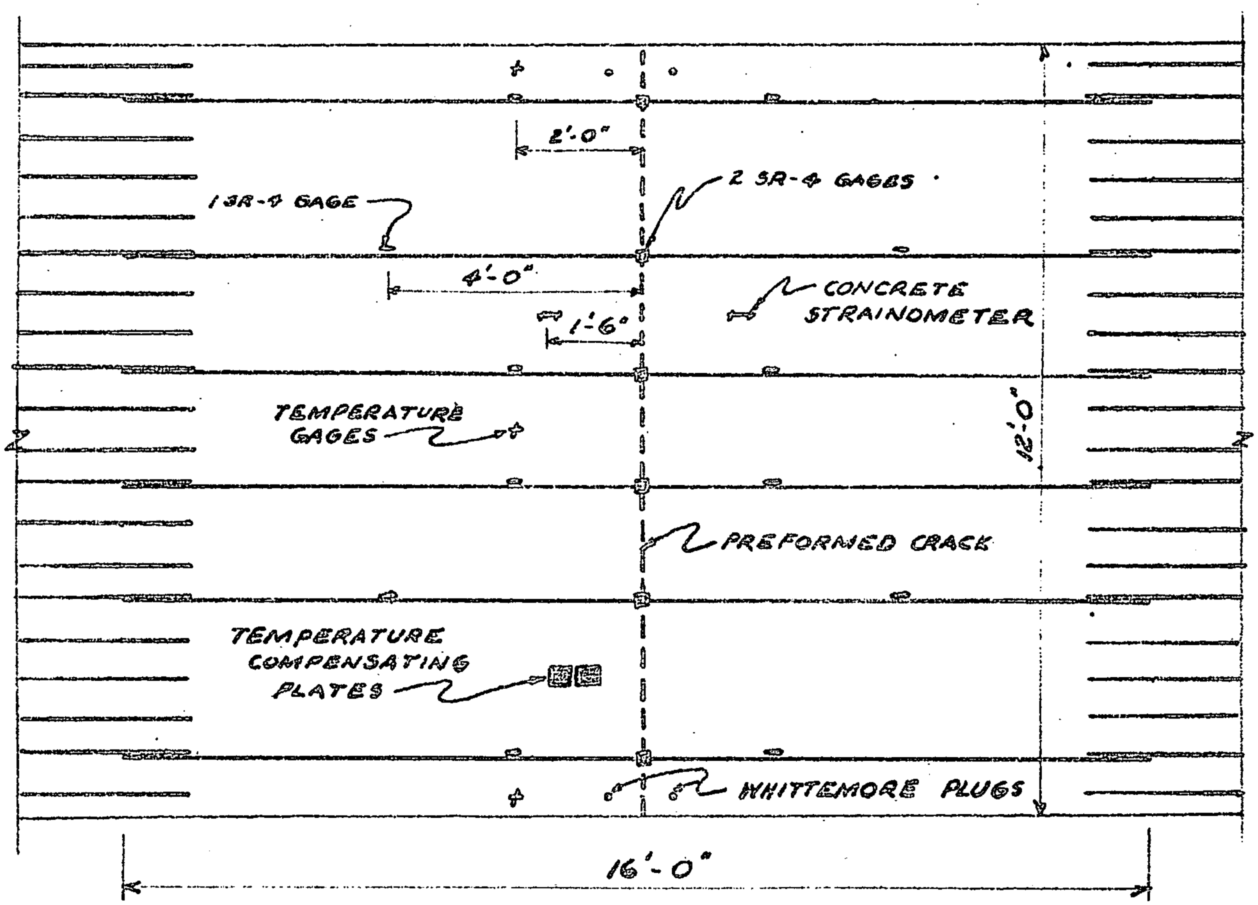

FIGURE 1 INSTRUMENTATION PLAN

SECTION 9

Table of Research Items Considered by State

Highway Departments

YEAR	STATE	ITEMS
1938	Indiana	Varied percentage of reinforcing steel for observation of crack results
1947	Illinois	Varied percentage of reinforcing steel, yeild points, and pavement thickness
1947	New Jersey	High percentage of reinforcing steel with high yeild points in order to study crack width and changes in length
1947	California	Varied reinforcing strength to study movement, strains, temperature influence, cracks, roughness, and condition
1951	Texas	Not a research project but observed for general items.

Table 1