National Cooperative Highway Research Program

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FLEXIBLE PAVEMENT DESIGN AND MANAGEMENT

Systems Formulation and Materials Characterization

An NCHRP staff digest of the essential findings from the final report on NCHRP Project 1-10, "Translating AASHO Road Test Findings--Basic Properties of Pavement Components," by Materials Research & Development, Inc., Oakland, Calif. The report has been submitted as two separate documents with subheadings "Materials Characterization," by K. Nair and C-Y Chang, and "Systems Formulation," by W. R. Hudson and B. F. McCullough

THE PROBLEM AND ITS SOLUTION

The structural design of highway pavements involves empirical techniques based to a large extent on long-time experience of highway agencies and augmented by test programs, the most ambitious of which was the AASHO Road Test conducted near Ottawa, Ill., and completed in the fall of 1960. Due to the fact that a field test program involving the many variables known to affect pavement performance would become unfeasible, the sponsors of the Road Test chose to include only a limited number of variables in the project. As a result, it is generally recognized that the relationships between traffic loadings and pavement performance developed at the Road Test apply only to the conditions at the test site. Applications of these relationships in other areas of the country must be based on experimental or other evidence of the effects of differences in subgrade soil, paving materials, construction practices, traffic, environment, and maintenance procedures. A number of early NCHRP projects dealt with extrapolation of Road Test findings to conditions other than those at the test site.

NCHRP Project 1-10 was initiated by a team of Materials Research and Development, Inc., researchers with the objective of using basic properties of pavement component materials to translate AASHO Road Test findings to other conditions and thus ultimately develop more rational pavement design procedures. The research has resulted in substantial progress toward the ultimate objective of developing more rational pavement design procedures, utilizing measured values for significant mat-

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erial properties, and being applicable to all geographic locations, environmental conditions, and traffic loadings in terms of both immediate application and long-range benefits. However, in the early stages of the study it was determined that measurement of basic properties of materials and components significant to pavement performance was a highly complex problem requiring (a) development of new testing equipment, (b) considerable laboratory data collection, followed by (c) field experimentation. It was also recognized that the pavement design decision-making processes involve factors other than the structural ability of a section to support predicted traffic loadings (e.g., maintenance strategies, user considerations, and long-term economics). The concept of considering management of a pavement system throughout its operational life during the initial design process was developing. Consequently, project efforts were divided into two separate but coordinated activities--materials characterization and systems formulation--with each activity under the direction of a separate research team.

An operational pavement systems model (SAMP5) has been formulated that organizes the over-all influencing factors such as materials characteristics, construction techniques, maintenance requirements, and economics within a suitable framework for flexible pavement design and management. A computer program has been prepared using 58 to 100 input variables and the AASHO Interim Guides for Design of Flexible Pavements as the structural subsystem. An earlier version of the system is currently being implemented by the Texas Highway Department. The procedure can be applied to flexible pavement design problems now by any agency having the proper input data and using the AASHO design guides. However, for the method to be more easily implemented, detailed descriptions for users' guides, input forms, and data feedback and storage systems are needed. These are to be prepared and the procedure is to be subjected to a sensitivity analysis and pilot testing during an implementation phase of future work in this problem area. Intermediate and long-range prospects for improvements in pavement design within the systems concept may depend to a large extent on the development of more rational approaches to the formulation of the structural subsystem based on properties of the subgrade and paving materials, rather than on the empirical relationships developed during the AASHO Road Test. A procedure, including the necessary laboratory equipment, has been developed for characterization of materials in terms of stress/strain relationships representative of loading and environmental conditions to which they are likely to be subjected as components of a pavement. The methodology is illustrated in the project reports by its application to the characterization of an asphaltic concrete, a granular base material, and a cohesive subgrade soil. The description of the testing equipment and accumulated materials characterization data should be of considerable interest to pavement design researchers.

FINDINGS

Pavements are extremely complex physical systems. A great deal of effort has been expended in the study of pavement design, behavior, and performance, but at the present time empirical relationships and experience are the basis for the most accepted methods of structural design of a pavement. The findings of this study, aimed at both immediate and long-range improvements in the pavement design and management process, are reported under the headings of systems formulation and materials characterization, two separate but coordinated activities responsive to over-all project objectives.

SYSTEMS FORMULATION

Systems engineering in its broad sense is a codified procedure for attacking complex problems in a coordinated fashion to permit realistic decisions that can be justified on the basis of selected decision criteria. A conceptual pavement systems diagram, as shown in Figure 1, was prepared primarily to illustrate the interrelation of many inputs and subsystems involved in the pavement design and management process. The inputs to the system include a range of load, environmental, structural, construction, and maintenance variables, all of which are stochastic in nature and are interrelated. Although conceptualizing the over-all pavement system was essential to solving the problem, it was necessary from an application standpoint to develop an operational system. After a review of the efforts of other researchers in the area of applying systems engineering concepts to pavement design, it seemed desirable to modify and extend the efforts of Scrivner, McFarland, and Carey*, who had developed the first known computer-oriented operational system for the design of flexible pavement, rather than expend time and effort on an entirely new system. Thus, the working method developed on this project, Systems Analysis Model for Pavements (SAMP), is an extension of the algorithms initially conceived by Scrivner et al. In the particular version described in the Project 1-10 report (SAMP5), there are seven classes of input variables as follows: (1) material properties, (2) environmental and serviceability, (3) load and traffic, (4) constraints, (5) traffic delay, (6) maintenance, and (7) program control and miscellaneous. An example problem using the operational model is included in the report. A limited sensitivity analysis and evaluation of the program was conducted, and the feasibility of revising the structural subsystem to permit the use of more rational concepts--such as elastic layered theory--was demonstrated.

The major conclusions and recommendations of this portion of the research are as follows:

1. An uncoordinated attack on the structural design of pavements will not be successful in solving the problem. A systems engineering approach is required that can be used to describe the over-all behavior and performance of the pavement system, as well as the functions of its component parts, during its entire life as a portion of the highway transportation network.

2. A conceptual pavement systems model has been formulated to show the relationships between the many groups of input variables that must be considered.

3. An operational flexible pavement systems model (SAMP5) has been developed, including a computer program using 58 to 100 input variables.

4. Possible improvements to SAMP5 are illustrated, including the use of elastic layered theory and the most recent materials characterization information to provide a more rational structural subsystem.

5. Efforts should be made to: (a) implement the present operational system in several states, (b) modify and improve each of the subsystems, and (c) ultimately upgrade the model toward a true "pavement management system" capable of evaluating the adequacy of the pavement, in terms of providing the intended service over its operational life.

MATERIALS CHARACTERIZATION

Use of the systems approach to pavement design and management requires the description and solution of the various subsystems, one of which is the structural (primary response) subsystem. In theoretical or rational approaches to structural subsystem solutions, it is assumed that the primary response of the pavement structure can be defined by its mechanical state. In conventional terms, determining the primary response involves the formulation and solution of appropriate boundary value problems to determine the stress/strain relationships (mechanical state) of each component in a pavement due to applied loads under a variety of environmental conditions. The results obtained from solution of specific boundary value problems are

*Scrivner, F. H., McFarland, W. F. and Carey, G. R., "A Systems Approach to the Flexible Pavement Design Problem," Research Report 32-11, Texas Transportation Institute (1968).

then evaluated in the light of established performance criteria to determine the capability of the pavement system to sustain the input. It is important to recognize the complexity of this task and the iterative nature of the procedure, as illustrated by Figure 2.

For the purpose of determining the mechanical state through the formulation and solution of boundary value problems, materials are currently described by simplified mathematical models. To determine the likelihood of distress, it is necessary to establish performance criteria for the various materials comprising the pavement system. These performance criteria are related to limiting values of stress and strain that can be permitted to occur in the material, the numerical magnitude of the material, the environment, and the loading conditions.

Characterization of materials, as defined for this project, is the selection of constitutive equations to adequately model the response of paving materials to the loading and environmental conditions to which they are likely to be subjected as components of a pavement. In the preliminary model selected for this study, no attempt was made to include environmental factors (e.g., temperature and moisture). However, the effects of these factors on material behavior were taken into account by testing over a range of temperatures and moisture contents likely to exist in actual pavements systems.

No equipment was found to be capable of fulfilling the desired project requirements, necessitating the design and fabrication of suitable laboratory testing equipment. Essentially, this consisted of modifications of conventional triaxial testing apparatus to provide for independent control of axial and radial stresses. Using the modified triaxial equipment, repeated load tests were conducted on three paving materials--an asphaltic concrete, a granular base material, and a cohesive subgrade soil. These tests were conducted on the assumption that the materials were elastic, though not necessarily linear; and, hence, the resilient deformations were measured. The data were analyzed on the basis of an incremental formulation of a physically non-linear elastic constitutive law. Recognizing that solution techniques currently available are for linear and "ad hoc" non-linear problems, the results have been presented in terms of an approximate modulus of elasticity and Poisson's ratio. The variations of these parameters with temperature and stress level have been indicated.

The following findings are considered significant with regard to the response of the particular material tested under the loading conditions of the investigation:

Asphaltic Concrete

1. The temperature is the most significant factor in determining the response of asphaltic concrete. This suggests that the characteristics of the asphalt cement are of major significance.

2. At any particular temperature the stress level influences the response of the asphaltic concrete. The asphaltic concrete is less resistant to deformation at higher temperatures. For a constant stress level the deformation increased with increasing temperature.

3. A non-linear elastic model can provide a suitable representation of the response of asphaltic concrete below temperatures of 55°F for the loading conditions of the study--a repeated load of short duration applied to the material after an initial period of conditioning under repeated load. Above this temperature the time-dependent effects are too significant to neglect, hence consideration should be given to a viscoelastic model.

4. The data indicate that the asphaltic concrete might be initially isotropic and that anisotropy was induced as a function of the stress state and temperature.

Granular Material

1. The response of granular materials is, for all practical purposes, time independent and completely recoverable.

2. The influence of stress level on the resistance to deformation is considerable and is indicated by the dependence of the response under load on the first stress invariant. The resistance to deformation increases with an increase in the value of the first stress invariant.

3. A non-linear elastic constitutive law is a reasonable representation of the response of a granular material.

Cohesive Soil

1. Water content exerts a significant influence on the response of the subgrade soil. An increase in water content causes a decrease in resistance to deformation of the soil.

2. There is a large influence of stress level on the response of the cohesive subgrade soil. In general, an increase in the axial stress or radial stress caused a decrease in the resistance to deformation. The effect is greatest at stress levels below 3 psi, and appears important for stress levels up to 6 psi. These stress levels are typical of those that exist in the subgrade of a well-designed pavement.

3. For this particular soil and within the range of water content at which it was tested, a non-linear elastic constitutive law is a satisfactory representation.

4. An evaluation of the data indicates that the effects of stress-induced anisotropy may be significant. However, the data are inadequate at this time to be definitive as to the importance of these effects.

APPLICATIONS

The information emanating from this study will be of interest and practical value to people of a number of disciplines in highway departments and other agencies. Although, in general, the findings of the systems formulation portion of the project effort are adequately developed for early implementation and the materials characterization investigation is considered to be a phase of a longer-range endeavor aimed at more substantial changes in the structural facet of the pavement design process, both efforts have produced information of immediate value and both will continue to contribute to improvements in pavement design and management. Significant insight has been gained into the additional research and development in both the areas of systems approach to pavement design and management and materials characterization that will lead to more rational procedures for design of the pavement structural subsystem. The next phase of research in this problem area, NCHRP Project 1-10A, "Systems Approach to Pavement Design--Implementation Phase," based on these recommendations, is scheduled to be initiated in early 1972.

Highway departments having the proper input variables, or methods for obtaining them, and sufficient expertise in computer programming can apply the operational SAMP5 program to design problems immediately. The materials characterization methodology described in the project report can be used by a well-equipped and well-staffed laboratory to collect data for determining approximate ranges of the modulus of elasticity and Poisson's ratio for any paving material that may be used in linear or "ad hoc" non-linear elastic layered theory structural design problems.

From the highway administrator's standpoint there should be considerable interest in the development of the systems engineering concept of pavement management to provide the desired level of service at the most economical over-all expenditure throughout its operational life. Obviously, this concept is practiced by many highway departments now in various forms as an alternate to the structural design of a pavement in response to given load and environmental conditions on the basis of lowest initial cost. However, this project has organized and codified the approach to an extent not previously available. The information developed by the project could provide a basis for adaptation of the approach in any individual State.

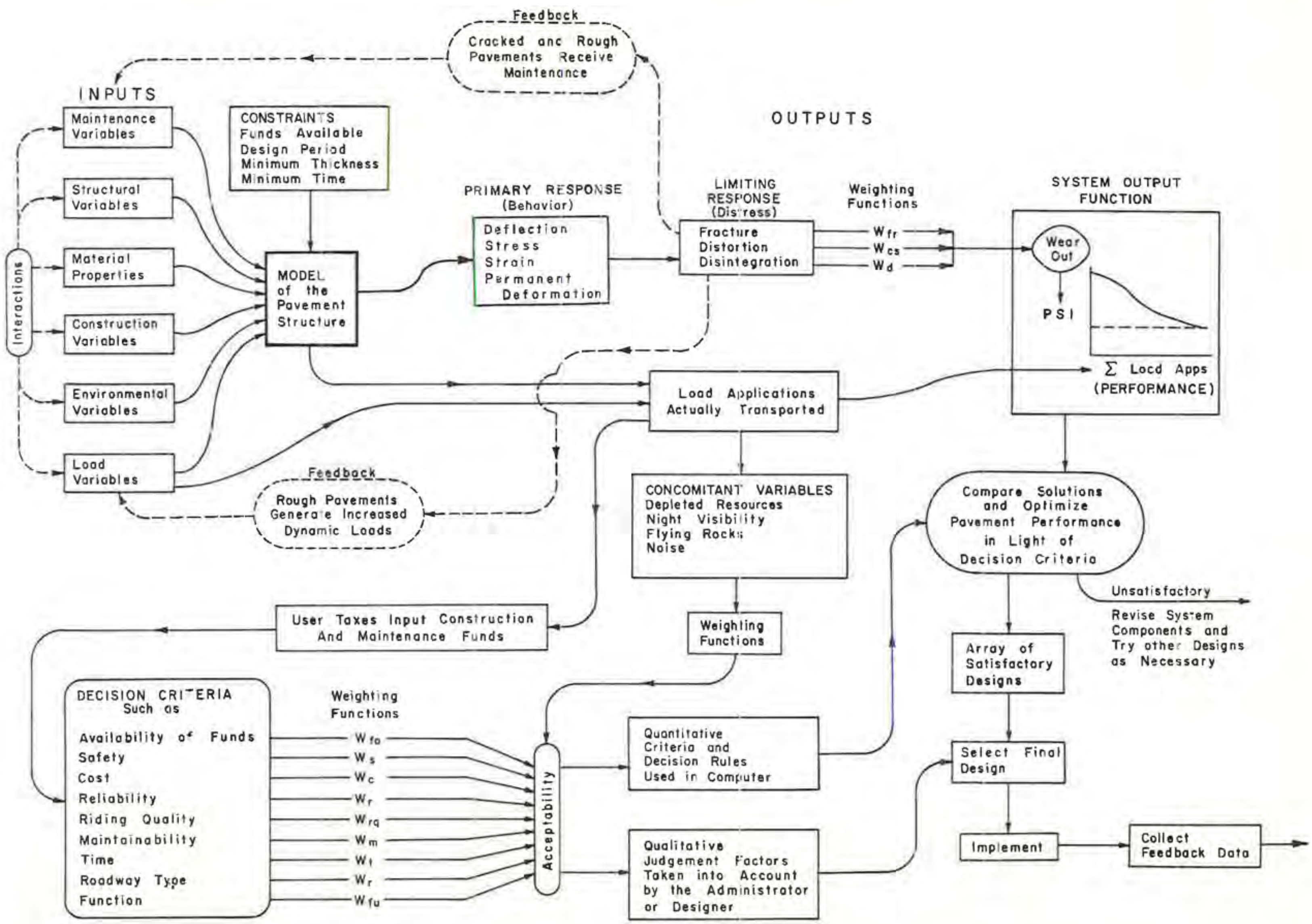
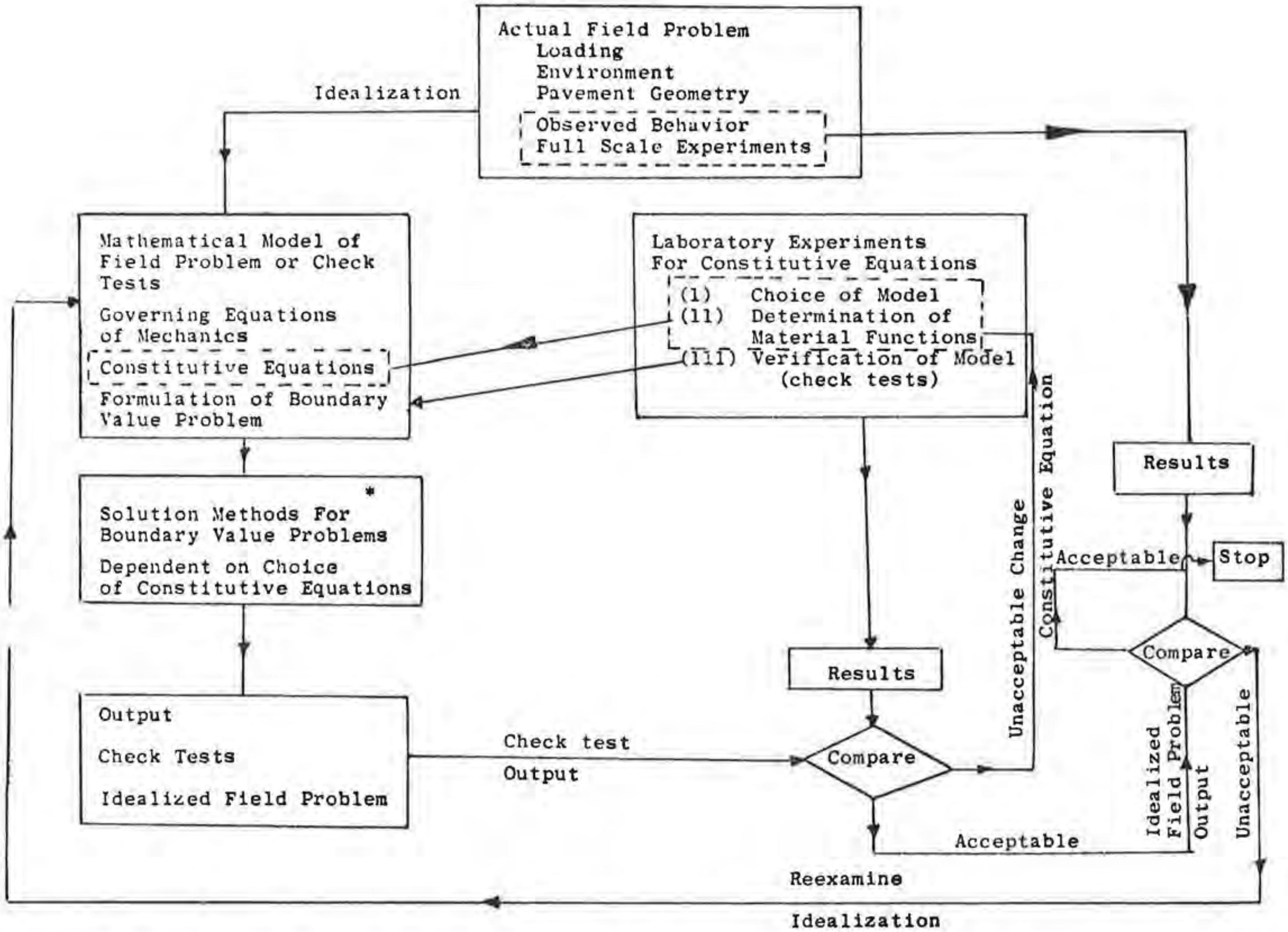


Figure 1. Block diagram of conceptual pavement system.



* The Solution Methods involve Iterative Techniques for Nonlinear Constitutive Equations

Figure 2. Development of a model for determining primary response.

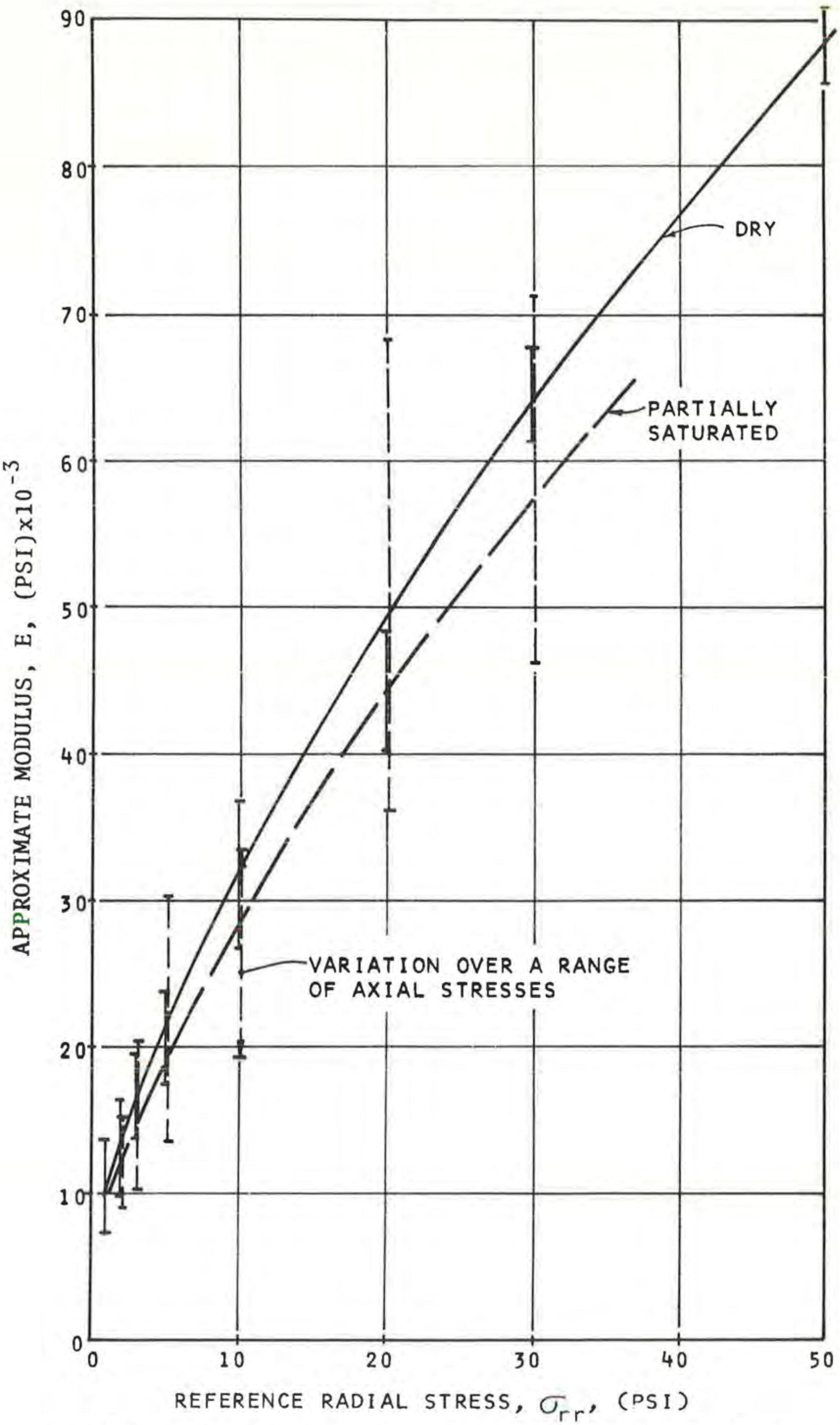


Figure 3. Variation of approximate modulus of elasticity with radial stress for dry and partially saturated granular materials.

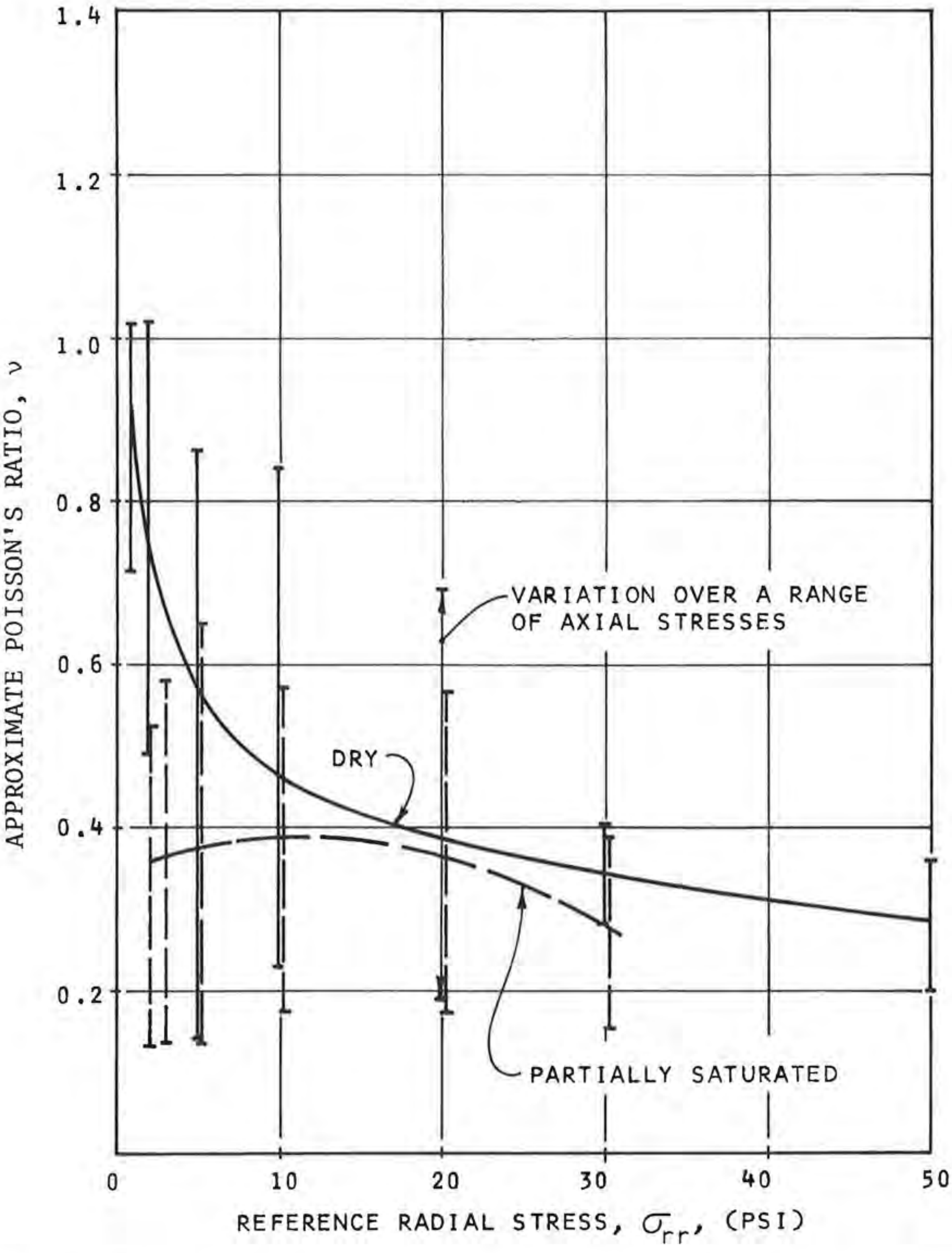


Figure 4. Variation of approximate Poisson's ratio with radial stress for dry and partially saturated granular materials.

TABLE 1
SUMMARY OF RANGE OF APPROXIMATE MODULUS OF ELASTICITY AND POISSON'S RATIO FOR AN ASPHALTIC CONCRETE

Test Temp. (F°)	Approx. Modulus of Elasticity* (psi X 10^{-3})	Poisson's Ratio*
40	2100 to 2600	0.18 to 0.35
55	1200 to 1680	0.28 to 0.43
70	470 to 790	0.32 to 0.44
100	30 to 150	0.40 to 0.56
140	6 to 12	0.39 to 0.57

*Range in values indicates the influence of stress levels.

TABLE 2
SUMMARY OF RANGE OF APPROXIMATE MODULUS OF ELASTICITY AND POISSON'S RATIO FOR A COHESIVE SUBGRADE SOIL

Sample	Moisture Content %	Dry Density (pcf)	Approx. Modulus (psi)	Approx. Poisson's Ratio
Undisturbed No. 40	19.1	111	69,000 to 40,000	0.46 to 0.33
Undisturbed No. 39	21.7	107	18,000 to 6,600	0.50 to 0.34
Laboratory Compacted No. SD33-1	23.3	100	13,000 to 4,000	0.45 to 0.38

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