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1783-S

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-99/1783-S		

4. Title and Subtitle
ASSESSMENT OF FIELD TESTS TO ENSURE STRUCTURAL DESIGN CRITERIA FOR RIGID PAVEMENTS

5. Report Date
June1999

6. Performing Organization Code

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8. Performing Organization Report No.
Report 1783-S

9. Performing Organization Name and Address
Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843-3135

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
Project No. 0-1783

12. Sponsoring Agency Name and Address
Texas Department of Transportation
Research and Technology Transfer Office
P. O. Box 5080
Austin, Texas 78763-5080

13. Type of Report and Period Covered
Project Summary:
September 1997—August 1998

14. Sponsoring Agency Code

15. Supplementary Notes
Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.
Research Project Title: Feasibility for the Development of Field Tests to be Performed During Construction to Ensure Structural Design Criteria for Rigid Pavements

16. Abstract

The focus of this report is to provide a state-of-the-art review of the research and developments in the area of field tests (both destructive and non-destructive) that can be used to ensure compliance between the properties of constructed pavements and the material properties assumed in design. This effort constituted a utility assessment of the potential of different testing methodologies for concrete pavement systems capable of being incorporated into future TxDOT testing regimens that are suitable for mechanistic design applications.

In light of this emphasis, key parameters that are used or could be used in design which have a relationship to performance. In conjunction with this emphasis, test procedures which involved parameters that tie construction quality to design were of particular interest, particularly if they displayed a certain amount of practicality and repeatability. Also, tests that represented a direct measurement rather than an indirect measurement of a parameter were preferred as well as those which made measurements in-place and could make use of department equipment where possible. In this regard, the recommendations from this study were partially based on the current TxDOT QC/QA specifications developments to ensure continuity since some of the key parameters were previously identified as part of the QC/QA effort. Although most of the key parameters pertained to the concrete surface layer (including bonded concrete overlays), parameters of each layer in a concrete pavement structure were considered in the report.

17. Key Words
Concrete, Performance, Tests, Mechanistic Design, Specification

18. Distribution Statement
No restrictions. This document is available to the public through NTIS:
National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	30	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Project Number 0-1783
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Sponsored by the
Texas Department of Transportation
In Cooperation with
U.S. Department of Transportation
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DISCLAIMER

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ACKNOWLEDGMENTS

Research findings presented in this report are a result of project efforts carried out at the Texas Transportation Institute (TTI), The Texas A&M University System, and the Center for Transportation Research (CTR), The University of Texas at Austin. The authors would like to thank the staff of the Texas Department of Transportation as well as the U.S. Department of Transportation, and the Federal Highway Administration for their support throughout this study.

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IMPLEMENTATION RECOMMENDATIONS

Findings from this study indicate that many of the tests TxDOT currently uses do not or are not being used to measure real material properties, properties relevant to performance, or structural behavior of concrete pavement systems. However, TxDOT has and is conducting research on many of the recent developments which will help TxDOT make vast improvements in its capability to make such measurements. Consequently, TxDOT is encouraged to continue to pursue these developments with the following recommendations:

1. propose research projects to formulate construction specifications incorporating performance-based test procedures,
2. identify mechanistic performance models to predict performance based on the materials properties determined using the tests identified in (1) above,
3. identify construction projects suitable to implement performance-related construction specifications on a trial basis,
4. evaluate the implementation of the construction specifications and identify where improvements can be made,
5. make adjustments to the construction specification and the manner in which performance models are utilized in the design process, and
6. validate improvements in construction quality and accuracy of the prediction models.

CONCRETE PAVEMENT PERFORMANCE AND CURRENT TxDOT DESIGN PRACTICE

In order to ensure how the structural design criteria for rigid pavement construction can be met, it was important to determine what TxDOT currently uses as structural design criteria in its design procedure for concrete pavements. This was accomplished by a careful review of the present TxDOT design practice in terms of identifying specific items which comprise the criteria for structural design. In this light, this report addresses the current TxDOT portland cement concrete (PCC) pavement design procedures and practices and suggests improvements to the design procedures that could feasibly expand the list of criteria to include many of the features related to the structural behavior of concrete pavements. As a part of this process, this report also covers properties and performance parameters included in current TxDOT construction specifications that may significantly influence the structural integrity of the pavement system relative to its performance. Finally, these are contrasted against proposed specifications to provide a baseline, for which, future developments can be referenced.

TxDOT RIGID PAVEMENT DESIGN PROCEDURES AND PRACTICES

TxDOT's scope of design practice includes mainly three types of concrete pavements: jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), and continuously reinforced concrete pavement (CRCP). In CRCP, the steel reinforcement is continuous throughout the length of the pavement and no transverse joints are used except at construction joints placed to facilitate construction scheduling. JRCP contains reinforcing steel in the form of deformed steel bars, deformed steel mats, or welded wire mats. The formation of transverse cracks at relatively close intervals is a distinctive characteristics of CRCP. These cracks are held tightly by the reinforcements and should be of no concern as long as they are uniformly spaced.

JPCP is a jointed concrete pavement in which no steel reinforcement is used except at the sawcut joints, either JPCP or JRCP may have doweled or undoweled joints. Jointed plain concrete pavements are constructed at 4.5 m (15 ft) intervals that can have either orthogonal or skewed joint patterns. If the transverse joints are skewed, the joints are undoweled, staggered at intervals of 3.7, 5.2, 5.5, and 4 m (12, 17, 18, and 13 ft), and are skewed at an angle of 1 to 6 across the lane. The JPCP design also has the option of a widened paving lane that encompasses an integral 1 m (3 ft) shoulder. Tie bars are used at longitudinal joints.

JRCP joints are spaced every 9.1 m (30 ft). Although a fewer number of joints are associated with a JRCP pavement design than a JPCP design, the joint movements are expected to be larger. Thus, the joint sealants may tend to fail more quickly in JRCP joints than in JPCP joints. Additionally, reflection cracking in asphalt overlays of JRCP generally occurs more quickly than asphalt overlays on the other concrete pavement types because of the larger joint movements in JRCP. The reinforcement in JRCP is intended to keep the naturally occurring cracks within the slabs tightly closed with the consequence that midslab cracks are allowed and expected to occur, since Westergaard curling theory clearly indicates that maximum curling stress occurs 4.4ℓ from any joint or edge where ℓ is:

$$\ell = \left(\frac{E_c h^3}{12(1-\nu^2)\,k} \right)^{1/4}$$

where

E_c	=	Concrete Elastic Modulus,
h	=	Slab thickness,
v	=	Poisson's R ratio, and
k	=	Subgrade modulus.

Midslab cracking initiated due to curling behavior actually occurs independent of whether the design is jointed plain or jointed reinforced.

Slab Thickness Design Procedure

The empirical performance equations derived from the American Association of State Highway Officials (AASHO) Road Test are used as a basis for the TxDOT design guide but have been modified and extended to make them applicable to all regions in the state. The design equations presented in the 1986 AASHTO Design Guide were empirically derived from the results of the AASHO Road Test. The equations were modified to include many variables originally not considered in the AASHO Road Test. TxDOT currently uses this version of the equation for the determination of concrete pavement thickness. The following are the design variables included in the current design procedure; the structural criteria associated with each are discussed in greater depth in the 1783-1 project report "Assessment of Field Tests to Ensure Structural Design Criteria for Rigid Pavements:"

- Mean Concrete Modulus of Rupture, psi;
- Concrete Elastic Modulus, psi;
- Effective Modulus of Subbase/Subgrade Reaction, pci;
- Initial Serviceability Index;
- Load Transfer Coefficient;
- Drainage Coefficient;
- Overall Standard Deviation;
- Reliability, %; and
- Design Traffic, 18 kip ESAL.

CURRENT CONSTRUCTION SPECIFICATIONS

Item 360 of the TxDOT construction specifications governs the construction of PCC pavement with or without monolithic curbs on a prepared subgrade or subbase course. Listed below are some of the important factors related to construction practices and to the structural integrity of the pavement system.

Concrete Mixing and Placing

Workability is an important aspect of fresh concrete. It is defined as the property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished. It is very important that the concrete is workable, cohesive, possesses satisfactory finishing qualities, and has consistency conforming to the specified slump requirements. The slump test is by far the oldest and the most widely used test of workability, but in many ways it fails to provide an indication of the mobility a mixture possesses. This is a critical characteristic of a mixture placed with a slump of 50 mm (2 in) or less.

Curing

The object of curing protection is to minimumize loss of pore water, until the originally water-filled space in the fresh cement paste has been filled to the desired extent by the products of hydration of cement. In order to obtain quality concrete, the placing of an appropriate mix must be followed by curing in a suitable environment during early stages of hardening. Curing is important to avoid low concrete strengths in the top 50 mm (2 in) of the pavement.

The standard specifies that all concrete pavement should be cured for a period of not less than 72 hours from the beginning of curing operations. Various methods are available for the curing of concrete. If a curing membrane is used, it should not be applied until after the bleed water has evaporated. Membrane curing also needs to be placed in a uniform manner. The use of polyethylene sheeting requires that adequate precautions be taken to weigh the sheeting in place to prevent displacement or billowing due to wind. Asphalt curing shall be used only when the concrete pavement is to be overlaid with asphaltic concrete. Monitoring relative to the effectiveness of the curing media is necessary to ensure against excessive moisture loss to avoid unnecessary cracking and the uniform development of strength.

CONSIDERATIONS FOR PERFORMANCE-BASED SPECIFICATION

Pertinent to the discussion of structural design criteria factors, is the consideration of the testing procedures and practices that are candidates for performance-based specifications. Prior to elaborating further on them, however, some discussion to the method of evaluation used in this study to rate both current and potential test methods to measure performance-related properties. Each test procedure was evaluated with respect to its overall utility and relevance to the structural design criteria of a concrete pavement system. The determination of the utility was done with respect to three categories: performance, nature and makeup of the test, and the test equipment requirements. The performance characteristics of each test procedure (relative to its impact and significance to the design and performance mechanisms associated with concrete pavements) were the most heavily weighted considerations in the evaluation. Consequently, the results of the performance category accounted for 50 percent of its overall utility. The nature of each test was evaluated with respect to whether the test was a direct or an indirect measure of a parameter, whether or not the test could be conducted in the field, and whether or not the test was non-destructive. A test procedure that directly measures a material property was rated higher than a test procedure that determines a property indirectly. The nature of the test was also an important consideration and accounted for 30 percent of the total utility. The third category refers to the equipment requirements associated with a given test procedure. Factors such as the use of current TxDOT equipment, practicality, accuracy, special training, and cost were considered in this category. The test equipment requirements, although included in the evaluation, were weighted less important than the previous categories and, consequently, accounted for only 20 percent of the total utility.

Each of the attributes noted above for each test was itemized and summarized in Appendix A of the 1783-1 project report. In Appendix B, each attribute for a particular test was assigned a point total as a form of a numeric rating as to how well the test satisfied the needs of that particular attribute. The points for each attribute were summed and served as a rating in each of the three categories of performance, nature of the test, and the test equipment. These ratings are translated into utility values by the relationships defined in Figure 1. The utility curve for the performance category showed that unless the test ratings are greater than 50, the utility is low. The utility value for performance varies greatly between a rating of 50 and 70. The utility value for the nature of a test does not decrease greatly as the rating decreases. The utility value for the test equipment decreases more rapidly as the rating decreases. Once the utility value for each category is determined, the overall utility for each test was calculated using the previously defined weights: performance 50 percent, nature of test 30 percent, and test equipment 20 percent.

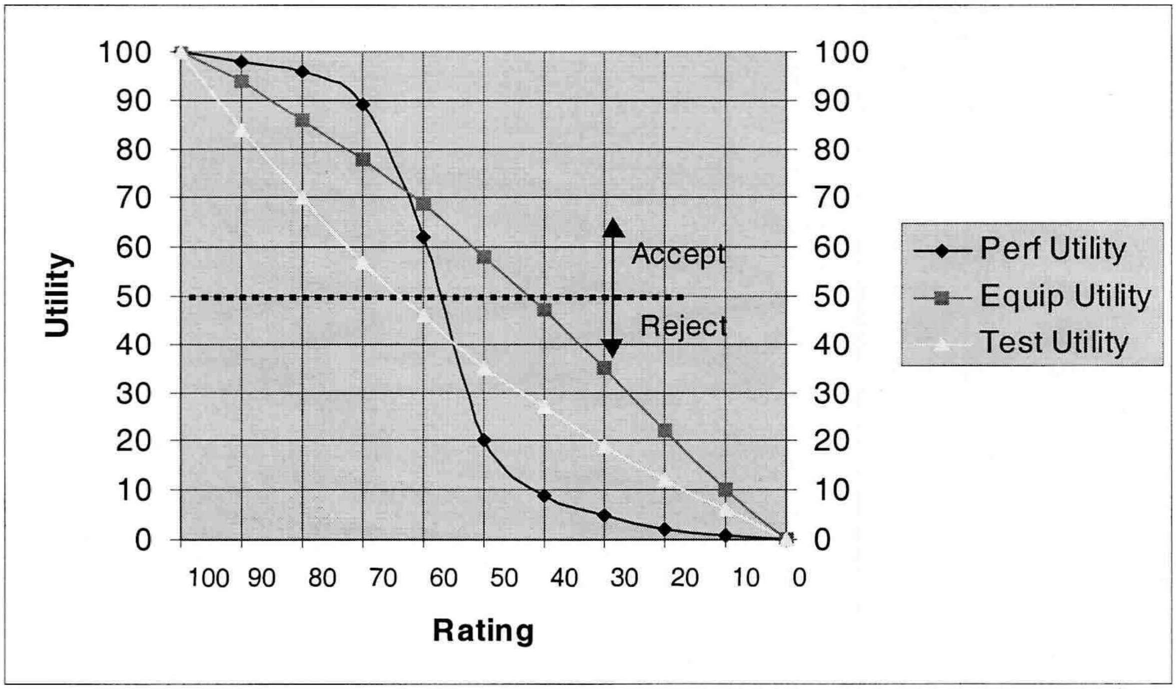

Figure 1 Utility Curves for Rating of Testing Procedures.

As noted in Figure 1, a utility value of 50 was selected as the threshold criteria for whether a particular test should be considered further. To facilitate further consideration, tests meeting this criteria are described in greater detail in the 1783-1 project report while the remaining tests that were rated in this study are simply listed in Appendixes A and B of the 1783-1 project report. Each description includes a short summary and greater detail of each test's assessment in terms of each category.

An important test properties/characteristics, is the measurement of the strength of the concrete in-place rather than from a specimen cast on site. The indirect tensile test specimen (taken as a core from the slab) to assess the pavement strength in-place provides a way to accomplish this. The knowledge of tensile strength is of value in estimating the load under which cracking will develop and the determination of remaining life as a function of the in-place properties.

Placing temperature is another characteristic that affects cracking behavior in concrete pavements. The contractor can employ various methods of temperature and crack control relative to the method of curing to affect projected pavement life in terms of adequate consolidation, strength gain, and durability. It will be important to monitor unit weight and water content in-place.

It is important to point out that concrete pavement design procedures, construction practices, and the prediction of performance need to be based upon interconnecting factors and mechanisms that tie them all together. Such a philosophy will guide improvements to construction specifications in a manner, both in practice and in design, that is mechanistically based. It is clear that the AASHTO Design Guide is based on the empirical equations obtained from the AASHO Road Test and needs modifications based on the use of mechanistic theory and experience. Such modifications will be effective in suggesting appropriate measures and practices if they conform to a rational approach steeped in engineering mechanics. Therefore, a review the merits of existing testing methodologies currently included in TxDOT testing specifications was conducted and reported in the 1783-1 project report. Given this review, the stage was set to consider new developments that complement current testing programs and the mechanisms that relate to performance. Recommendations are given as to what additional measures should be made to more completely ensure adherence to key structural design criteria.

PERFORMANCE ASPECTS RELATED TO DESIGN AND CONSTRUCTION OF CONCRETE PAVEMENT

One aspect behind the design of PCC is the representation of the deterioration processes that affect pavement conditions over time. Design algorithms should be configured to represent these processes such that concrete pavement performance can meet the increased demand for longer performance lives with minimal maintenance. Inherent in meeting these requirements is an understanding and embedment within the design algorithm itself of how selected material components, combinations, and construction practices work together to affect the performance life of a pavement and the relationship of each to structural design criteria.

The significance of these relationships, which are more often than not taken for granted, is that they are key to the identification of important material and pavement characteristics that are, firstly, related to the performance and structural behavior of the pavement over its design life and, secondly, are able to be monitored previous to and during the construction of the pavement. In terms of construction specifications, the question that must be always be put at the forefront is, what are the "properties" that are characteristic of "quality" concrete pavement both in terms of construction and performance; how do these properties relate to the structural criteria; and what are the tests that provide an indication of those "properties" to ensure compliance between the design aspects and the construction aspects of concrete pavement systems.

Most construction specifications are oriented to prevent early or premature failure of the pavement. In other words, the focus of tests conducted in the field or lab are really intended to reveal defects in the constructed product that are not necessarily tied to a particular mode of distress which could be represented in a design algorithm. In recent efforts to develop performance-based specifications, for instance, the purpose of tests to measure concrete strength have been popularly interpreted from a construction engineering standpoint as a means to identify areas of poor consolidation rather than the resistance to crack development, which is a feature pertinent to the interest of the design engineer. It is apparent that certain assumptions not necessarily addressed or relevant to the basis of most construction specifications are associated with design algorithms and how they represent deterioration relative to pavement failure. Consequently, algorithms for design do not represent premature failure well, as may result in a concrete pavement constructed with poorly consolidated concrete. Field testing, whether destructive or non-destructive, tends to focus on the measurement of parameters indirectly related to performance since many of them focus on characteristics relative to the placement of fresh concrete. Unfortunately, it is very difficult to draw or find relationships between the properties of fresh concrete prior to placing, relative to pavement performance after the concrete has attained a hardened state, that are useful in design from a structural aspect. Since coarse and fine aggregates comprise 60 to 80 percent of the volume of PCC, many construction specification tests have traditionally focused on aggregate characteristics, as aggregates may pertain to premature pavement failure due do poor bond, low abrasion, or crushing strength.

The consequence of these factors is that many field tests for concrete pavements have changed little since before World War II. These tests were developed empirically with little need to weigh any significance to long term pavement performance or structural behavior. In spite of these shortcomings, there has been very slow improvement, if any, in field tests used to characterize material properties or pavement parameters as they may be related to performance or design of the pavement. This lack of improvement may have resulted because of the lack of emphasis to make advancements, but with the recent interest in adoption of performance-based specifications, expect that construction specifications will need to address the parameters not only related to premature failure but to parameters related to long-term performance and design. In this regard, it is necessary that existing and new field tests be identified which can accurately reflect performance of the pavement and ensure meeting structural design criteria. Describing the major concrete pavement performance factors relative to the basis of pavement design that point out key performance and design relationships and indicate the connection to design that laboratory and field-testing parameters bear.

DESIGN APPROACHES AND MATERIAL MODELS CONSISTENT WITH DISTRESS MECHANISMS

Most design procedures for concrete pavements are configured to represent the load conditions pavements are subjected to over the performance period. This

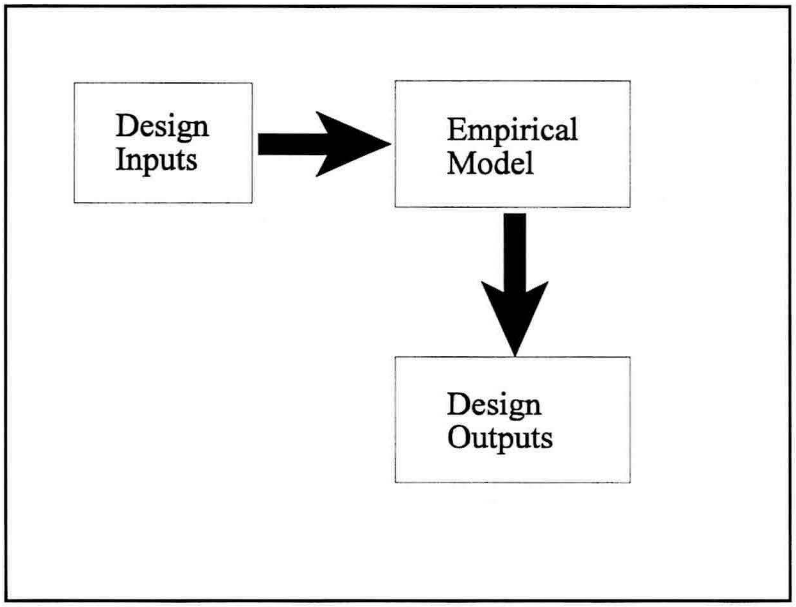

Figure 2 Typical Framework of Empirically Based Design.

configuration has been approached from two large diametrically opposed perspectives, one of which can be characterized as empirically based while the other one is mechanically based. The configuration that is largely based upon empirical concepts is illustrated in Figure 2 and basically yields a pavement thickness for design purposes to address all distresses that were originally considered within the development of the empirical model. The model is empirical because it makes no presuppositions relative to how the distress developed with respect to time, traffic, or structural slab behavior in its development. The AASHTO Design Guide generally falls within this classification. As far as material properties, the Design Guide principally uses the strength of the concrete and the subbase/subgrade to determine the structural thickness of the pavement. The thickness is selected to maintain the roughness of the pavement to within certain limits for a given traffic level, but the relationship between concrete strength, pavement thickness, and pavement roughness, rationally speaking, has never been described. This is one reason why the AASHTO Design Guide is empirical in nature and also why AASHTO is now in the process of moving to a less empirically based design approach. Consequently, the assurance of structural design criteria via measurement of selected properties of concrete, such as compressive strength, is, at best, indirect assurances in terms of empirical design methodologies and the relationship to design life.

Figure 3 illustrates a framework of rationally or mechanically based design processes. In design procedures that fit into this classification, pavement responses are predicted by

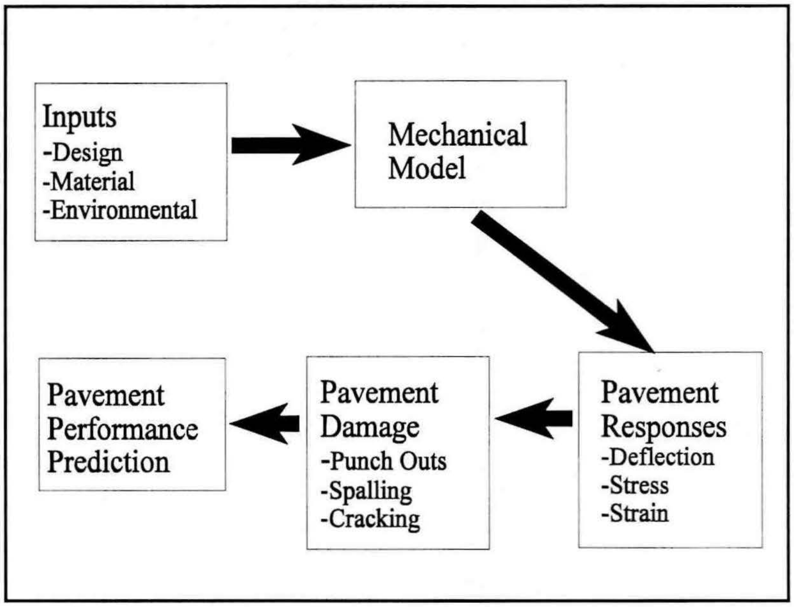

Figure 3 Typical Framework of Mechanically Based Design.

use of analytical tools that are based on engineering mechanics. These tools typically incorporate the use of constitutive equations that relate material properties to structural responses. The requirement for material properties is typically higher in these procedures than for empirical procedures, which provides more opportunity to identify candidate properties that would be suitable for structural assurance testing in the field. The mechanical model(s) incorporated in the design process is developed in such a way that it addresses a specific distress type or mechanism of distress. Therefore, for every distress type (i.e., cracking, spalling, etc.), there is a different mechanical model and a different set of material or pavement properties associated with that distress mechanism. Although, these procedures are more intensive than empirical models, they are more suitable for the development of performance-based specifications since they address the factors which directly affect performance. The design criteria associated with these procedures are often related to fatigue life, joint spacing, slab thickness, bond strength (bonded concrete overlays), concrete thermal characteristics, and drying shrinkage, etc.

With this background, model relationships tying characteristics of the distress mechanisms to the factors affecting performance can be elaborated with the intended purpose of justifying the measurement of selected parameters to ensure structural design criteria. Several models are presented and discussed relative to the important features they possess in terms of structural design criteria.

DESIGN RELATED MATERIAL AND PERFORMANCE-BASED CONSTRUCTION TESTING

RECOMMENDATIONS

In terms of where TxDOT currently stands, researchers reviewed and assessed several different types of tests with respect to their utility to

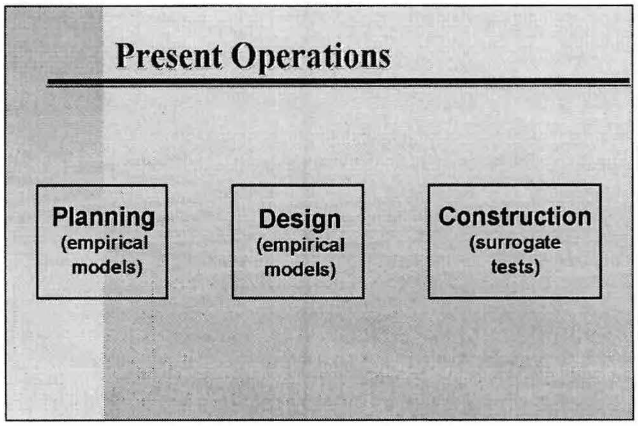

Figure 4 Present Operations.

provide a measure of structural design criteria. Ranking of the various tests in the manner outlined in this report has emphasized the status of current design and construction specifications with respect to performance-related design and construction specifications. Figure 4 depicts the current relationship between pavement design and construction used by many highway agencies. This figure also includes the operation of planning, which is where pavement type selection occurs in the process of pavement construction. Currently, models for pavement design and planning are empirical in nature and, consequently, rely on relationships and test properties that do not appear to relate well to performance. Furthermore, construction specifications, which are based upon such test properties and parameters, do not provide adequate basis to control quality. The assessment of existing TxDOT test procedures and design methodologies warranted consideration of a new approach (Figure 5) to the identification of material tests more relevant to structural design criteria.

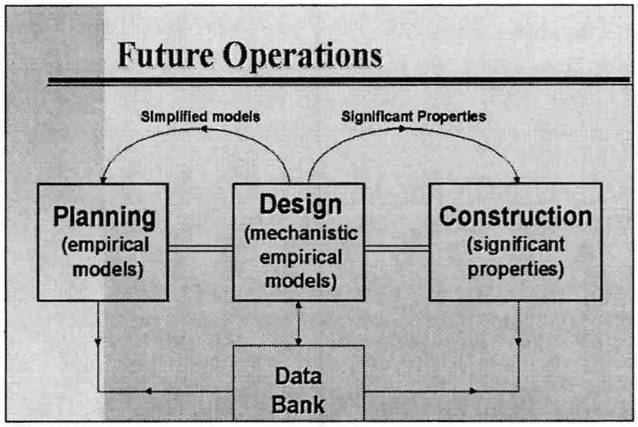

Figure 5 Future Operations.

Identification and use of significant material properties and pavement design parameters are key to improvement of the characterization of structural design criteria. The parameters included in the design criteria must have a relationship to both performance and distress development in order to clearly provide an indication of how the quality of construction can be improved. Focus on methods the contraction industry can use to reduce the coefficient of variability of key material and performance parameters will improve pavement quality and the ability of the contractor to target critical quality levels. Collection of key parameter data will also improve the capability of performance data bases to include data useful for the improvement of performance prediction models.

PARAMETERS KEY TO PERFORMANCE

Table 1 lists key parameters that generally had an overall utility greater than 80 or a performance utility greater than 90 that could be included in construction specifications to monitor quality and performance relative to structural design criteria. Some of these parameters relate to the constructed product in-place, while others pertain to pre-qualification of materials and their capability to perform under certain conditions that result in structurally sound crack patterns.

Concrete strength needs to be determined independent of geometry so as to have universal application to any type of crack development in concrete pavement systems associated with tensile stress. Also, mechanistic cracking models will require the use of fracture mechanics in order to represent crack growth processes due to fatigue damage. Pavement stiffness needs to be characterized at the joints and cracks since these are the points of weakness and distress in concrete pavements. Subgrade properties which can be measured in the lab have no relationship to those that can be measured in the field using the current subgrade theories. This suggests that a new subgrade model should be adopted for concrete pavement design. Thermal characteristics of cement, aggregates, and concrete need to be qualified so that thermally-related pavement behavior can be maintained within certain limits to ensure that structural criteria relative to the crack pattern is met. For construction quality, concrete unit weight, air voids, and aggregate moisture need to be monitored to better control and ensure consolidation, water content, and durability. Development and use of mixtures with sufficient mobility will also improve consolidation during placement. Finally, a better understanding of the variability of key performance parameters would also be beneficial to the utilization of performance-based specifications.

PROMISING TESTS FOR FUTURE OPERATIONS

Based on the need to develop performance-based specifications, several tests standout for future consideration. We have addressed below the tests to be recommended with respect to the categories noted in Table 1.

Table 1 Framework of Structural Pavement Design Criteria.

Structural Criteria Category	Material/Pavement Property	Test Method
Strength	Concrete Tensile Strength Concrete Fracture Properties (K_{if}, c_f) Aggregate/Mortar Bond Bond Strength (overlays) Maturity (based on temperature and relative humidity)	ASTM C 496 ASTM C 496 (mod), Pullout Fracture Torsional Shear ASTM C 1074
Stiffness	Concrete Modulus (E_c) Load Transfer Efficiency (LTE) Effective Crack Width Pavement/Joint Stiffness (ℓ_k) Foundation Modulus (k-value) Subgrade Modulus (E_{SG}) Subgrade Unit Weight and Moisture Content	Tex-418, Stress wave FWD, RDD FWD, RDD FWD, RDD Triaxial test (mod) GPR
Volumetric	Total Heat (H_U) Activation Energy (E) Thermal Coefficient of Expansion (α) Coarse Aggregate Oxide Analysis	Adiabatic Temp Rise ASTM C 1074 Volumetric Dilatometer SEM
Volumetric	Moisture Diffusivity (D) and Effective Curing Thickness	Dew Point Indicator
Volumetric	K_1, K_2, K_3, and K_4 (key subbase friction and steel reinforcement parameters)	
Construction Quality	Concrete Unit Weigh (in-place) Debonding/Delamination Mobility Air Voids Aggregate Moisture Content Paving Thickness Steel location	GPR Infrared Thermographic Drop Test GPR GPR GPR Magnetic/Electrical

Strength

Given the latest developments, a need exists to measure the strength of concrete in-place to gain a more representative measure of performance and adequate assurance of meeting structural strength criteria. Taking cores from the pavement and testing them using the split tensile test specimens alone has not proven to be an entirely practical solution. Other practical developments may be possible, based on the use of fracture theories, to provide the necessary practicality and at the same time expand the versatility of the results. The advantages of using a fracture-based approach are multi-dimensional and provide a fundamental approach to strength of concrete that will be universally applicable to any cracking distress type included in pavement design. This approach would lie in a combination of maturity and pullout fracture testing. The maturity-strength curve would need to be determined with respect to the degree of moisture (i.e., relative humidity) available for hydration and calibrated with a pullout fracture result for the given paving conditions. It should also be noted that the pullout test will damage the pavement surface which will need repair but not to the same extent that a drilled core hole will need repair.

A similar approach is recommended with respect to the use of torsional shear strength testing. This test measures one component of the bond strength of a bonded overlay and can be used with maturity to provide a useful measure of structural strength criteria.

Stiffness

Several methods to measure the modulus of elasticity are available, but the most promising seems to be of the stress wave type. Although details of how this technology will be used in the field, the potential is high in that it can be adopted to confirm structural integrity with respect to E_c. In terms of overall pavement stiffness, the Rolling Dynamic Deflectometer (RDD) offers some promising advantages to the Falling Weight Defectometer (FWD) that would provide a thorough examination since the data are continuous in nature. The results of the RDD can be used to obtain Load Transfer Efficiency (LTE), effective crack widths in the assessment of the overall pavement stiffness.

It may even be possible to extract a composite subgrade modulus as well. These advantages warrant serious consideration of the RDD with respect to assessment of structural stiffness criteria.

In terms of subgrade properties, new developments are available to measure elastic modulus, unit weight, and moisture, but pursuit of this technology will depend, to some extent, on the foundation model to be used for concrete pavement design. If the decision to remain with Westergaard theory is made, there will be little utility in measuring the subgrade stiffness since it cannot be readily correlated to the subgrade modulus. But in either case, both are sensitive to moisture variations. Subgrade unit weight is valuable in assessing the degree of compaction achieved during construction. The use of the Humbolt stiffness guage may have some application to the determining of subgrade stiffness, if it can be shown to cover the range of stiffnesses encountered in pavement design, but the modified triaxial test may have greater applicability.

Volumetric

Several important test methods are now available to pre-qualify and characterize materials relative to their thermal behavior. Thermal behavior affects both strength and cracking stress development, and both need to be held in balance during the first 72 hours after placement to ensure against loss of structural integrity. The adiabatic temperature signature, activation energy, and cement fineness play a role in the models to predict stress and strength development for a given pavement design and curing condition. We did not list the cement fineness (Tex-310-D) test, but this information, along with the oxide analysis of the cement, is available on the mill certificate provided by the supplier and can provide valuable information on the thermal behavior of the cement. Equipment for the measurement of the thermal coefficient of expansion of both concrete aggregates and concrete is now available to pre-qualify aggregate materials or a blend of materials. Relative to the development of adequate cracking patterns and concrete strength (top 50 mm (2 in) of the pavement), curing effectiveness should be tested on site during the hardening of the concrete using the dew point temperature technology. The determining of curing effectiveness is particularly important in the construction of bonded concrete overlays where excessive moisture loss will cause debonding of the overlay from the existing pavement surface. Moisture monitoring technology has made several advancements in the past decade, and equipment is available for application to concrete paving.

Construction Quality

Use of ground-penetrating radar offers several advantages to in-place monitoring of important parameters that affect the quality of the constructed product. GPR can potentially provide data which can be interpreted to provide in-place measurements of unit weight, water to cement ratio, and air content. Unit weight of freshly placed concrete will be important to monitoring the degree of consolidation and the existence of rock pockets. The in-place water to cement ratio has been difficult to assess since the water in the aggregate has been a virtual unknown. Given the ability to exact moisture data from GPA scans of the aggregate materials as they are fed into the mixer, a basis is provided to determine water to cement ratios of the concrete placed on the subbase. Paving thickness can also be determined from the GRP scan. This technology warrants further consideration. Also important to constructibility is the mobility of a paving mixture. Slump does not provide sufficient information regarding the workability of a paving mixture. A measure of how easily the mixture moves under vibration would serve as a better indicator than slump. Such a measure can be provided by use of the drop test. This would be a convenient test to run since it utilizes the slump test equipment and can be conducted in conjunction with the slump test. This test will provide both objective (number of drops) and subjective (how the mixture moves) data valuable to the assessment of the mixture. The magnetic test was included because of its potential to locate the position of the reinforcing steel.

FUTURE DIRECTIONS

In order to achieve more accurate prediction of highway pavement performance and better use of highway materials, pavement design procedures must become more mechanistic in nature and construction specifications more performance oriented. Such advancements will involve a clear understanding of the performance mechanisms and material properties elaborated in this report and the link between them. This understanding serves a key role in the formulation of a research program to develop implementation plans for the adoption of the recommended technology summarized in this chapter. The implementation plans should consist of the following stages:

1. propose research projects to formulate construction specifications incorporating performance-based test procedures,
2. identify mechanistic performance models to predict performance based on the materials properties determined using the tests identified in (1) above,
3. identify construction projects suitable to implement performance-related construction specifications on a trial basis,
4. evaluate the implementation of the construction specifications and identify where improvements can be made,
5. make adjustments to the construction specification and the manner in which performance models are utilized in the design process, and
6. validate improvements in construction quality and accuracy of the prediction models and update current specifications accordingly.

The last stage of this outline is important to justify the entire development process and to indicate the benefits to both the department and the contracting industry. Efforts should be made to educate the construction industry as to how their benefits can be recognized and utilized to improve construction quality and reduced variability. This process will facilitate the development of a new vision of how continued improvement in both the design and construction processes can be achieved.