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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 were identified. In conjunction with this emphasis, test procedures which involved parameters that tie construction quality to design were of particular interest, especially 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 in addition to those that made measurements in-place and could make use of department equipment where possible. In this regard, the recommendations from this project were partially based on the current TxDOT QC/QA specification 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.

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ASSESSMENT OF FIELD TESTS TO ENSURE STRUCTURAL DESIGN CRITERIA FOR RIGID PAVEMENTS

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CHAPTER 1
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 will be important to determine what TxDOT currently uses as structural design criteria in its design procedure for concrete pavements. This is 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 chapter addresses the current TxDOT Portland Cement Concrete (PCC) pavement design procedures and practices and discusses some of the improvements to the design procedures which are discussed in other portions of this report and could feasibly expand the list of criteria to include more features related to the structural behavior of concrete pavements. As a part of this process, this chapter also covers properties and performance parameters included in current TxDOT construction specifications which may have significant influence pertaining to the structural integrity of the pavement system relative to its performance. Finally, these are contrasted against the proposed specifications to provide a baseline for which future developments can be referenced.

TxDOT RIGID PAVEMENT DESIGN PROCEDURES AND PRACTICES

Mainly three types of concrete pavements are included within TxDOT's scope of design practice: 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. JPCP is a jointed concrete pavement in which no steel reinforcement is used. The sawcut joints, either JPCP or JRCP may have doweled or undoweled joints.

The formation of transverse cracks at relatively close intervals is a distinctive characteristic of CRCP. These cracks are held tightly by the reinforcements and should be of no concern as long as they are uniformly spaced.

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 degrees 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 the number of joints are reduced in JRCP, 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; Westergaard curling theory clearly explains that maximum curling related stress occurs 4.4ℓ from any joint or edge. 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 obtained from the AASHTO Road Test are used as the basic model in the current TxDOT guide for design but were modified and extended to make them applicable to all regions in the state. The design equations presented in the 1986 AASHTO design guide were obtained empirically from the results of the AASHTO Road Test. The equations were modified to include many variables originally not considered in the AASHTO Road Test. TxDOT currently uses this version of the equation for the determination of concrete pavement thickness. The following are the variables included in the current design procedure; the structural criteria associated with each will be discussed in greater depth:

- 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, %
- Design Traffic, 18 kip ESAL.

Mean Concrete Modulus of Rupture and Concrete Elastic Modulus

The flexural strength of concrete is defined by the modulus of rupture. Tex-420-A test procedure uses the center point loading and conducts the test at a concrete age of seven-days. TxDOT specifies a minimum average seven-day modulus of rupture of 4.48 Mpa (650 psi - center point loading). The AASHTO rigid pavement design procedure requires an average 28-day modulus of rupture based on third point loading. A correlation is being made between the two test procedures using a factor of 1.07; the TxDOT specification can be equated with a value of 4.96 MPa (720 psi) for 28-day third point loading.

Correlations of strength for design have always presented difficulties for design engineers because of the uncertainty associated with the application to different strength models available in the literature to the different types of methods available to measure strength. Chapter 2 addresses issues relative to strength in greater detail, but current concrete pavement design is deficient in the characterization of the strength of concrete in the pavement versus the strength of concrete determined by a strength specimen. The two have practically never actually been the same - particularly for slab thicknesses greater than 130 mm (6 in). Concrete pavement engineers for years have erroneously assumed that the theory to calculate stresses in a concrete slab can be used in the same manner to calculate strength in a concrete test specimen. The fact that concrete strength is very much a function of the size and geometry of the specimen used to determine it has been evident for many years in research on the strength of concrete, but this has been virtually unrecognized by the pavement design community. The discussion provided in Chapter 2 elaborates on how thickness design can incorporate measures of 'true' strength that are appropriately interpreted relative to size and geometry factors.

The design equation also requires a value for concrete elastic modulus. Concrete elastic modulus varies depending on the coarse aggregate type. Although the value selected for design varies significantly, it does not have significant effect on the final thickness generated by the equation. In terms of load-related behavior, it has an important effect on overall pavement stiffness and load distribution. The recommended concrete elastic modulus value for concrete containing crushed limestone is 27580 MPa (4×10^6 psi) and for siliceous river gravel concrete is 34500 MPa (5×10^6 psi). Several methods are reviewed in Chapter 3 for the non-destructive measurement of this parameter.

Modulus of Subgrade / Subbase Reaction

The property of roadbed soil used for rigid pavement design is the modulus of subgrade reaction k which has been used in concrete since pavement design since the 1920s when it was first proposed by Westergaard relative to a dense liquid foundation model. However, the TxDOT design procedure follows the AASHTO guide in making a contrived substitution for k-value with the resilient modulus M_R. Although there is no theoretical relationship between k-value of a subgrade and the soil elastic modulus, the design procedure does make a conversion between M_R and k-value. Similar to the adjustments made to M_R, the values of k are varied with the season of the year and the relative damage.

The k-value is determined from a loading test using a 762 mm (30 in) diameter circular plate. The load is applied at a predetermined rate until a pressure of 69 KPa (10 psi) is reached. The k-value is then calculated by dividing 69 Kpa (10 psi) by the measured deflection of the layers under the plate. Since k-value is determined from a field test, it cannot be conducted at various moisture contents and densities to simulate the different service conditions or the worst possible condition during the design life. To modify the k-value for conditions other than those during the field test, laboratory specimens can be fabricated, one having the same moisture content and density as those in the field and the other having a different moisture content and density to simulate the service conditions. The modified k-value (k_s) then can be computed by:

$$k_s = (d_u/d_s)k_u \tag{1.1}$$

in which subscript s indicates the service or saturated condition and u indicates the unsaturated or field condition.

If a subbase is to be used between the slab and the subgrade, the composite modulus of subgrade reaction is often determined from a nomograph that is included in the 1986 AASHTO Guide. The modulus is based on a subgrade of infinite thickness and is denoted by k_∞. The nomograph was developed using the same method as for a homogeneous half space except that the 762 mm (30 in) plate is applied on a two-layer system. Typically, the k-values obtained from the chart are too large and do not represent what actually resides in the field.

For a slab placed directly on the subgrade without a subbase, AASHTO suggested the use of the following theoretical relationship based on an analysis of plate bearing test:

$$k = M_R / 19.4 \tag{1.2}$$

in which k is in pci and M_R is in psi. Theoretical considerations which provide direct correlations between M_R and k-value suggest the following:

- Units between M_R (elastic theory) and k-value (Westergaard theory) are different.
- Correlation is a function of slab thickness.

- Correlation is dependent upon slab response (i.e., deflection, bending stress, or subgrade stress).

Figure 1.1 illustrates the implications associated with the second item in the above list by the variation in k-value with respect to thickness of the slab for the same M_R value. Moreover, the correlation in Figure 1.1 is based upon assuming equal deflection between the two foundation theories. If equal bending stresses or equal subgrade stresses were assumed between the theories, the correlations would again be different. The only conclusion to be drawn from this discussion is that a correlation between M_R and k-value does not exist, and the use of empirical relations attempting such correlation will only lead to fictitiously high design k-values.

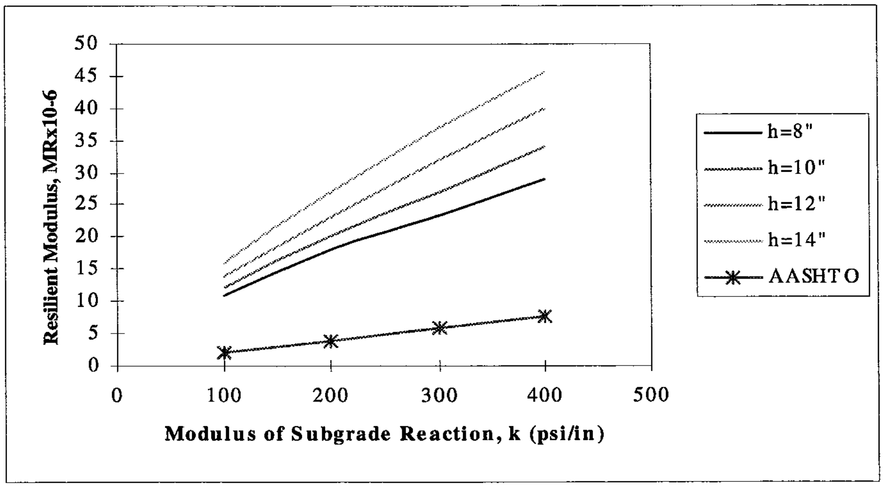


Figure 1.1 Correlation Between k-value and M_R.

To account for the potential loss of support by foundation erosion or differential vertical movements, the effective modulus of subgrade reaction must be reduced by a factor, LS. Table 1.1 shows suggested ranges of loss of support values for different types of subbase and subgrade materials. Asphalt and cement stabilized subbases have lower loss of support values than their unbound counterparts.

A bondbreaker should always be used between concrete pavement and cement stabilized subbases. Excessive cracking and premature failures can occur when concrete pavement is placed directly on a stabilized subbase. Due to the development of a bond directly to cement stabilized subbases, the potential for cracks in the subbase to reflect

Table 1.1 Typical Ranges of Loss of Support (LS) Factors for Various Types of Materials.

Type of Material	**Loss of Support (LS)**
Cement Treated Granular Base (E = 1,000,000 to 2,000,000 psi)	0.0 to 1.0
Cement Aggregate Mixtures (E = 500,000 to 1,000,000 psi)	0.0 to 1.0
Asphalt Treated Base (E = 350,000 to 1,000,000 psi)	0.0 to 1.0
Bituminous Stabilized Mixtures (E = 40,000 to 300,000 psi)	0.0 to 1.0
Lime Stabilized (E = 20,000 to 70,000 psi)	1.0 to 3.0
Unbound Granular Materials (E = 15,000 to 45,000 psi)	1.0 to 3.0
Fine Grained or Natural Subgrade Materials (E = 3,000 to 40,000 psi)	2.0 to 3.0

through the overlying pavement is increased. It also significantly increases curling and warping stresses in the concrete pavement due to temperature and moisture changes, which promote early-aged crack initiation.

Serviceability Loss

The pavement serviceability-performance concept was developed during the AASHTO Road Test. The inclusion of serviceability as a factor of pavement design is the outstanding feature of the AASHTO design methods. The present serviceability index (PSI) is a mathematical combination of values obtained from certain physical measurements so formulated as to predict the PSR for those pavements within prescribed limits.

For concrete pavement design, the difference between the initial and terminal serviceability is the most important factor. An initial serviceability value of 4.5 and a terminal serviceability value of 2.5 are recommended to be used in the design procedure.

Load Transfer Coefficient

The load transfer coefficient *J* is a factor used in rigid pavement design to account for the ability of a concrete pavement structure to transfer a load across joints and cracks. The use of load transfer devices (aggregate interlock, dowel, and tie bars) and tied concrete shoulders increases the amount of load transfer and decreases the load transfer coefficient and hence, reduces the stress due to traffic loading. The recommended J factors adopted by TxDOT are shown below.

Table 1.2 Recommended Load Transfer Coefficients.

Tied PCC Shoulders, Curb and Gutter, or Greater Than Two Lanes in One Direction		Yes	No
Load Transfer Devices at Transverse Joints or Cracks or Dowels at Joints	Yes	2.9	3.2
	No	3.7	4.2

The joint efficiency is defined as the ratio of deflections between the unloaded and loaded slabs forming both sides of the transverse joint and is a function of the several factors noted in Table 1.2. Dowel bars are effective in reducing the amount of joint faulting when compared with nondoweled sections of comparable designs. The diameter of dowels has an effect on performance since larger diameter bars provide better load transfer and control of faulting under heavy traffic than do smaller dowels.

The type of shoulder significantly affects the load carrying capacity across the longitudinal joint of the pavement. The placement of a tied concrete shoulder next to the mainline pavement can substantially increase the load carrying capacity of the pavement; however, an integral shoulder is more efficient in achieving this. The concrete shoulder provides support to the edge of the pavement and reduces stresses and deflections in the mainline slab. The shoulder also benefits by receiving support from the mainline slab, so the damage due to encroaching traffic can be greatly reduced.

Nondoweled JPCP slabs generally develop significant faulting, regardless of pavement design or climate. This effect is somewhat mitigated by the use of permeable bases. The use of lean concrete subbase increases pavement environmental stresses but can provide improved support and load transfer at the joints and resistance to subbase erosion caused by repeated pavement deflections.

As far as improvements to the design, the J factor should be replaced with load transfer efficiency since this can be measured directly in the field. Design algorithms elaborated in Chapter 2 suggest relationships between load transfer efficiency and shear stress on the crack or joint face between two slabs. These relationships provide a fundamental framework to relate the factors associated with the structural criteria connected to faulting and midslab cracking.

Drainage Coefficient

The drainage coefficient characterizes the quality of drainage of subbase layers under the concrete pavement. The quality of drainage is measured by the length of time for water to be removed from bases and subbases and depends primarily on their permeability. The percentage of time during which the pavement structure is exposed to moisture levels approaching saturation depends on the average yearly rainfall and the prevailing drainage conditions. Pavement structures with good drainage minimize the potential for erosion of subbase and subgrade.

The drainage coefficient C_d has the same effect as the load transfer coefficient J. Higher drainage coefficients represent better drainage. The general philosophy used in Texas is to prevent water intrusion and pumping by using subbases that are densely graded, non-corrosive, and stabilized. Drainage coefficients for such subbases are based on the anticipated exposure of the pavement structures to water. Table 1.3 shows the recommended drainage coefficients for TxDOT.

Reliability in Design and Overall Standard Deviation

Reliability is defined as the probability that the design will perform its intended function over its design life. Thus, higher reliability represents pavement structures with less chance of failure. TxDOT usually uses higher reliabilities for pavements where the consequences of failure would be very detrimental; consequently, thicker concrete pavements are required.

Table 1.3 Recommended Drainage Coefficient.

Annual Rainfall, inches	**Drainage Coefficient, C_d**
58 - 50	0.91 - 0.95
48 - 40	0.96 - 1.00
38 - 30	1.01 - 1.05
28 - 20	1.06 - 1.10
18 - 8	1.11 - 1.16

Reliability values are based on the average daily traffic (ADT) per lane, whether or not the facility is a controlled access facility. Therefore, higher reliabilities are provided in critical high traffic areas where traffic delays need to be minimized. Higher reliability levels would also produce facilities that require less maintenance over their design lives, thus causing fewer delays to traffic.

To determine the reliability of a design, the variances due to various sources must be known or estimated. This information can be obtained from field observations, laboratory tests, or from past experience on similar projects. The 1986 AASHTO Guide recommends values of the overall standard deviation in the range of 0.30 to 0.40, with 0.35 being the standard deviation at the AASHTO Road Test. A value of 0.39 is used for thickness design in Texas. Higher values represent more variability, thus, the pavement thickness increases with higher overall standard deviations.

In terms of performance-based specifications, the coefficients of variation used in design need to be reflected in both the design and performance predictions associated with the pavement. The coefficients need to be more accessible to the design engineer in terms of the different components that contribute to performance variability instead of working with an overall variability. In this manner, performance predictions can be directly based upon the degree of construction variability achieved in the field by the contractor since the models are configured to specific components such as variability in paving thickness. A part of structure design criteria should be the variability of key design parameters that significantly affect performance.

Design Traffic

The consideration of traffic should include both the loading magnitude and configuration and the number of load repetitions. To design a highway pavement, the 1986 Guide requires a prediction of the number of 18 kip equivalent single axle loads that the pavement will experience over its design life. Traffic for a 30-year design period is used.

Texas Department of Transportation Planning Division provides the equivalent axle load for the design lane over the design period. The traffic analysis report provides a directional distribution factor as well as a lane distribution factor. The lane distribution factor varies with the volume of traffic and the number of lanes. The design lane is the one that carries the most traffic. Usually, it is assumed that the outer lane of a highway with two lanes in each direction carries the most traffic. For a three-lane facility, the middle lane is assumed to carry the most traffic. Recommended lane distribution factors are shown in Table 1.4.

Table 1.4 Lane Distribution Factor Values.

Number of Lanes in Both Directions	**Lane Distribution Factor**
4 lanes and less	1.0
6 lanes	0.7
8 lanes or more	0.6

Directional distribution factors indicate the percent distribution of the design hourly volume in each direction of a highway facility. The transportation planning division assumes that the directional distribution of heavy vehicles on any project is evenly split in both directions. The AASHTO equivalencies are based on surface roughness, but other distress types should be considered since pavements fail in other modes besides roughness. Different equivalencies for design should be developed for different distress types based upon the behavior mechanism associated with that distress type.

Concrete Pavement Reinforcement

It has been found in the field that if steel is lapped at the same location in CRCP, premature failures occur at the lap location in the form of excessive cracking and punchouts. Another important aspect related to the design of the reinforcing steel in CRCP pavement is its bond characteristics. Development of the bond length is important to ensure adequate cracking restraint and factors associated with the rebar pattern and the concrete mix design. Bond slip characteristics discussed in Chapter 2 are important structural criteria not currently considered in design that vary as a function of the rebar pattern. Proper consolidation of the concrete is also important to develop adequate bond lengths.

Pavement Sawcutting Requirements

Sawcut notches are placed in concrete pavements to control random cracking to desired locations. The factors which affect the efficiency to control cracking with sawcut notches are timing, type of coarse aggregate, and depth of cut. TxDOT specifies the following sawcut depths for sawed joints:

- One-fourth of the pavement thickness for concrete pavements containing limestone, or
- One-third of the pavement thickness for concrete pavements containing siliceous river gravel.

Sawcut timing is especially critical for skewed jointed concrete pavements since the chances of the pavements not cracking at skewed joints are even higher than for normal transverse joints.

Sawcut timing is related to the strength characteristics of the concrete pavement. By considering the fracture toughness of the concrete, which is controlled largely by the coarse aggregate type, the effect of slab thickness and aggregate type relative to sawcut depth and timing requirements can be properly evaluated. The Texas Transportation Institute has developed and applied fracture theory in both the laboratory and the field to obtain concrete properties that can serve as sawcutting depth and timing criteria as shown in Figure 1.2. Developments from these efforts have clearly shown that sawcut depths for gravel mixtures must be placed at shallower depths and at earlier times than mixtures containing limestone coarse aggregate. Current sawcut specifications should be modified to reflect the correct trends between aggregate types based on a new test procedure described in Chapter 3.

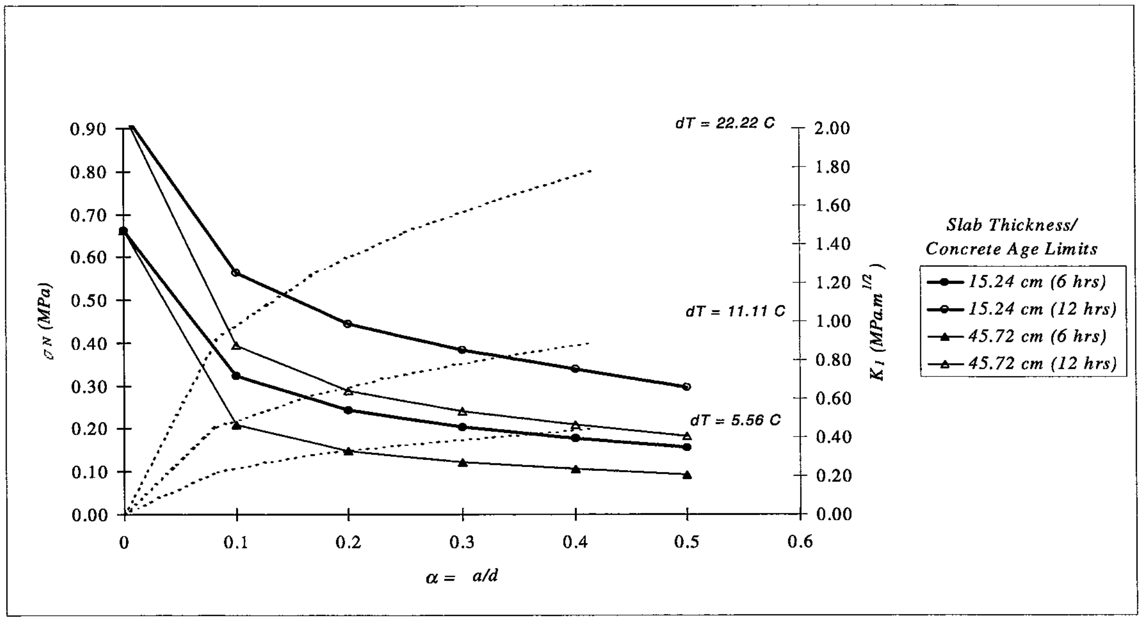


Figure 1.2 Criteria for Sawcut Depth and Timing Requirements. (Soares and Zollinger, 1997).

CURRENT CONSTRUCTION SPECIFICATIONS

Item 360 of the TxDOT construction specifications governs the construction of portland cement concrete 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 or less. Chapter 3 describes workability measurements using vibrational techniques that provide an indication of mixture mobility.

Curing

The object of curing is to keep concrete saturated, or as nearly saturated as possible, 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 good 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 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. Chapter 3 provides a discussion of curing effectiveness.

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 is dedicated to the method of evaluation used in this study to rate both current and potential test methods to measure performance-related properties. Each test 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 evaluated with respect to three categories: performance, nature and makeup of the test, and the test equipment requirements. The performance characteristics of each test (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 account for 50 percent of its overall utility. The nature of each test is evaluated with respect to whether the test is a direct or an indirect measure of a parameter, whether or not the test can be conducted in the field, and whether or not the test is non-destructive. A test that directly measures a material property will be rated higher than a test that determines a property indirectly. The nature of the test is also an important consideration and will account 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 is also considered but is less important than the previous categories and, consequently, will account for only 20 percent of the total utility.

Each of the attributes noted above for each test was itemized and summarized in Appendix A. 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

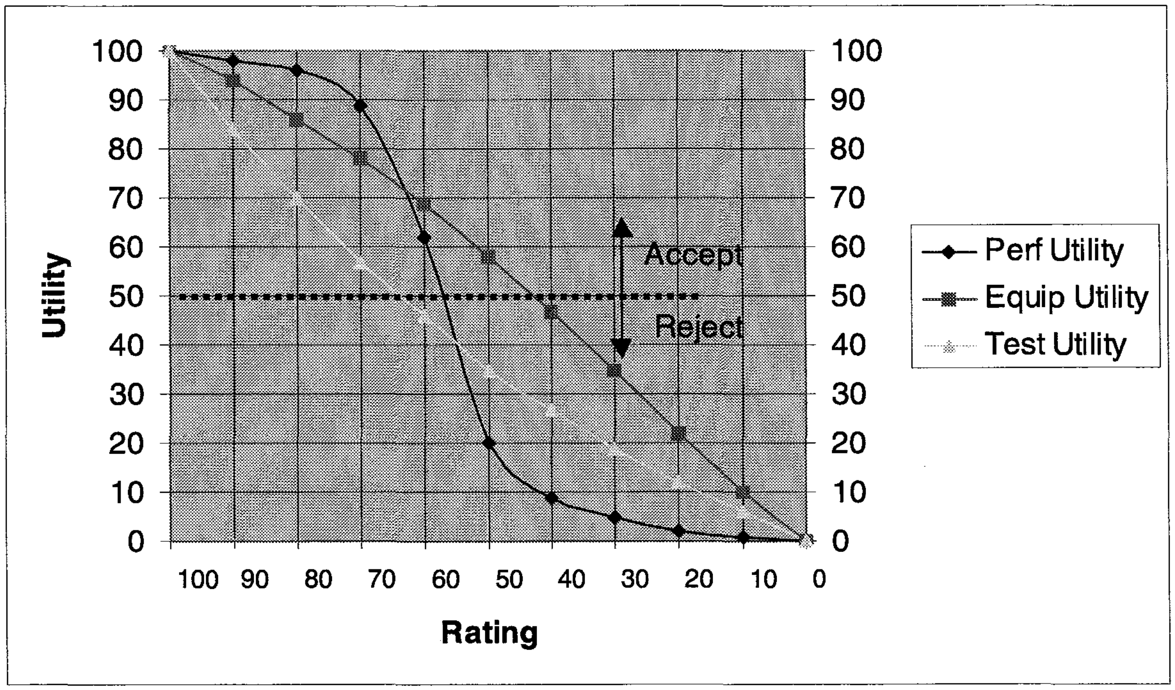


Figure 1.3 Utility Curves for Rating of Testing Procedures.

attribute. The points for each attribute are summed for each category, which serves as a rating in each of the three categories: performance, nature of the test, and the test equipment. These ratings are translated into utility values by the relationships defined in Figure 1.3. The utility curve for the performance category shows 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 can be calculated using the previously defined weights: performance 50 percent, nature of test 30 percent, and test equipment 20 percent.

As noted in Figure 1.3, a utility value of 50 was selected as the criteria for whether or not a particular test should be considered further. To facilitate further consideration, tests meeting this criteria are described in greater detail in this chapter while the remaining tests that were rated in this study are simply listed in Appendixes A and B. Each description includes a short summary and greater detail of each test's assessment in terms of each category. A similar approach is taken with respect to new tests and developments and is reported in Chapter 4.

Relative to important test properties/characteristics, one that stands out is the need to measure the strength of the concrete in-place rather than concrete cast in a test specimen mold. 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. Various methods of temperature and crack control can be employed by the contractor 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. Methods to make such measurements will be noted in Chapter 3.

It is important to point out that the 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. As is elaborated in Chapter 4 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 which is based on the empirical equations obtained from the AASHTO Road Test, 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, which is the approach taken in the remainder of this report. Therefore, prior to considering the mechanisms that are associated with performance, it is prudent to review the merits of existing testing methodologies currently included in TxDOT testing specifications. Given this review in Appendix E and discussion of the mechanisms in Chapter 2, it will then be appropriate to consider new developments in Chapter 3 that complement current testing programs and the mechanisms that relate to performance. Chapter 4 will make recommendations as to what additional measures should be made to more completely ensure adherence to key structural design criteria. With respect to Project 0-1735, "Development of Structural Field Testing of Flexible Pavement Layers," a discussion of how the procedures suggested in that study pertain to the methods and approaches recommended in this study are addressed in both Chapter 2 and Chapter 4.

CHAPTER 2
NEW CRITERIA FOR DESIGN AND CONSTRUCTION

The emphasis of this report up to this point has been on current design and testing procedures and the material or testing properties associated with them. With this background, it is appropriate to consider recent developments that potentially may serve as either new test procedures for typical or traditional material properties, new test procedures to measure new material properties, or as entirely new approaches to characterize material behavior. However, prior to such discussions, it is well to clarify the aspects associated with the objectives behind the design and construction of concrete pavement systems. With this clarification, a description of the types of distresses which form in concrete pavements is provided along with a discussion of the slab behavior and performance mechanisms associated with them as they pertain to design. Following this, important material properties are presented that are related to these mechanisms along with theoretical models to characterize and represent either the behavior or the distress. The remainder of the chapter is focused on the identification of the key parameters associated with design and construction and the relationship between them.

PERFORMANCE ASPECTS RELATED TO DESIGN AND CONSTRUCTION OF CONCRETE PAVEMENT

One aspect related to the objective behind the design of portland cement concrete (PCC) is the representation of the deterioration processes that affect pavement condition 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 is 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 questions that must 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 is 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 (as was indicated from the evaluation conducted in Appendix E). 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, it is expected 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. In this frame of mind, the subject of this chapter can best be addressed by 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.

CONCRETE PAVEMENT BEHAVIOR AND DISTRESS MECHANISMS

Review of some of the significant pavement distress types will bring into focus the mechanisms behind these distress types and serve as an example of how the most important material properties that are associated with the development of the distress type can be used to identify field test procedures that should be adopted or developed. This review is warranted from the standpoint that lack of structural integrity (as would be assured by meeting the structural design criteria) leads to the development of distress and is associated with distress mechanisms that ultimately affect the long-term performance of the pavement. The identification of the relevant material characteristics will highlight the types of measures that should be considered in field testing programs. It is interesting to note that this would be basically the same philosophy behind developing the list of tests to be included in a quality control program for concrete pavement construction. The following discussion is not all inclusive of all pavement distress types but, as an example, addresses those that most logically can or are included in current pavement design methodologies. Key material properties will be summarized with each distress type referred to below to help demonstrate how the understanding of distress mechanisms aids in the discovery of pertinent material properties and testing parameters.

Concrete Spalling (Jointed and CRC Pavements)

Spalling refers to the breakdown or dislodging of concrete segments along a joint or crack in a concrete slab within 0.6 m (2 ft) of a joint or crack (SHRP Distress Manual, 1994; Sanadherra and Zollinger, 1996) that can affect the structural slab integrity. This form of distress has several different modes of failure but has been noted to be primarily related to pre-existing horizontal delaminations that can later result in a spall due to a variety of causes from accumulation of incompressibles within the joint or crack and due to repeated traffic loads. A significant contributor to spalling is the existence of shallow, horizontal delaminations that result primarily from early-age shrinkage strains within the top 25 mm of the pavement surface. If the loss of moisture is great enough in terms of evaporation and time, a failure plane, horizontally oriented near the pavement surface and in the vicinity of transverse cracks or joints, can develop resulting in a weakening or lowering of the resistance of the pavement surface to spall damage. In concretes made with certain coarse aggregate types, a greater tendency exists to cause early-age delamination and eventual spalling. For that reason, spalling has been related to certain aggregate types, their associated aggregate-mortar bond characteristics, and the tendency of concrete to allow water to evaporate during curing. The resistance of the concrete to moisture loss can be referred to as diffusivity, and the resistence to moisture loss by the curing compound can be referred to as curing effectiveness. Evidence collected from extensive field studies have indicated that the bond of the aggregate-mortar interface at an early age is one of the most significant factors affecting the development of spalling.

Spalling is a common distress in continuously reinforced concrete pavements but occurs in all concrete pavement types. Spalls that have been initiated by horizontal delamination can result from a number of load-related causes that result from slab flexure and shear imposed loading (Sanadheera and Zollinger, 1996). Spalling does affect the performance of concrete pavements in that it affects the quality of the pavement smoothness and ride. Obviously, in terms of basic material properties that are related to this distress type, those which are pertinent to the aggregate-mortar bond are of interest. These are: aggregate surface texture and shape, early-age aggregate-mortar bond as characterized by the concrete fracture toughness, and aggregate chemistry and residual oxide content are all important and vary significantly with aggregate type. Other properties of high importance are those related to the effectiveness of the curing membrane in their effect on moisture loss during the hydration of the concrete. This distress type is inherently related to the coarse aggregate properties and characteristics used in the concrete mixture.

Transverse Cracking (Jointed Concrete Pavement)

Transverse cracking in jointed concrete pavements normally occurs at the mid-slab region and is manifested as either early-age cracking (which often occurs prior to extensive traffic application) that is largely caused by environmentally related factors or as fatigue cracking that is commonly due to load-induced stresses that can also affect the slab structural integrity. Transverse cracking in continuously reinforced concrete pavements is an expected phenomenon that occurs at much closer intervals. As previously indicated, jointed concrete pavements typically manifest transverse cracking in the mid-slab region, but cracking may occur in other regions of a slab depending on joint spacing and support conditions. These cracks are perpendicular to the pavement centerline (SHRP Distress Manual, 1994). Early-age concrete shrinkage and thermal effects (due to the coefficient of thermal expansion) can have a significant effect upon the incidence of transverse cracking. Under these circumstances, the aggregate-mortar bond is the aggregate property pertinent to early-age cracking distress because the fracture faces often follow along the aggregate-mortar interface. Improved construction specifications should include factors that address minimization of early-age damage.

Uncontrolled transverse cracking is undesirable and is typically in a form of early-age cracking distress that often results from poor sawcutting or curing practice and can affect the structural integrity of concrete pavement if it is allowed to occur. Coarse aggregate type does play an important role in the management of sawcut timing and depth with respect to proper contraction joint formation in terms of the strength of the bond between the aggregate and the cement paste. Coarse aggregate type also affects the brittleness of the concrete at an early age, which relates to how "susceptible" a particular concrete mixture may be to random cracking. Transverse cracking in jointed plain concrete pavements that is due to fatigue loading at the mid-slab area is largely unrelated to the coarse aggregate type if it is unrelated to early-age crack initiation which, in this sense, aggregate type may have little effect on the formation of this particular mode of distress. The strength of the aggregate-mortar bond in aged or mature concrete tends to override any effects relevant to the material characteristics referred to above that are important in early-age cracking. Also related to this distress type is the amount of heat generated during the hardening of the concrete and the concomitant rise in concrete temperature. High temperatures can result in premature cracking that may ultimately affect pavement performance. Again, construction specifications can be improved by addressing the factors relative to weather conditions at the time of construction.

Jointed reinforced concrete pavements can, given the right weather conditions, develop transverse cracking at certain intervals that is intended to be held tightly closed by the distributed reinforcing steel in the pavement. In order for this pavement type to provide adequate service, the widths of the transverse cracks must be held tightly closed in order to ensure adequate shear and structural capacity of the transverse crack and transfer of load across the crack. The width of the cracks will in part be affected by the thermal coefficient of expansion of the concrete, which is directly related to the characteristics of the coarse aggregate.

In terms of aggregate and material characteristics, early-age cracking is the primary distress type of interest with a focus on the aggregate-mortar bond and the diffusivity of the concrete during curing. With all things considered within the scope of this distress mechanism, most properties relative to this distress type are aggregate related: gradation, percent voids, aggregate fracture toughness, texture, shape, and aggregate chemical or residual oxide content.

Faulting of Transverse Joints and Cracks (Jointed Plain Concrete (JPC) Pavements)

Faulting occurs in jointed plain concrete pavements when a discontinuity in the profile of the pavement surface occurs across the transverse joint due to the buildup of debris under the concrete slab in the vicinity of the joints. The mechanism associated with development of this discontinuity is multi-faceted and involves the resistance of the subbase to erosive force caused by the movement of water under the concrete slab. The movement of water is affected by the ability of the slab on one side of a joint or crack to move independently of the slab on the other side of the joint or crack. The greater this independence, the greater the erosive forces. Also, the width of the transverse crack is an important factor in the freedom of movement across a crack or joint since it controls the shear capacity of the joint interface and its capacity to resist the mechanism associated with fault development. The width of transverse joints at any temperature condition is related to the thermal coefficient of expansion of aggregate and concrete. Therefore, in many respects, the coarse aggregate type plays an important role in performance of this pavement type. Important aggregate and material properties associated with this distress type are aggregate texture, aggregate shape, aggregate abrasion and wear-out resistance, aggregate gradation, and concrete thermal coefficient of expansion.

Corner Breaks (Jointed Reinforced Concrete (JRC) Pavements)

Corner breaks are primarily a load-related distress type. The development of corner breaks in jointed reinforced concrete pavements is of greater potential in JRC pavements than it is in jointed plain concrete pavements, particularly at random transverse cracks that serve as unsawcut joints. If the reinforcing steel in jointed reinforced concrete pavements is inadequate or the joint/crack widths are too great to maintain aggregate interlock at these cracks, any type of an unsupported condition may eventually result in corner breaks. The role of the coarse aggregate in the development of this distress type may be primarily through the thermal effect in the opening and closing of the transverse cracks manifested by the thermal coefficient of expansion of the concrete and in the development of the distance between crack intervals. In circumstances where random cracks are widest (at low temperature conditions), potential for development of loss of support and structural integrity may be the greatest. Important aggregate properties relative to this distress type are the aggregate thermal coefficient of thermal expansion and the chemical nature of the aggregate. Aggregate properties relative to cracking and the development of fatigue cracking are typically of lesser importance due to the strength of the aggregate mortar bond of mature concrete and, consequently, are expected to be masked under the effect of other properties related to the characteristics of the concrete mixture.

Close Crack Spacing (Continuously Reinforced Concrete (CRC) Pavement)

Closely spaced transverse cracks are related to cluster cracking and represent potential locations of low structural capacity and for punchout distress, which is the primary distress type in continuously reinforced concrete pavements. Closely spaced cracks frequently occur with continuously reinforced concrete pavements made with concrete having coarse aggregates that manifest low aggregate-mortar bond strength (at an early age) and relatively high coefficients of thermal expansion. Coarse aggregate type plays a significant role in these factors, as previously explained. Therefore, aggregate properties, such as coarse aggregate type and chemistry, aggregate thermal coefficient of expansion, aggregate-mortar bond as characterized by concrete fracture toughness, aggregate gradation, aggregate shape and texture, and season and time of placement are also important in the occurrence of close transverse cracking.

Cluster Cracking (Continuously Reinforced Concrete (CRC) Pavement)

Continuously reinforced concrete pavements commonly develop a random cracking pattern that forms initially from three days to approximately 28 days after placement and are very dependent upon the temperature conditions at the time of construction (whether placement occurs during the morning or the afternoon) and the type of coarse aggregate used in the concrete. Consequently, the nature of the resulting crack pattern is very dependent upon the thermal properties of the concrete and its constituents. An ideal transverse crack pattern for CRC pavement is one that is uniformly distributed and where all cracks open and close uniformly. Cluster cracking consists of combinations of closely and widely spaced transverse cracks that are evident in the crack pattern which result in non-uniformity and wide disparity in crack widths of the transverse cracks. These characteristics can reduce crack stiffness and structural integrity at certain locations. Poor crack patterns and, consequently, reduced pavement performance and increased punchout potential result from frequent clusters of closely spaced cracks. Aggregate properties, such as coarse aggregate type, the aggregate thermal coefficient of expansion, aggregate-mortar bond as characterized by concrete fracture toughness, aggregate grading, aggregate shape and surface texture, and season and time of placement are important in the occurrence of cluster cracking.

Punchouts (Continuously Reinforced Concrete (CRC) Pavement)

Cluster cracking, close transverse cracking, and crack spalling are precursors to development of punchouts in continuously reinforced concrete pavement systems. Punchouts most commonly occur at locations of closely spaced transverse cracks that become unsupported over time along with increased traffic. Punchouts develop as the shear strength of the aggregate faces or interlock in the transverse crack reduces or wears out with load application. The loss of support underneath the pavement layer results from several different causes related to the effects of subbase moisture but can result in significant increases in aggregate interlock shear stress (and loss of load transfer across the transverse cracks) and in the rate of punchout distress. Coarse aggregate effects are important from the standpoint of how they affect the development of the crack pattern previously discussed and the shear capacity of the aggregate interlock. Important aggregate properties are aggregate texture, aggregate shape, aggregate abrasion and wear-out resistance, aggregate gradation, and aggregate properties previously listed relative to the development of the crack pattern in CRC pavements.

Joint Seal Failures

Joint seals are intended to fill the joint well to maintain freedom of movement of the joint by preventing debris from accumulating within the joint while it is in an open position. Relative to the movement of the joint, the sealant can fail due to loss of bond to the concrete side walls or due to cracking in the interior of the sealant unless it is a pre-compression type seal (in which case a different mode of failure is involved). Loss of bond occurs with time and aging due to weathering and the effects of solar radiation. Most sealants, whether they are synthetic polymers or silicones, are susceptible to aging due to ultraviolet radiation. The aging effect causes the material to stiffen and to lose creep capability. This leads to an increase in stress at critical points along the interface between the sealant and the concrete or within the sealant itself as the joint well opens and closes due to climatic effects. The increase in stress increases the potential for debonding at the interface or to develop a longitudinal cracking at the interior of the sealant. An important feature of sealant materials is its resistance to stiffening and its bond strength. Bond strength is affected by coarse aggregate type; gravel aggregates tend to develop greater bond strength particularly to silicone sealants.

Compression sealants are subject to weathering and aging effects as well, but the mode of failure is different. These types of seals are designed to maintain a high level of compression against the side walls of the joint well. As the joint opens and closes, aging of the compression seal reduces the responsiveness of the seal to deform and to maintain the necessary pressure against the joint wall to prevent dislodging of the sealant.

Subbase Considerations

Subbase layers under concrete pavement structures serve a variety of purposes however, the least of which is structural related. Subbase layers can potentially serve any of the following functions:

1. Minimization of erosion and loss of support,
2. Enhancement of the breadth and uniformity of support,
3. Provision of a drainage layer and overall enhancement of drainage,
4. Provision a construction platform,
5. Control interlayer friction levels (bonded vs. unbonded), and
6. Minimization of damage due to swelling soils and frost heave.

Since many subbase materials consist of stiffness and densities significantly less than that of PCC, structural and load carrying contributions to those provided by a concrete slab are relatively insignificant. Nonetheless, a primary function of a subbase layer is the minimization of erosion and loss of support. Closely tied to this is the provision and enhancement of uniform support from point to point within the pavement system. This particular feature is critical at slab edges and along joints where water has a tendency to accumulate along with erosion under pumping action of the slab. Subbase materials need to be erosion resistant. Use of stabilized base layers to minimize erosion must be carefully employed due to the enhanced bond conditions which result at the slab/subbase interface. In many of these instances, it is appropriate to use bond breakers to reduce the frictional restraint. Unstabilized bases have the distinct advantage of providing varying degrees of drainability, depending upon the grading, dry-rodded unit weight, and the degree of porosity and compaction. Inclusion of too finely graded materials will result in a highly erosive subbase since pore water pressure may be great enough to eject the finer materials from the matrix of the base. Consequently, unstabilized bases have been placed with an open grading and should have permeability greater than 300 m/day (1,000 ft/day) to keep pore-water pressure buildup to a minimum. The open graded material should be protected from contamination and clogging by use of a fiber fabric or a layer of densely graded material.

Open graded stabilized bases tend to create too much interlocking at the slab/subbase interface and should be used with caution.

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 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 2.1 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 there were no presuppositions made relative to how the distress developed with respect to time, traffic, or structural slab behavior. 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,

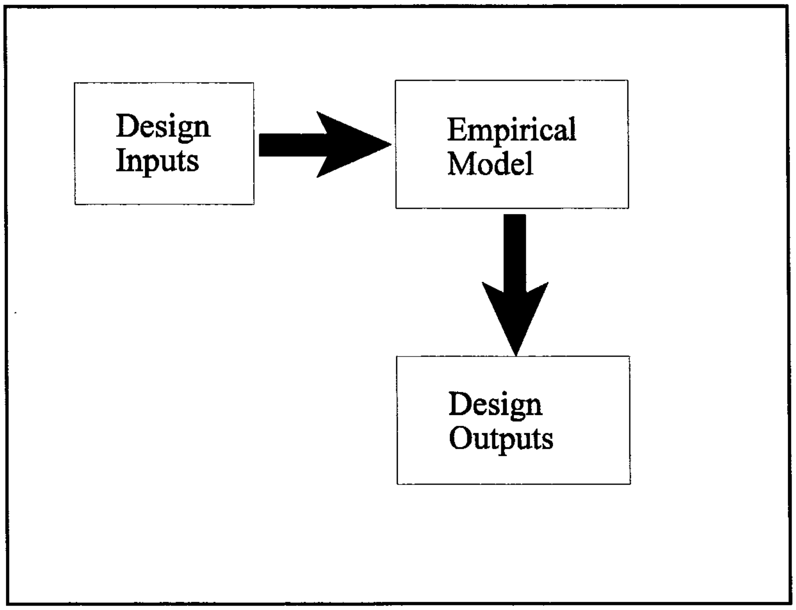


Figure 2.1 Typical Framework of Empirically Based Design.

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.

A framework of rationally or mechanically based design processes is illustrated in Figure 2.2. In design procedures that fit into this classification, pavement responses are predicted by use of analytical tools that are based on engineering mechanics. These tools typically incorporate the use of constitutive equations which 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

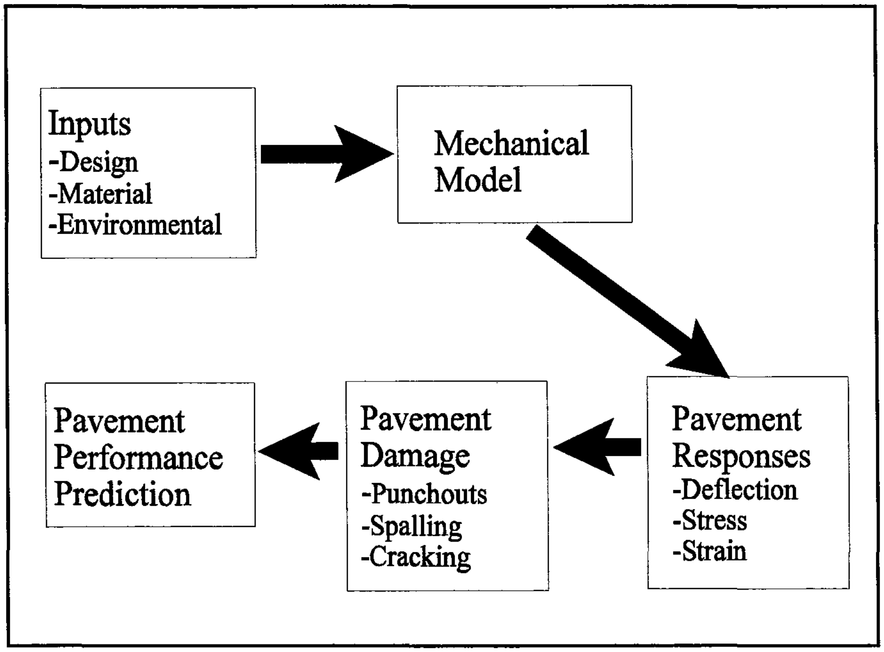


Figure 2.2 Typical Framework of Mechanically Based Design.

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 will be presented and discussed relative to the important features they possess in terms of structural design criteria.

Concrete Strength and Cracking Resistence

One of the aspects of structural design criteria is the strength of the concrete. Strength values obtained from small test specimens have traditionally been used to control the quality of highway construction and assumed to be applicable to the design stress calculated in the thickness design. This has been standard practice despite the fact that load/support conditions and the stress distribution in a continuous (or near-continuous) pavement slab are quite different from those in a simply supported beam or split tension cylinder. Furthermore, a pavement slab is considerably larger than a laboratory specimen in any dimension. These differences make the estimation of the strength of field structures from laboratory specimens questionable at best. Even in the event of identical load/support conditions for laboratory and field configurations, the effect of size on strength needs to be considered. The strength value obtained with the same type of specimen does, in fact, vary with the specimen size. Also, strength values obtained with different types of tests are different (Wright and Garwood, 1952; Mindess and Young, 1981).

Given that material fracture parameters can be used to determine concrete strength by accounting for geometry and size effects, the use of any type of empirical correlation between actual structure strengths and laboratory strengths is unnecessary and not recommended. This is particularly important as it relates to pavements, where there has been an increased interest in using compressive strength for quality control purposes in the form of correlations to flexural strengths. Although compressive strength may be used as a practical index for quality control purposes, it is important to note that neither compressive nor flexural strength represent the strength as it is configured within the pavement. The use of fracture parameters allows for strength to be interpreted in a consistent manner by use of the one-size variable-notch method (Tang et al., 1996) with the use of the strength of notchless specimens as suggested by Bažant (1995) for determination of fracture parameters defined in the size effect law.

By use of linear elastic fracture mechanics (LEFM) theory, the propensity for a crack to initiate in a brittle material can be characterized by a parameter called the stress intensity factor. The critical value of this parameter can be obtained in laboratory tests elaborated in Chapter 4. The ability to show the effect of specimen or structure size on strength is a fundamental difference between linear elastic fracture mechanics (LEFM) and traditional strength theory. The latter assumes strength to be constant with respect to structure size. It has been experimentally shown (Bažant, 1984; Bažant and Pfeiffer, 1987) that the size effect of concrete follows a transitional curve that approaches the limit stress criterion for very small specimens and approaches the limit defined by LEFM for very large specimens. The size effect of concrete is due to the presence of a fracture process zone of numerous microcracks in front of a macroscopic crack. Formation and growth of these microcracks consume energy in the cracking process. Therefore, crack growth requires extra energy over the amount of energy needed for formation of fracture surfaces. Unstable crack growth does not occur until the fracture process zone develops a certain length. Based on the critical stress intensity factor K_{If} and the critical process zone length c_f, for any structure of finite size d, the nominal strength can be determined from the generalized form of the size effect law proposed by Bažant and Kazemi (1990):

$$\sigma_N = c_n \frac{K_{If}}{\sqrt{g'(\alpha_o)\ c_f + g(\alpha_o)\ d}} \tag{2.1}$$

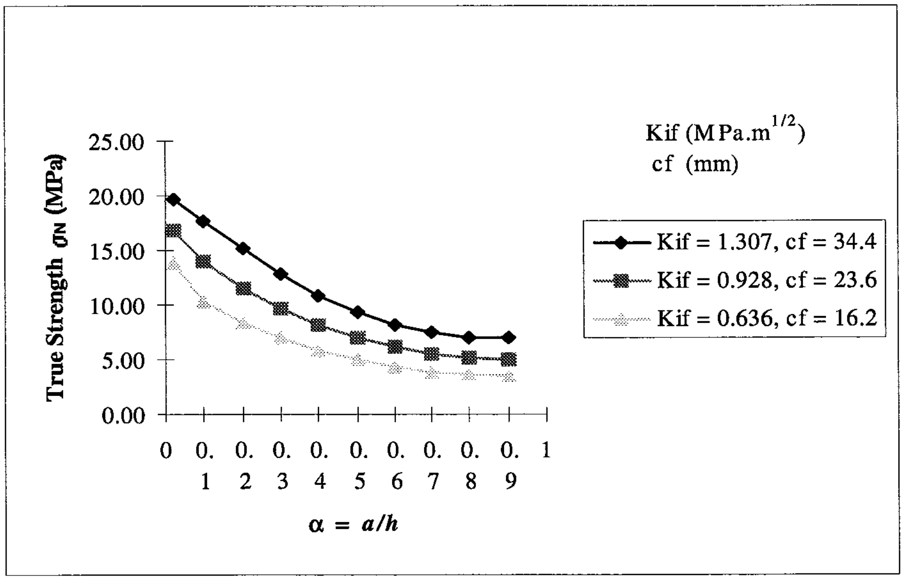


Figure 2.3 True Concrete Strength as a Function of Crack Development.

where $\sigma_N = c_n P/bd$, P is the ultimate load, α_0 = is the initial crack ratio (a_0/d), $g(\alpha)$ and its derivative $g'(\alpha)$ are functions of specimen geometry evaluated where $\alpha = \alpha_0$. The two material factors, K_{If} and c_f, and the geometry functions evaluated at $\alpha = \alpha_0$, are used in equation 2.1 to determine the nominal strength σ_N corresponding to a particular specimen or structure size d (e.g., slab thickness).

It is important to recognize the significance of the parameters included in equation 2.1 and their relationship to structural design criteria. The term σ_N represents the true strength of concrete as a function of the thickness of the concrete slab and the degree of cracking the slab has undergone as depicted in Figure 2.3.

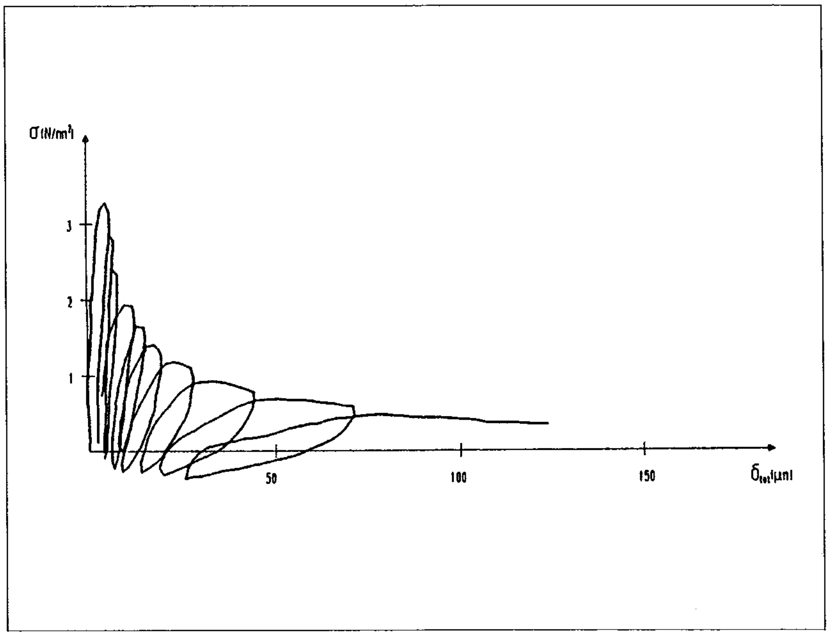


Figure 2.4 Reduction on Concrete Modulus Due to Cracking Damage.(Grzybowski 1989).

As the degree of cracking develops, the strength of the concrete diminishes to zero. The relationship shown in Figure 2.3 is significant from the standpoint of explaining why the stiffness of concrete and the slab is reduced by cracking damage. This type of damage is also accompanied by a reduction in the modulus of elasticity of the concrete (Figure 2.4). The cracking model shown in equation 2.1 is also useful in determining the degree of cracking based on non-destructive test results. The c_f term represents the brittleness of concrete and represents the susceptibility to crack propensity.

Pavement Support and Stiffness at Transverse Joints and Cracks

The characterization of the support under a CRC pavement (or overlay) is based upon assessment of the structural stiffness across the transverse cracks. A distinction needs to be made between structural stiffness and material stiffness of a concrete pavement. Material stiffness is characterized by the modulus of elasticity where structural stiffness represents an 'effective' material stiffness since the structural stiffness includes the effect of a crack or joint in the slab. Structural stiffness is also affected by the degree of support provided by the base or subgrade and, as will be explained later, can be represented by back-calculated values of the radius of relative stiffness (RRS - ℓ_k). Stiffness of this nature can only be determined from deflection data generated by such devices as the FWD or the rolling dynamic deflectometer (RDD).

The use of deflectometer data plays a key role in this approach to CRC pavement evaluation since it provides a measure of the deflected slab profile under load. The use of a FWD to evaluate pavement support conditions has been previously used (Zollinger and Barenberg, 1990) but use of a rolling dynamic deflectometer (McNerney et al., 1997) for evaluating CRC pavements is a possibility as well. Further discussion with regard to the use of NDT is included in Chapter 3, but data of this nature is used to calculate the deflection basin area and the load transfer efficiency across each joint or crack. The calculated basin area and the load transfer efficiency are then used in the analysis to characterize support conditions provided by the pavement system. Consideration of RDD is warranted from the standpoint that deflection basin data provided on a continuous basis are expected to be extremely valuable to the assessment of pavement stiffness.

Application of theoretically sound, mechanistic concepts to the structural evaluation of an existing CRC pavement is key to formulation of a rational characterization of an existing pavement structure. This can be achieved by matching the theoretically predicted response of the system under load, typically in the form of a deflection basin, with corresponding behavior (as may be represented by an 'effective' ℓ-value) observed *in situ* through the selection of appropriate system parameters, such as layer thicknesses and moduli (i.e., material stiffness) (Ioannides et al., 1992).

A deflection profile (and resulting pavement and material properties) for a loaded slab may be generated using the ILLI-SLAB finite-element computer program (Tabatabaie and Barenberg, 1978). However, a closed-form solution has been suggested for back-calculation purposes and is preferred (Ioannides et al., 1992). For this purpose, a slab with a joint/crack is characterized to represent field conditions with respect to support and load transfer conditions of the transverse cracks. The purpose of this is to back-calculate either an 'effective' layer modulus or a composite k-value as determined by the collected field data. This information is used in the determination of an 'effective' stiffness (ℓ_k) of the transverse crack.

There are two different extremes that will arise when considering an existing pavement. The slab may either be bonded to the base or it may be unbonded. In either case, it is most appropriate to consider the base or the subbase as a part of the pavement system rather than part of the pavement support. For modeling an unbonded condition, a two-layer analysis may be used where the existing pavement is modeled atop a stabilized base (if one exists) and the subgrade. This approach can provide a back-calculated k-value or an effective layer modulus (Ioannides et al., 1992). In a bonded slab, the ILLI-SLAB program treats two layers as one equivalent layer with a composite layer thickness. If the existing slab has no stabilized base, a two-layer analysis is most appropriate (Darter et al., 1995).

A back-calculated k-value (whether the pavement is bonded or unbonded) as approximated from a Westergaard analysis for an interior load condition is determined from the following equation:

$$k = \frac{P}{8D_o(\ell_m)^2}\left[1-\left(\frac{a}{\ell_m}\right)^2(0.217 - 0.367 \log\left(\frac{a}{\ell_m}\right))\right] \tag{2.2}$$

The effective elastic modulus, if of interest, (E_{eff}) may also be back-calculated as:

$$E_{eff} = \ell_m \; 12 \; (1-\nu^2) \; \frac{k}{h^3} \tag{2.3}$$

where

P = load applied in lbs,

D_o = maximum deflection under the load,

ℓ_m = radius of relative stiffness corresponding to the measured basin area,

ν = Poisson's ratio,

k = back-calculated subgrade modulus, and

a = loaded radius.

This approach of back-calculation can also be used to characterize the overall pavement behavior in terms of the structural parameters of the original pavement system. It may be shown that the overall pavement stiffness ($E_c h_c^3$) can be defined in terms of the existing pavement system and an unbonded overlay as (Zollinger et al., 1998):

$$E_c h_c^3 = E_1 h_1^3 + E_2 h_2^3 \tag{2.4}$$

where

$E_c h_c^3$ = composite pavement stiffness,

E_i = flexural moduli of the pavement layers (1 = Overlay, 2 = Existing Slab), and

h_i = thicknesses of the pavement layers.

The subscript "c" denotes the properties of the composite pavement system imagined to rest on the same foundation as the original pavement. Although not shown here, a similar approach may be applied to the case of a bonded overlay. In this case, the flexural stiffness of the composite pavement may be determined in terms of the properties of the original pavement system and a bonded overlay using the parallel axes theorem (Ioannides et al., 1992). It should be noted that an effective pavement stiffness ($E_e h_e^3$) may also be determined based on a field measured ℓ-value (ℓ_m) as:

$$E_e h_e^3 = \ell_m^4 \, 12 \, (1-v^2) \, k \tag{2.5}$$

and,

$$\ell_m = a_1 + a_2 \cdot \text{Area} + a_3 \cdot \text{Area}^2 \tag{2.6}$$

where

a_1 = 74.32,
a_2 = -4.185, and
a_3 = 0.003163.

The a_1 values are regression constants with $r^2 = 0.9949$ and the SEE = 0.7548. This expression is applicable and dependant upon the configuration of the pavement system that exists at the time of the FWD testing, whether it be a single or two-layer system. This value is used to calculate the composite pavement stiffness with an overlay.

Therefore, an overall stiffness ($E_c h_c^3$) may be determined, for design purposes, for unbonded as well as bonded layer conditions relative to the basin area and the radius of relative stiffness of the existing pavement system. For an unbonded system, the composite stiffness is given as in equation 2.4, and for a bonded system, it is determined by similar equations. E_1 and h_1 are the elastic modulus and the thickness of the pavement surface (or overlay), and E_2 and h_2 are those of the lower pavement layer and may be considered to be effectiveness values since they may include the effect of the transverse cracks and joints.

CRC Transverse Effective Crack Width and LTE

The effective width of a transverse crack in a CRC pavement system can be determined from load transfer data by use of a load transfer function that incorporates a joint stiffness parameter - Agg/kℓ. Relating deflection load transfer (LTE) and joint stiffness (Buch, 1995; Ioannides, 1990):

$$\text{LTE}\ (\%) = (a + cx + ex^2 + gx^3)/(1 + bx + dx^2 + fx^3) \tag{2.7}$$

where

x = Ln(Agg/kℓ)
a = 45.973
b = -0.00855
c = 19.588
d = 0.056
e = 2.785
f = -1.205 e-05
g = 0.130

Figure 2.5 illustrates the relationship between dimensionless shear stress ($s = \tau P/h^2$ where τ is the shear stress on the crack face, P is the wheel load, and h is the thickness of the slab) of the transverse crack and the stiffness of the transverse crack as a function of the degree of load transfer offered by a tied concrete shoulder at varying degrees of load transfer. As the degree of load transfer across the concrete shoulder joint increases, the dimensionless shear stress

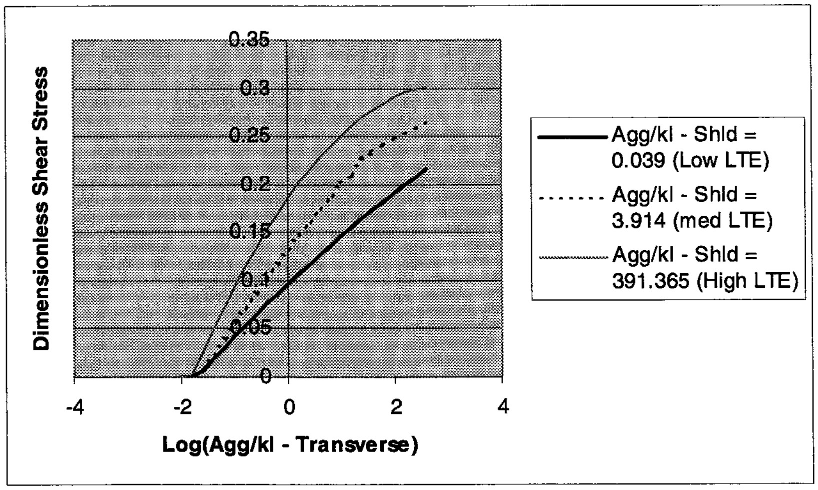


Figure 2.5 Shear Stress as a Function of Load Transfer Efficiency Provided by a Concrete Shoulder. (Zollinger et al., 1998).

on the transverse crack decreases as characterized in the following equation form for a specific crack spacing:

$$Lns = a + bLn\left(\frac{Agg}{Kl}\right)_{s} + ce{-}\log\left(\frac{Agg}{Kl}\right)_{T} \qquad (2.8)$$

Note: T: load transfer on the transverse crack; S: load transfer on the longitudinal joint. Shear stress also depends upon the distance between cracks and decreases as the crack spacing increases.

It should also be noted that shear capacity (opposite of shear stress) is a function of the width of the transverse crack as characterized in the following form (Buch, 1995):

$$s_{capacity} = \tau h^{2}/P = a\ e^{-0.039\ cw} \qquad (2.9)$$

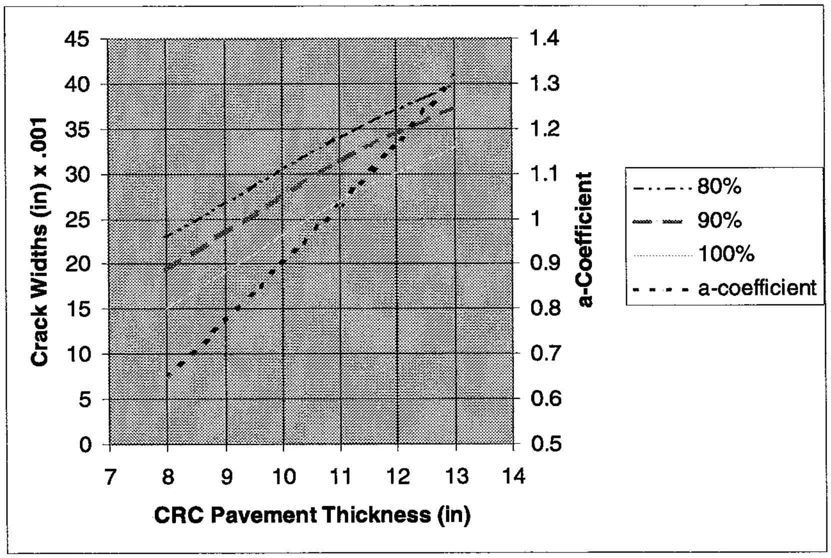


Figure 2.6 Maximum Crack Width Limits Based on Shear Capacity Requirements. (Zollinger et al., 1998). (25.4 mm = 1 in)

where cw = crack width. The value of 'a' ranges from 0.55 to 1.3 as a function of thickness as shown in Figure 2.6. Equation 2.9 can be used to determine the effective width of the transverse cracks as a function of the shear capacity and load transfer efficiency of the crack.

Equation 2.10, shown below, demonstrates how the opening of the crack width can be calculated relative to the temperature of a concrete pavement:

$$\overline{cw} = L\,(z + \alpha_c t_{max}) + \frac{f_t}{E_c}\left(L - \frac{f_t d_b}{4up}\right) \qquad (2.10)$$

where

α_c = thermal coefficient of expansion,

t_{max} = maximum drop in pavement temperature,

d_b = reinforcing steel bar diameter,

z = concrete drying shrinkage,

f_t = concrete tensile strength,

E_c = concrete modulus of elasticity,

L = crack spacing,

p = percent steel, and

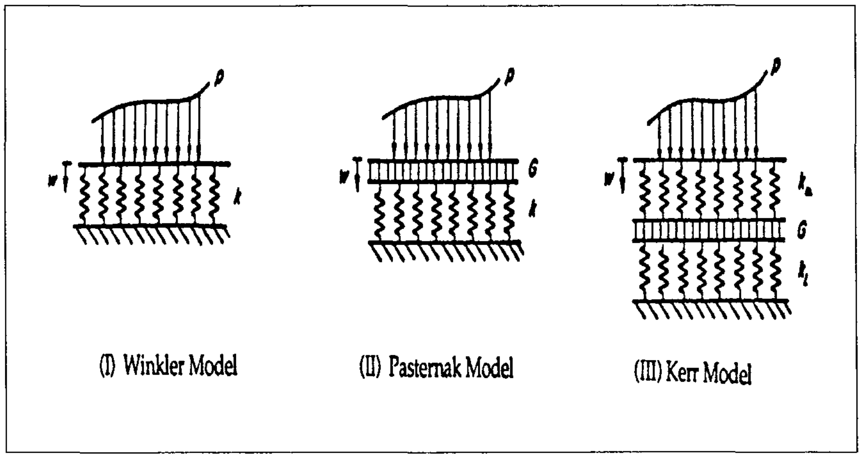
u = bond strength between the steel and concrete.

Figure 2.6 also demonstrates design limits, based on the shear capacity as determined from equation 2.9, associated with crack width versus the level of load transfer efficiency to prevent punchout development and to ensure structural integrity of the pavement system. For a given level of LTE, the crack width should effectively be equal to or less than the limits indicated in Figure 2.6.

Subgrade Characterization

The model used for analyzing a concrete pavement consists generally of an elastic plate that rests on a foundation model. The models for plates that are subjected to pavement loads and thermal restraints are reasonably well established, but the modeling of the supporting media is not. The characterization of subgrade materials under concrete pavement systems, since the inception of Westergaard's analysis, has been based upon dense liquid behavior. The basic characteristic of a dense liquid or Winkler subgrade is a spring constant referred to as a k-value (Figure 2.7 (I)).

$$q = kw \quad (2.11)$$



(I) Winkler Model (II) Pasternak Model (III) Kerr Model

Figure 2.7 Foundation Models for Concrete Pavement Analysis. (Kerr, 1992).

where q is the subgrade stress and w is the subgrade deflection. A k-value is simply a linear spring constant consisting of units of force/unit area/unit length (i.e., psi/in) where springs are individually grouped in parallel as a series of springs under the slab that are void of any type of shearing behavior within the supporting medium, which has been one of the primary shortcomings of this type of model. A k-value foundation model characteristically displays a discontinuity in the pattern of the subgrade deformation at the edge of the slab. If the soil model included a shear strength term, the pattern of the displacement would be more gradual in nature at the slab edge, as would be displayed by elastic solid behavior. Consequently, it has been noted by several researchers that although the Westergaard solution agreed fairly well with their observations for interior loading conditions, it failed to give even a close estimate of the response for edge and corner loads.

Nonetheless, the most accepted subgrade characterization for concrete pavement design is the Winkler foundation; other foundation models have been suggested primarily because of the difficulty of conducting a plate-load bearing test in the field. However, the Winkler foundation is an easy model to understand and apply to the design process. It should be pointed out that 'k-value' is not an intrinsic property of the soil or the supporting medium which consequently has led to difficulties of consistency in the evaluation of soil strength and stiffness using different testing procedures and methodologies. On the other end of the subgrade idealization spectrum, due to its ease of determination in the laboratory, there has been a great interest in using the elastic modulus of the soil for design rather than the soil k-value, which means making use of a correlation between k-value and the soil elastic modulus so that the result from a resilient modulus test in the lab could be substituted into the Westergaard design analysis. Although k-value may only be remotely associated with subgrade elastic modulus (E_s - which has units of force/unit area), correlations between k-value and subgrade modulus are drawn in recent versions of the AASHTO Design Guide. In reality, such correlations are complicated due to the necessity for the development of an equivalence between these vastly different theories (a k-value subgrade versus an elastic-layer subgrade) at the interior portions of a concrete pavement slab. Either of these theories can be used to predict subgrade stress, subgrade deflection, or slab bending stress of a loaded pavement slab. However, as previously noted, the establishment of a correlation between k-value and E_s parameters requires the assumption that one of the three above pavement responses are equal between the two theories, with the problem being that either one of the equivalencies will yield a different answer as to what that correlation should be. In order to avoid the limitations associated with such correlations, it is recommended to focus the characterization of the subgrade support on material properties or parameters that directly correlate to the subgrade model, at hand and not determine a material characteristic relative to one model, and substitute an interpretation of it into another model for use in design.

In light of these findings, other 'k-type' foundation models have been suggested, as noted in Figure 2.7 (II) and (III), as being more suitable for subgrade support characterization. It is well to point out that the Westergaard solution at loaded positions within the interior portions of a concrete slab is reasonable, most likely due to the 'forced' spring interaction caused by the stiffness of the slab itself, whereas, at the corner and edge positions, this interaction is missing. Thus, the predicted slab responses have not accurately reflected measured responses. These interactions, however, are provided in the Pasternak model (Figure 2.7 (II)):

$$q = k\,w - hG\nabla^2 w \qquad (2.12)$$

where G is the shear stiffness of the subgrade and h is the thickness of the subgrade layer and the Kerr foundation (Figure 2.7 (III) Kerr and El-Sibaie, 1989) model:

slab edge according to Boussinesq theory that warrants further consideration. Other approaches to address such weaknesses, such as the Pasternak and Kerr foundation models, have been developed. It should also be pointed out that the Pasternak foundation includes the soil shear modulus (G, which requires the use of E_s and the Poisson's ratio of the soil) and a soil k-value. The Kerr foundation not only requires a similar shear parameter but also an upper and lower k-value.

Relative to the evaluation of the subgrade support, it appears that considerable improvement in the analysis of concrete pavement systems can be achieved by the provision of either a three-parameter or even an elastic solid foundation model. Although, some assumptions may need to be adopted for implementation purposes, it appears that the Kerr model is the most appropriate characterization for further consideration. This would require that both k-value and elastic moduli be considered in future subgrade modeling efforts and that test models to evaluate these parameters should be identified and evaluated relative to their application to meeting structural design criteria. In addition, further consideration should also be given to an elastic solid subgrade relative to the degree of improvement in representation of real subgrade behavior and the suitability of testing procedures and methodologies to assess key material properties associated with this model.

Heat and Temperature Dissipation

Temperature development in concrete due to hydration and ambient temperature conditions can be determined from the general differential equation for heat transfer. The governing equation of heat transfer in a two-dimensional domain can be expressed as below where thermal conductivities, k_x and k_y, are assumed to be constant:

$$k_x \cdot \frac{d^2T}{dx^2} + k_y \cdot \frac{d^2T}{dy^2} + Q_h(t,T) = \rho \cdot C_p \cdot \frac{dT}{dt} \tag{2.14}$$

where

k_x, k_y = thermal conductivities of concrete, W/M·°C,

ρ = concrete density, Kg/M^3,

C_p = specific heat, J/Kg·°C, and

Q_h = generated heat from heat of hydration of cement and external sources, W/M^3.

All the thermal parameters included in equation 2.14 are also basic material properties which can be characterized by laboratory tests. In heat transfer analysis, the ratio of the thermal conductivity to the products of specific heat and density is termed as the thermal diffusivity. Due to low thermal conductivity or diffusivity of cementitious materials, temperature of concrete changes slowly for a given set of environmental conditions.

Heat energy is also transferred between a concrete surface and the environment through convection, irradiation, and solar absorption. Figure 2.9 presents heat transfer between a concrete pavement and the surrounding environment. Equation 2.14, which represents the physical mechanism of conduction, may be used to analyze the heat transfer between a concrete pavement and the atmosphere above and the subbase layers below. Convection heat transfer takes place where a concrete surface is exposed to a moving fluid, that is, an air stream (caused by wind) which is at a different temperature than that of the concrete pavement.

The concrete surface is also affected by irradiation heat transfer which is transported by electromagnetic waves between a surface and its

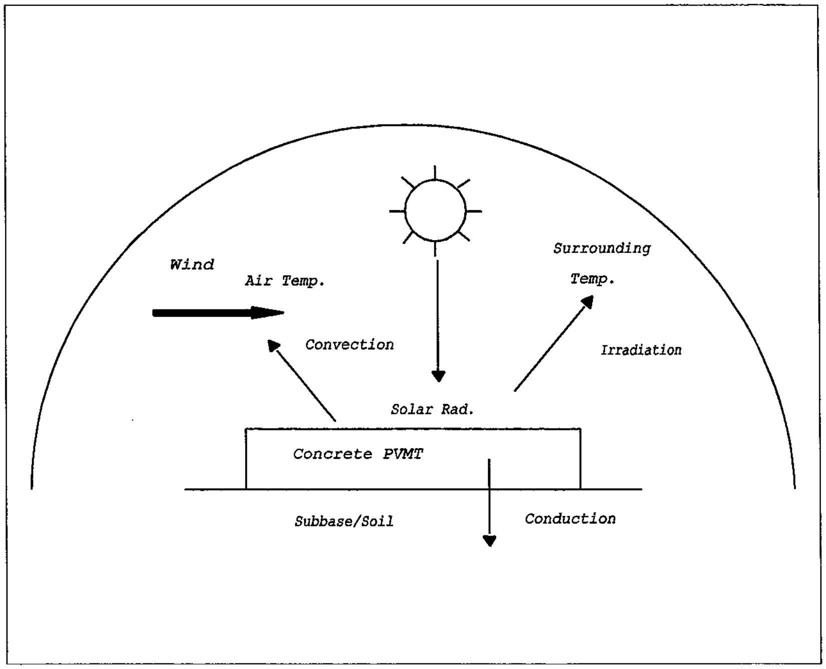


Figure 2.9 Heat Transfer Between a Concrete Surface and the Environment.

surroundings. Among the various wavelengths of electromagnetic waves, solar radiation is an intermediate subdivision of the electromagnetic spectrum and pertinent to heat transfer. For simplicity, the rate of its heat absorbed by a concrete surface is the solar radiation absorption and is termed solar absorption.

The boundary conditions associated with equation 2.14 can be represented mathematically by the environmental factors noted above. Boundary conditions associated with a concrete pavement, as indicated above, consist of conditions associated with both the pavement surface and bottom conditions. At the pavement surface, heat transfer is affected by all the heat mechanisms, such as convection, irradiation, and solar absorption, through

$$-k\tilde{\nabla}T \cdot \tilde{n} + q_c + q_r - q_s = 0 \textit{ on pavement surface} \tag{2.15}$$

$$k\tilde{\nabla}T \cdot n = 0 \textit{ on pavement bottom} \tag{2.16}$$

where

k = thermal conductivity, W/M·°C,

q_c = heat flux due to convection, W/M^3,

q_r = heat flux due to irradiation, W/M^3,

q_s = solar radiation absorption, W/M^3,

∇ = gradient notation, and

n = unit direction of heat flow by vector notation.

the environment. At the bottom of the concrete layer, heat transfer is affected by conduction according to the subbase thermal properties which were listed in equation 2.14. Similar to the boundary conditions in the subbase, heat transfer to the soil under the subbase is affected only by conduction and is dependent on the thermal properties of soil. These two conditions are summarized as follows:

Concrete Properties Related to Moisture Loss in Curing Concrete

Moisture in concrete materials is comprised of two parts - one referred to as structural or water chemically bound within the cement paste hydration products (w_n) and the other as water contained within the pore structure of the CSH (w_g). The sum of these portions equals the total water content (w) in the paste. One aspect of the effect of moisture in concrete pavements can be reflected in drying shrinkage and creep behavior. These behavioral characteristics are of concern with respect to concrete slab deflections and formation of cracks or development of delaminations in bonded concrete overlay systems. Material-related moisture properties (permeability, diffusivity, slope of the moisture isotherm, etc. - to be subsequently discussed) of concrete play a key role in the mathematical modeling and representation of stress and strain due to drying shrinkage and creep under varying humidity conditions. Material tests are necessary to determine these pertinent material properties. The properties are identified by moisture flow models which represent the variation of moisture with time. In terms of engineering applications, an important need exists for the prediction of humidity and water diffusion in consideration of warping and other related stresses, strains, and deformations induced in concrete pavements.

Moisture properties affect how moisture is distributed in a concrete material either while hardening or in a mature state. There are trends in the drying characteristics of concrete, such as when drying develops in concrete materials where the remaining moisture in the paste moves or diffuses into the atmosphere at decreasing rates of flow with time. This is reflected in high initial diffusion rates followed by gradually lower moisture flow rates. This characteristic is inherently related to a material property referred to as the moisture diffusivity (D) which has been generally accepted to be dependent upon the pore water content of the paste. It has been observed that the value of D may change significantly with variations in the moisture content or the relative humidity (from 100 to 70 percent) of the concrete material (Pihlajavaara, 1964; Kasi and Pihlajavaara, 1969; Bažant, 1970; Bažant and Najjar, 1972).

Moisture in concrete materials has been measured in the past by actual weight measurements which reflect the remaining water in the bulk sample. Recently, moisture quantities have been estimated based on direct measurements using relative humidity sensors. Several papers have been published regarding moisture flow and diffusion in concrete materials (Bažant and Najjar, 1972; Parrot, 1988; Parrot, 1991; Xin and Zollinger, 1995; Buch and Zollinger, 1993). Further elaboration on this topic will require discussion of

diffusion mechanisms and the form of the diffusion equation or model in terms of basic physical principles.

Diffusion of Water in Drying Concrete

The best way to describe and to understand the flow of moisture in concrete is by examination of the expressions relative to moisture transport in a porous medium, such as concrete. The rate of moisture movement through concrete materials may be characterized by the velocity of flow (v) representing the mass of evaporable water (w_g) passing through a unit area perpendicular to the direction of flow per unit time. Darcy's Law inherently assumes that the driving force of the moisture flow is derived from energy gradients:

$$v = \hat{c}\ grad\ \psi \tag{2.17}$$

where ψ is Gibb's free energy (GFE) per unit mass of evaporable water. The above relationship is consequently restricted to small energy gradients and laminar flow conditions meeting Darcy's Law requirements. The coefficient (ĉ) characterizes the permeability of the porous, concrete material. This relation is also a function, as is pointed out later, of temperature and evaporable water content. Assuming water vapor behaves as an ideal gas (Bažant and Najjar, 1972):

$$\psi = \frac{RT}{MV_w}\cdot\ln(h) + \psi_{sat}(T) \tag{2.18}$$

where

R = Universal Gas Constant (8.3143 J/mol·°K),
T = Absolute Temperature (°K),
M = Molecular Weight of Water (18.015 g/mol),
V_w = Specific Volume of Water (1 cm^3/g), and
h = Pore Humidity.

It should be pointed out that ψ at any point in a mass of concrete material, as measured by a relative humidity sensor, represents the state of stress or the tension within the various phases of pore water that is assumed to be translated into the measured resultant bulk relative humidity of the different phases of pore water. These phases, which consist of water vapor, capillary water, and unhindered adsorbed water, are assumed to be in mutual thermodynamic equilibrium at any time (Bažant and Najjar, 1972).

Rewriting equation 2.17 in terms of pore humidity (h) and temperature yields:

$$v = -\hat{c}\ grad\ h \tag{2.19}$$

where

$$c = (RT/MV_w) \cdot (\hat{c}/h)$$

Therefore, the coefficient c, referred to as the permeability, is a function of humidity and temperature. Moisture diffusion through concrete typically is a slow process, particularly in the hardened or mature state, which tends to justify that the pore water phase equilibrium described above exists. The relationship between h and w at a constant temperature and the degree of hydration is described or governed by the desorption or sorption isotherms (Bažant and Najjar, 1972). It is evident that the relationship between the moisture in the concrete and the measured relative humidity will vary as a function of the age. This is true, as will be subsequently shown, with respect to other moisture properties (such as diffusivity). These relationships, consequently, will need to be corrected as a function of time in analysis of the behavior of concrete while in the hardening stages.

The total mass of water per unit volume of concrete (w) can also be described in terms of the adsorbed water (w_a), the capillary water (w_c), and the non-evaporable water (w_n) which is, as pointed out before, water structurally bound in the hydrated cement paste products. The dependance of w on humidity (as a function of temperature) is a function of the porosity of the pore structure within the paste and is represented empirically in the form of desorption or sorption isotherms that are illustrated in Figure 2.10. It should be noted that the isotherm for sorption is different from the isotherm for the preceding desorption. This characteristic may be due to the various states of equilibrium of the pore water (Bažant and Najjar, 1972). An investigation recently completed by Parrot (1988) implied the significance of porosity with respect to the position of the desorption/sorption isotherm. His results indicated that a greater amount of moisture loss in drying specimens will occur in regions near exposed drying surfaces which may also be regions of high porosity. Based on the experience of the authors, it may be suggested that the porosity of the paste varies with distance from the exposed surface. Apparently, there is a greater volume of coarse pores at positions nearer to an exposed surface, and consequently, the h-w relationship will vary with respect to an exposed surface (i.e., paste porosity). It should also be noted that the resulting desorption isotherm at any time during hydration of hardening concrete must be interpreted not only as a function of the degree of hydration, but also as a function of

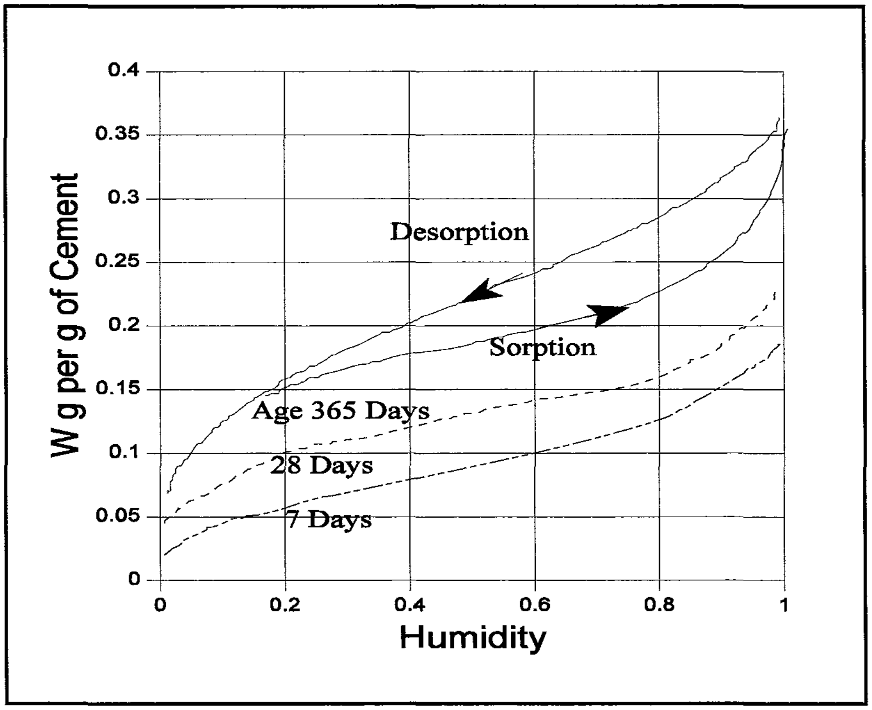


Figure 2.10 Desorption-Sorption Isotherms. (Bažant, 1970).

porosity. At a given porosity, the desorption isotherm may be expressed in the differential form as:

$$dh=kdw \tag{2.20}$$

where

$$k=(\frac{\partial h}{\partial w})_T$$

The parameter k represents the slope of the moisture isotherm where the mass of water (w) is described as a function of relative humidity (h). Under variable temperature conditions, the calculation of humidity in hydrating concrete specimens requires additional terms to be added to equation 2.20:

$$dh = kdw + KdT + dh_s \tag{2.21}$$

where

$$K = (\frac{\partial h}{\partial T})_w$$

K = hygrothermic coefficient, and

dh_s = change in h due to hydration at a constant w and time (t).

The term K represents the change in h due to one degree change in temperature (T) at a constant w and a given level of hydration. It should be noted that the pore water content (w) includes both the evaporable or capillary water (w_c) and the non-evaporable water (w_n) per unit volume of materials (Bažant and Najjar, 1972).

The flow of water (w) per unit volume of concrete determined from the expression:

$$\frac{\partial w}{\partial t}=-div \cdot v \tag{2.22}$$

is based on the conservation of mass. Substituting (w) in equation 2.21 (differentiated with respect to time) from equation 2.22 and substituting (v) from equation 2.19 leads to (Bažant and Najjar, 1972):

$$\frac{\partial h}{\partial t} = k \cdot div(c \cdot grad\ h) + \frac{\partial h_s}{\partial t} + K\frac{\partial T}{\partial t}$$

which is the diffusion equation for the drying of concrete under variable temperature conditions. Developing further,

$$\frac{\partial h}{\partial t} = kc\frac{\partial^2 h}{\partial^2 x} + k\frac{\partial c}{\partial x}\frac{\partial h}{\partial x} + \frac{\partial h_s}{\partial t} + K\frac{\partial T}{\partial t} \qquad (2.23)$$

Although the above discussion implies that the permeability (c) is also a function of the porosity and indirectly a function of position x, the second term in equation 2.23 is considered to be negligible and is consequently dropped from the diffusion equation:

$$\frac{\partial h}{\partial t} = D\frac{\partial^2 h}{\partial x^2} + \frac{\partial h_s}{\partial t} + K\frac{\partial T}{\partial t} \qquad (2.24)$$

where D = k·c = diffusion coefficient (L^2/t).

The characterization of diffusivity (D) is important in order to accurately model moisture flow in hardening concrete. At a constant w, diffusivity changes very little with time in a hardened concrete. However, dramatic changes occur in diffusivity during the early stages of hardening (during the first 24 hours after placement). Figure 2.11 illustrates the variation in the

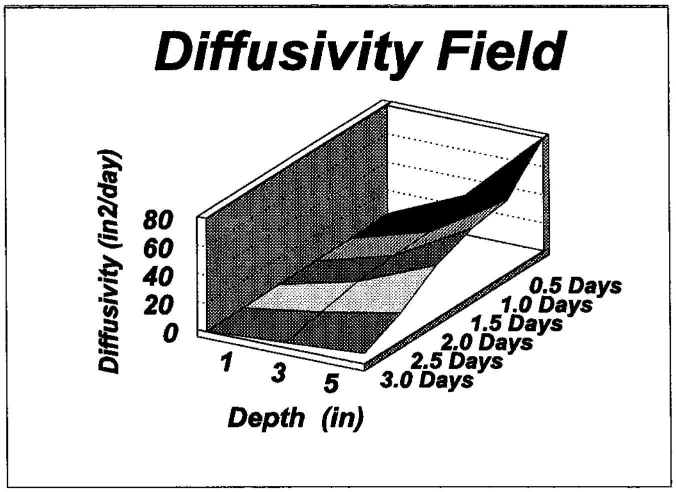


Figure 2.11 Resulting Diffusivity as a Function of Time and Location.

diffusion coefficients with time in a concrete specimen at an early age. This figure shows data developed by Xin and Zollinger (1995) based on data taken from a drying concrete specimen and illustrates how D is a function of age and position. From the characterization of D, it is possible to account for varying moisture loss at an early age as an input to drying shrinkage strain prediction as demonstrated by other studies (Buch and Zollinger, 1993; Kadiyala and Zollinger, 1992). Diffusivity has been found to be a function of humidity, concrete age, and paste porosity.

The rate of moisture exchange between the pavement surface and the environment can be characterized in a simple expression relative to the difference between the Gibb's free energies (GFE) per unit mass of water in concrete and in the environment stated as:

$$\psi(h_{en}) - \psi(h) = \ln h_{en} - T/T_{en}(\ln h)$$

where h_{en} is the environmental humidity (Bažant and Najjar, 1972). For small rates of flow (ν) across the concrete surface interface:

$$\nu = -B(\ln h_{en} - T/T_{en}(\ln h)) \qquad (2.25)$$

where B is the surface emissivity in units of area per length per unit time. The flow of moisture just below the surface (equation 2.19) can be assumed to be equivalent to the flow across the surface interface (equation 2.25). Therefore, equating equations 2.19 and 2.25:

$$d{\cdot}grad\ h = \ln h_{en} - T/T_{en}(\ln h) \qquad (2.26)$$

where d = c/B. Note that d is in units of length and may be used to represent the effectiveness of surface curing in terms of an equivalent thickness of concrete that numerically replaces the curing system (curing compound, polyethylene sheeting, mats, etc.) used to retain moisture at the pavement surface. By using the measured values of relative humidity and temperature just above and below the pavement surface, equation 2.26 forms the basis for an estimate of d which should be very useful in monitoring the curing effectiveness during and immediately following the placement of the concrete slab.

Frictional Restraint

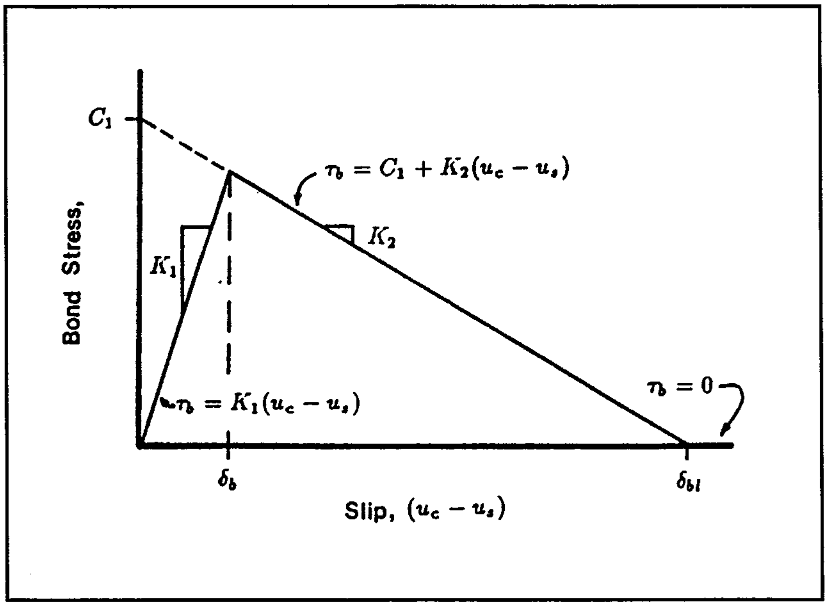


Figure 2.12 Bond Stress Model for Reinforcing Steel.

Another aspect of structural characterization of a concrete pavement system is the restraint to movement due to frictional affects along the subbase/slab interface and along the reinforcing steel/concrete interface. Frictional behavior, in this respect, primarily pertains to CRC pavements which involve a bond stress along the rebar (Figure 2.12) and along the subbase (Figure 2.13). The bond stress distribution along reinforcing steel is determined by a model shown in Figure 2.12 as a function of the relative slip between the concrete and the reinforcement. As the slip increases from zero, the bond stress increases at a rate of K_1 to the peak value which occurs at a slip of δ_b. Increasing slip leads to a decrease in the bond stress at a rate of K_2. Zero bond stress occurs at slips equal to or greater than δ_{b1}. The parameters K_1, K_2, and δ_b are material properties that are functions of the characteristics of the concrete and the reinforcing steel pattern.

The frictional resistance between the subbase and the pavement is also modeled. The friction force is determined as a function of the slab displacement where the general shape of the friction force - displacement curve is quite uniform. The friction force is represented as a friction stress which is the friction force divided by the area over which it acts. Figure 2.13 shows the friction stress model. The slope value K_4 is taken as negative, which means the sliding friction decreases slightly with slab displacements greater than δ_f. It is assumed the accuracy of the model will not be compromised with this generalization since it is accepted that the friction stress is constant beyond the threshold displacement. This slope value allows a similarity to exist between the bond stress function and the friction stress function which permits a more convenient mathematical modeling of the functions. As with K_1 and K_2, the parameters K_3 and K_4 are material properties characteristic of the subbase materials.

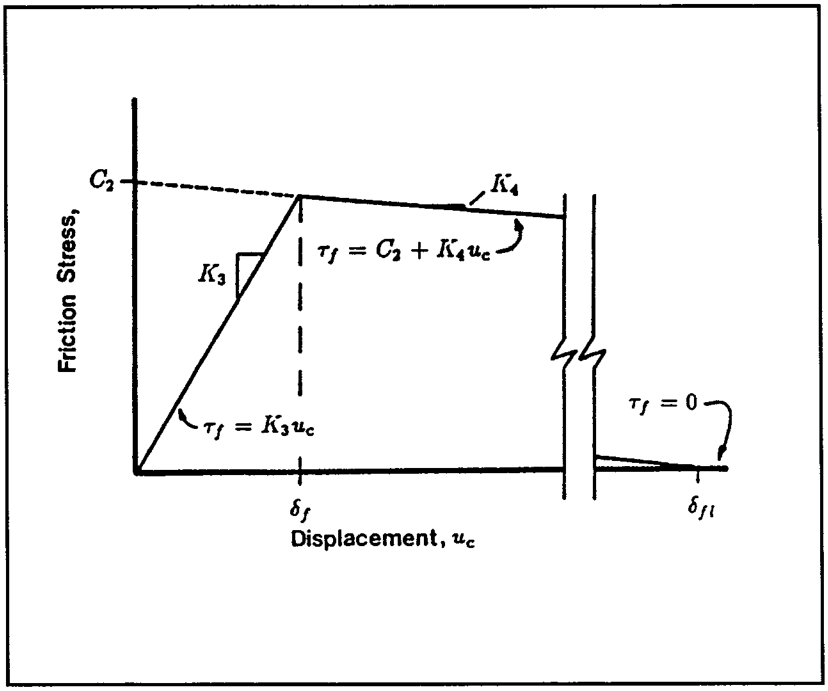


Figure 2.13 Bond Stress Model for Subbase Friction.

KEY PERFORMANCE PARAMETERS FOR CONSTRUCTION AND DESIGN

Performance of concrete used in rigid pavements is associated with several manifestations of distress as previously indicated. Most of the distress types occur in the form of cracking, with other types in the form of spalling, punchouts, and faulting - all of which affect structural integrity of the pavement. Many of these distress manifestations are related to crack growth or the overall stiffness of the pavement system, while others are aggregate related, associated with pavement support, and temperature gain and loss of moisture during curing. The model relationships previously elaborated provide a basis to identify candidate properties and pavement features for testing and assurance purposes. A framework of structural criteria with a list of related material/pavement properties and model relationships are shown in Table 2.1. Some of the properties listed are currently included in TxDOT testing specifications as noted by the (✓) symbol. The following

Table 2.1 Framework of Structural Pavement Design Criteria.

Structural Category	**Material/Pavement Property**	**Model/Analysis**
Strength	Concrete Tensile Strength (✓) Concrete Fracture Properties (K_{if}, c_f) Aggregate/Mortar Bond Concrete Modulus (E_c)(✓)	Cracking
Stiffness	Concrete Modulus (E_c)(✓) Load Transfer Efficiency (LTE)(✓) Effective Crack Width Pavement/Joint Stiffness (ℓ_k) Foundation Modulus (k-value)(✓) Subbase Moisture-Density and Triaxial Compression Test (Unstabilized)(✓) Subbase Unconfined Compressive Strength (Stabilized)(✓) Subgrade Modulus (E_{SG}) Subgrade Unit Weight and Moisture Content (✓)	Support
Volumetric	Total Heat (H_U) Activation Energy (E) Thermal Coefficient of Expansion (α) Coarse Aggregate Oxide Analysis	Thermal
Volumetric	Moisture Diffusivity (D) Effective Curing Thickness	Curing
Volumetric	K_1, K_2, K_3, and K_4	Subgrade and Rebar Friction

(✓) Included in current TxDOT test protocols

discussion illustrates why some of these can be used to develop a list of candidate testing properties to address important aspects of structural design criteria. Other parameters will be discussed later in Chapter 3.

Strength Category

Concrete strength has a direct relationship to fatigue life of the cracking resistence manifest by concrete pavement. It is also related to other distress types associated with cracking of the concrete which relates directly to structural criteria. It is often used for quality control purposes due to its broad indirect application to premature development of a variety of pavement distress types. Another aspect of structural criteria relates to how susceptible a concrete mixture, under a given set of climatic conditions, may be to crack development - such as may be the concern in sawcutting applications. Use of the fracture properties of concrete provides a means to qualify many cracking characteristics pertinent to structural criteria. Aggregate types and methods of curing should be balanced for the given curing conditions to ensure the structural integrity of the pavement system with respect to cracking. Recently, questions have also arisen as to how concrete strength, as determined from the testing of a test specimen, relates to the strength of concrete in a pavement structure. It has been noted that the size or the thickness of a pavement structure has a significant effect upon the strength of concrete and that the strength of a test specimen should be adjusted for the size of the structure in order to assure compliance between the design and the constructed product. A test procedure based on a modified split tensile test specimen has been recently developed at TTI and will be described in Chapter 3. It allows for size effects due to slab thickness to be taken into account.

Although up until recently difficult to measure and quantify, the aggregate-mortar bond is of prime importance in the development of concrete strength, especially compressive strength, tensile strength, and flexural strength. Normally, the coarse aggregate, rather than the fine aggregate, is involved. The tensile and flexural strengths have a very significant role in the amount of cracking which may occur in a concrete pavement and the time requirements associated with proper sawcutting and joint formation. Presently, it is considered that the factors that mostly affect this bond include non-aggregate properties, such as water-to-cement ratio, cement type, age, and compaction to reduce air voids, which also affect the flexural and tensile strength of concrete. Flexural and tensile strength are also related to aggregate-mortar bond. However, it is believed that absorption capacity, mineralogical composition, and surface texture and shape of aggregates also influence the bond between the paste and the aggregate.

Stiffness Category

Stiffness relates to structural criteria from a material and pavement standpoint. Material stiffness is important to provide durability under load and to resist crack growth. Pavement stiffness at the joints and cracks is important to maintain load transfer and shear capacity. Pavement stiffness is the result of an interaction between the supporting base and the slab, and is well characterized by the radius of relative stiffness. Pavement thickness also affects the stiffness of joints, the shear capacity of the joint against development of faulting, and the wear-out of the aggregate interlock. The greater the stiffness of the joint, the greater the resistence against loss of load transfer across the transverse joint. Other factors can be measured to assure assumptions relative to load transfer.

Volumetric Category

All the models under this category relate to the development of cracking which effect structural criteria. Set temperature of concrete must not be allowed to occur at a high level since this results in increased restraint to displacement. The temperature rise in concrete is directly related to the total heat of hydration and the activation energy of the cement used in the mixture. The thermal coefficient of expansion also affects the amount of concrete strain under a given change in temperature. Typically, higher coefficients of thermal expansion of the coarse aggregate particles result in higher coefficients of thermal expansion and contraction of the concrete. Furthermore, higher aggregate contents in the concrete mixture have greater influence on the coefficient of thermal expansion of the concrete. The coefficient of thermal expansion varies from 6×10^{-6} mm/mm/°C for limestone to 12×10^{-6} mm/mm/°C for quartzite. Previous research has clearly identified concrete pavements made with aggregates having high coefficients of expansion and contraction as exhibiting significantly greater cracking. Findings have also indicated a high potential to predict thermal coefficient of expansion of aggregates as a function of the original mineral composition of the aggregates obtained from an oxide content analysis. Recent developments have led to procedures to measure this important aggregate property.

The method of curing affects the amount of moisture loss and the amount of drying shrinkage that occurs during the hardening of concrete. Too much shrinkage may result in excessive cracking that will degrade the structural integrity of the pavement. The diffusivity of concrete controls, to a large extent, how readily moisture movement occurs within the concrete. The effectiveness of the curing medium controls how readily moisture moves out of the concrete and evaporates into the atmosphere. These parameters are important to ensuring structural integrity and should have criteria established relative to it.

Frictional behavior is another aspect of the structural criteria. Restraint to cracking in a CRC pavement system is related to the degree of bond to the bottom of the slab and between the rebar and the concrete. The frictional parameters previously described are important to cracking models to predict cracking levels and should be characterized relative to required structural behavior.

CHAPTER 3
EVALUATION OF NEW OR SPECIAL DEVELOPMENTS AND RELATED ASTM TESTS

This chapter will address recently developed tests or tests not presently included in current TxDOT testing protocols that potentially provide a means to measure key performance parameters or could improve how certain properties are presently measured to enhance the utility of them in both construction monitoring and in design of concrete pavement systems. Several candidate tests are listed in Appendix C along with pertinent information regarding the utility of each test in the assessment of structural design criteria. The assessment of each test is conducted in a similar manner as will be outlined in Chapter 3. Appendix C provides descriptive data relative to each test, and Appendix D contains the utility evaluation. As noted in Chapter 2, test methods valued at a utility greater than 50 are described in this chapter in greater detail.

SOILS AND SUBGRADE MATERIALS

The Humboldt Stiffness Gage to Measure Stiffness in Place

The Humboldt stiffness gage (HSG) is a recently developed field instrument for measuring soil stiffness. It is a product of Humboldt Mfg. Co., Norridge, Illinois. Soil density is conventionally used in highway construction to specify, estimate, measure, and control soil compaction, and soil density is determined via weight and volume measurements.

Performance

Compaction is the process to densify and stabilize soils. The engineering property that can be used to characterize the effect of compaction is stiffness of the soil. The stiffness gage determines stiffness directly from the ratio of the load to the deflection through a method to nondestructively measure the stiffness of soil in the work site. The mechanism of HSG is to apply the theory of vibration of a single mass. When the mass vibrates, displacement and vibration frequency are measured. The force that acts on the soil is calculated from the measured displacement and frequency so the stiffness can be calculated. The instrument is portable, and operation of it is reasonably straightforward.

Nature of Test

Conventionally, when the stiffness is needed, the so-called plate load test is commonly conducted by jacking against a large truck to provide a load, while taking great care to measure the deflection. Comparatively, use of HSG is very easy. Although jacking against a large truck in the plate test is cumbersome and provides a load similar to those loads acting in service, some question may exist as to whether the stiffness measured by HSG through a comparatively small load can represent the stiffness of the soil in service. Apparently, the HSG measured stiffness is a parameter characterizing the response of the soil to dynamic loading, and it may be appropriate to consider how the stiffness varies with the vibration frequency.

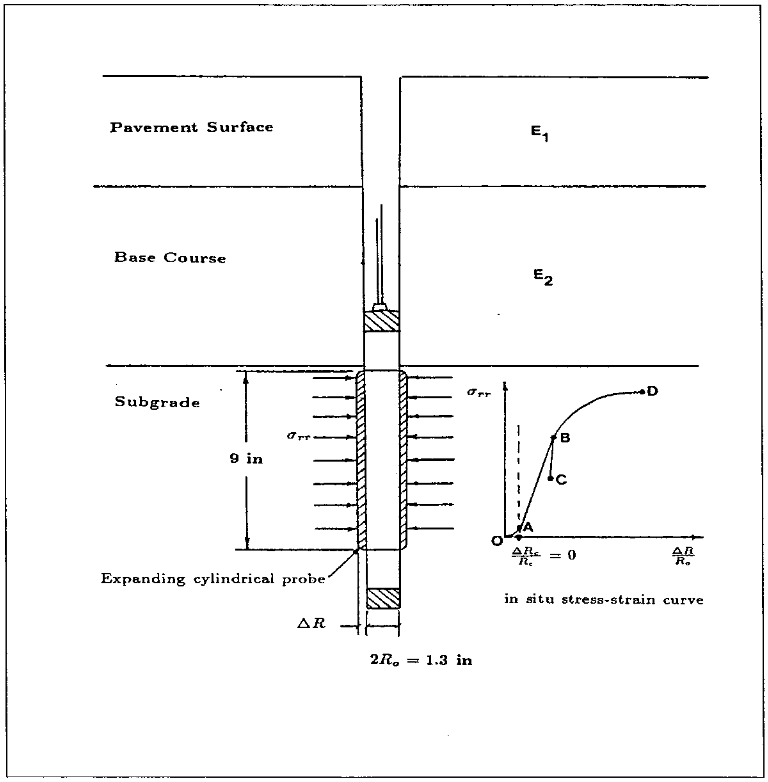


Figure 3.1 Typical Pressure Meter Test Configuration. (Briaud et al., 1987).

Test Equipment

The test equipment as supplied by the manufacturer is an integral unit that can be operated in the field with little training.

Pressure Meter

The pressure meter is a device to measure strain in a soil layer in which to base calculations for the modulus of elasticity of the layer. The use of the pressure meter requires the placement of a bore hole in a pavement structure to allow for the insertion of a probe to collect displacement and pressure data at specific points below the surface. The concept behind the pressure is illustrated in Figure 3.1. The pressure meter probe allows for the direct determination of the layer modulus in the field and at a variety of depths based on the data collected.

Performance

The results for the pressure meter are useful for determining layer moduli which fit well into pavement stiffness models described in Chapter 2. These are, of course, important to the prediction of performance and also relate well to structural criteria. A test of this nature provides a direct indication of this key structural parameter rather than making an estimate from another parameter, such as density or the degree of compaction. It is also useful from the standpoint of improving the accuracy of stiffness analysis based on non-destructive methods, such as the falling weight deflectometer.

Nature of Test

This test methodology should be considered to be destructive to some extent, but it does obtain soil and base layer data in situ. The procedure may be time consuming since it includes the pre-boring of access holes in which to place the probe. The probe is pressurized with water which causes a

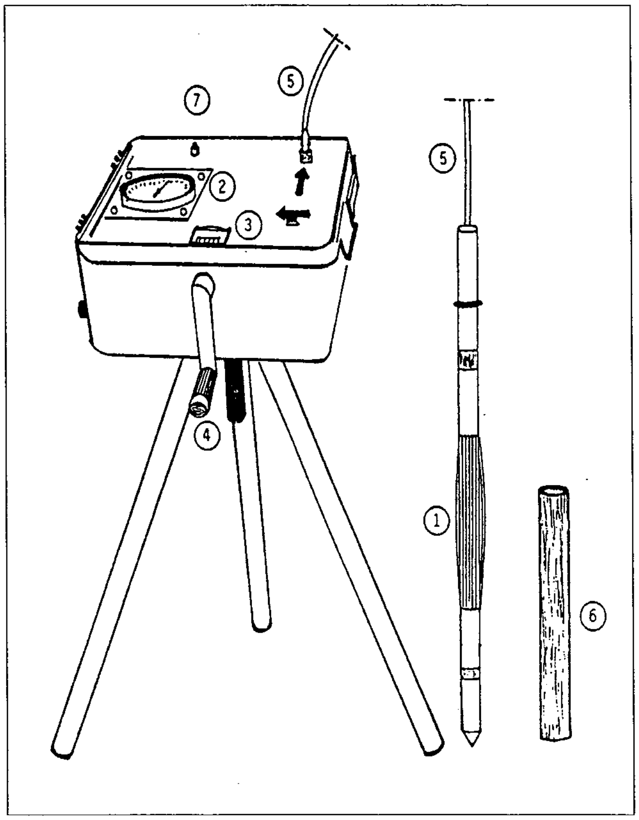


Figure 3.2 Pressure Meter Equipment.
1. Probe, 2. Pressure Gage, 3. Displacement Indicator, 4. Manual Actuator, 5. Tubing, 6. Steel Pipe for Volume Calibration, 7. Connection to Water Reservoir. (Briaud et al., 1987).

pressure against the walls of the bore hole. While the test is being conducted, the pressure in the probe along with the increase in volume is recorded for a given test position below the surface. Conducting the test at various points, several pressure-displacement data points can be generated. From these data, stress-strain curves are developed since the volumetric expansion within the bore hole is relative to the radial stress (σ_{rr}) and the hoop strain ($\epsilon_{\theta\theta}$) that develops in the soil layer next to the probe. During the test, the expanding probe initially fills the gap between the probe and the wall of the bore hole (OA - Figure 3.1). At that point, the soil deforms linearly (AB - Figure 3.1) in which the soil modulus E_0 is calculated from the slope of the linear region. Other data, such as the point of yielding and the limit of soil pressure, are also obtained from the test data (Briaud et al., 1987).

Test Equipment

The equipment associated with the pressure meter is shown in Figure 3.2. The control unit is separate from the probe and the tubing. Typically, the bore holes are drilled with a hand-held portable auger once a bore hole is made through the pavement surface layer in the case of an existing pavement, which may require the use of a concrete drill. After the bore hole is in place, the pressure meter test can be conducted in a short period of time. The cost of this equipment is in the $6,000 to $8,000 range.

Moisture Measurement

Soil moisture measurements can be obtained through the measurement of the dielectric constant of the soil. Probes are available for measuring the amounts of free water in subgrade materials. The dielectric constant of water is approximately 80, and the dielectric constant of soils and aggregates is typically 4. Any change in the measured dielectric constant reflects changes in the moisture content. Instruments that measure the dielectric constant require calibration to actual moisture contents to actually correlate to the dielectric of the soil.

Performance

Moisture in the subgrade affects the strength of the stiffness of the subgrade. Moisture contents may change seasonally and cause the stiffness of the subgrade to change with it. As the soil moisture increases, the stiffness decreases. So in this manner, the soil moisture should be verified to confirm the assumptions of the design.

Nature of Test

The dielectric constant of the material is proportional to the capacitance of the material and is a measure of its specific polarization or electric dipole moment per unit volume. For most common solid materials in soil, the value of the dielectric constant ranges from 2 to 4. Water, however, has a much higher dielectric constant than these materials. The free water molecule has a particularly high value for dielectric constant. The dielectric constant of free water ranges from 78 to 81, varying slightly with temperatures above 0°C. Since water has a much higher dielectric constant, or capacitance, than the solid constituents of soil, a measure of the dielectric constant of a material can serve as a measure of the moisture content of the material. The capacitance of soil increases with an increase in the number of water molecules per unit volume of soil.

Test Equipment

The equipment for this method, as available from a variety of manufacturers, is simple to operate but does require calibration with actual moisture measurement from dried soil samples. The cost for this equipment is in the $5,000 to $7,000 range.

Tex-117 Triaxial Compression Tests for Disturbed Soils and Base Materials (Modified)

Key aspects of this test procedure are discussed in Appendix E relative to performance, nature of the test, and the equipment used to conduct the test in terms of the current convention. Recent developments at TTI have significantly expanded the applicability of this test to measure key performance characteristics. The notations provided in Appendixes C and D are based upon these developments. Consequently, only the nature of the test with respect to these changes will be considered in this section.

Nature of Test

Materials for unstabilized bases can be tested using the triaxial test device using a new analytical approach that allows for determination of five resilient properties needed to fully describe a cross-anisotropic material. These properties are:

E_x = resilient modulus in any horizontal direction;
E_y = resilient modulus in a vertical direction;
μ_{xy} = Poisson's ratio for strain in the vertical direction due to a horizontal direct stress;
μ_{xx} = Poisson's ratio for strain in any horizontal direction due to a horizontal direct stress at right angles; and
G_{xy} = resilient shear modulus of shear deformation in a vertical plane.

It is anticipated that these properties will be very useful in delineating layer behavior relative to the grading of the base material. The amount of dilation that occurs in dense granular layers upon loading depends on the particle shape. Naturally, if the volume change depends upon the shape of the particles, then the Poisson's ratio depends on particle shape.

The AASHTO standard procedure (AASHTO T294-94; "Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils" - SHRP Protocol P46) provides specifications for measuring axial deformations on the specimen using externally mounted LVDTs. A modification to the AASHTO T-294-94 has been developed to characterize the cross-anisotropic behavior of granular materials. Samples are prepared in general accordance with AASHTO T-294-94. However, the sample height-to-diameter ratio is 1:1 instead of 2:1. The IPC testing device (similar to the University of Illinois FastCell) is used to perform the triaxial test. Different triaxial stress states are applied to the sample to determine the effects of stress state to the resilient properties of granular materials.

At each stress state, incremental stresses are applied to the sample so that there is conventional triaxial compression, triaxial compression, and conventional triaxial extension, and unloaded back to the stress state. A stress state is defined by the axial stress (σ1), and the radial or confining stress (σ3). In each case, the axial and radial strains are measured with LVDTs, and these are repeated for all the stress states.

An iterative method is used to resolve the resilient properties into the

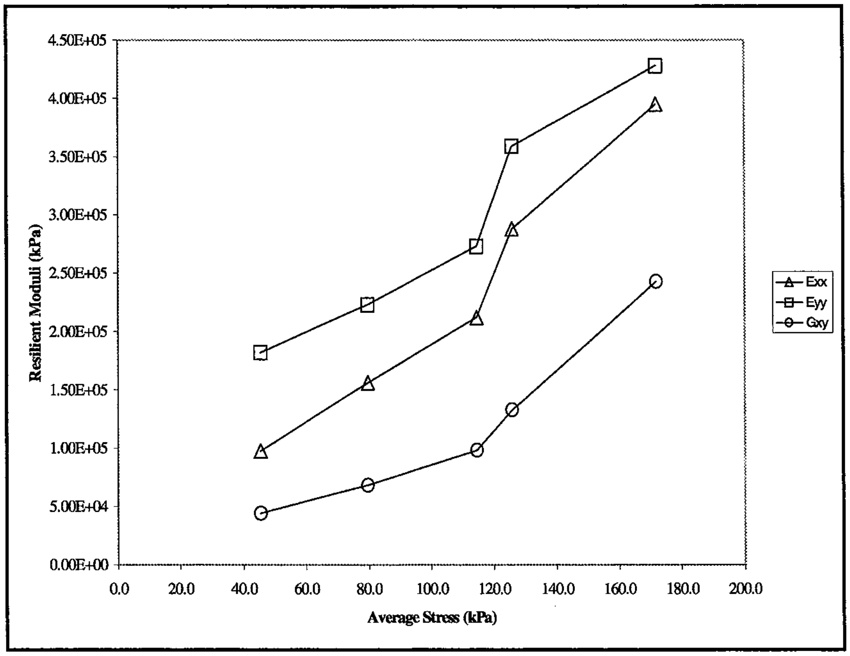


Figure 3.3 Elastic Properties Derived from the Triaxial Test.

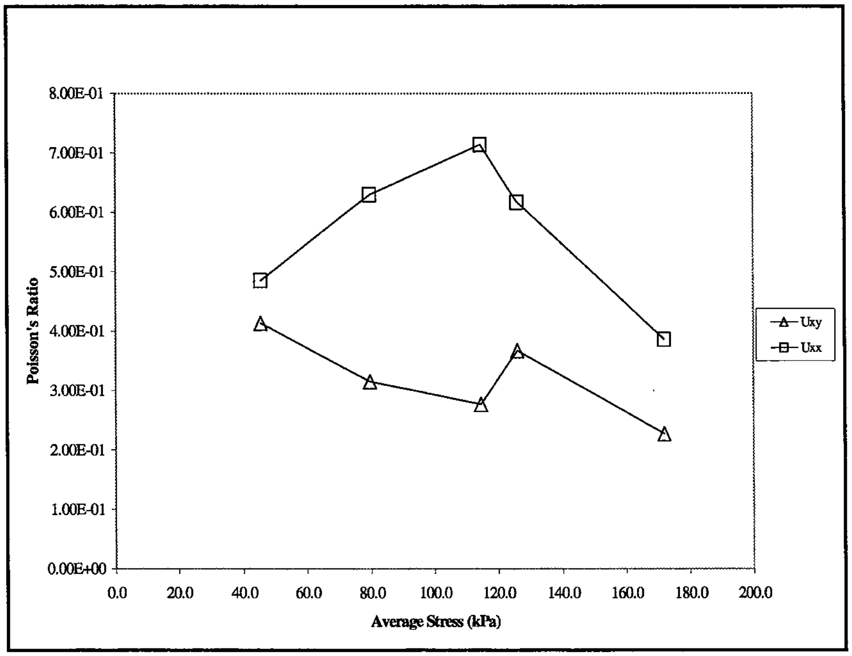


Figure 3.4 Poisson's Ratio Derived from Triaxial Test.

vertical and horizontal components. The variation of resilient properties with stress states is established to determine the material parameters necessary to characterize a full cross-anisotropy model. Figure 3.3 shows a typical variation of vertical resilient modulus (Ey), horizontal resilient modulus (Ex), and resilient shear modulus (Gxy) for a typical crush limestone. Figure 3.4 shows how Poisson's ratio changes with respect to average stress for a typical crushed limestone.

CEMENT, AGGREGATE, AND CONCRETE MATERIALS

Resonant Frequency

All materials have a natural frequency of vibration that is a function of its modulus of elasticity. This method measures the natural frequency of vibration of concrete beams. From this measured frequency, the modulus of elasticity can be calculated. The equipment used in this procedure consists of a unit that generates vibrations, an oscillator, and a unit that detects these vibrations, a piezoelectric transducer. This method can also produce data from which the rigidity and Poisson's ratio can be calculated. Durability can also be determined using resonant frequency principles. Resonant frequency tests are significantly affected by the concrete mix design, specimen size, and curing conditions. The limitation to this type of test is that it must be performed on cylindrical or prismatic specimens. It cannot be performed on in-place sections of concrete pavement.

Performance

Resonant frequency methods are useful in obtaining the dynamic modulus of elasticity of concrete. This is important in terms of stiffness characterization and for damage determination that may occur during construction or over time. Development of damage due to fatigue loading or microcracking should be detectable by lower modulus determinations obtained from resonant frequency testing if the method can be adopted to field applications.

Nature of Test

Recently, improvement of resonant frequency testings methodology has been of interest in the SHRP program in terms of the test method "Fundamental Transverse Frequency and Quality Factor of Concrete Prism Specimens" proposed as SHRP Product 2019. Relative to freeze/thaw durability tests, AASHTO T-161 originally uses the sinusoidal excitation method (ASTM C 215-85) to examine damage in concrete prisms, but ASTM C 215 was revised in 1991 to include impulse excitation as an alternate method (ASTM C 215-91). The proposed test method uses impulse to induce transverse vibration of the concrete prism specimen. In ASTM C 215-91, all transverse, longitudinal, and torsional modes of vibration in the cylindrical or prismatic specimen are included, whereas the proposed test procedure suggests transverse vibration in the prismatic specimen only.

When sinusoidal excitation is used, the specimen should be forced to vibrate at varying frequencies. At every frequency, the amplitude of the specimen vibration should be recorded. After a series of tests, the natural frequency can be determined at the maximum reading of the amplitude. When the impulse excitation method is used, only one test is needed. After the specimen is struck by an impact hammer, the time response of the specimen should be recorded. This time response (a signal in time domain) is converted into a frequency response (a signal in frequency domain) by the fast fourier transform (FFT) technique. The resonance frequency is the frequency with the highest peak in the frequency response (or amplitude spectrum). With the impulse excitation method, the test procedure is very simple, and precise results are obtained.

Test Equipment

The FFT technique and the fourier analyzer have been available for a long time. The test procedure uses a fourier analyzer, impact hammer, acceleromer and power supply, specimen support, data analysis and control equipment. The test procedure requires the fourier analyzer of a maximum frequency capability greater or equal to 8 kHz, whereas ASTM C 215 requires 20 kHz. A lower frequency band is allowed for only transverse vibration of the prismatic specimen because the natural (or resonance) frequency of the same concrete specimen (either prismatic or cylindrical) in transverse vibration is lower than in longitudinal vibration, and the natural frequency of a 152 × 152 × 710 or 102 × 102 × 510 mm prism in transverse vibration is lower than that of a 152 × 305 mm concrete cylinder.

Ultrasonic Pulse Velocity (ASTM C 597)

Maintaining the quality of a pavement requires knowledge of the condition of that pavement after it has been in use for a period of time. This test is a non-destructive method for determining the internal deterioration of a pavement. Any pavement in use is exposed to chemical components, weathering impacts such as freezing and thawing, and the impacts of daily traffic loading. It is important to know the weaknesses of a pavement if it is to be improved. The ultrasonic pulse velocity test provides measurements which can be correlated to material stiffness and, to some extent, strength (Malhorta and Carino, 1991).

Three types of stress waves are created when a solid material is placed into contact with a vibratory load. The waves that travel at the highest rate are the compression, or longitudinal, waves followed by the transverse, or shear, waves and the Rayleigh, or surface, waves. By determining the speed of a wave through a material and the mass of that material, the elastic properties can be determined. To create compression and shear waves, a pulse must be created inside the material. However, surface, compression, and shear waves can be produced if a pulse is originated at the surface. This test is conducted by generating an ultrasonic pulse on the surface and then determining the speed from the origin to a second point at a known distance. The compression wave velocity of an infinite, homogeneous, isotropic, elastic medium can be calculated by employing the following equation (Naik, 1979):

$$V = (KE / D)\text{\^{}}1/2 \tag{3.1}$$

where:

V = Compression wave velocity,

K = $(1-\mu)g/(1+\mu)(1-2\mu)$,

E = Modulus of elasticity,

D = Unit weight,
g = Acceleration due to gravity, and
μ = Poisson's ratio.

Due to the variations in the K-value, the estimation can lead to a velocity value error of as much as 6 percent (Malhotra and Carino, 1991).

Performance

This test measures the velocity of an ultrasonic pulse applied at the surface of the material which allows the modulus of elasticity to be determined. This property will assist in determining a pavement's ability to resist cracking, freeze/thaw damage, and structural deterioration. This test method can also be used in determining if there are any existing cracks or deterioration due to chemical breakdown in a pavement that is currently in use. This can assist in determining if the pavement is damaged, possibly needing to be repaired.

Nature of Test

This test method is useful in making measurements that can be directly related to material stiffness and Poisson's ratio which are from equation 3.1 for calculating the velocity of an ultrasonic pulse. The measurements can also be related indirectly to the compressive strength (that has limited value in pavement design), which is determined from the results of passing a pulse through the material and measuring the velocity. The test method is non-destructive, allowing the same specimen to be tested as many times as required (Figure 3.5). If the concrete contains reinforcing steel, interpretation of the V-meter results are complicated and can limit the utility of this method.

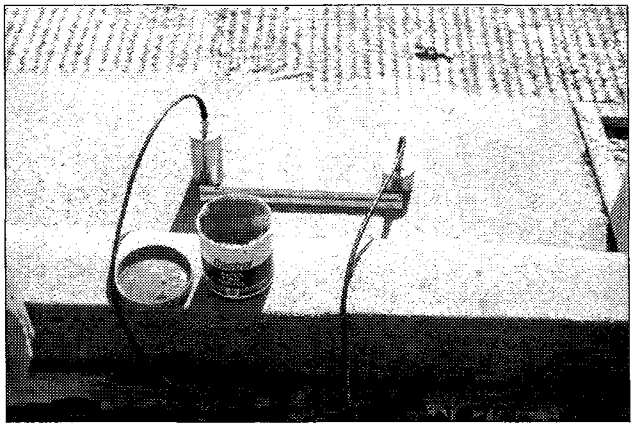


Figure 3.5 Pulse Velocity Test Configuration.

Test Equipment

The equipment needed to conduct this test is a pulse velocity test instrument, manufactured as a portable device known as a V-meter. The device can be attached to an oscilloscope to convert wave patterns into visual form and requires no special training.

Magnetic/Electrical (ASTM C 876 Half-Cell Potential Measurements)

Magnetic/electrical methods are primarily useful for locating and verifying the position of reinforcing steel and for the determination of moisture content in concrete. These procedures do not measure any properties directly and are based upon the theory of magnetic induction, magnetic flux leakage, and nuclear magnetic resonance. They use electrical and magnetic relationships to determine the above noted characteristics. These tests can be performed in the lab on hardened specimens but are more useful in the field. All of the electrical and magnetic procedures are non-destructive.

Performance

These methods use electrical and magnetic relationships to primarily determine concrete cover, location and size of reinforcement, and possible and severity of corrosion of rebar. The benefits of determining these properties in a non-destructive way are obvious. The integrity of a concrete structure or pavement is dependent on the condition of the reinforcement. If the exact location of damaged rebar due to corrosion can be determined, this increases maintenance efficiency drastically. The same can be said for a pavement that has possibly developed cracks or shows evidence of rutting. This test method exploits magnetic and electrical material properties to determine these characteristics.

A pavement design is given an expected performance life with little or no maintenance. When the pavement is near its expected life, these test procedures can be employed to determine the areas that do not meet the performance requirements, such as, corroded rebar, cracked pavement, or excessive rutting. This allows replacement of pavement to be focused on the areas that need it and allows the areas that still meet the performance requirements to be given additional years of performance life. The most important property of these tests is that they are non-destructive. The pavement or structure can be tested in various locations yielding important information without causing any damage.

Nature of Test

Three different magnetic principles can be used to locate reinforcing bar used in concrete pavement. The first principle is magnetic induction. Magnetic induction measures the voltage induced in a coil by a nearby coil with a known electrical current. If there is no metal between the coils, the induced voltage is small. When metal is placed between the coils, the induced voltage is considerably higher. The shape, location, and characteristics of the metal influence the voltage induced in the second coil. This principle is used to determine the depth, size, and location of the rebar. The second principle, flux leakage theory, involves magnetic lines of force running through a magnetized metallic bar. Where imperfections or cracks in the bar occur, there is leakage flux that will leave the bar. This leakage flux can be measured, and the imperfections in rebar can be determined. The final magnetic principle that can be used to evaluate the moisture level in concrete pavement is nuclear magnetic resonance (NMR). The amount of moisture in concrete pavements can be determined by detection of a signal from the hydrogen nuclei in the water molecules. The difficulty associated with this technique is the differentiation between signals from free or bound water. Methods have been proposed to address this distinction.

Electrical methods are also available for moisture detection in concrete. The moisture content of concrete can be determined by connecting two electrodes to an alternating current source and placing them a certain distance apart on the concrete. The moisture loss is then calculated using the power loss of the flow through the concrete. The moisture content can alternatively be measured by determining the resistance of the concrete. The resistance can be obtained by placing two insulated probes on the concrete pavement and measuring the resistance between them. The electrical resistance of concrete decreases with an increase in moisture content. The resistivity of a material is also useful in differentiating between material types. If the resistivity at increasing depths is measured, a significant change in resistivity will occur when the interface between the base layer and the concrete slab is encountered. By determining the depth when this change occurs, the thickness of the pavement can be determined.

Electrical methods can also be applied to corrosion evaluation. The half-cell potentials of reinforcing bars made at selected locations are used to calculate the corrosive activity in the bar. This procedure is covered in ASTM C 876. An electrical connection is made with the rebar, and the half-cell is moved over the pavement area. Readings are obtained in a grid pattern using a high impedance voltmeter, and an equi-potential contour map is created. The potential can be used to indicate the likelihood of corrosion. The rate of corrosion cannot be determined with this method.

Test Equipment

The equipment used in these procedures cannot be readily found in most material labs. Some of the equipment is common and commercially available. These tests are relatively difficult to perform and require a significant amount of technical training. Most values obtained using these procedures should be used as an estimate and not an exact value.

Radioactive/Nuclear (ASTM C 1040 Radiometry)

The radioactive, nuclear procedures refer to tests that measure the interaction of radiation within concrete materials on a continuous basis to determine certain physical information. These procedures are divided into three categories: radiometry, radiography, and neutron-gamma techniques. Gamma radiometry is used to determine the density of a variety of construction materials. Neutron radiometry can be used to determine the density of soils and asphalt concrete and, more recently, the water-cement ratio in fresh concrete. Radiometry is most useful in providing information on the density, thickness, and variability of density for concrete pavements. Radiography refers to techniques where a radiation source and photographic film are located on opposites of a concrete sample. The exposed film represents a photographic image of the concrete which can be used to indicate defects. Neutron-gamma has been rarely used in concrete construction (Malhotra and Carino, 1991). These procedures do not measure any properties directly but are correlated through the use of radioactive and nuclear relationships to estimate them. These tests can be performed in the lab on hardened specimens or in the field. All of the radioactive and nuclear procedures are non-destructive but require calibration in order to provide useful results relative to the materials used in the concrete mixture.

Performance

These methods use radioactive and nuclear relationships to determine primarily material unit weigh. Pavement thickness can also be assessed, to some extent. Material unit weight may have some correlated relationship to design criteria (such as strength, material stiffness, and bond to reinforcing steel) but is more directly correlated with the degree of consolidation. Certainly, pavement thickness is an important aspect of structural design criteria, particularly in terms of the variability associated with it. Both of these parameters are oriented towards assurance of construction quality. Also of value is the continuous nature of these test measurements.

Nature of Test

In gamma radiometry using direct transmission, a portion of the concrete pavement must be placed between a radioisotope source of gamma rays and a radiation detector. The intensity of the ray that passes through the specimen is measured. This intensity is a function of the specimen's density and thickness. The interaction of gamma and x-rays with concrete is described relative to penetration with attenuation. As a beam of gamma ray strikes a portion of concrete, some of the radiation passes through the concrete while another portion is removed by absorption and scattering. The intensity of the beam (I) varies exponentially according to:

$$I = I_0 e^{-\mu x} \tag{3.2}$$

where

I_0 = intensity of the incident beam,

x = distance from the concrete surface, and

μ = absorption coefficient.

The amount of scattering which occurs is a function of the unit weigh of the concrete, and the amount of absorption is mainly a function of the chemical composition. A similar principle is applied when characterizing the interaction of neutrons with concrete (Malhotra and Carino, 1991).

In back-scatter measurement, the gamma ray source and the radiation detector are placed side by side. This procedure measures the amount of radiation that is scattered and deflected back at the detector. This procedure is easier to perform because the concrete does not have to be between the source and the detector. It is, however, more sensitive to the chemical makeup of the concrete and only measures the top portion of the pavement. Radiometry (in the back scatter mode) is fairly well developed and is suitable for fresh or hardened concrete. It can be used to scan large volumes of concrete on a continuous basis; however, it is limited as noted above.

Radiography consists of x-ray, gamma ray, and neutron techniques that can be used to determine the placement and condition of rebar and to find voids in concrete pavement. Recently, radiography has also been used to determine the thickness of the carbonating layer and the water permeability of concrete samples. Radiography is performed by emitting radiation through a sample of a pavement and capturing an image on the film on the other side of the pavement. This yields an image of the structure of the concrete pavement. All radiography techniques are suitable for examining the internal microstructure of concrete, but gamma ray is the most portable (Malhotra and Carino, 1991). X-radiation provides a very accurate picture of concrete pavements but is expensive and requires high voltage. Gamma radiography utilizes smaller units that use less power but takes longer and will only provide images for pavements up to 460 mm (18 in) thick. Neutron-Gamma methods have no practical application to concrete pavements.

Test Equipment

The equipment for the most promising method, radiometry, is a radioisotope source of gamma rays, a radiation detector, and a counter. This type of equipment is not readily found in a materials lab, but most of it is commercially available. Recently, Troxler has introduce a gauge for the determination of water-cement ratio in fresh concrete (Model 4439 - water/cement gauge). These tests are relatively difficult to perform and require a significant amount of technician training. The values obtained using these methods are very accurate if the calibration curves are properly interpreted.

Stress Wave Propagation

There are several types of stress waves used too determine specific properties of a pavement. The stress waves included in this test method are the pulse-echo, impact-echo, impulse-response, and spectral analysis of surface waves. The following equations will be needed. The P-wave speed for an infinite elastic solid is represented by the following equation:

$$Cp = \sqrt{\frac{E\ (1-\upsilon)}{\rho\ (1+\upsilon)\ (1-2\upsilon)}} \tag{3.3}$$

where,

E = Young's modulus of elasticity,
ρ = Mass density, and
υ = Poisson's ratio.

For bounded solids, the P-wave speed can be determined using this equation:

$$Cp = \sqrt{\frac{E}{p}} \tag{3.4}$$

The S-wave speed for an infinite solid is given by the following equation:

$$Cs = \sqrt{\frac{G}{p}} \tag{3.5}$$

where G is the shear modulus of elasticity = E/2(1- υ).

The ratio between the S- and P-wave is a useful parameter and is represented by the following equation:

$$\alpha = \frac{c_s}{c_p} = \sqrt{\frac{(1 - 2\upsilon)}{2\ (1 - \upsilon)}} \tag{3.6}$$

The speed of an R-wave is given in the following approximate equation:

$$Cr = \frac{0.87 + 1.12\upsilon}{1 + \upsilon}\ Cs \tag{3.7}$$

Pulse-Echo

This method determines the location of interior flaws or interfaces by sending a stress pulse using a transducer at the surface, which is then reflected by the flaw or interface. The echo is then received by a transmitter or by a second transducer. This can be done by either using the transmitter as the receiver which would be a true pulse-echo or by using a second transducer near the source which is considered a pitch-catch arrangement. The output can be captured on an oscilloscope as a time-domain waveform (Malhotra and Carino, 1991). This test method can also be used to determine the depth of the material being tested by using the following equation:

$$T = \tfrac{1}{2}\,(t)Cp$$

where,

t = round-trip travel time,

T = the depth, and

Cp = is the P-wave speed.

Time domain analysis has been used exclusively in all applications where the pulse-echo or pitch-catch methods have been used to test concrete structures (Thorton and Alexander, 1987).

Impact-Echo

This method is similar to the echo-method except that instead of a transducer creating the stress pulse, an impact causes it. This method does not have the capability to control the stress waves direction as the echo method has. It is generally used in testing piles (Malhorta and Carino, 1991). The way this test method is performed is to introduce a transient stress pulse into the material by mechanical impact. The stress wave travels through the material as P- and S-waves. A surface wave also travels along the top of the material this is known as the R-wave. The P- and S-waves are reflected back by any boundary within the material. The reflected waves at the surface produce displacements. It is important to note that the success of this test is dependent on the proper impact used.

This test method employs frequency analysis to assist in determining the depth of the material. A stress pulse created by the impact propagates back and forth between the flaw and the surface plate. Each time the pulse returns to the surface it creates a displacement. If the frequency (f) and the speed of the P-wave (Cp) are known then the thickness (T) can be calculated using the following equation:

$$T = Cp/2f$$

In practice, the frequency content of the digitally recorded waveforms is obtained using the fast Fourier transform (FFT) technique (Stearns, 1975). The FFT is based on the principle that any waveform can be represented as a sum of sine curves with a change in amplitude, frequency, and phase shift. This technique is used to calculate the frequency (f) in the waveform.

Impulse-Response

This test method is a combination of the pulse- and impact-echo methods. A hammer is used to generate a stress pulse by a mechanical impact at the surface. A transducer close to the location of impact monitors the velocity of the pulse as it travels and is reflected back by the flaw or interface (Stain, 1982; Higgs, 1979; Davis and Dunn, 1974).

The impulse response is the structures response to an input having a force-time function that is a single spike at time zero. The impulse response function is a characteristic of a structure, and its changes depending on geometry, support conditions, and the existense of flaws or cracks. Digital signal processing techniques are used to obtain the impulse response function, often referred to as the transfer function (Malhotra and Carino, 1991). A procedure for computing the transfer function is outlined in the following steps (Higgs, 1979):

1. Calculate the Fourier transforms of the measured force-time function, $f(t)$, and the measured response, $v(t)$. These will be denoted as $F(\omega)$ and $V(\omega)$.
2. Using the complex conjugate of the Fourier transform of the force-time function, $F^*(\ )$, compute the cross-power spectrum, $V(\omega)\cdot F^*(\omega)$.
3. Compute the power spectrum of the force-time function, $F(\omega)\cdot F^*(\omega)$.
4. Divide the cross-power spectrum by the power spectrum to obtain the transfer function:

$$H(\omega) = [V(\omega)\cdot F^*(\omega)] / [F(\omega)\cdot F^*(\omega)]$$

The accuracy of the results can be improved if the test is repeated and the average power spectra is used to compute the transfer function. These calculations can be carried out automatically with a dynamic signal analyzer.

Spectral Analysis of Surface Waves (SASW)

This method is useful in determining the stiffness profiles and layer thicknesses of a pavement (Heisey, Stokoe, and Meyer, 1982; Nazarin, Stokoe, and Hudson, 1983). A hammer is used to create an impact at the surface of the pavement, and two receivers are placed to record the disturbance. The wave that is dominant at the surface and is, therefore, the only wave recorded is the R-wave. This wave contains a range of frequencies that are based on the impact time. The shorter the contact time the broader the range of frequencies or wavelengths. The depth also influences the R-wave. The amplitude of the R-wave decreases exponentially as the depth increases. It is concluded that in order to obtain information about the properties of the underlying layers, deep penetration must be acquired and therefore longer wavelength components must be used.

An impact is chosen that will create a high frequency with a speed determined by measuring the S-wave speed and will therefore probagate strictly through the top layer. An impact that creates a low frequency will be used to penetrate deeper into the pavement allowing an analysis of deeper layers to be made. A layered system is a dispersive medium for R-waves, which means that different frequency components in the R-wave will propagate with different speeds called "phase velocities" (Malhorta and Carino, 1991).

Performance

Pulse-Echo and Impulse-Response Measurement and detection of flaws are of interest during the construction and placement of concrete pavements. Such information may be very useful in determining the quality of concrete placement but rarely maintains a direct correlation to performance or structural criteria relative to design. Although, it is well accepted that concrete poorly placed may cause a pavement to experience early failure at localized areas.

Impact-Echo and Spectral Analysis of Surface Waves (SASW) These methods are useful since the material stiffness is a parameter associated with the structural design criteria of a concrete pavement. Stiffness is a key factor in the load carrying capacity and distribution of a concrete pavement system and, as was noted in Chapter 3, is an indicator of damage accumulated due to microcracking or other flaws which may result in localized areas of low strength.

Nature of Test

Pulse-Echo and *Impulse-Response* These test methods are a direct measure of how fast a stress wave can move through the pavement and is an indirect measure of the location of flaws and/or interfaces. A short-duration impact is produced by tapping a small steel sphere against a concrete surface to generate a low-frequency stress wave that propagates into the surface and is reflected by flaws and external surfaces. Surface displacements caused by the arrival of reflected waves at the impact surface are recorded by a transducer, located adjacent to the impact site, which produces an analog voltage signal proportional to displacement. The resulting voltage-time signal is digitized and transferred to the computer memory, where it is transformed mathematically into a spectrum of amplitude versus frequency. Both the waveform and spectrum are plotted on the computer screen. The dominant frequencies, which appear as peaks in the spectrum, are associated with multiple reflections of stress waves within the structure and they provide information about the thickness of the structure, its integrity, and the location of flaws. The test causes no damage to the pavement, so it is considered a non-destructive test.

Impact Echo and Spectral Analysis of Surface Waves (SASW) Impact-echo is a method for non-destructive evaluation of concrete and masonry structures, based on use of impact-generated stress (acoustic) waves that propagate through a structure and are reflected by internal flaws and external faces. It can be used to determine the location and extent of flaws, such as cracks, delaminations, voids, and other defects. Recently, McNerney et al. (1997) applied this technique in the evaluation of an airfield pavement through core holes as depicted in Figure 3.6. This particular technique is referred to as the cross-hole seismic test. Testing was performed by initiating stress waves in one core hole and monitoring their arrivals in the adjacent core holes. The purpose of these tests was to evaluate the stiffness of each component of the pavement system independently and in-place.

The SASW test method is a direct measure of the disturbance at the surface caused by an impact and the speed of the R-wave. A transient stress pulse results from the surface impact and is monitored by two receivers. At the surface, the R-wave is the most dominant and overrides the other types of waves. The characteristics of the R-wave are a function of the contact time of impact and the depth of travel from the surface. The longer wave length components of the R-wave penetrate more deeply and can yield information regarding layers at different depths. In a layered system, a variety of R-waves will be generated and will travel with different speeds. The high frequency components of the wave travel within the top portion of the slab and provide information regarding the shear modulus, Poisson's ratio, and density of the concrete where lower frequency components provide information of the deeper layers. The indirect measure is the thickness of the pavement. This test method is also non-destructive.

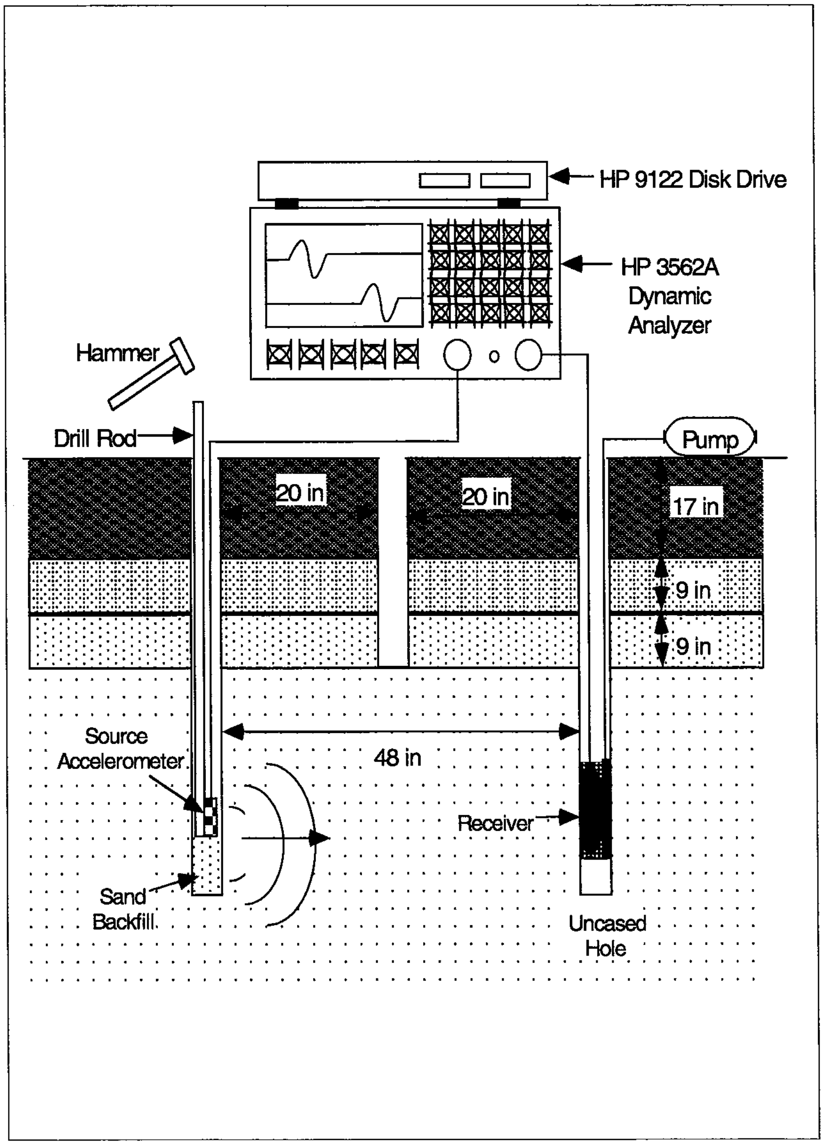


Figure 3.6 Example Cross-hole Seismic Test. (McNerney et al., 1997).

Test Equipment

Pulse-Echo The equipment necessary to perform this test is a pulser/oscilloscope, transmitter, and a receiver. This equipment is commonly used and should be available in any standard lab. There is no special training required to conduct the test and will yield an accurate location if procedure is followed.

Impulse-Response The equipment necessary to perform this test is an instrumented hammer, geophone (low frequency velocity transducer), and a two-channel dynamic signal analyzer. The test is non-destructive and requires no special training.

Impact-Echo An impact-echo system consists of an impact source, a receiving transducer, and a digital processing oscilloscope or waveform analyzer that is used to receive the output from the transducer, store the digitized waveforms, and perform signal analysis. Apparently, these systems have not been commercially available until recently but typically require assembly from the commercially available components. The impact-echo test systems are developed by Impact-Echo Instruments, LLC, P.O. Box 3871, Ithaca, NY. Its price to universities is $21,000 (for Type A) or $23,000 (for Type B).

Spectral Analysis of Surface Waves (SASW) The three components necessary to perform this test are a hammer, two geophones or accelerometers, and a two-channel spectral analyzer (Malhorta and Carino, 1991). This test method is non-destructive and is an accurate measurement of the pavement thickness, if the procedure is followed.

Ground-Penetrating Radar to Measure Density, Moisture Content, and Voids in Place

The ground-penetrating radar (GPR) technology developed at TTI is a powerful methodology to monitor in-place density and moisture content of soil and concrete materials and to possibly detect the air void content of fresh concrete. This technology measures reflected electromagnetic (EM) waves where EM speed and reflection coefficient depend on the relative dielectric constant ϵ_r of the materials. From recorded reflected waves, voids in the materials can be detected because the dielectric constant changes from the material to the air. Water has a high dielectric constant. For actual density of soil, for instance, the dielectric constant can be calculated using a mixture model, which is based on the dielectric constants of air, water, and solids. TTI has developed the nondestructive test method to determine the density and moisture content in soil from the measured wave signals in place. It should also be possible to apply the same technology in a similar manner to concrete materials.

Performance

The use and potential of GRP has yet to be fully recognized in the construction of concrete pavements. Its most undeveloped use is in the continuous detection of moisture content in soils and concrete aggregates. Knowledge of the moisture of aggregate materials as they are fed in the mixer would provide valuable information regarding the production of quality concrete - particularly high performance concrete. Another untapped use of GPR is the ability to monitor unit weight of in-place concrete and the detection of rock pockets created by poor workability. GPR has the potential to monitor several key factors, such as the degree of hydration and strength gain and other parameters that may affect the quality of construction and the structural design criteria and the performance of the pavement system.

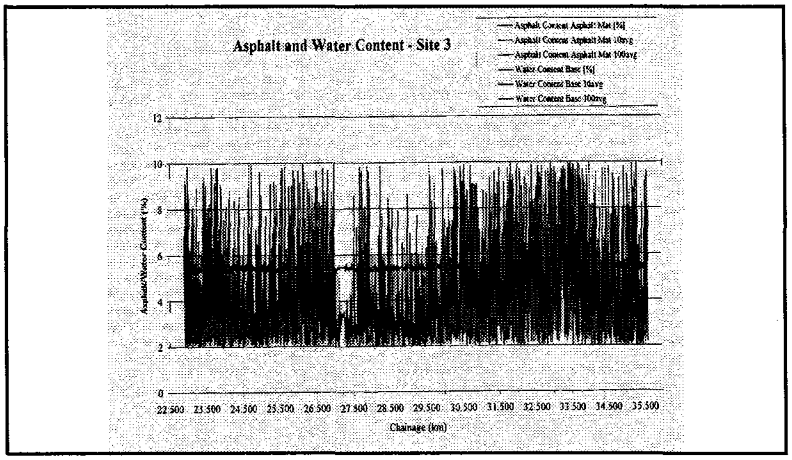


Figure 3.7 Example of Moisture and Asphalt Cement Content Derived from Use of GRP.

As an example of how GRP can function is a demonstration of its capability to non-destructively determine layer moisture content of an asphalt concrete pavement structure. An example of this capability is illustrated in Figure 3.7. Not only can the moisture content of the base layer be determined but also the asphalt cement content from GPR data analysis. Most researchers can derive layer thicknesses from GPR data, but the developments by TTI allow one to go far beyond that with the capability to not only retrieve moisture and asphalt cement content, but also layer unit weight, air content, and porosity as well as layer thickness. It is capability of this nature that will allow TxDOT to make significant advancements in the monitoring and determination of the key in-place layer properties that affect performance.

Nature of Test

Ground-penetrating radar is an electromagnetic wave in the microwave range of frequencies. Microwave techniques have been used widely in remote sensing of vegetation growth, soil moisture monitoring (Newton et al., 1983), and terrain profiling. Recently, this technique has been applied in areas such as detection of buried utility pipes, railroad embankment, and pavement layer thickness.

In general, electromagnetic waves are propagated by simultaneous periodic variations of electric and magnetic field intensity and include radio waves, microwave, infrared, visible light, ultraviolet, x-ray, and gamma rays. The wavelength of microwave is usually between 100 centimeters and 1 centimeter and has a frequency between 0.1 gigahertz (GHz) and 30 GHz.

The speed of electromagnetic (EM) waves in any physical medium is shown as:

$$\upsilon_p = \frac{1}{\sqrt{\mu_0 \, \mu_r \, \epsilon_0 \, \epsilon_r}} \tag{3.8}$$

where

μ_0 = permeability constant of free space,

μ_r = relative permeability constant,

ϵ_0 = permittivity (dielectric) constant of free space,

ϵ_r = relative permittivity (dielectric) constant,

ν_p = propagation velocity of EM wave,

μ_0 = 1.26×10^{-6} Henry/meter, and

ϵ_0 = 8.85×10^{-12} Faraday/meter.

In free space or vacuum where $\mu_r = \epsilon_r = 1$, the propagation velocity is computed to be 3×10^8 meter/second, which is the speed of light (C) as:

$$C = 1\sqrt{\mu_0 \epsilon_0} \tag{3.9}$$

The relative dielectric constant is the measure of the ability of a medium to store an electric charge while the relative permeability is a measure of the modification of magnetic flux in the region. Some typical relative dielectric constants are tabulated for different construction materials below.

Table 3.1 Typical Relative Dielectric Constants of Construction Materials.

Materials	**Constant**
Air	1.0
Distilled Water	81.0
Asphalt Concrete	3 - 9
Crushed Limestone	10 - 23
Cement-Stabilized Limestone	12 - 24
Concrete	8 - 12
Polyethylene	2.26
Polystyrene	2.55

The propagation speed of EM waves in soil and base materials which are mostly non-magnetic dielectric materials can be rewritten as follows:

$$v_p = \frac{C}{\sqrt{\mu_r \, \epsilon_r}} \tag{3.10}$$

Since $\mu_r = 1$ for non-magnetic material, the wave propagation speed (v_p) is shown as follows:

$$v_p = \frac{C}{\sqrt{\epsilon_r}} \tag{3.11}$$

In a multi-media system, such as a pavement system where there is dielectric discontinuity at the interfaces of the concrete and subbase, a fraction of the EM wave will be reflected back and the remaining portion will propagate into the next layer. The reflection coefficient prescribes the fraction of the incident wave that is reflected at the interface. Assuming the wave travels from medium 1 to medium 2, the reflection coefficient (ρ) is given as:

$$\rho = \frac{\sqrt{\epsilon_{r_1}} - \sqrt{\epsilon_{r_2}}}{\sqrt{\epsilon_{r_1}} + \sqrt{\epsilon_{r_2}}} \tag{3.12}$$

where

ϵ_{r_1} = relative dielectric constant of medium 1,

ϵ_{r_2} = relative dielectric constant of medium 2, and

ρ = reflection coefficient.

The transmission coefficient (Γ) at the interface can be derived by applying the principle of power conservation at the boundary between medium 1 and 2 and the result is:

$$\Gamma = 1 + \rho$$

Notice that the reflection coefficient can bear a negative sign when the dielectric constant of the first (top) layer is smaller than the second (bottom) layer. Physically, this could be a layer closer to the concrete surface than another layer which has a higher moisture content. Based on the two basic principles mentioned above, namely the propagation speed and the reflection coefficient, the layer thicknesses of a pavement base can be estimated.

The Texas Transportation Institute has developed a method of measuring the dielectric constants of multiple layers and their thicknesses without taking cores, and of automating the analysis of the reflected wave signal. This is one of the important breakthroughs that has been made in TxDOT Study 2-18-90-1233 which will not be elaborated on here. However, computation of the actual density of a subbase and subgrade soil requires the use of a mixture model of the dielectric constant that depends upon the volumetric quantities of solids, water, and air. Several mixture models are available for this purpose, including the linear mixture model.

$$\epsilon_r = \epsilon_a \theta_a + \epsilon_w \theta_w + \epsilon_s \theta_s \tag{3.13}$$

where

$\epsilon_a, \epsilon_w, \epsilon_s$ = the dielectric constants for the air, water, and solids

$\theta_a, \theta_w, \theta_s$ = the volumetric ratios of air, water, and solids to the total volume

the complex refractive index method (CRIM)

$$\sqrt{\epsilon_r} = \theta_a\sqrt{\epsilon_a} + \theta_w\sqrt{\epsilon_w} + \theta_s\sqrt{\epsilon_s} \tag{3.14}$$

the continuous grain size distribution model (CGSD) which is stated in differential form

$$\frac{d\,\epsilon_r}{3\,\epsilon_r} = \frac{d\,\theta_a}{\theta_a + \theta_w + \theta_s} \cdot \frac{\epsilon_a - \epsilon_r}{\epsilon_a + 2\,\epsilon_r} + \frac{d\,\theta_s}{\theta_a + \theta_w + \theta_s} \cdot \frac{\epsilon_s - \epsilon_r}{\epsilon_s + 2\,\epsilon_r} \tag{3.15}$$

and $\frac{\partial\theta_a}{\partial\theta_s} = \frac{\theta_a}{\theta_s}$ for all incremental changes in the relationship. There is also a discrete grain size distribution model (DGSD) which requires a knowledge of the grain size distribution of the material. Although its accuracy has been demonstrated experimentally, its application in the field would appear to be problematical. Still, other mixture models are available in the literature. The importance of the selection of a good model is in the accuracy with which the relative volumetric quantities can be estimated. The gravimetric water content is found from:

$$w = \frac{\theta_w}{\theta_s} \cdot \frac{1}{G_s} \qquad (3.16)$$

where

G_s = the specific gravity of the solids

and the in-place density of the material is given by:

$$\gamma_t = \theta_w \cdot \frac{1 + w}{w} \cdot \gamma_w \qquad (3.17)$$

where

γ_w = the unit weight of water, and

γ_t = the in-place density.

Reviewing the sources of error in determining the density of the material in-place, it is apparent that: (1) the signal noise must be reduced to a minimum; (2) the specific gravity of the solids must be known or estimated accurately; and (3) a good mixture model must be used. An approach to reducing the error associated with the values of the volumetric ratios, referred to as an inverse analysis method, has been developed at TTI for this purpose. It is a systematically converging trial-and-error process known as the Systems Identification method. This approach is not described here, but preliminary test results on a TTI pavement test section were promising. As an example, the time increments of the peaks from the radar return signal, along with an initial estimate of layer thickness and volumetric ratios of solid and fluid are input into the model; the calculated asphalt concrete layer thickness converged to 127 mm ± 21.6 mm (5 in ± 0.85 in) despite a wide range of initial estimates. The recorded actual layer thickness for the test pavement is 127 mm (5 in). The volumetric ratios of solid and fluid were calculated to be 0.845 and 0.09. From these output results, the asphalt content is calculated to be 4 percent and a density of 146 1b/ft^3 for the surface layer, which are very reasonable.

One difficulty that has been encountered is the rapid attenuation of the radar return signal where the second peak and third peak are not very distinct. A signal processing technique will be an appropriate tool to pre-process the radar signal to suppress the noise and emphasize the peaks.

The net result of the investigations that have been done up to the present time on ground-penetrating radar on pavements is that it is a sensitive measurement technique which is capable of detecting where changes occur in the pavement layer structure and of providing a sufficient amount of additional information to permit a diagnosis of the cause of the disturbance in the normal pattern. Equipment hardware and electronics have been developed to the point where the system is reliable.

Test Equipment

The equipment to generate, transmit, receive, digitize, record, and display the radar pulses is available from commercial radar corporations, such as Geophysical Survey Systems, Inc. There are two types of radar devices in use at present, one of which uses a horn antenna and maintains a 152 mm (6 in) air gap between itself and the upper surface, and the other of which keeps a dipole antenna in contact with the surface and transmits radar waves by conduction into the surface. It is the latter type which holds the greatest promise for the purpose of this project.

The measurements of GPR are accurate, but the equipment is costly, and training is needed to use the equipment properly. The equipment associated with GPR technology is commercially available and requires the use a ground-launched antenna.

Infrared Thermographic Techniques

This test helps to determine the present condition of a concrete pavement relative to voids, deliminations, and cracks. Using infrared thermographics, it is possible to analyze the condition of the concrete without disturbing it, which is based on the principle that subsurface defects and voids affect heat flow through the material. These changes in heat flow cause localized differences in surface temperature, and the measurement of temperature and the ability of a material to conduct heat can be used to detect the extent and location of subsurface defects. If an air void exists within a concrete pavement, it can be distinguished from the surrounding concrete by its thermal conductivity value. The density of the concrete can also be determined. The more dense the concrete, the greater is its ability to conduct heat and its quality (Malhorta and Carino, 1991). This method may be most applicable to bonded concrete overlays.

Performance

This test method can provide a measure of the extent of delamination in a bonded concrete overlay. The extent of delamination is critical to the performance of this type of pavement. This device may be very useful in detecting flawed areas for possible repair or replacement.

Nature of Test

This test is considered to be a field test. The direct measurement made is the thermo-conductivity of the pavement. The indirect measurement is the location and severity of the deterioration of the pavement. This test requires certain weather conditions and pavement surface conditions, to be considered accurate. There should be plenty of sunshine, and the pavement should be dry. The range of time this test should be conducted in is two to three hours after sunrise and two to three hours before sunset; this will ensure rapid heat transfer. Another benefit of this test is that it gives accurate information about the interior condition of the pavement and yet is non-destructive (Malhorta and Carino, 1991).

Test Equipment

The equipment to perform this test has four parts. The first part is the infrared scanner head and detector that can be used with interchangeable lenses. The second part is a real-time microprocessor coupled to a black and white display monitor. The third component needed to conduct this test is the data acquisition and analysis equipment. This will require an analog to digital converter, a computer with a high resolution color monitor, and data storage software. The final component includes the image recording and retrieving devices. The equipment should be carried in a van that has several power supplies to facilitate use in the field. This equipment is technical and expensive and should be handled and operated by an experienced technician (Malhorta and Carino, 1991).

Rolling Dynamic Deflectometer (RDD)

The rolling dynamic deflectometer (RDD) is a truck-mounted device that measures continuous deflection profiles of pavements. A drawing of the RDD is shown in Figure 3.8. The device consists of a large truck with a gross weight of about 195 kN (44,000 lb) on which a servo-hydraulic vibrator is mounted. The vibrator has a 33 kN (7,500 lb) reaction mass which is used to generate vertical dynamic forces as large as 310 kN peak-to-peak (70,000 lb peak-to-peak) over a frequency range of about 10 to 100 Hz. Simultaneously, the hydraulic system generates a constant hold-down force ranging from 65 to 180 kN (15,000 to 40,000 lb). The static and superimposed dynamic forces are transferred to the pavement through two loading rollers.

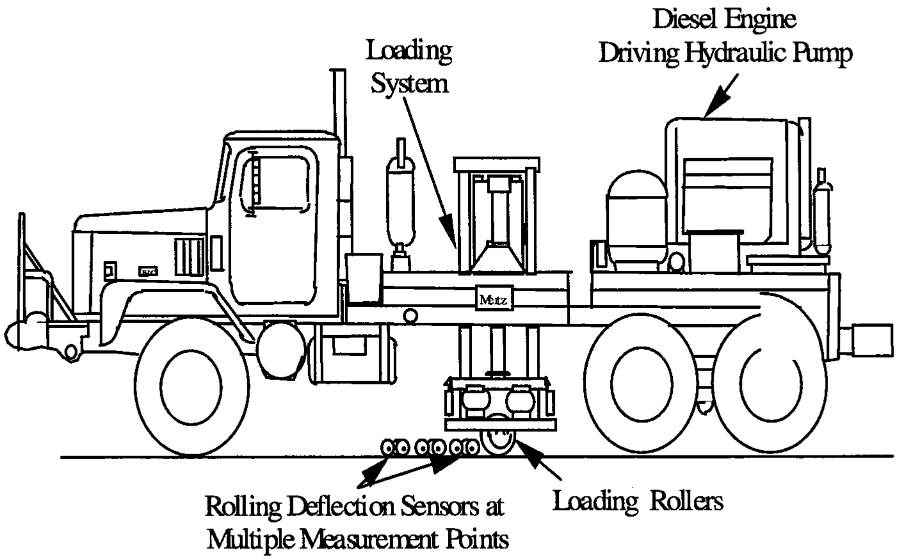


Figure 3.8 Configuration of the RDD. (McNerney et al., 1997).

Performance

The RDD provides a continuous record of the pavement deflection profile which can be used to interpret the pavement stiffness, which is different from the material stiffness, because it takes into account the effect of joints and cracks. Pavement stiffness at the joint or crack is criteria to pavement performance and must be limited to a high level to ensure adequate performance. Other properties of the slab and subgrade can be back-calculated as indicated in Chapter 2.

Nature of Test

As the RDD slowly rolls over a pavement, it applies a cyclic load to the pavement surface through the loading rollers. Dynamic displacements are measured with four rolling sensors. By measuring the applied forces and the resulting deflections, a continuous deflection profile for the pavement is determined, with soft regions of the pavement exhibiting large deflections and stiff regions lower deflections. Remaining life determinations can be made on a continuous basis from the pavement stiffness determinations.

Test Equipment

The test equipment is illustrated in Figure 3.8 and is not common among testing laboratories. The equipment also requires training to operate but can collect data at a rapid pace.

Pullout Test to Measure In-Place Strength

To accurately estimate how a concrete pavement will perform over time, it is necessary to know the strength properties of the concrete after it has been placed and allowed to cure. Few methods provide direct measurements of the concrete strength in-place. Typically during concrete placement operations, concrete strength specimens are allowed, most often, to cure in conditions dissimilar to those of the actual pavement. This creates discrepancy in the information pertaining to the concrete, as different curing

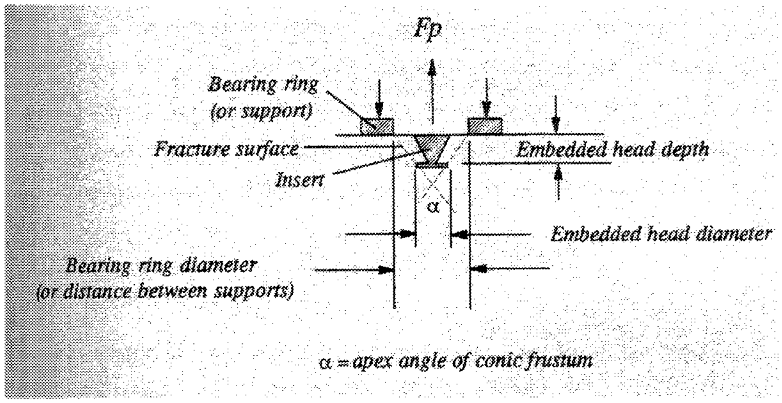


Figure 3.9 Insert of Pullout Test. (Dilly, 1994).

conditions yield different concrete strength capacities. Pullout testing is performed by using metal disks (or inserts - Figure 3.9) installed within the concrete while the concrete is in a fresh state. The inserts are allowed to remain in place while the concrete hardens. To measure the in-place concrete strength, a loading apparatus is used to measure the force required to fracture the concrete and extract the insert from the concrete mass. The pullout load is used to estimate the compressive strength or the tensile strength of concrete based on a regression correlation with the pullout load.

Performance

The pullout strength does not relate directly to a strength parameter associated with present structural design criteria. Efforts in the past have primarily focused on correlations with compression strength (Mahotra and Carino, 1991). Recently, however, work has been accomplished to relate pullout load to fracture toughness of concrete and crack resistence at a sawcut notch (Dilly and Zollinger, 1998). Since crack resistence is directly related to fracture toughness and the tensile strength of concrete, advancements of this nature increase the utility of this test methodology considerably for application to structural design criteria.

Nature of Test

Pullout strength applied directly to concrete in the pavement is more representative of the in situ strength than the strength measured from a test specimen prepared alongside a concrete pavement during construction. The test procedure for the test method was previously proposed in ASTM C 900. Research conducted under the Strategic Highway Research Program (SHRP) (SHRP Product 2022) (SHRP Report C376) suggested that this method should be combined with the maturity method for field use. This basically would involve the development of a relationship obtained in advance between the pullout strength and a concrete specimen strength (preferably tensile) that would be used to verify the design strength or to control strength quality construction of a project. The pullout strength would be predicted for a specific time from the strength-maturity and pullout strength-tensile strength relationships. In this manner, an in-place test of the strength in the pavement for the purpose of quality control could be provided. However, it is well known that data from pullout tests are often largely scattered. The SHRP report does not provide error analysis of the pullout method.

Recent efforts by Dilly (1994) to relate pullout strength or fracture to the fracture toughness (K_I) of concrete resulted in the development of a loading frame (Figure 3.10) to allow the fracture plane to develop uninhibited by the load reaction. The loading frame can be used in the field, but the fracture plane is much larger (approximately 300 mm in diameter) than the fracture plane caused by the conventional pullout apparatus. Dilly showed that a critical K_I value is proportional to 0.42 times the pullout fracture load.

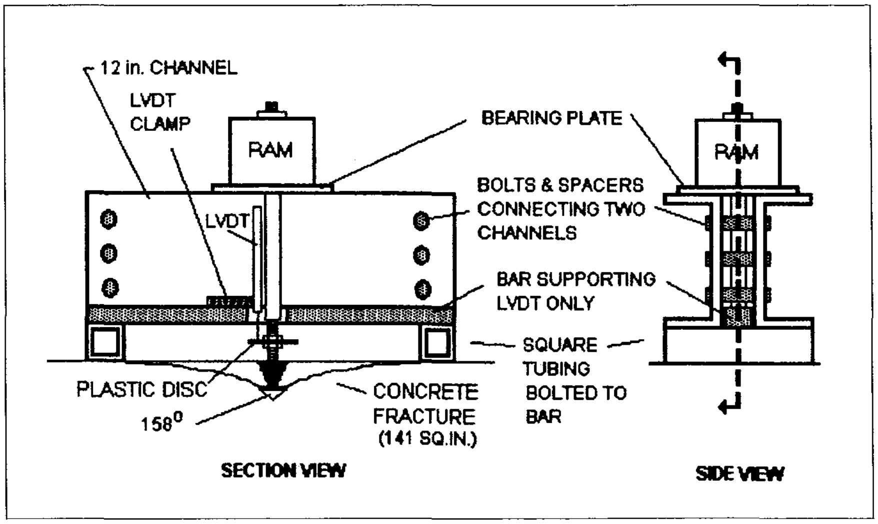


Figure 3.10 Pullout Loading Frame for Fracture Testing. (Dilly, 1994).

Test Equipment

The test equipment involves the use of a load cell, hydraulic jack, and pullout bolts machined to a specific size and shape. The bolts are typically recovered after each test. In developments suggested by Dilly (1994), a special support apparatus is used to prohibit interference with the fracture radius of the concrete. The pullout load associated with the wider fractured area is used to determine the fracture toughness of the concrete.

Break-Off Test

The break-off test method is another way to provide relatively direct information about the in situ strength of the concrete after it has been placed and hardened. It consists of breaking off an in-place cylindrical concrete specimen at a failure plane parallel to the finished surface of the concrete element (Malhotra and Carino, 1991).

The break-off (BO) method allows several concrete properties to be determined. It presently provides a method for determining a strength parameter that is related to the flexural strength of in-place concrete, where a linear relationship between the BO strength and modulus of rupture is determined by the flexural beam test. This method, like the pullout test, is considered to be a non-destructive test even though some damage is incurred at the surface of the concrete.

Performance

The flexural strength of concrete is an important parameter in predicting the performance of the pavement and its load capacity. The BO test differs from standard practice in that it represents a form of the flexural strength of the in-place concrete although it has been claimed to be identical to the flexure strength. The advantage of this test is the provision of a strength measure on the materials placed in the pavement and not on the material placed in a specimen, which is typically cured differently than the concrete in the pavement. Therefore, the strength of the pavement is used in prediction of performance, which should improve the ability to make an accurate estimate of the performance capacity of the pavement.

Nature of Test

The test apparatus is placed, similar to the pullout test, while concrete is fresh and is cured in-place with the pavement. After hardening, the cell is removed, and the loading mechanism is placed in the void (Figure 3.11). Load measurements are made on the isolated pedestal or cylinder of concrete. Acquiring the test sample is simple and requires no special training. A plastic disposable cylinder is placed in the concrete after it has been placed. Some care must be taken to ensure that the sleeve is properly placed. It is best pushed in-place by a rocking and twisting action. Concrete inside the sleeve and the top of plastic sleeve itself should then be tapped by fingers to ensure good compaction for the BO specimen (Malhorta and Carino, 1991). Once the concrete has hardened, the cell is removed and the test is conducted on walls of the void space. This will leave a hole in the pavement but will not affect the pavement strength or performance capacity in any way. The hole may be required to be patched over for aesthetic reasons if it is exposed. If procedures are followed and care is taken in forming the core, the results of this test can yield a useful measurement of the flexural strength of the pavement.

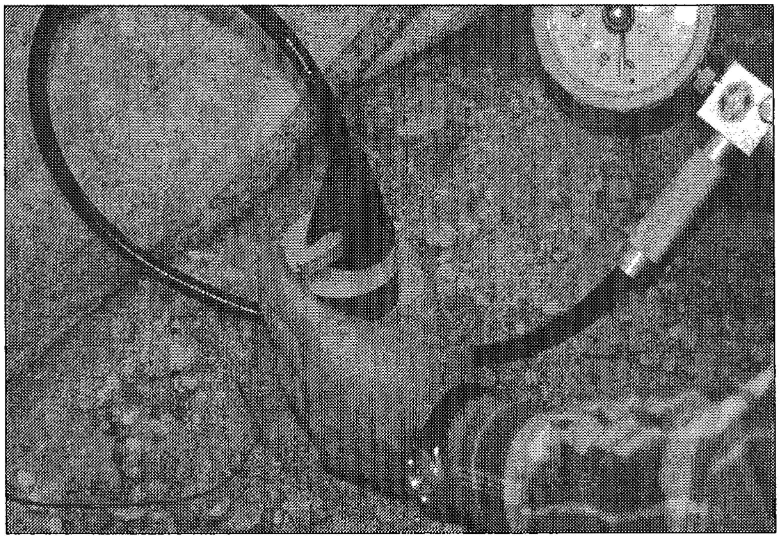


Figure 3.11 Break-Off Test Apparatus.

Test Equipment

The following equipment is required to conduct the break-off test: load cell, manometer, and a manual hydraulic pump that is capable of breaking a cylindrical concrete specimen. This equipment is standard and requires no special training to use.

Indirect Splitting Tensile Strength

Recent developments using fracture mechanics strength theories and a modified version of ASTM C 496 have resulted in new approaches, specimen geometries, and strength parameters that have allowed researchers to identify parameters relative to the brittleness and the crack resistance of concrete. Fracture mechanics theories applied to concrete materials provide for the explanation of the cracking mechanisms that are sensitive to coarse aggregate characteristics relative to the aggregate-mortar bond. This sensitivity is referred to in terms of two fracture properties known as fracture toughness and the length of the cracking process zone or the brittleness factor. Concrete brittleness is descriptive of a material's resistance to crack growth or the rate at which a crack may grow and is very sensitive to the type of coarse aggregate used in a concrete mixture.

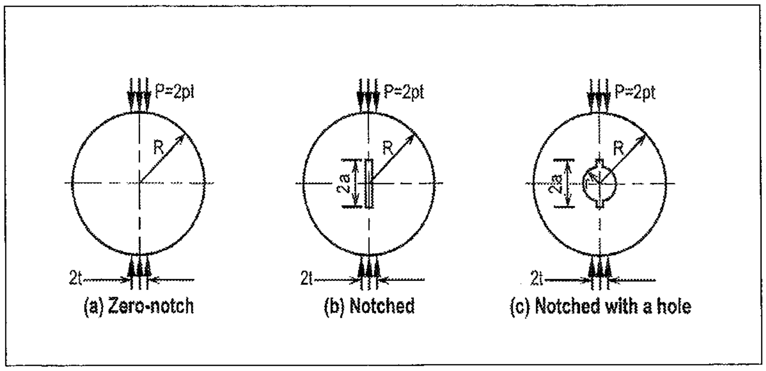
Performance

Load-associated failures of concrete pavements involve crack formation and stable growth under certain load levels. The application of the above fracture properties is directly applicable to conventional concrete strength properties and cracking mechanisms. The fracture properties of the concrete are particularly sensitive to the shape and texture of the aggregate.

Nature of Test

A test procedure has been suggested by the RILEM Committee on Fracture Mechanics to determine the fracture properties of toughness and brittleness of a concrete mixture. The RILEM procedure is based upon beam type specimens that range in size depending upon the loaded span. One type of fracture model that has been associated with the RILEM procedure is referred to as the Size Effect Law (SEL). SEL involves two fracture parameters: fracture toughness (K_{If}) and the process zone length (c_f, i.e., the brittleness factor) that may be interpreted to reflect the aggregate-mortar bond of early-age concrete on the basis of an the infinitely large strength specimen (this size of specimen is used as a reference base only). SEL suggests that the determination of K_{If} and c_f is found from testing several beam specimens of different sizes as indicated in the RILEM procedure. TTI has applied this fracture model in several research projects sponsored by

TxDOT using K_{If} and c_f to characterize early-age concrete strengths. Recently, TTI has developed a new test method using a modified split tensile specimen based on SEL. This method determines K_{if} and c_f from specimens of the same size (diameter), providing for a greater amount of convenience in specimen preparation. The various configurations illustrated in Figure 3.12 are utilized in order to enhance the accuracy of the test method relative to specimen geometry effects.



(a) Zero-notch (b) Notched (c) Notched with a hole

Figure 3.12 Split Cylinder Specimens.

The split tension of concrete cylinders, also known as the Brazilian disk test, is a standardized ASTM test method (ASTM C 496) typically used to obtain concrete tensile strength (Figure 3.12a). In order to evaluate the fracture parameters, modified split tensile specimens are needed as shown in Figures 3.12b and 3.12c. A notch is needed in the test specimen shown in Figure 3.12b. A test specimen as shown in Figure 3.12c is needed to provide a required geometrical configuration represented by special functions noted as F(a), g(α), and g'(α). A small modification of the cylinder, such as a hole drilled at the specimen center (Figure 3.12c), dramatically improves the accuracy of these functions.

The three cylindrical specimens used in the new procedure are 152.4 mm (6 in) in diameter. The first specimen contains no notch ($2a_0 = 0$); the second specimen contains a small notch of $2a_0 = 25.4$ mm (1 in); the third specimen contains a 25.4 mm (1 in) diameter hole with a 38.1 mm (1.5 in) notch extending on each side of the hole (3.12c), in such a way that $2a_0$ is 101.6 mm (4 in). The method requires the use of the elastic modulus of concrete which can be calculated from the compressive strength using the ACI building code formula $E = 57{,}000(f'c)^{1/2}$, where, f'c is the compressive strength in units of psi.

In the split tension specimens shown in Figures 3.12b and 3.12c, the crack length is denoted as 2a and $\alpha = 2a/d = a/R$, where d is the diameter and R is the radius of the cylinder. Cylinders without a hole and cylinders with a hole will be called regular and holed cylinders, respectively. The ratio t/R in Figures 3.12a and 3.12b is 0.16, and r/R for the holed cylinder is 0.12. A combination of regular split tension cylinders and holed split tension cylinders provides a large range of specimen geometries. Sawcutting of cored specimens, or properly coated inserts in cast specimens, are used to form the notch of both regular and holed cylinders. Along with the regular notched and the holed cylinders, the method includes a zero-notch specimen (α_o=0).

For specimens cored from a pavement, the notch in the specimen in Figure 3.12c may be cut by a saw blade threaded through the hole after a hole is drilled at the specimen axis. Otherwise, the hole and notch can be formed by using a rod insert with wings when casting the concrete. The specimens are then tested in split tension. The maximum load is recorded, and the results are placed in a spreadsheet, such as the one shown in Table 3.2. The only inputs necessary in the spreadsheet are shaded in.

Table 3.2 Calculation of Fracture Parameters.

Spec #	b (in)	d (in)	2a (in)	P (lb)	α	F (α)	g(α)	g ′(α)	X (in) (g/g ′) d	Y (psi in ½) 1/g ′ σ^2
1	3	6	0	13000	0	0.9640	0.0000	2.9195	0.0000	1.620×10^{-6}
2	3	6	1	10000	0.1667	0.9994	0.5230	3.6023	0.8711	2.219×10^{-6}
3	3	6	4	3500	0.6667	1.6497	5.6997	10.0214	3.4125	6.512×10^{-6}

Assuming that the cylinder specimen length (b), diameter (d), and the crack lengths ($2a_o$) will always be the same for a standardized procedure, the only input necessary for the calculations is the maximum applied load for each of the three different specimens. From the fracture mechanics theory, the fracture parameters are calculated. Figure 3.13 shows the results of Table 3.2 in graphical form. From analysis of the data shown in Table 3.2 and plotted in Figure 3.13 the fracture toughness, K_{If}, and the fracture process zone length, c_f, can be determined as $K_{i\ f}$ = 28.8 mPa $mm^{1/2}$ (818.95 psi $in^{½}$), and $c_f = 22.5$ mm (0.886 in). With the fracture parameters identified, the following expression can be used to calculate the strength of any pavement (or structure) made of this concrete:

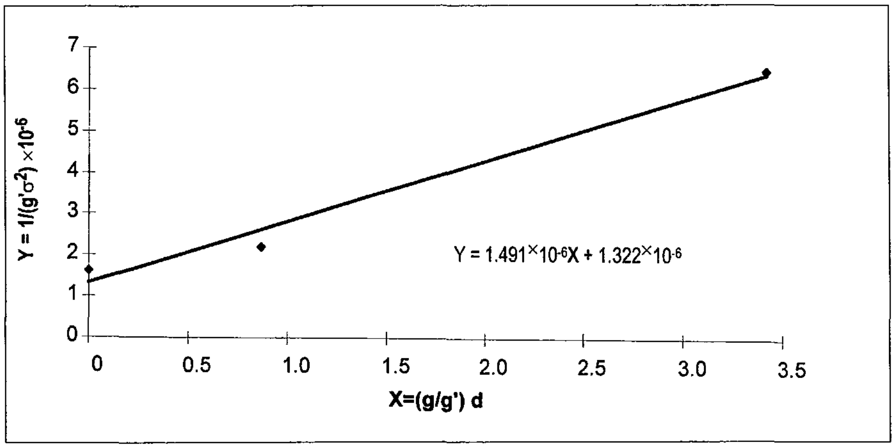


Figure 3.13 Fracture Test Results.

$$\sigma_N = c_n \frac{K_{If}}{\sqrt{g'(\alpha_0)\, c_f + g(\alpha_0)\, d}} \tag{3.18}$$

This expression is now applied to obtain the strength of a concrete pavement slab. The factor c changes for each structure type and for a concrete pavement is a function of the radius of relative stiffness which is 1.72 for this example. With a slab thickness of h = 254 mm (10 in), the pavement slab strength, σ_N, can be calculated as a function of the crack ratio (α) and the fracture parameters. The fracture parameters can be obtained from the cylindrical specimens as explained in the application above and will vary according to aggregate type, shape, and texture. Figure 2.3 shows how the pavement slab strength, s_N, varies with the crack ratio, a. The plot also shows the strength variation for more brittle concretes, i.e., concretes with lower K_{If} and c_f values.

Test Equipment

No special test equipment or training is necessary for this test procedure other than the provision for the specially made inserts which are used to shape the slots in the concrete cylinder specimens.

Maturity Test to Measure In-Place Strength

The maturity test method has been continuously developed since SHRP Product 2022 appeared. It is a nondestructive in-place test method that can be used to determine the degree of hydration of hardening concrete as a function of the time-temperature history of the concrete. Maturity (M) can be calculated as:

$$M = \sum \left(T - T_0\right)\Delta t \tag{3.19}$$

where T is the temperature of the concrete, and T_0 is a reference temperature dependant upon the characteristics of the cement. Maturity can also be found in terms of equivalent age, which is a function of the activation energy of the cement and is a key material characteristic. Many advancements have been made in measuring of maturity and techniques for correlating maturity and strength. A simple method has been developed by TTI (Johnson et al., 1994), referred to as the "one-graph" method. This method combines data from lab tests and field tests in a single graph to predict the strength of concrete pavement or structure in the field. The maturity method is a very promising, nondestructive test method for concrete quality control/assurance.

Performance

The degree of hydration serves as a very good indicator of the strength of concrete, which is a direct indicator of concrete performance. This implies that a correlation must be worked out prior to prediction of the concrete strength. Such correlations based on the degree of hydration are independent of placement temperature but are limited to a specific concrete mixture. However, the approach is very useful and can be calibrated quite easily for field applications. The factors that affect the development of strength, in most instances, are related to the development of temperature. Consequently, there is a natural correlation between the parameters encompassed within the maturity relationships which can be used to the construction engineer's benefit in terms of qualifying a given mixture proportioning for certain field applications. The degree of hydration is also useful in the assessment of the time of sawcutting during the placing operations and the time of opening for accelerated construction applications.

Nature of Test

The relationship between strength and temperature and the factors that affect it are related to the activation energy. The use of activation energy can be used to qualify concrete strength gain characteristics relative to different field conditions. A procedure can also be worked out between maturity and elapsed time since placement (in addition to strength) is useful in predicting the time of opening for a given mixture, as demonstrated in Figure 3.14. In this sense, the mixture can be qualified with respect to opening requirements for a given set of project conditions. Other factors can be brought into

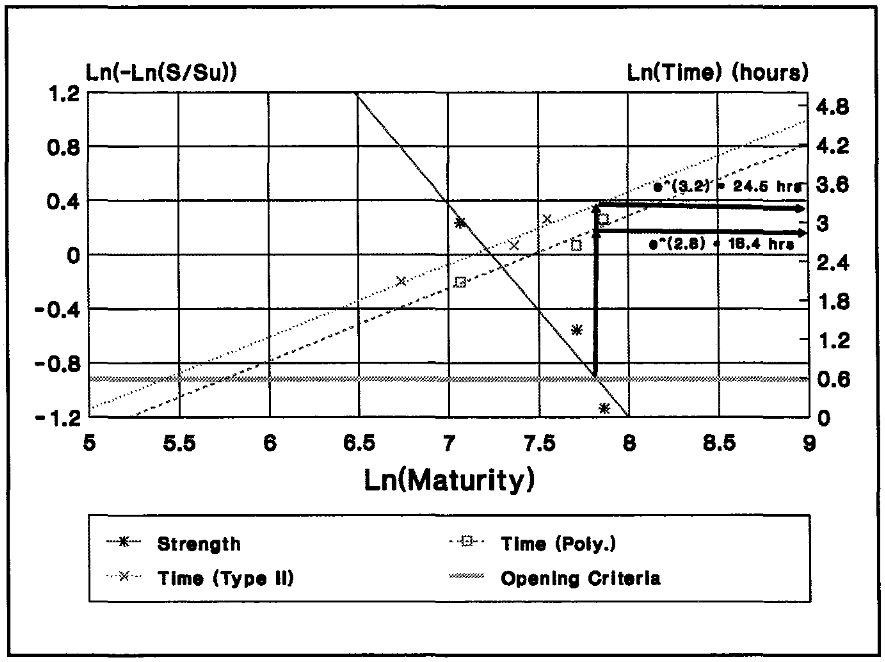


Figure 3.14 Characterization of Strength Gain Characteristics of Concrete Using Maturity Concepts.

perspective in the qualification process, such as other methods of curing, increased amounts of cement, and the use of different admixtures.

Regardless of the concrete mix constituents, it is important to note that the activation energy property plays a key role in determination of the rate of strength gain and how rapidly a certain amount of strength will be achieved under field conditions. The activation energy is a measure of how much energy is needed for a reaction (concrete hydration) to occur. For example, the activation energy of a Type III cement is lower than a Type I cement. This is because a Type I cement needs more energy than a Type III cement to complete hydration in the same amount of time. Energy can be provided to the mix by higher mixing water temperature, different curing methods, or a variation in temperature conditions. The effect of these measures will depend upon the activation energy (E) exhibited by the mix constituents. Energy exhibited by the mix constituents in combination with certain methods and conditions of curing may be useful to represent the effect on time of opening.

As a matter of interest, comparison is also made in Figure 3.14 from test data of two beams cured by different methods. Each beam, in this instance, was cured using Type II curing compound, with one of the beams covered with polyethylene sheeting. As can be observed, polyethylene sheeting affected the time of opening by eight hours, under the given field conditions. It should be noted that the field measurements can be made in terms of maturity (referred to as the temperature-time factor in ASTM C-1074) or as the equivalent age (t_e) at a specified reference temperature T_s. Depending on the method, the laboratory procedure (based on ASTM C-1074) should either provide the datum temperature or the activation energy (E). If the datum reference curing approach is taken in the field, it may be necessary to correct the maturity readout from the instrumentation according to the guidelines given in ASTM C-1074, if an inappropriate datum temperature is employed by the maturity meter.

Test Equipment

The test equipment only involves a maturity meter. These are available as single and multiple channel and can be set up to collect either maturity or equivalent age data. The inputs for the material properties of activation energy or reference temperature can be determined from following ASTM C-1074 or assumed, if necessary.

Torsion/Bond Shear Strength

Several different shear strength tests have been proposed in the literature and test standards, but only one has application to testing in the field. ASTM C-1042 provides a lab test method to measure the shear strength of a slanted bonded surface under compression stress state. SHRP Product 2025 refers to a direct shear test procedure in the lab for determining the shear strength of an interfacial bond layer. The ASTM C-1042 test is relatively simple compared with that of the shear test specified by Product 2025. Variability in the shear test data may be quite high which suggests that one should be cautious using this test. Report SHPR C-361 states that no precision criterion for the shear test has been available.

The direct shear test, which is conducted in the lab, was designed to estimate the bond strength of concrete overlay to the existing concrete pavement. However, a pure shear stress state hardly exists in the bond interface. Since failure occurs in a complex stress state, with only the shear strength determined by a direct shear test, a failure criterion cannot be established. A Mohr-Coulomb type (or Drucker-Prager) criterion is required.

The most promising in-place shear test consists of a torsional test device (torque wrench - Figure 3.15) to

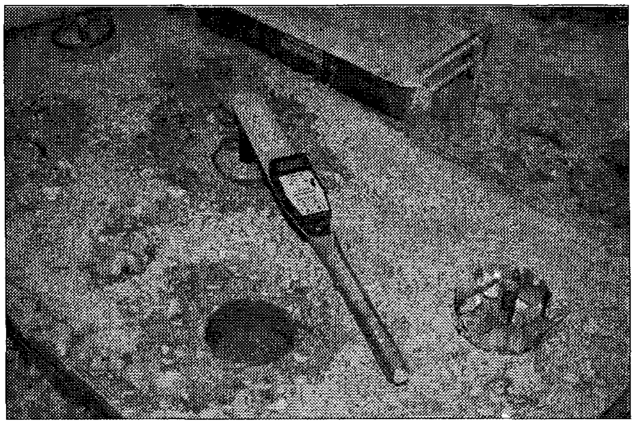


Figure 3.15 Digital Torque Wrench for Torsional Shear Strength Test.

measure torsional shear strength of a bonded overlay. This test was originally developed at the Center for Transportation Research, The University of Texas at Austin, and was modified based on work done at TTI for the FHWA. Practice at TTI has shown that careful operation of the test equipment results in data with very little variation.

Performance

The performance of the overlay bond can be characterized in terms of the measured early-aged shear strength in terms of the curing conditions at the time of placement. In this regard, early-aged strength gain of the overlay bond needs to be greater than the shrinkage stresses which develop during the curing of the concrete overlay. The measured strength of the overlay bond can be correlated with the characteristics of the existing surface and the quality or effectiveness of the curing during the hardening stages.

Nature of Test

It should be pointed out that the strength of the overlay bond interface can be broken down into two components: one of tensile strength and the other of shear strength. The combination of these components help describe the total strength envelope of the interface, as illustrated in Figure 3.16 in the

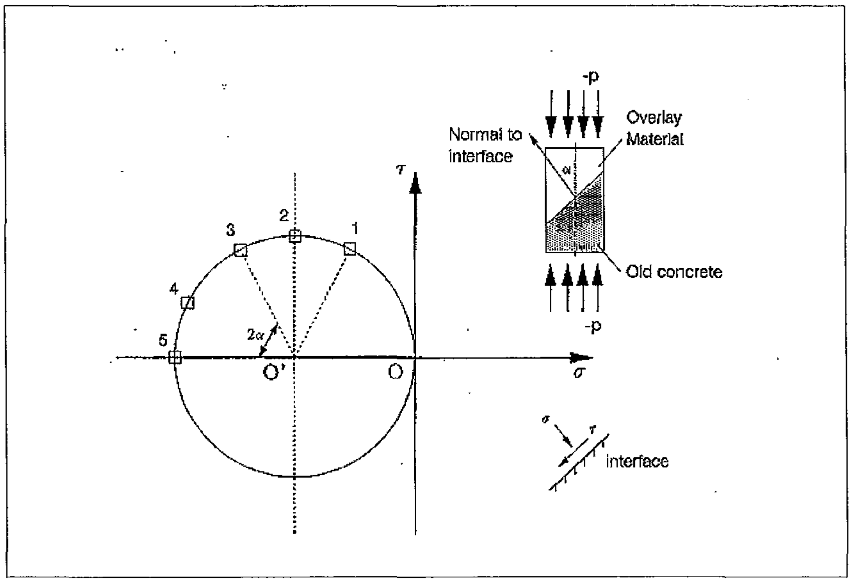


Figure 3.16 Strength Components of the Bond Interface as Illustrated in the Form of Mohr's Circle.

format of Mohr's circle. The strength components, as associated with the ASTM C 1042 shear strength specimen, are also illustrated as different orientations (α). As the specimen axis rotates from $\alpha = 0°$ to $\alpha = 90°$, the shear component (τ) increases to a maximum of ½ σ.

The shear strength of the interface can be measured in the field using specially made vane shear devices and a commercially available torque wrench which has the capability to automatically record the maximum torque value. The torque value (T) of the wrench can be related to the rotational shear strength as follows:

$$\tau_{max} = Tc/J \tag{3.20}$$

where

$J = \pi\, c^4/2$ (polar moment of inertia)
c = specimen radius

with specimen a radius of 50 mm (2 in), $\tau_{max} = 0.955T$ (or conveniently taken as T) where T is in foot-pounds and τ_{max} is in units of pounds per square inch (psi). Measured shear strengths taken on two different occasions are shown in Figure 3.17 and Table 3.3 relative to the maturity of the bond interface. As noted, the ultimate strength of the each trend curve is different (which can be predicted from the trend in the data) and is actually a function of the curing or weather conditions at the time of construction.

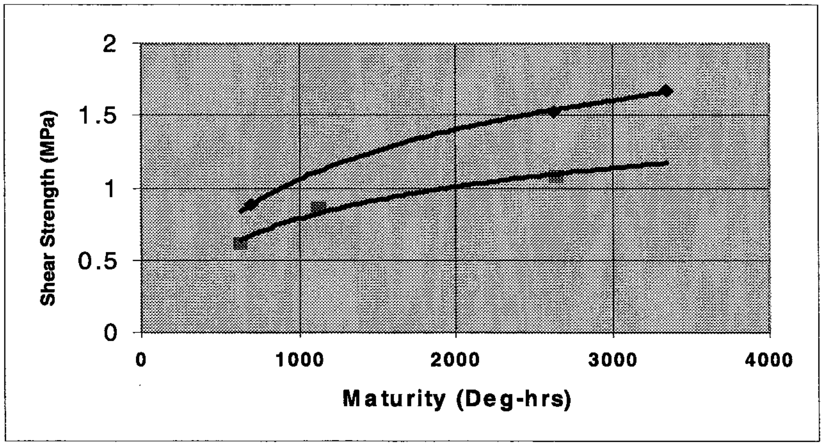
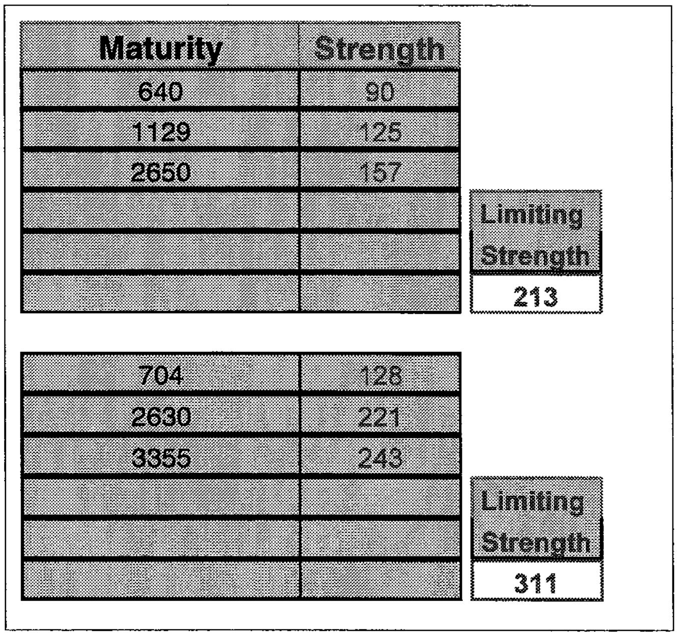


Figure 3.17 Maturity-Shear Strength Trendline for BW-8 5.1 cm (2 in) BCO.

As a demonstration of the maturity method, the strength of the bond can be represented independent of weather and curing conditions if it is characterized in terms of

Table 3.3 Field Shear Strength Data from BW-8 BCO (1psi = 6.89 Kpa).



Maturity	Strength	
640	90	
1129	125	
2650	157	
		Limiting Strength
		213
704	128	
2630	221	
3355	243	
		Limiting Strength
		311

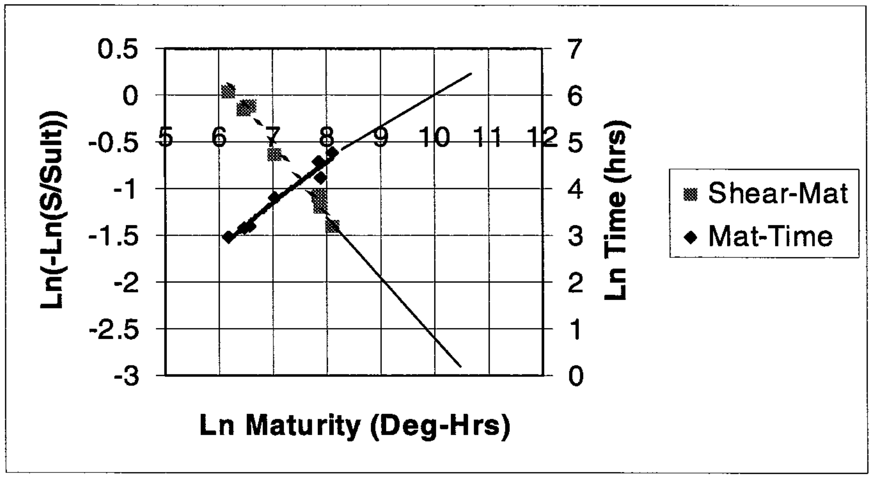


Figure 3.18 Relative Strength/Maturity/Time Relationship for BW-8 5.1 cm (2 in) BCO.

relative strength (where each measured value is divided by the ultimate strength value), as shown in Figure 3.18. The strength relationship can also be extrapolated reasonably accurately to provide an estimate of the maturity at future times, such as when the opening strengths will be achieved. Also shown in Figure 3.18 is the relationship between the maturity of the interface and the time since placement of the overlay concrete. As a demonstration of the prediction of the opening time, if the strength of 1.38 Mpa (200 psi) is considered to be adequate for opening bond strength (1.38 MPa - this corresponds to a relative value of 1.38/2.14 = 0.64 or -0.82 on the y-axis in Figure 3.18 and projecting to the x-axis), it can be determined that a Ln maturity of 7.3 is required before a strength of 1.38 Mpa (200 psi) is achieved. Projecting over to the time axis, this degree of maturity can be achieved at a Ln time of 4 (two to three days of age). Figure 3.18 is a demonstration of how maturity can be used to project the expected strength performance of the BCO to control the strength gain of the overlay bond at the interface relative to a QC/QA program for the construction of bonded overlays.

Test Equipment

The test equipment for the torsion device is fairly simple and does not require special training to use. The shear vane devices must be specially made but are not a costly item. The torque wrench for this test procedure is commercially available at most hardware stores.

Adiabatic Heat Signature

The reaction associated with the hydration of concrete releases heat which, along with the ambient temperature conditions, affects the temperature at which concrete ultimately sets. The set temperature can be predicted with information such as the adiabatic heat signature curve for a given mixture of concrete. Determination of this curve can be obtained by use of an adiabatic calorimeter (Figure 3.19) which provides an insulated container for a concrete mixture to harden while its temperature-time data is recorded.

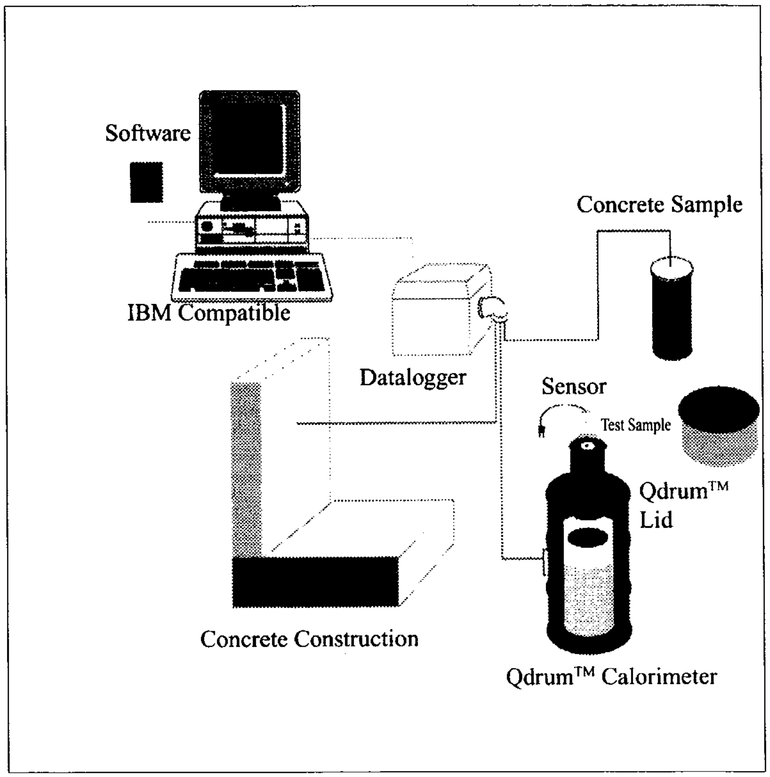


Figure 3.19 AHS System.

Performance

The set temperature of concrete is a key factor in the development of temperature related cracking. The relationship to structural criteria is how well the concrete thermal characteristics balance with prevailing temperature and curing conditions at the time of placement. This criterion constitutes a precondition for the materials and the method of curing to be qualified prior to and during construction of the pavement. Failure to meet this critical balance may result in excessive cracking and a deteriorated structural condition. The adiabatic heat signature (AHS) of concrete has been found to be closely correlated to strength, water-cementitious ratio, initial and final setting times, and the chemical makeup of the mix.

Nature of the Test

The AHS test is a new NDT method for concrete during its early-age curing and hardening. The AHS method can be used to generate heat of hydration data (Figure 3.20) for a variety of concrete mix designs. The concrete in a fresh state is placed in the calorimeter and allowed to hydrate. This procedure can be followed in both the lab and the field. The results are used to assess potential cracking and strength development for a given construction project.

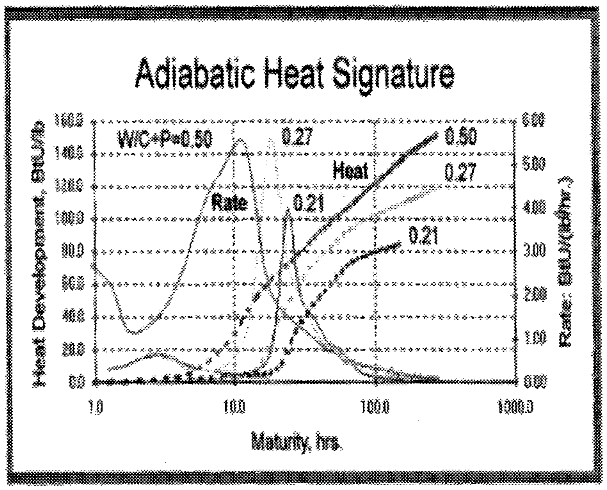


Figure 3.20 AHS Curve.

Test Equipment

A computer software package named Quadrel (product of Digital Site Systems, Inc., Pittsburgh, PA as shown in Figure 3.19) was recently developed to computerize the AHS measurement and strength determination. The equipment modules and the software cost approximately $25,000.

Volumetric Dilatometer

A dilatometer developed at TTI provides a laboratory test method to measure the coefficient of thermal expansion (CTE) of coarse and fine aggregate. This device consists of a stainless steel camber in which to place aggregates, crushed concrete, or partial concrete cores in which the thermal coefficient of expansion is desired. This method is particularly adaptable to the study of saturated aggregate, sand, or concrete and provides a means of testing a representative sample of a heterogeneous aggregate.

Performance

Concrete is a heterogeneous mix of cement, water, and fine and coarse aggregates. The complex interaction between its components and the nature of its components and their proportion in the mix determine the properties of concrete. The fine and coarse aggregates normally constitute about 75 percent of concrete, and their physical characteristics have a considerable effect on properties of concrete. During the past decade, several investigators have shown that low durability of concrete could be caused by the incompatibility between the thermal properties of cement mortar and the aggregate. Pavement distresses, such as blowups, faulting, corner breaks, and spalling, are indirectly related to the thermal properties of concrete. The coefficients of thermal expansion of the aggregates determine the thermal expansion of concrete to a considerable extent. This parameter also ties into the AHS previously described since it relates the amount of temperature strain to the amount of the temperature change in reference to the set temperature. Proper characterization of aggregate properties allows us to predict the behavior of concrete with greater confidence and leads to more accurate design.

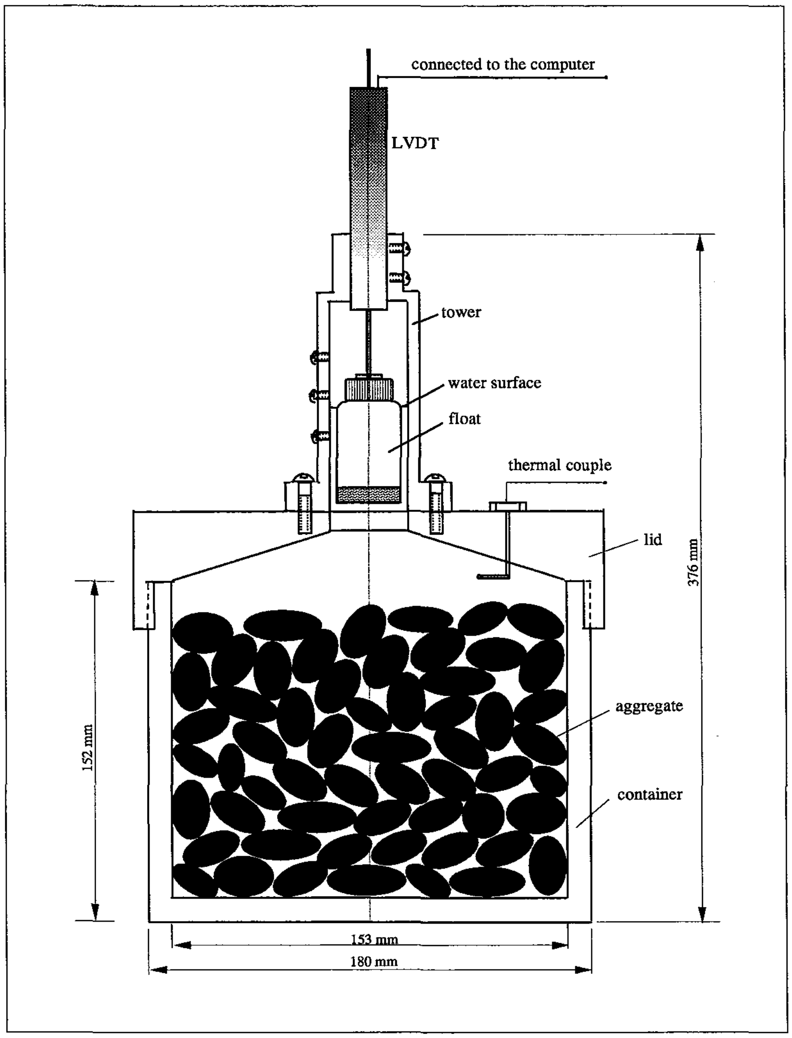


Figure 3.21 Schematic Diagram of Volumetric Dilatometer.

Nature of Test

The dilatometer shown in Figure 3.21, developed in Project 2992 "Development of Thermal Coefficient of Expansion Test," consists of a stainless steel container, a brass lid, a glass float to which a LVDT is attached, a thermocouple, and a data acquisition system. Heated in a water bath, the dilatometer allows the aggregates to be submerged in water. The dilatometer is calibrated to allow for a method to separate the volumetric expansion of the water and the dilatometer from the volumetric expansion of the aggregate. The coefficient of linear thermal expansion is one-third of the coefficient of volumetric thermal expansion. The dilatometer is 153 mm (6 in) in diameter and therefore capable of measuring aggregates of large sizes, large blocks of concrete specimen, or hardened cement paste specimen. It allows aggregates of different sizes in a sample, which is particularly useful in obtaining the overall average coefficient of thermal expansion of a saturated heterogeneous mix of aggregates in a gradation, which is commonly found in a concrete paving mixture.

In operation, the container is placed in the water bath and heated by the water surrounding it. When the temperature is raised from T_1 to T_2, the aggregate, the water, and the container all expand. Therefore, the apparent volume change that the LVDT detects consists of three parts:

$$\Delta V_1 = Ah = \Delta V_a + \Delta V_w - {}_{\Delta vf} \tag{3.21}$$

where

ΔV_1 = observed total volumetric increase due to temperature change ΔT,

A = inner sectional area of tower,

Δh = rise of the water surface inside the tower,

ΔV_w = volumetric increase of water due to temperature ΔT,

ΔV_f = volumetric increase of inside volume of the dilatometer due to ΔT,

ΔV_a = volumetric increase of aggregate V_a due to ΔT, and

ΔT = temperature increase from T_1 to T_2.

Since

$$V_f = V_a + V_w = V$$

$$\Delta V = V_a \gamma_a \Delta T$$

$$\Delta V_f = V \gamma_f \Delta T$$

$$\Delta V_w = V_w \gamma_w \Delta T = (V - V_a)\gamma_w \Delta T \tag{3.22}$$

where

V = total inner volume of the flask,

V_w = volume of water in the flask,

V_f = volume of the flask,

V_a = volume of aggregate in the flask,

γ_a = coefficient of volumetric thermal expansion of aggregate,

γ_w = coefficient of volumetric thermal expansion of water, and

γ_f = coefficient of volumetric thermal expansion of flask, we have

$$V_a\gamma_a\Delta T + (V - V_a)\gamma_w\Delta T = \Delta V_1 + V\gamma_f\Delta T \tag{3.23}$$

$$\gamma_a = \frac{\Delta V_1}{V_a\Delta T} - \left(\frac{V}{V_a} - 1\right)(\gamma_w - \gamma_f) + \gamma_f$$

It can be seen from the above expression that, besides ΔV_1, T_1 and T_2, γ_w and γ_f are required due to the temperature increase from T_1 to T_2 in order to determine the coefficient of thermal expansion of the aggregate γ_a.

Other methods are also available to measure the thermal coefficent of expansion of concrete, including a variation of the volumetric dilatometer known as the linear dilatometer which is still under development. The linear device is specifically designed for the measurement of the thermal expansion of a concrete cylinder and not rated in this report, but it is expected to have a high utility value. Three other methods, using a length comparator, a demac gage, and a strain gage, have also been used for determining the coefficient of thermal expansion of concrete or mortar specimens. The test method using the length comparator is described in ASTM C531, "Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical - Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concrete." Generally, the experience with these devices has not been satisfactory; neither the length comparator or the Demac gage provided adequate accuracy, and use of strain gages can be difficult to manage. All these tests are laboratory tests except that the Demac can be used in the field. Both the length comparator and the Demac gage are low-cost and portable.

Test Equipment

The dilatometer consists of a stainless steel cylindrical container, a brass lid, a hollowed tower standing on the lid, and a float. The inner surface of the lid is configured at a certain angle so that the entrapped air bubbles can easily move along the surface. A linear variable differential transducer (LVDT) is installed, and its core is connected to the float to measure the rise of the water surface. Electrical signals from the LVDT are generated as the core moves. The signals are acquired and amplified by a signal conditioner and then recorded by a computer data acquisition system. The LVDT used is a lucas/schaevitz Model MHR .050, which provides a voltage of 10.00 volts for a displacement of 1.27 mm (0.050 in). A guide rod is installed above the core of the LVDT to keep the float/LVDT core assembly vertically aligned. A thermocouple is immersed in the water to monitor the temperature inside the container. The dilatometer is equipped with a computerized data acquisition system to simultaneously record the temperature and aggregate's volumetric change. With this device, volumetric change of aggregate can be measured in a larger temperature range from 4°C to 60°C.

Figure 3.22 View of the Dew Point Indicator.

Dew Point Indicator

Material-related moisture properties (permeability, diffusivity, etc.) of concrete play a key role in the mathematical modeling and representation of stress and strain due to drying shrinkage and creep under varying humidity conditions. Conventionally, moisture in concrete has been measured by actual weight measurements which reflect the remaining water in the bulk sample. Measurement of relative humidity in the pore of concrete makes it possible to assess the moisture content in concrete in-place. Recently, work at TTI has involved the use of dew point indicators (Figure 3.22) to provide measurements that can be used for the determination of the relative humidity in both field or laboratory concrete. The relative humidity is determined from measured dew point and dry bulb temperature.

Performance

The determination of relative humidity during paving operations is important for an indication of the degree of drying shrinkage that is occurring in the concrete and the associated degree of cracking. The amount of cracking energy supplied by the loss of moisture from the concrete must be controlled to ensure that it is not excessive but sufficient to initial cracking at sawcut joints. In this accord, dew point indicators placed at selected depths from the concrete pavement surface can be used to assess the curing effectiveness, which forms an index for QC/OA measure in pavement curing. The other aspect of moisture loss during curing is its effect upon strength. This effect can be reflected in the effect the level of relative humidity has on the development of maturity of hydrating concrete. The maturity equation is typically expressed as:

$$dM = (\beta_{rh})\beta_T dt; M = (\beta_{rh})\sum \frac{T - T_0}{T - T_r}\Delta t \tag{3.24}$$

This is, in reality, missing the moisture term β_{rh} (shown in the parenthesis) since it has always been assumed to be equal to 1.0. Bažant and Najjar (1972) suggest that β_{rh} can be calculated as: $\beta_{rh}=[1+(7.5-7.5*rh)^4]^{-1}$. As shown in Figure 3.23, the values of β_{rh} drop rapidly at a relative humidity below 92 percent, which can induce significant loss of strength. The degree of hydration is affected by the amount of moisture available for curing. If the water evaporates during the hardening stages, strength reductions will be encountered, as has been demonstrated by

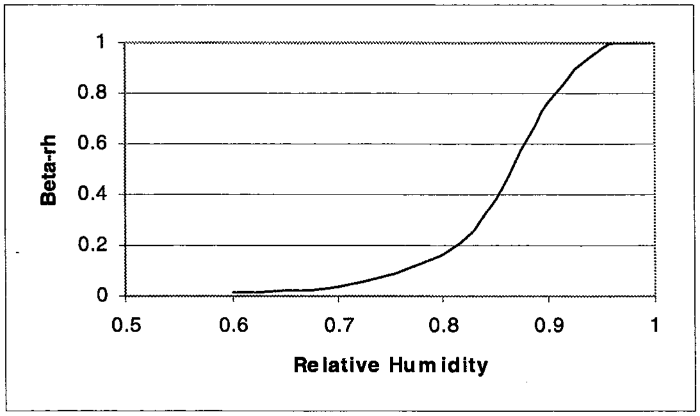


Figure 3.23 Moisture Factor on Concrete Curing.

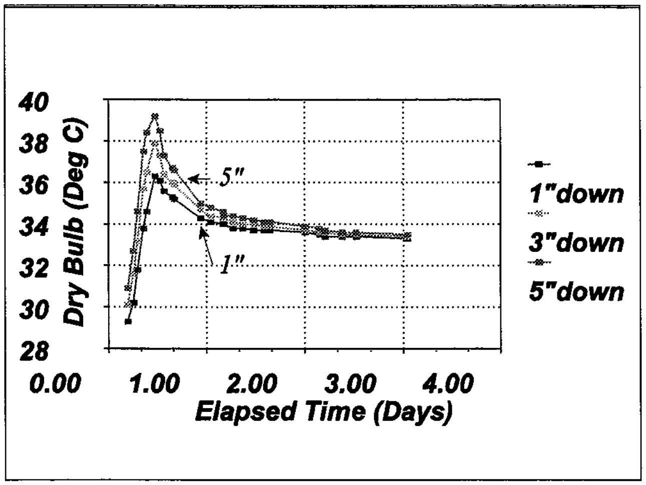


Figure 3.24a Collected Dry Bulb Temperature Data. (1 in = 25.4 cm)

using the split tensile method on cored strength specimens (Nelson et al., 1997).

Nature of Test

Measurements of dry bulb temperature and dew point temperature at specified locations can be made in either hardening or hardened concrete in the field or the laboratory with the dew point indicators. Examples of measurements are illustrated in Figures 3.24a - d. In these figures, moisture measurements were taken 25, 76, and 127 mm below the exposed surface of a hardening concrete specimen. The specimens were placed in an "environmental chamber" after casting where the room temperature and relative humidity were controlled at 32°C and 50 percent, respectively. The dew point and temperature data (Figures 3.24a and b) were recorded from the dew point indicator over a period of three days. The pore relative humidity shown in Figure 3.24c at 25, 76, and 127 mm below the surface of the specimen was calculated from the dew point and temperature measurements. During the early-age drying of concrete, the heat of hydration changes the temperature of concrete. This temperature variation affects the relative humidity since relative humidity is a function of temperature. The calculation of relative humidity can be corrected to a constant temperature condition which is independent of the temperature effect. Figure

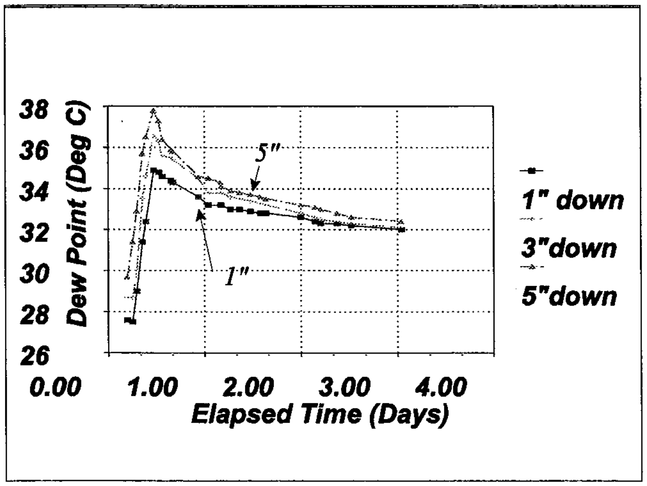


Figure 3.24b Collected Dew Point Temperature Data. (1 in = 25.4 cm)

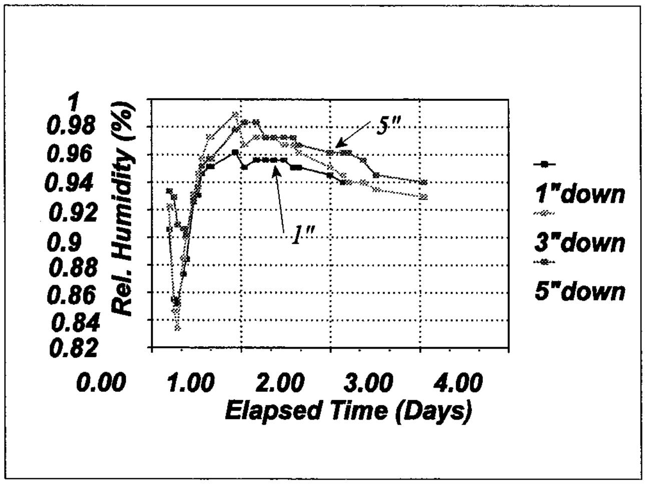


Figure 3.24c Relative Humidity Under Variable Temperature Conditions. (1 in = 25.4 mm)

3.24c shows the relative humidity vs. time data for a variable temperature (before correction), while Figure 3.24d shows relative humidity at a constant temperature (after correction). It can be seen that the greater the distance from the drying surface, the higher the pore relative humidity of the concrete.

This type of data can be used to characterize the quality of the curing in terms of the curing effectiveness provided to a paved concrete surface. The effectiveness of curing can be assessed by determining the relative humidity (rh) of the concrete at two points below the surface and that of the ambient weather conditions immediately above the surface of the concrete (such as by use of a weather station).

The effectiveness of curing can be characterized in terms of the equivalent thickness of concrete that would be required to achieve the same degree of curing provided by a curing membrane or compound placed on the concrete surface to inhibit the loss of moisture from the concrete to the atmosphere. The rate of moisture loss through the curing compound may be represented by the difference in Gibb's free energy (μ) per unit mass of water in the concrete below the interface and in the atmosphere above the curing membrane. Gibb's energy (μ = RT/M

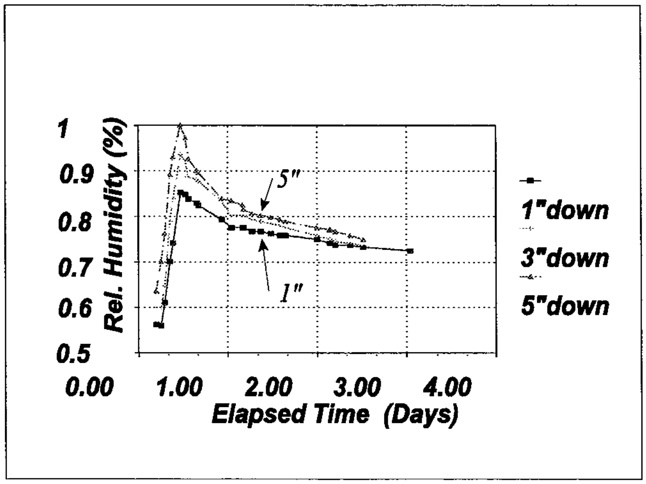


Figure 3.24d Relative Humidity Under Constant Temperature Conditions. (1 in = 25.4 mm)

•ln (rh)) is a function of the universal gas constant (R), the molecular weight of water (M), and the absolute temperature (T). Neglecting the effect of a difference between the surface and environmental temperatures (which is small if the moisture evaporates slowly), the difference in μ is proportional to Ln (rh_{env}) - Ln (rh). Thus, for small rates of tranfer:

$$n\,J = -B(\mathrm{Ln}\,(rh_{env}) - \mathrm{Ln}\,(rh)) \tag{3.25}$$

where

B = surface emissivity, which depends on T and the circulation of air, and
n = unit outward normal at the surface.

The rate of diffusion of water (J) through concrete is also represented in terms of Gibb's energy as:

$$J = -c \bullet \mathrm{grad}\,\mu \tag{3.26}$$

where c = coefficient characterizing the permeability of concrete. Combining the two above expressions, the boundary interface conditions can be represented as:

$$L \bullet n \bullet \mathrm{grad}\,(rh) = \mathrm{Ln}(rh/rh_{env}) \tag{3.27}$$

where

L = c_1/B (equivalent thickness of curing membrane), and
c_1 = permeability of concrete.

The term L is in units of length and represents the effective thickness of the curing membrane or the equivalent amount of additional concrete to achieve the same degree of curing as the curing membrane. Using the expression for L, data collected from paving projects in the field using a double coat of curing compound are illustrated in Figure 3.25. The data shown in this figure represents a quality of curing that has been sufficient to ensure against delamination for bonded concrete overlay construction. Note that the required quality of curing is a function of the ambient environmental conditions.

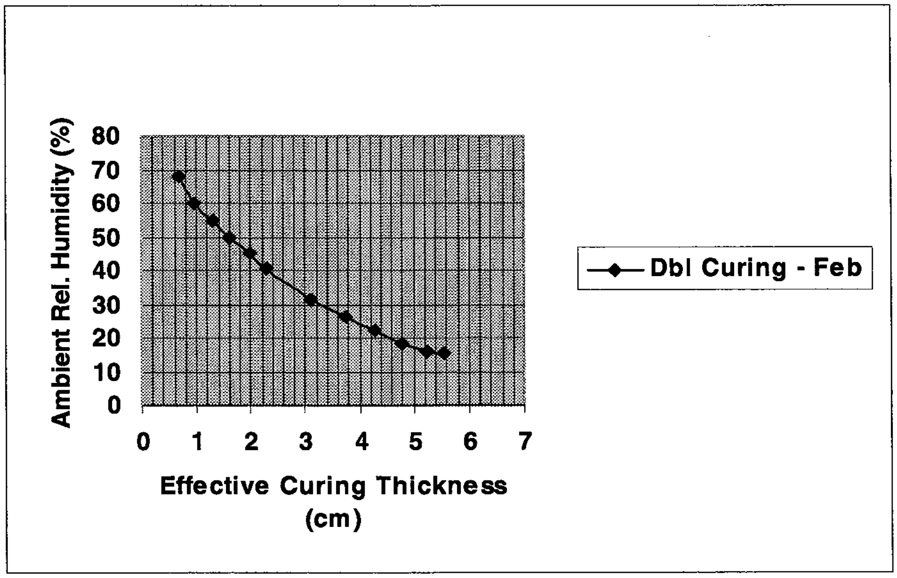


Figure 3.25 Standard for Curing Effectiveness Based on Field Data.

Test Equipment

The test equipment for the dew point indicator is commercially available only in the configurations illustrated above. Devices to monitor curing effectiveness are under development but will consist of two dew point indicators and a bulk polymer type relative humidity indicator for use in ambient condition monitoring. Depending upon how the device is implemented in the field, a datalogger will also be used to record data with time and to provide calculated effective curing thicknesses. The cost of this equipment is expected to be under $20,000.

Oxide Analysis

Although not elaborated here, the thermal coefficient of expansion of an aggregate can be found from the oxide content of the aggregate. Aggregates can be analyzed chemically to determine their oxide content. These results can be used to predict aggregate thermal behavior. Such an analysis can be carried out using the technique of Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) (Pfeifer and Scali, 1981; Varma, 1991, Thompson, 1989). This method has a wide range of applications. It is used in geochemistry for silicate rock analysis which involves determination of major element constituents like SiO_2, Al_2O_3, FeO, MgO, CaO, Na_2O, K_2O, MnO, and P_2O_5. It is also used in rare earth element determinations and in trace element analysis. ICP-AES is also used to determine the quality of water, both for waste and consumption. There are various environmental applications, such as analysis of domestic dust, road dust, and industrial dust. It is also used in the analysis of plant and animal tissue.

Performance

The results of this test related to performance for the same reasons the results of the volumetric dilatometer do. The results require correlation with the results from the dilatometer in order to be useful in assessment of the structural design criteria.

Nature of Test

The ICP-AES is an analysis technique conducted in the laboratory and used for determining the elements in solution samples using the spectra emitted by free atoms or ions. The method is based on AES coupled with an ICP source. The ICP source produces a stream of high energy ionized gas, known as plasma, by inductively coupling (i.e., inducing current flows in the ionized medium) an inert gas, generally argon, with a high frequency field. The current flows cause resistive heating of the plasma gas. The resulting plasma will have a temperature of 10,000 K, with the help of which it dissociates and atomizes the element present in the sample. The plasma excites the atoms resulting in emission of light of unique frequencies for each of the given elements. The light emitted from the plasma is proportional to the concentration of the elements in the sample. The emission spectrometer has the capability of separating the unique frequencies into discrete wavelengths, each wavelength or frequency being a function of the element present. Depending on the concentration of the different samples present the ion sample, a light of corresponding frequency is emitted. Since the concentration of the element is proportional to the emitted light intensity, the measuring electronics in the spectrometer compute the correlation between them and quantify the results.

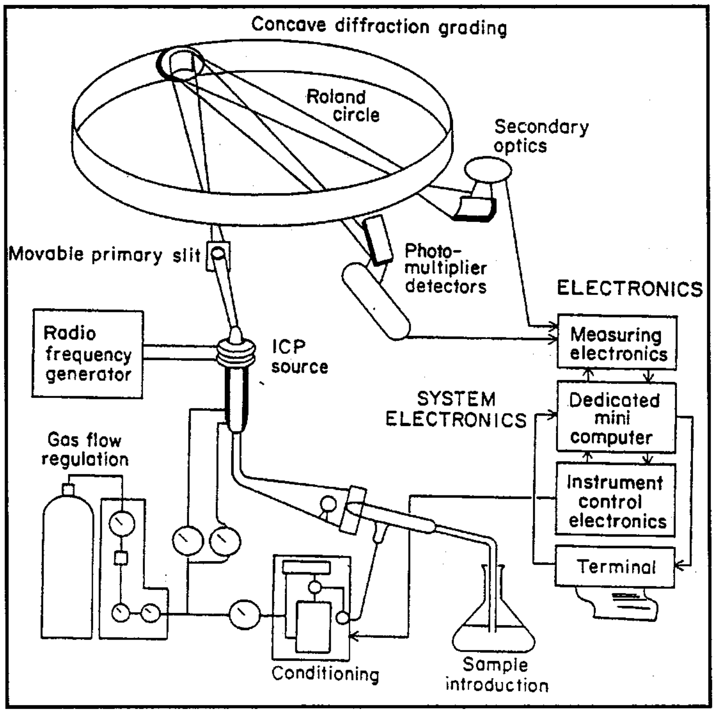


Figure 3.26 Schematic View of ICP-AES. (Fassel, 1974).

Test Equipment

A schematic of the Spectrometer is shown in Figure 3.26. The basic components of the Inductively Coupled Atomic Emission Spectroscopy Instrument are spectrometer, detector, ICP source, nebulizer, spray chamber, design torch for sample introduction, along with a minicomputer for data storage analysis. Argon gas, sulfuric acid, nitric acid, hydrochloric acid, and deionized water constitute the required reagents, and glassware such as pipettes, and volumetric flasks are required for sample dilution. The ICP-AES is one of the most versatile analytical tools for quantitative multi-element analysis but is only available in certain laboratories. Due to this limitation, oxide analysis can also be conducted using scanning electromagnetic technology, which is more readily available.

Compression Test to Measure Elastic Modulus

As for compressive strength, ASTM C-39 is widely used, and the results can be used to estimate the modulus of elasticity of the concrete. SHRP Product 2024 is a proposed improvement of the compression test by the use of steel caps with neoprene pads instead of sulfur caps. This alteration of specimen capping technique has actually been proposed by AASHTO T-22. Product 2024 suggests use of the linear voltage differential transducers (LVDTs) to measure the length change of the specimen. With this suggestion, this procedure can be considered as an advancement over the procedure outlined in ASTM C-469. ASTM C-469 uses a compressometer and an extensometer to measure the dimensional change of the specimen during the compression test for determining the modulus of elasticity and the Poisson ratio.

Performance

The modulus of elasticity found from this procedure would improve the accuracy of a back-calculation scheme to find the in-place pavement stiffness. As pointed out previously, the elastic modulus of the concrete is important to the load bearing and load distribution capability of the pavement system.

Nature of Test

This test is strictly limited to the laboratory and is destructive but provides a very accurate indication of the modulus elasticity of concrete. During the test, both load and deflection are recorded and used in the determination of this property. The modulus determined from the stress and strain data can also be checked against the ACI equation that uses the compressive strength of the concrete to estimate the modulus of elasticity.

Test Equipment

The ASTM standard does not require automatic recording of data from the compressometer and extensometer. Instead, data can be read manually through the dial gage. As the electronic technology develops, automatic recording of data is more likely.

Drop Test

A test procedure to measure the mobility of a concrete mixture with a slump less than 50 mm is needed to ensure sufficient workability during placing operations of reinforced concrete pavements. Mobility of a concrete mixture may be defined in terms of its response to vibration and movement without segregation of the coarse aggregate. Mobility also relates to the degree and consolidation as it would be indicated by the in-place unit weight.

Performance

Mobililty is not directly related to performance but is an indicator of how easily it is to place a concrete mixture that consists of a slump less than 50 mm. Poor consolidation and placement will lead to rock pockets and long bond development lengths in reinforced concrete pavements. Poor mobility may also result in vibrator trails and other related defects in the pavement surface.

Nature of Test

The test is a simple measure of the number of drops it takes to cause a concrete mixture placed in a slump cone to bulge laterally outward to a given diameter. This test can be conducted in both the lab and the field (Figure 3.27). The concrete is placed in the slump cone according to standard procedures which allows the drop test to be conducted in conjunction with the slump test. The drop table is constructed with a pre-set drop height and is used to place the cone of fresh concrete during the drop test. The table platform is manually raised and dropped until the concrete has bulged to a pre-selected diameter.

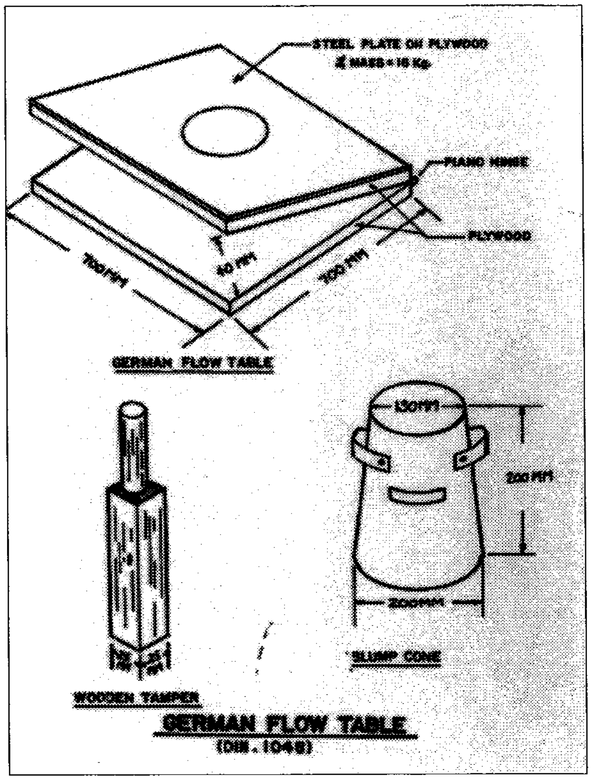


Figure 3.27 Drop Test Configuration.

Test Equipment

The test equipment uses a standard slump cone and a drop table. The drop table can be easily manufactured.

JOINT SEALANT MATERIALS

Tensile Bond Strength Between Sealant Material and Concrete

Testing bond strength of polymer, rubber, or silicone sealants can be done with a laboratory test method of measuring the tensile bond strength between concrete blocks and sealant material. This test method was developed at TTI for the purpose of evaluating the degree of bond provided by different sealants. The test procedure tests the bond strength to concrete made with crushed limestone as coarse aggregate.

Performance

The strength of the bond between the sealant and the side of the concrete joint well governs the performance of the sealant material. Most sealants fail or debond at the joint well interface. The level of stress on the bonded interface depends upon the spacing between joints and how wide the joint well widens due to daily and seasonal temperature change. Bond stress can be tied directly to joint width opening calculations. Performance models for joint sealants are based on debonding.

Nature of Test

Procedures of test specimen preparation, curing, and testing are all specified according to ASTM D 3583. This test is strictly conducted in the laboratory but can be conducted on specimens retrieved from the field.

Test Equipment

A conventional laboratory material strength testing machine is needed to record the maximum load. The test is simple and low-cost.

Stress Relaxation Test for Joint Sealant Materials

A laboratory test method of measuring the amount of stress relaxation has been devised for a polymer, rubber, or silicone joint sealant material. This test method was developed at TTI for the purpose of characterizing the stress relaxation properties of these materials.

Performance

Stress relaxation reduces the stress level of the sealant, and it is an indirect measure for the service time of the sealant joint. Many factors affect the relaxation modulus of a sealant material, including age, temperature, and deformation level.

Nature of Test

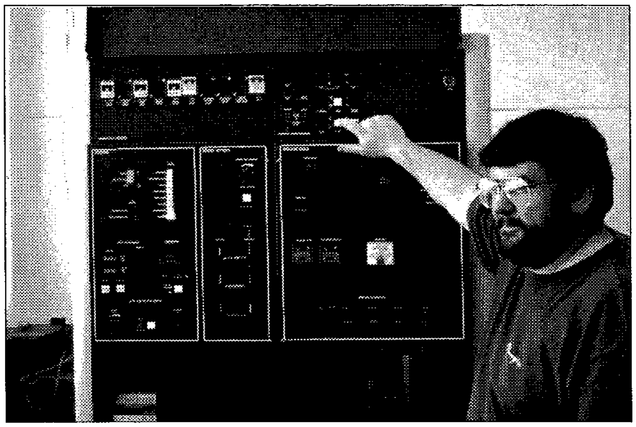


Figure 3.28 Atlas Weatherometer.

Sealant specimens are prepared and artificially aged. The artificial weathering procedure is simple and can be performed by a moderately skilled technician. The test method is a laboratory procedure, and the results of this test will be an indirect measure of how much weathering the material will undergo in the field. However, this test method will assist greatly in making a decision on which material should be used for given a weather cycle or climate. The test procedures specify the environmental conditions within the weatherometer and other details of specimen preparation, curing, and aging. In the testing, specimens are subjected to a unit extension of 10 percent, and load is recorded until 60 minutes. Tests of two aged specimens are required to observe the aging effect. Besides a material testing machine, a Weatherometer is needed to age specimens (Figure 3.28).

Test Equipment

The weatherometer is expensive and not available in most laboratories. The test equipment used for the relaxation procedure, however, can be found in any standard lab and can be operated by a moderately skilled technician.

Summary

Several tests presented in this chapter have application of varying degrees to the field and provide, in many instances, a direct measure of a key property or parameter relevant to performance and structural design criteria. Based on discussions in Chapter 2, it is also apparent how these parameters are included in mechanisms of distress that affect structural behavior. Identification and further discussion of promising test methodologies are presented in Chapter 4.

CHAPTER 4

DESIGN RELATED MATERIAL AND PERFORMANCE-BASED CONSTRUCTION TESTING RECOMMENDATIONS

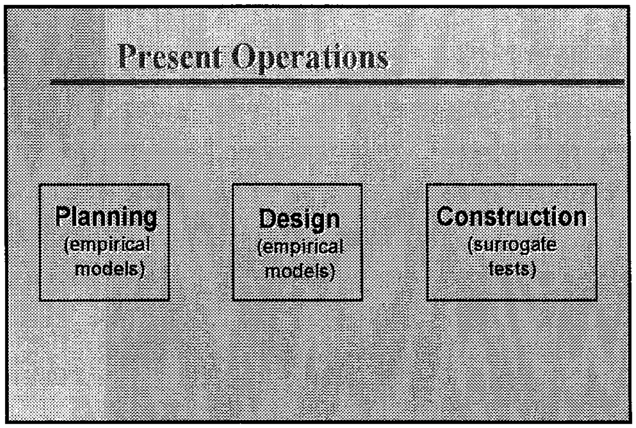


Figure 4.1 Present Operations.

In terms of where TxDOT currently stands, several different types of tests have been reviewed and assessed with respect to their utility to 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 4.1 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. Consequently, construction specifications, which are based upon such test properties and parameters, do not provide adequate basis to control quality. Discussion in Chapter 1 indicated the parameters that make up the current list of structural criteria and certain implications related to them relative to their deficiencies in addressing all aspects of pavement structural design criteria. Similar conclusions were drawn from the discussion in Appendix E which examined further the applicability of existing tests to pavement performance and structural criteria. All in all the assessment of existing TxDOT test procedures and design methodologies noted in this report were not particularly overwhelming and have warranted consideration of a new approach (Figure 4.2) to the identification of material tests more relevant to structural design criteria.

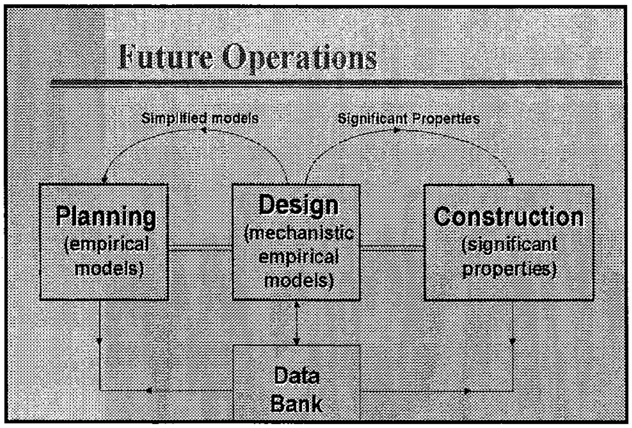


Figure 4.2 Future Operations.

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 contractor 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 4.1 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. These parameters match well to those associated with specific performance mechanisms described in Chapter 2. 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

Table 4.1 Structural Pavement Design Criteria Configurations.

Structural Criteria Category	Material/Pavement Property	Test Method
Strength	Concrete Tensile Strength	ASTM C 496
	Concrete Fracture Properties (K_{if}, c_f)	ASTM C 496 (mod),
	Aggregate/Mortar Bond	Pullout Fracture
	Bond Strength (overlays)	Torsional Shear
	Maturity (based on temperature and relative humidity)	ASTM C 1074
Stiffness	Concrete Modulus (E_c)	Tex-418, Stress wave
	Load Transfer Efficiency (LTE)	FWD, RDD
	Effective Crack Width	FWD, RDD
	Pavement/Joint Stiffness (ℓ_k)	FWD, RDD
	Foundation Modulus (k-value)	
	Subgrade Modulus (E_{SG})	Stiffness Gauge
	Subgrade Unit Weight and Moisture Content	GPR
Volumetric	Total Heat (H_U)	Adiabatic Temp Rise
	Activation Energy (E)	ASTM C 1074
	Thermal Coefficient of Expansion (α)	Volumetric
	Coarse Aggregate Oxide Analysis	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)	GPR
	Debonding/Delamination	Infrared
	Mobility	Thermographic
	Air Voids	Drop Test
	Aggregate Moisture Content	GPR
	Paving Thickness	GPR
	Steel location	GPR
		Magnetic/Electrical

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. As far as 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. Many of the tests reviewed in Chapter 3 lend themselves to rapid data collection and the collection of sufficient volumes of data to be used to accurately assess the coefficient of variation for some parameters noted in Table 4.1.

PROMISING TESTS FOR FUTURE OPERATIONS

Based on the review in Chapter 3 and the need to develop performance-based specifications, several tests stand out for future consideration. The promising tests to be recommended are addressed below with respect to the categories noted in Table 4.1. An additional category was added to those noted in Table 2.1 because of the impact these parameters have on the structural integrity of the pavement system. These tests did not necessarily meet the utility criteria of 80.

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 insurance of meeting structural strength criteria. Taking cores from the pavement to accomplish this, using the split tensile test specimens alone, has not proven to be an entirely practical solution. Other practical developments maybe 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 and 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. This test measures one component of the bond strength of an bond 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 are not discussed, 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 RDD offers some promising advantages to the FWD that would provide a thorough examination since the data are continuous in nature. The results of the RDD can be used to obtain LTE, effective crack widths in the assessment of the overall pavement stiffness. It may even be possible to exact a composite k-value 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 E value since it cannot be readily correlated to the subgrade k-value. 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 gauge 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.

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. The cement fineness (Tex-310-D) test was not listed, 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 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 GPR 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 GPR 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.

PROJECT 1735

Work under project 0-1735 "Development of Structural Field Testing of Flexible Pavement Layers" has focused on methods to determine layer moduli and thickness using conventional resilient modulus testing, deflection (FWD) methods, and seismic (stress wave) methods. Due to a number of complicating factors, it was determined that these methods yield different values of moduli that are a function of strain level and test method which are not applicable to design. With this finding, the project team has refocused on a combination of seismic and deflection methods to find a method to determine layer moduli. Three other methods are suggested to accomplish this objective:

1. Modified portable seismic pavement analyzer (PSPA),
2. Modified DCP with seismic sensors, and
3. A combined deflection/seismic device.

The PSPA seems to be aligned with the family of test methods that fall under the stress wave category and shows strong potential for the in-place determination of E_c of the concrete based on reduction of the data in the frequency domain. The modified DCP method appears to be a promising method to obtain the in-place elastic modulus of the base and subgrade layers as well but needs verification with respect to in-field testing. No assessment is made of the third item since it is still in the development stages, but it appears that some form of all these methods should have application to assessing the layer stiffness under a concrete pavement system if either an elastic solid or a Pasternak foundation model is incorporated for concrete pavement design which currently neither of these are. Based on the discussion of subgrade properties in Chapter 1, it is apparent that a decision needs to be made if a change in subgrade models for design will be made prior to selection of a test method for in-place verification of structural design criteria. Further consideration can be given to the Project 1735 approach when it is further developed with regard to its applicability to this study, but an approach of back-calculation was presented in Chapter 2, including the material characteristics that are used as inputs, and was matched to the tests recommended in this chapter. This approach should provide a starting point for the recommended test methods and their combined suitabililty in the assessment of the many aspects associated with structural design criteria for a concrete pavement.

FUTURE DIRECTIONS

In order to achieve a 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:

A. Propose research projects to formulate construction specifications incorporating performance-based test procedures.
B. Identify mechanistic performance models to predict performance based on the materials properties determined using the tests identified in A) above.
C. Identify construction projects suitable to implement on a trial basis performance-related construction specifications.
D. Evaluate the implementation of the construction specifications and identify where improvements can be made.
E. Make adjustments to the construction specification and the manner performance models are utilized in the design process.
F. Validate improvements in construction quality and accuracy of the prediction models.

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 how their benefits can be recognized and utilized particularly by the industry relative to improved construction quality and reduced variability. Following this process will facilitate the development of a vision of how continued improvement in both the design and construction processes can be achieved.

CHAPTER 5
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APPENDIX A

SUMMARY OF TxDOT TEST EVALUATION DATA

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Soils and Subgrade Materials						
Tex-100-E Surveying and Sampling Soils for Highways	need for stabilization; supporting values foundation materials	Moisture Density Location of soils	Suitability materials for construction	Sample taken from field and test in lab	Destructive - requires sample of soils including cores	Special equipment varies with soil characteristics
Tex-101-E Preparation of Soils and Flexible Base Materials for Testing	Gradation can be useful in determining suitability of soils for construction purposes	% soil binder Gradation		Lab	Destructive - requires sample of soils	Set of Sieves Mechanical Pulverizer
Tex-102-E Determination of Slaking Time for preparing Base Materials	none	Slaking time		Lab	Destructive - requires sample of soils	Set of Sieves Pressure Vessel
Tex-103-E Determination of Moisture Content in Soil Materials	none	Moisture Content		Lab	Destructive - requires sample of soils	None
Tex-104-E Determination of Liquid Limit of Soils	Liquid Limit can be useful in determining suitability of soils for construction purposes	Liquid Limit		Lab	Destructive - requires sample of soils	Grooving tool
Tex-105-E Determination of Plastic Limit of Soils	Plastic Limit of soils is useful when needing data on soils that support foundation materials	Plastic Limit		Lab	Destructive - requires sample of soils	None
Tex-106-E Method of Calculating the Plasticity Index of Soils	Plasticity Index must be considered when designing structures on soils that are greatly affected by moisture		Plasticity Index of Soils	Calculations based off Tex-105-E and Tex-104E	Non-destructive	None
Tex-107-E Determination of Shrinkage Factors of Soils	Shrinkage factors of soils is useful when needing data on soils that support foundation materials	Shrinkage Limit Volumetric Shrinkage	Shrinkage ratio	Lab	Destructive - requires sample of soils	Grooving tool
Tex-108-E Determination of Specific Gravity of Soils	none	Specific Gravity		Lab	Destructive - requires sample of soils	Vacuum Pump

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Tex-109-E Pressure Pycometer Methods for Determination of S.G., M.C. and for Slaking	none	Specific Gravity Moisture Content		Lab	Destructive - requires sample of soils	Compressed Air (100 psi)
Tex-110-E Determination of Particle Size Analysis of Soils	none	Particle Size Distribution		Lab	Destructive - requires sample of soils	Set of Sieves
Tex-111-E Determination of the Amount of Minus No. 200 Sieve Materials in Soils	Large quantities of particles smaller than No. 200 sieve can adversely affect soil conditions and may warrant consideration	% particles smaller than No. 200		Lab	Destructive - requires sample of soils	No. 200 Sieve
Tex-112-E Method of Admixing Lime to Reduce Plasticity Index of Soils	Method reduces the plasticity of soils and flexible base materials to improve the quality for road building purposes		Effect of lime on plasticity index of soils	Lab	Destructive - requires sample of soils	None
Tex-113-E Determination of Moisture-Density Relations of Soils and Base Materials	None		Relationship of moisture content to density	Lab	Destructive - requires sample of soils	Automatic Tamper Circular porous stones
Tex-114-E Compaction Ratio Method for Selection of Density of Soils and Bases	Determines the levels of compaction necessary to get desired results from soils or base materials		Determines desired compaction levels	Lab	Destructive - requires sample of soils	Motorized soils press Compaction molds
Tex-115-E Field Method for Determination of In-Place Density of Soils and Bases	None	Density of soil and granular materials		Field	Destructive - requires sample of soils	Volumeter
Tex-116-E - Ball Mill Method for Determination of the Disintegration of Flexible Base Materials	Resistance to disintegration of soils in the presence of water may be a design consideration in high rainfall areas	Resistance of aggregate to disintegration with water		Lab	Destructive - requires sample of soils	Wet ball mill Set of Sieves Crusher

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Tex-117-E Triaxial Compression Test for Disturbed Soils and Base Materials	Shearing resistance, water absorption and expansion of soils should be a design consideration	Shearing Resistance Water absorption Expansion		Lab	Destructive - requires sample of soils	Axial Cells Screw Jack Press Vacuum pump
Tex-118-E Triaxial Compression Test for Undisturbed Soils	Determines Stress-Strain relationships that only apply if no drainage occurs	Strength properties Stress-Strain Relationships		Lab	Destructive - requires sample of soils	Axial Loading Device Many pieces of various special equipment
Tex-119-E Soil Asphalt Strength Test Methods	If waterproofing qualities of soils are a priority, this procedure is essential in the design process		Determines optimal amounts of asphalt for waterproofing	Lab	Destructive - requires sample of soils	Axial Cells Screw Jack Press Vacuum pump
Tex-120-E Soil-Cement Compressive Strength Test Methods	Cement stabilized soil is a commonly used construction material. This test is valuable where it is used	Compreessive Strength of soil-cement samples		Lab	Destructive - requires sample of soils	Compressive Testing Machine **see Tex-117-E**
Tex-121-E Soil-Lime Compressive Strength Test Methods	Lime stabilized soil is a commonly used construction material. This test is valuable where it is used	Triaxial Classif. Compressive Strength		Lab	Destructive - requires sample of soils	Compressive Testing Machine **see Tex-117-E**
Tex-122-E Cohesiometer Test for Stabilized Mixtures of Soil-Asphalt, Lime or Cement	None		Cohesiometer value of stabilized soils	Lab	Destructive - requires sample of soils	Cohesiometer Pressure pycnometer
Tex-123-E Method for Determination of the Drainage Factor of Soil Materials	This test is valuable when placing base of subbase on a clay subgrade		Drainage Factor	Lab	Destructive - requires sample of soils	Triaxial test cells **see Tex-117-E** **see Tex-118E**
Tex-124-E Method for Determining the Potential Vertical Rise, PVR	If vertical rise can be predicted with accuracy, many problems with highway structures could be prevented	Potential Vertical Rise		Samples from field and analyzed in lab	Destructive - requires sample of soils	Core drilling rig
Tex-125-E Method for Determination of Subgrade Modulus of Reaction	None		Modulus of subgrade reaction (K-value)	Field	Destructive	Loading Device Hydraulic jack Bearing plates

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Tex-126-E Molding, Testing and Evaluation of Bituminous Black Base Materials	None		Relationship for percent voids to percent asphalt	Lab	Destructive - requires sample of soils	Motorized gyratory soils press Other equipment
Tex-127-E Fly Ash Compressive Strength Test Methods	This test determines the compressive strength of fly ash treated bases. This may be an important design consideration	Unconfined Compressive Strength		Lab	Destructive - requires sample of soils	Compressive Tester **see Tex-117-E** **see Tex-126-E**
Tex-128-E Determination of Soil pH	None	pH of soils in an aqueous solution		Lab	Destructive - requires sample of soils	pH meter
Tex-129-E Method of Test for the Resistivity of Soils Material	Resistivity is an important factor when including metal pipe, earth-reinforcing strips and other metals in earthwork	Resistivity		Field	Destructive - requires sample of soils	Portable resistivity meter No. 8 sieve
Tex-130-E Standard Test Method for Density of Drilled Slurries	Important for slurry construction techniques	Density of slurry		Field	Destructive	Mud Balance

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Concrete, Aggregates, and Cement Materials						
Tex-300-D Sampling Hydraulic Cement	None			Field	Non-Destructive	None
Tex-301-D Normal Consistency of Hydraulic Cement	None		Normal consistency of hydraulic cement	Lab	Non-Destructive	Apparatus described in ASTM C187
Tex-302-D Time of Setting of Hydraulic Cement by Gillmore Needles	None	Time of setting of hydraulic cement		Lab	Non-Destructive	Apparatus described in ASTM C266
Tex-303-D Time of Setting of Hydraulic Cement by Vicat Needle	None	Time of setting of hydraulic cement		Lab	Non-Destructive	Apparatus described in ASTM C191
Tex-304-D Tensile Strength of Hydraulic Cement Mortars	Tensile strength of cement can be an important mix design concern	Tensile strength of hydraulic cement		Lab	Non-Destructive	Apparatus described in ASTM C190
Tex-305-D Air Content of Hydraulic Cement Mortar	Air content of cement mortar can be an important mix design concern	Air content of hydraulic cement mortar		Lab	Non-Destructive	Apparatus described in ASTM C185
Tex-306-D Mechanical Mixing of Hydraulic Cement Paste and Mortars	None			Lab	Non-Destructive	Apparatus described in ASTM C305
Tex-307-D Compressive Strength of Hydraulic Cement Mortars	Compressive strength of cement can be an important mix design concern	Compressive strength of cement mortar		Lab	Non-Destructive	Apparatus described in ASTM C109
Tex-308-D Autoclave Expansion of Portland Cement	None		Soundness of portland cement	Lab	Non-Destructive	Apparatus described in ASTM C151
Tex-309-D Soundness of Hydraulic Cement over Boiling Water	None		Soundness of portland cement	Lab	Non-Destructive	Apparatus described in **Tex-301-D** Steam bath

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Tex-310-D Fineness of Portland Cement by the Turbidimeter	None		Fineness of portland cement	Lab	Non-Destructive	Apparatus described in ASTM C115
Tex-312-D Early Stiffening of Portland Cement (mortar method)	None		Determines false set in portland cement	Lab	Non-Destructive	Apparatus described in ASTM C359
Tex-313-D Early Stiffening of Hydraulic Cement (paste method)	None		Determines false set in hydraulic cement	Lab	Non-Destructive	Apparatus described in ASTM C451
Tex-314-D Test for Sulfur Trioxide in Portland Cement	None	Determination of sulfur trioxide		Lab	Non-Destructive	Turbidimeter Barium Chloride Stannous Chloride
Tex-315-D Determination of Sodium Chloride Equivalent in Concrete Mixing Water	Chemicals in mixing water can be a very important design consideration for concrete	Determination of chloride ion or sodium chloride		Lab	Non-Destructive	Chemicals
Tex-316-D Quality of water for use in Portland Cement Concrete	Quality of mixing water can be a very important design consideration for concrete		Effect of different waters on the tensile strength	Lab	Non-Destructive	Apparatus described in ASTM C190
Tex-317-D Test for Relative Mortar Strength of Fine Aggregate for Concrete	The mortar-making qualities of fine aggregates can be an important design consideration for concrete		Effect of different fine aggregates on strength	Lab	Non-Destructive	Apparatus described in ASTM C190 & 109 Ottawa sand
Tex-318-D Measuring Mortar-Making Properties of Fine Aggregate	The mortar making qualities of fine aggregates can be an important design consideration for concrete		Effect of different fine aggregates on compr. strength	Lab	Non-Destructive	Ottawa sand
Tex-319-D Test for Relative Mortar Strength of Lightweight Aggregate for Concrete	The mortar making qualities of lightweight fine aggregates can be an important design consideration for concrete		Effect of different lightweight aggregates on tension strength	Lab	Non-Destructive	Apparatus described in ASTM C190 & 230

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Tex-400-A Method of Sampling Stone, Gravel, Sand and Mineral Aggregates	None			Field	Destructive-requires sample	None
Tex-401-A Sieve Analysis of Fine and Coarse Aggregate	Particle size distribution can be an important consideration in mix design	Particle distribution		Lab	Non-Destructive	Set of Sieves Quartering Machine
Tex-402-A Fineness Modulus of Fine Aggregate	Fineness modulus can be an important consideration when analyzing fine aggregates used in concrete	Fineness modulus		Lab	Non-Destructive	Set of Sieves Quartering Machine
Tex-403-A Saturated Surface-Dry Specific Gravity and Absorption of Aggregates	Specific Gravity is an essential value used in concrete mix design. Absorption of aggregates is also very important	Specific Gravity Absorption of Aggregates		Lab	Non-Destructive	Pycnometer
Tex-404-A Determination for Unit Weight of Aggregate	Unit weight is used in concrete mix design	Unit Weight		Field or Lab	Non-Destructive	Unit weight bucket
Tex-405-A Determination for Percent Solids and Voids in Concrete Aggregate	Percent voids is used in concrete mix design	% voids		Lab	Non-Destructive	Unit weight bucket
Tex-406-A Materials Finer Than No. 200 Sieve in Mineral Aggregates	High volumes of particles passing the No. 200 sieve can adversely affect many properties of concrete	% particles passing No. 200 sieve		Lab	Non-Destructive	No. 200 sieve
Tex-407-A Method for Sampling Freshly-Mixed Concrete	None			Field	Requires sample of freshly-mixed concrete	None
Tex-408-A Organic Impurities in Fine Aggregate for Concrete	The inclusion of organic materials in fine aggregate used in concrete means more testing is required before use		Presence of organic materials in fine aggregate	Lab	Non-Destructive	Sodium Hydroxide Glass color standard
Tex-409-A Free Moisture and Water Absorption in Aggregate for Concrete	Free moisture and water absorption are important factors in concrete mix design	Water absorption	Free moisture	Field	Non-Destructive	Pycnometer

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Tex-410-A Abrasion of Coarse Aggregate by Use of the Los Angeles Machine	The abrasion resistance of aggregates is an important design consideration for concrete used on pavement surfaces		Abrasion resistance of aggregates	Lab	Destructive	Los Angeles machine
Tex-411-A Soundness of Aggregate by Use of Sodium or Magnesium Sulfate	Resistance to chemical breakdown is important in regions with Sodium and Magnesium Sulfate in the soil	Resistance of aggregates to chemical breakup		Lab	Destructive	Hydrometer Sieves
Tex-412-A Lightweight Pieces in Aggregate	None		Amount of lightweight pieces in aggregate	Lab	Destructive	Apparatus described in ASTM C123
Tex-413-A Determination of Deleterious Material in Mineral Aggregate	None		Deleterious materials in aggregate	Lab	Non-Destructive	None
Tex-414-A Design of Portland Cement Concrete	This is the procedure for preparing mix designs of Portland Cement Concrete			Any	Non-Destructive	None
Tex-415-A Slump of Portland Cement Concrete	Slump can be used as an indication of workability and consistency	Slump	Workability Consistency	Field	Non-Destructive	Slump Cone
Tex-416-A Air Content of Freshly Mixed Concrete	Air content is an important concrete design consideration where exposure to freeze-thaw cycles occur.	Air content		Field	Non-Destructive	Air meter (several types)
Tex-417-A Weight per Cubic Foot and Yield of Concrete	Unit weight is an important design consideration when the weight of the structure is a concern	Weight per ft^3 Yield		Field	Non-Destructive	Unit weight bucket
Tex-418-A Compressive Strength of Cylindrical Concrete Specimens	Compressive strength is one of the most important quantities considered in the design of concrete structures	Compressive strength		Lab and Field	Destructive	Compressive strength testing machine
Tex-419-A Compressive Strength of Concrete Using Portions of Broken Beams	Compressive strength is one of the most important quantities considered in the design of concrete structures	Compressive strength		Lab	Non-Destructive	Compressive strength testing machine

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Tex-420-A Flexural Strength of Concrete	Tensile strength is one of the most important quantities considered in the design of concrete structures	Tensile strength		Lab and Field	Destructive	Tensile strength testing machine
Tex-421-A Determination of Modulus of Elasticity of Concrete	Modulus of elasticity is an important design consideration where deflections are a concern	Modulus of elasticity		Lab	Destructive	Compressometer **see Tex-418-A**
Tex-422-A Lineal Shrinkage of Portland Cement Concrete	Shrinkage is always an important design consideration because shrinkage is an important factor in concrete cracking	Shrinkage		Lab	Non-Destructive	None
Tex-423-A Resistance of Concrete to Rapid Freezing and Thawing	Resistance to freeze thaw is an important design consideration in certain climates		Resistance to freeze-thaw	Lab	Non-Destructive	Freeze-thaw equipment, Electronic equipment to find Dynamic Modulus
Tex-424-A Obtaining and Testing Drilled Cores of Concrete	Testing cores gives data on the actual concrete properties of the structure			Field	Destructive	Core drill
Tex-427-A Tension Testing of Metallic Materials	Properties of metallic materials are important in any concrete structure that contains rebar or structural steel	Yield strength Tensile strength Elongation		Lab	Destructive	Tensile tester
Tex-428-A Method of Bend Test for Ductility of Metals	Properties of metallic materials are important in any concrete structure that contains rebar or structural steel	Resistance to bending		Lab	Destructive	Testing machine
Tex-429-A Determination of the Percent Solids in Lightweight Coarse Aggregate	Percent solids of lightweight aggregate is in important design consideration in lightweight concrete	Percent solids in lightweight aggregate		Lab	Non-Destructive	Pycnometer Unit weight bucket
Tex-430-A A Method for Testing the Impact Resistance of Pavement Markers	Provides indication of impact resistance of pavements subjected to cushioned blows like that of a tire		Impact resistance of pavement markers	Field	Non-Destructive	200 lb Steel ball assembly
Tex-431-A Pressure-slaking Test of Synthetic Coarse Aggregate	Dehydration can be an important design consideration when synthetic aggregates are used		Amount of dehydration in synthetic aggregates	Lab	Destructive	Pressure cooker Centrifuge bottles Sieves

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Tex-432-A Coarse Aggregate Freeze-Thaw Test	Resistance to freeze-thaw can be an important design consideration when synthetic aggregates are used		Resistance to disintegration from freeze-thaw	Lab	Destructive	Freezing chamber
Tex-433-A Absorption and Dry Specific Gravity of Synthetic Coarse Aggregate	Absorption and specific gravity can be an important design consideration when synthetic aggregates are used	Absorption Specific gravity		Lab	Non-Destructive	None
Tex-434-A Breaking Strength of Traffic Buttons	Only useful when the strength of the traffic buttons is an important factor	Strength of traffic buttons		Lab	Destructive	Testing Machine as described by ASTM E4
Tex-435-A Impact Resistance of Traffic Buttons	Only useful when the impact resistance of the traffic buttons is an important factor	Impact resistance of traffic buttons		Lab	Destructive	Steel ball Steel plate
Tex-436-A Measurement of Texture Depth by the Sand-Patch Method	Texture can be an important factor in concrete pavement	Texture depth		Field	Non-Destructive	Natural silica sand Metal cylinder
Tex-437-A Method of Test for Flow of Grout Mixtures (Flow-Cone Method)	Flow of grout is a consideration when grout is used	Consistency of grout mixtures		Field or Lab	Non-Destructive	Flow Cone
Tex-438-A Accelerated Polish Test for Coarse Aggregate	The tendency of aggregate to polish is an important design consideration for the wearing surface of the roadway		Initial friction value Polish value	Lab	Destructive	Wessex Polish Mach. British pendulum tester Metal molds
Tex-439-A Absorption Test for Concrete Pipe	These properties are only important when concrete pipe is used	Absorption of concrete pipe		Lab	Non-Destructive	None
Tex-440-A Time-of-Setting of Fresh Retarded Concrete	Set time of retarded concrete is very important for any concrete that has been retarded	Set time		Field or Lab	Non-Destructive	Metal Cones Penetration resistance apparatus
Tex-441-A Method of Test for Flexible Delineator Posts	These properties are only important when delineator posts are used	Impact resistance Resistance to deflection and temperature		Lab	Destructive	Steel ball Environmental chamber

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Tex-444-A Microscopical Determination of Air-Void Content	These factors are very important factors in freeze-thaw environments	Air void content	Specific surface Spacing factor Past content	Lab	Destructive	Apparatus described in ASTM D856 & C457
Tex-445-A Petorgraphic Examination of Hardened Concrete	This test allows for the examination of concrete that has been in place		Condition of concrete	Field and Lab	Destructive	Petrographic equipment
Tex-446-A Rebound Number of Hardened Concrete	The rebound number can be used to assess the uniformity of concrete across a construction site	Rebound number		Field	Non-Destructive	Apparatus described in ASTM C805
Tex-447-A Making and Curing Concrete Test Specimens	None	None		Field and Lab	Non-Destructive	Molds
Tex-448-A Flexural Strength of Concrete	Flexural strength is a very important design consideration for most concrete structures	Flexural strength		Lab	Destructive	Testing machine
Joint Sealant Materials						
Tex-613-J Testing of Preformed Joint Seals (Class 6)	Prevent incompressibles from entering the joint	Compression stiffness		Lab	Destructive	Compression machine, dial gage, etc.
Tex-525-C Tests for Asphalt and Concrete Sealants	Prevent incompressibles from entering the joint	Bond Strength	Resilience and resistence to aging	Lab	Destructive	Apparatus described in ASTM D 3407 and 1851

APPENDIX B

UTILITY ANALYSIS OF TxDOT TESTS

Name of Test	Performance 50%		Nature of Test 30%			Test Equipment 20%				Performance		Nature of Test		Test Equip.		Total
	Material Property	Perfor. Mechan.	Indirect or Direct	Lab or Field	Destruc. or Non	TxDot Equip.	Is test Practical	Is test Accurate	Require Training	Rating	Utility	Rating	Utility	Rating	Utility	Utility
	50 pts	50 pts	50 pts	30 pts	20 pts	20 pts	30 pts	30 pts	20 pts							
Soils and Subgrade Materials																
Tex-102-E Determination of Slaking Time for Preparing Base Material	10	10	10	30	10	20	10	20	20	20	40	50	35	70	78	46.1
Tex-103-E Determination of Moisture Content in Soil Materials	40	30	40	10	10	20	30	20	20	70	89	60	48	90	95	77.9
Tex-104-E Determination of Liquid Limit of Soils	40	30	40	10	10	20	15	15	20	70	89	60	48	70	78	74.5
Tex-105-E Determination of Plastic Limit of Soils	40	30	40	10	10	20	15	10	20	70	89	60	48	65	72	73.3
Tex-106-E Method of Calculating the Plasticity Index of Soils	30	10	50	10	10	20	15	10	20	40	9	70	58	65	73	36.5
Tex-107-E Determination of Shrinkage Factors of Soils	30	30	30	10	10	0	10	10	0	60	62	50	35	20	22	45.9
Tex-108-E Determination of Specific Gravity of Soils	40	25	40	10	10	20	30	20	20	65	78	60	48	90	95	72.4
Tex-109-E Pressure Pyco. Methods for Determination of S.G., M.C. and for Slaking	20	20	20	10	10	10	20	20	10	40	9	40	28	60	69	26.7
Tex-110-E Determination of Particle Size Analysis of Soils	40	30	50	10	10	20	20	30	15	70	89	70	57	85	90	79.6
Tex-111-E Determination of the Amount of Minus No. 200 Sieve Materials in Soil	35	25	35	10	10	20	20	20	10	60	62	55	40	70	86	60.2

Name of Test	Performance 50%		Nature of Test 30%			Test Equipment 20%				Performance		Nature of Test		Test Equip.		Total
	Material Property	Perfor. Mechan.	Indirect or Direct	Lab or Field	Destruc. or Non	TxDot Equip.	Is test Practical	Is test Accurate	Require Training	Rating	Utility	Rating	Utility	Rating	Utility	Utility
	50 pts	50 pts	50 pts	30 pts	20 pts	20 pts	30 pts	30 pts	20 pts							
Tex-113-E Determination of Moisture-Density Relations of Soils and Base Materials	25	20	30	10	10	10	15	15	10	45	12	50	35	50	59	28.3
Tex-114-E Compaction Ratio Method for Selection of Density of Soils and Bases	40	30	30	10	10	20	20	20	20	70	89	50	34	80	86	71.9
Tex-115-E Field Method for Determination of In-Place Density of Soils and Bases	40	25	25	20	10	10	15	25	10	65	77	55	40	60	69	64.3
Tex-116-E Ball Mill Method for Determination of the Disintegration of Flexible Base	25	20	30	10	10	0	10	15	10	45	13	50	34	35	40	24.7
Tex-117-E Triaxial Compression Tests for Disturbed Soils and Base Materials	35	30	40	10	10	20	25	25	20	65	77	60	47	90	95	71.6
Tex-118-E Triaxial Compression Test for Undisturbed Soils	35	35	40	10	10	20	25	25	20	70	89	60	47	90	95	77.6
Tex-119-E Soil Asphalt Strength Test Methods	20	20	20	10	10	10	10	15	10	40	9	40	27	45	52	23
Tex-120-E Soil-Cement Compressive Strength Test Methods	35	35	40	10	10	20	25	25	20	70	89	60	47	90	95	77.6
Tex-121-E Soil-Lime Compressive Strength Test Methods	35	35	40	10	10	20	25	25	20	70	89	60	47	90	95	77.6
Tex-122-E Cohesiometer Test for Stabilized Mixtures of Soil-Asphalt, Lime or Cement	30	30	35	10	10	10	20	25	20	60	62	55	40	75	82	59.4
Tex-123-E Method for Determination of the Drainage Factor of Soil Materials	25	25	40	10	10	10	15	20	10	50	20	60	47	55	63	36.7

Name of Test	Performance 50%		Nature of Test 30%			Test Equipment 20%				Performance		Nature of Test		Test Equip.		Total
	Material Property	Perfor. Mechan.	Indirect or Direct	Lab or Field	Destruc. or Non	TxDot Equip.	Is test Practical	Is test Accurate	Require Training	Rating	Utility	Rating	Utility	Rating	Utility	Utility
	50 pts	50 pts	50 pts	30 pts	20 pts	20 pts	30 pts	30 pts	20 pts							
Tex-124-E Method for Determining the Potential Vertical Rise, PVR	10	20	30	10	10	20	15	15	10	30	5	50	35	60	69	26.8
Tex-125-E Method for Modulus Determination of Subgrade of Reaction	35	40	30	25	10	20	20	15	10	75	92	65	50	55	65	74.0
Tex-126-E Molding, Testing and Evaluation of Bituminous Black Base Materials	20	20	30	10	10	10	15	20	10	40	9	50	35	55	63	27.6
Tex-127-E Fly Ash Compressive Strength Test Methods	30	30	40	10	10	10	20	15	10	60	62	60	48	55	63	58
Tex-128-E Determination of Soil pH	40	10	30	10	10	0	15	15	10	50	20	50	35	40	48	30.1
Tex-129-E Method of Test for the Resistivity of Soils Material	30	10	25	10	10	0	10	15	10	40	9	45	30	35	30	19.5

Name of Test	Performance 50%		Nature of Test 30%			Test Equipment 20%				Performance		Nature of Test		Test Equip.		Total
	Material Property 50 pts	Perfor. Mechan. 50 pts	Indirect or Direct 50 pts	Lab or Field 30 pts	Destruc. or Non 20 pts	TxDot Equip. 20 pts	Is test Practical 30 pts	Is test Accurate 30 pts	Require Training 20 pts	Rating	Utility	Rating	Utility	Rating	Utility	Utility
Concrete, Aggregates, and Cement Materials																
Tex-301-D Normal Consistency of Hydraulic Cement	30	25	35	10	10	10	10	10	20	50	20	55	40	50	58	33.6
Tex-302-D Time of Setting of Hydraulic Cement by Gillmore Needles	30	35	35	10	10	10	10	10	20	65	78	55	40	50	58	62.6
Tex-303-D Time of Setting of Hydraulic Cement by Vicat Needle	30	35	35	10	10	10	10	5	20	65	78	55	45	45	51	62.7
Tex-304-D Tensile Strength of Hydraulic Cement Mortars	40	40	50	10	10	0	10	20	10	80	96	70	56	40	48	74.4
Tex-305-D Air Content of Hydraulic Cement Mortar	25	20	35	10	10	10	5	15	20	45	10	55	40	50	58	28.6
Tex-307-D Compressive Strength of Hydraulic Cement Mortars	50	10	50	10	10	20	30	20	20	60	62	70	56	90	94	66.6
Tex-308-D Autoclave Expansion of Portland Cement	30	20	25	10	10	0	15	20	10	50	20	45	30	45	51	29.2
Tex-309-D Soundness of Hydraulic Cement over Boiling Water	5	5	10	10	10	0	10	10	10	10	1	30	19	30	35	13.2
Tex-310-D Fineness of Portland Cement by the Turbidimeter	45	35	45	10	10	10	10	15	0	80	96	65	50	25	28	68.6

Name of Test	Performance 50%		Nature of Test 30%			Test Equipment 20%				Performance		Nature of Test		Test Equip.		Total
	Material Property	Perfor. Mechan.	Indirect or Direct	Lab or Field	Destruc. or Non	TxDot Equip.	Is test Practical	Is test Accurate	Require Training	Rating	Utility	Rating	Utility	Rating	Utility	Utility
	50 pts	50 pts	50 pts	30 pts	20 pts	20 pts	30 pts	30 pts	20 pts							
Tex-312-D Early Stiffening of Portland Cement (mortar method)	10	15	10	10	10	10	15	15	20	25	5	30	20	60	69	22.3
Tex-313-D Early Stiffening of Hydraulic Cement (paste method)	10	15	10	10	10	10	15	15	20	25	5	30	20	60	69	22.3
Tex-314-D Test for Sulfur Trioxide in Portland Cement	10	15	45	10	10	0	5	15	10	25	5	65	51	30	35	24.8
Tex-315-D Determination of Sodium Chloride Equivalent in Concrete Mixing Water	10	10	40	10	10	0	5	15	10	20	3	60	47	30	35	22.6
Tex-316-D Quality of Water for Use in Portland Cement Concrete	10	10	15	10	10	10	10	10	10	20	3	35	23	40	48	18
Tex-317-D Test for Relative Mortar Strength of Fine Aggregate for Concrete	25	30	30	10	10	10	15	15	20	55	40	50	35	60	69	44.3
Tex-318-D Measuring Mortar-Making Properties of Fine Aggregate	25	30	30	10	10	10	15	15	20	55	40	50	35	60	69	44.3
Tex-319-D Test for Relative Mortar Strength of Lightweight Aggregate for Concrete	25	30	30	10	10	10	15	15	20	55	40	50	35	60	69	44.3

Name of Test	Performance 50%		Nature of Test 30%			Test Equipment 20%				Performance		Nature of Test		Test Equip.		Total
	Material Property	Perfor. Mechan.	Indirect or Direct	Lab or Field	Destruc. or Non	TxDot Equip.	Is test Practical	Is test Accurate	Require Training	Rating	Utility	Rating	Utility	Rating	Utility	Utility
	50 pts	50 pts	50 pts	30 pts	20 pts	20 pts	30 pts	30 pts	20 pts							
Tex-401-A Sieve Analysis of Fine and Coarse Aggregate	35	35	45	10	10	20	30	30	20	70	89	65	40	100	100	76.5
Tex-402-A Fineness Modulus of Fine Aggregate	15	30	25	10	10	20	30	30	20	45	12	45	30	100	100	35
Tex-403-A Saturated Surface-Dry Specific Gravity and Absorption of Aggregates	50	10	45	10	10	20	30	25	20	60	62	65	40	95	97	62.4
Tex-404-A Determination for Unit Weight of Aggregate	50	10	50	30	10	20	30	25	20	60	62	90	83	95	97	75.3
Tex-405-A Determination for Percent Solids and Voids in Concrete Aggregate	40	10	30	10	10	20	25	25	20	50	20	50	35	90	97	39.9
Tex-406-A Materials Finer than No. 200 Sieve in Mineral Aggregates	30	25	40	10	10	20	30	15	20	55	40	60	48	85	90	52.4
Tex-408-A Organic Impurities in Fine Aggregate for Concrete	10	20	25	10	10	10	20	20	10	30	5	45	30	60	69	25.3
Tex-409-A Free Moisture and Water Absorption in Aggregate for Concrete	35	20	40	10	10	20	30	25	20	55	45	60	48	95	97	56.3
Tex-410-A Abrasion of Coarse Aggregate by Use of the Los Angeles Machine	30	30	25	10	10	0	5	5	0	60	62	45	30	10	10	42

Name of Test	Performance 50%		Nature of Test 30%			Test Equipment 20%				Performance		Nature of Test		Test Equip.		Total
	Material Property	Perfor. Mechan.	Indirect or Direct	Lab or Field	Destruc. or Non	TxDot Equip.	Is test Practical	Is test Accurate	Require Training	Rating	Utility	Rating	Utility	Rating	Utility	Utility
	50 pts	50 pts	50 pts	30 pts	20 pts	20 pts	30 pts	30 pts	20 pts							
Tex-411-A Soundness of Aggregate by Use of Sodium or Magnesium Sulfate	10	25	25	10	10	20	15	15	20	35	8	45	30	70	78	28.6
Tex-412-A Lightweight Pieces in Aggregate	15	15	20	10	10	10	15	15	10	30	5	40	27	50	59	22.4
Tex-413-A Determination of Deleterious Material in Mineral Aggregate	10	25	35	10	10	20	15	20	20	35	8	55	40	75	82	32.4
Tex-415-A Slump of Portland Cement Concrete	10	35	25	30	10	20	30	15	20	45	12	65	51	85	90	39.3
Tex-416-A Air Content of Freshly Mixed Concrete	35	5	40	30	10	20	20	30	15	40	10	80	70	85	90	44
Tex-417-A Weight per Cubic Foot and Yield of Concrete	40	15	40	30	10	20	30	30	20	55	40	80	70	100	100	61
Tex-418-A Compressive Strength of Cylindrical Concrete Specimens	50	15	50	10	10	20	30	25	20	65	75	70	56	95	98	73.9
Tex-419-A Compressive Strength of Concrete Using Portions of Broken Beams	50	10	20	10	10	20	5	10	20	60	62	40	27	55	63	51.7
Tex-420-A Flexural Strength of Concrete	40	40	35	10	10	20	20	15	20	80	97	55	40	75	62	72.9
Tex-421-A Determination of Modulus of Elasticity of Concrete	40	45	25	10	10	20	5	20	10	85	97	45	30	55	64	70.3

Name of Test	Performance 50%		Nature of Test 30%			Test Equipment 20%				Performance		Nature of Test		Test Equip.		Total
	Material Property	Perfor. Mechan.	Indirect or Direct	Lab or Field	Destruc. or Non	TxDot Equip.	Is test Practical	Is test Accurate	Require Training	Rating	Utility	Rating	Utility	Rating	Utility	Utility
	50 pts	50 pts	50 pts	30 pts	20 pts	20 pts	30 pts	30 pts	20 pts							
Tex-422-A Lineal Shrinkage of Portland Cement Concrete	20	50	40	10	10	10	5	15	10	70	89	60	46	30	20	62.3
Tex-427 Tension Testing of Metallic Materials	50	35	50	10	0	10	15	30	20	85	97	60	46	75	82	78.7
Tex-428-A Method of Bend Test for Ductility of Metals	35	15	35	10	0	0	10	15	20	50	20	45	30	45	52	29.4
Tex-429-A Determination of the Percent Solids in Lightweight Coarse Aggregate	30	25	35	10	10	20	20	20	20	55	40	55	40	80	86	49.2
Tex-431-A Pressure-slaking Test of Synthetic Coarse Aggregate	20	15	20	10	10	10	10	20	20	35	8	40	28	60	69	26.2
Tex-433-A Absorption and Dry Specific Gravity of Synthetic Coarse Aggregate	20	35	35	10	10	20	20	20	20	55	40	55	40	80	86	49.2
Tex-612-J Acid Insoluble Residue for Fine Aggregate	32	25	50	10	10	20	25	25	10	57	50	70	57	45	50	52.9
Joint Sealant Materials																
Tex-613-J Testing of Preformed Joint Seals (Class 6)	40	40	40	5	10	20	30	20	20	80	97	55	40	90	95	79.5
Tex-525-C Tests for Asphalt and Concrete Sealers	35	40	35	5	15	20	30	10	10	75	93	55	40	70	79	56.8

APPENDIX C

SUMMARY OF NEW OR RELATED ASTM TESTS EVALUATION DATA

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Soils and Subgrade Materials						
Stiffness Gage	Stiffness affects the deflection of the pavement	Measurement of soil stiffness by vibration frequency and displacement measurement		Field test	Non-destructive	Stiffness gage
Pressure Meter	Stiffness affects the deflection of the pavement	Direct measurement of soil stiffness by measurement of the stress-strain curve		Field test	Non-destructive but requires repair of the pavement structure	Pressure gage, displacement indicator, actuator, etc.
Moisture Measurement	Moisture affects subgrade stiffness		Calibrated correlation to soil dielectric constant	Field test	Non-destructive but must use an access tube	Radar probe
Tex-117 E Triaxial (Mod) Compression Test for Disturbed Soils and Base Materials	Elastic properties affect load stresses and deflections	Direct measurement of soil elastic properties		Lab test	Destructive	Axial Cells Screw Jack Press Vacuum Pump
Concrete, Aggregates, and Cement Materials						
Surface Hardness ASTM C 805 (Rebound)	Hardness may be an indicator of age and compressive strength		Based on a correlation between empirical hardness measurement to strength	Both lab and field application	Non-destructive but makes indentation in concrete or rebounds off concrete; test is limited	Spring, Pendulum, or Schmidt rebound hammer, no special training required
Penetration Resistance ASTM C 803	Penetration into concrete provides a measure of hardness		Based on a correlation between the depth of penetration, hardness, and compressive strength	Both lab and field application	Non-destructive but makes indentation in concrete; test is limited	Windsor probe and driver, no special training required
Resonant Frequency ASTM C 215	Monitor degradation of the modulus of elasticity of concrete	Dynamic modulus of elasticity and Poisson's ratio derived from fundamental resonant frequency	Compressive, flexural strengths correlated with dynamic modulus of elasticity	Laboratory test	Non-destructive	Sonometer

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Ultrasonic Pulse Velocity ASTM C 597	Detect structural deterioration due to chemical attack, cracking, freeze-thaw damage; Measure and detect cracks, defects; Assess quality (homogeneity) of concrete; Determine thickness	Dynamic modulus of elasticity and Poisson's ratio derived from velocity of ultrasonic pulse	Compressive strength correlated with pulse velocity	Both lab and field application	Non-destructive	Pulse Velocity Test Instrument (V-Meter), no special training required
Magnetic / Electrical ASTM C 876 (Half-Cell Potential Measurements)	Measure moisture content; measure reinforcement corrosion potential; locate reinforcement; locate defects and corrosion; determine thickness	Induced current, magnetic flux leakage, signal from hydrogen nuclei under magnetic field, dielectric constant, resistivity, polarization resistivity, electrode potential of reinforcement	Moisture content correlated to signal from hydrogen nuclei or dielectric constant; location of defects and corrosion correlated to magnetic flux leakage, resistivity, or electrode potential of reinforcement; location of reinforcement and thickness correlated to induced current or resistivity; corrosion rate correlated to polarization resistivity	Field test	Non-destructive	NMR moisture measurement system; magnetic field producer and sensor; meter to locate reinforcement; capacitance instrument; electrical resistance probe; system for measuring electrode potential; system for measuring polarization resistance
Radioactive / Nuclear ASTM C 1040 (Radiometry)	Determine density, microstructure, composition, structural integrity	Photographic image of sample interior	Detected pulses or rays counted and correlated to density or composition	Both lab and field application	Non-destructive	Radiation source (radioisotope sources, X-ray generators, nuclear reactors); radiation detector and counter (dynamic nuclear density gauge)

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Stress Wave Propagation	Evaluate internal structure; determine thickness and elastic moduli	Travel time for stress wave, surface displacement or force waveforms from impact, high frequency impact surface waves in top layer	Thickness and defects are correlated to stress wave travel times or surface displacement waveforms, elastic properties and thicknesses correlated to high frequency surface waveforms	Field test	Non-destructive	Transmitter or impact source; receivers (geophones or accelerometers); signal, waveform, or spectral analyzer; cross-hole seismic is an example
Short-Pulse Radar (GPR)	Detect delaminations, other defects; monitor strength development; evaluate effect of admixtures on curing; determine moisture content, thickness	Reflected radar signals, dielectric properties (reflection coefficient, dielectric constant), two-way transit time of reflected radar signals	Location of delaminations and other defects by interpreting reflected radar signals; strength development correlated with changes in dielectric property; moisture content correlated with dielectric property; thickness correlated with two-way transit time	Field test	Non-destructive	Control unit, antenna, oscillographic recorder
Infrared Thermographic	Detect delaminations, defects, cracks	Surface temperatures	Location of subsurface anomalies correlated to surface temperature under conditions of heat flow	Field test	Non-destructive	High resolution infrared thermographic scanner, analysis system
Acoustic Emission	Monitor cracking	Acoustic emission signals	Cracking correlated to acoustic events	Laboratory test	Non-destructive	Microphone, amplifier, oscillograph, signal analysis system
Rolling Dynamic Deflectometer	Measures slab deflections on a continuous basis	Slab deflections are used to determine the stiffness of the slab		Field test	Non-destructive	Truck mounted servo-hydraulic vibrator
Pullout ASTM C 900	Concrete fracture resistance to bolt pullout	Fracture toughness derived from pullout load	Pullout load correlated to compressive strength	Primarily a field test	Non-destructive but creates a large fractured repair area	Load cell and pre-placed pullout bolts, no special training required
Break-Off	Concrete break-off resistance to flexural or compressive strength	Provides an indication of flexural strength	Break-off resistence correlated to compressive strength	Primarily a field test	Non-destructive but creates a large fractured repair area	Load cell, manometer, and hydraulic hand pump, no special training required

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Split Tensile/Fracture Toughness ASTM C 496 (mod)	Crack growth and tensile strength	K_{IF} and c_f are cracking behavior parameters		Primarily a laboratory test but can be conducted on field cores	Destructive	Compression testing equipment and specially made cylinder inserts
Maturity ASTM C 1074	Time and temperature relationship with degree of hydration	Maturity to the degree of hydration	The degree of hydration to strength of concrete	Both lab and field application	Non-destructive	Maturity meter
Torsional Shear Strength	Shear strength of bond interface of concrete overlay	Shear strength versus shear stress		Field test	Non-destructive but requires repair of the pavement	Calibrated torque wrench and specially made torsion vane devices
Adiabatic Heat Signature	Measure of adiabatic temperature rise of hydrating concrete	Temperature at setting relates to the cracking stress due to temperature drop		Set up for the lab but can be adopted for the field	Non-destructive	Data logger and adiabatic temperature container
Volumetric Dilatometer	Thermal coefficient of expansion affects cracking stress	Measurement of the volumetric expansion of concrete and aggregates due to temperature change		Lab test	Non-destructive	Dilatometer, data recorder, and temperature bath
Oxide Analysis	To predict thermal coefficient of expansion		Based on correlation	Lab test	Destructive	SEM
Modulus of Elasticity	Load carrying capacity	Measurement of stress and strain		Lab test	Destructive	Compression machine
Dew Point Indicator	Relative humidity affects the degree of drying shrinkage	Measurement of dew point temperature		Lab and field test	Non-destructive; uses a permanent insert	Chilled mirror dew point indicator
Drop Test (DIN 1048)	Bond development length	Measurement of workability relative to mobility		Field and lab test	Destructive	Slump cone and drop table
Joint Sealant Materials						
Bond Strength	Function of sawcut spacing and joint opening	Direct tension test		Lab test	Destructive	Tensile test machine

Name of Test	Relevance to Design	Test Measurement		Type of Test	Nature of Test	Equipment
		Direct	Indirect			
Relaxation Test	Stiffness of sealant affects the bonding stress	Direct effect of ageing on stiffness		Lab test	Destructive	Tensile test machine and atlas weatherometer

APPENDIX D

UTILITY ANALYSIS OF NEW OR RELATED ASTM TESTS

Name of Test	Performance 50%		Nature of Test 30%			Test Equipment 20%				Performance		Nature of Test		Test Equip.		Total
	Material Property	Perfor. Mechan.	Indirect or Direct	Lab or Field	Destruc. or Non	TxDot Equip.	Is test Practical	Is test Accurate	Require Training	Rating	Utility	Rating	Utility	Rating	Utility	Utility
	50 pts	50 pts	50 pts	30 pts	20 pts	20 pts	30 pts	30 pts	20 pts							
Soils and Subgrade Materials																
The Humbolt Stiffness Gage to -Measure Stiffness in Place	40	50	50	20	20	0	25	20	10	90	98	90	83	55	63	86.5
Pressure Meter -stress-strain curve	45	45	45	30	10	5	15	20	5	90	98	85	76	45	54	82.6
Moisture Measurement -dielectric constant	40	40	30	30	10	5	15	15	10	80	96	75	63	40	28	72.5
Tex-117 E Triaxial (Mod) Compression Test for Disturbed Soils and Base Materials	50	50	50	15	10	20	25	25	15	100	100	75	63	85	75	83.9
Concrete, Aggregates, and Cement Materials																
Surface Hardness -measure surface rebound	20	20	20	25	15	10	25	5	20	40	10	60	48	60	70	33.4
Penetration Resistance -measure depth of penetration	20	20	20	25	15	10	25	5	20	40	10	60	48	60	70	33.4
Resonant Frequency -material stiffness	50	40	35	5	20	0	15	25	10	90	99	60	48	50	58	75.5
Ultrasonic Pulse Velocity -material stiffness and strength	50	40	35	30	20	0	15	15	10	90	99	85	75	35	22	76.4
Magnetic/Electrical -material moisture, thickness, locate steel	30	35	40	30	20	0	15	20	15	65	74	90	85	50	58	74.1

Name of Test	Performance 50%		Nature of Test 30%			Test Equipment 20%				Performance		Nature of Test		Test Equip.		Total
	Material Property	Perfor. Mechan.	Indirect or Direct	Lab or Field	Destruc. or Non	TxDot Equip.	Is test Practical	Is test Accurate	Require Training	Rating	Utility	Rating	Utility	Rating	Utility	Utility
	50 pts	50 pts	50 pts	30 pts	20 pts	20 pts	30 pts	30 pts	20 pts							
Radioactive/Nuclear -moisture, density measurements	40	40	40	30	20	0	10	10	5	80	97	90	85	35	22	78.4
Stress Wave Propagation -material stiffness	45	45	40	30	20	0	20	25	10	90	97	90	85	55	64	86.8
Ground Penetrating Radar -measure density, moisture content and voids in place	50	50	20	20	20	0	15	20	0	100	100	60	47	35	40	72.1
Infrared Thermographic -to measure flaws and debonding	30	35	40	30	20	0	25	20	10	65	74	90	83	55	64	74.7
Acoustic Emission -to measure cracking	25	30	30	5	20	0	15	15	10	55	40	55	40	60	70	46
RDD -continuous pavement deflection	50	50	50	30	20	5	25	25	5	100	100	100	100	60	70	94
Pullout Test to Measure In-place Strength	45	40	40	20	20	0	20	25	10	85	97	80	70	55	62	81.9
Break Off -measure break-off load	35	35	30	25	25	10	20	25	10	70	89	80	65	74	78	80.3

Name of Test	Performance 50%		Nature of Test 30%			Test Equipment 20%				Performance		Nature of Test		Test Equip.		Total
	Material Property	Perfor. Mechan.	Indirect or Direct	Lab or Field	Destruc. or Non	TxDot Equip.	Is test Practical	Is test Accurate	Require Training	Rating	Utility	Rating	Utility	Rating	Utility	Utility
	50 pts	50 pts	50 pts	30 pts	20 pts	20 pts	30 pts	30 pts	20 pts							
Split Tensile Strength ASTM C 496 (mod.) Fracture Toughness	45	45	40	20	10	10	25	25	20	90	98	70	58	80	88	84
Maturity -measure degree of hydration	40	50	35	30	20	10	20	25	20	90	98	85	76	75	82	88.2
Torsion/Bond -torsional shear strength	45	45	40	25	10	10	25	25	15	90	98	75	63	75	82	84.3
Adiabatic Heat Signature -maximum temperature rise	40	45	45	20	15	5	20	30	5	85	97	80	70	60	70	83.5
Volume Dilatometer -coeffiecient of thermal expansion of concrete	40	40	50	10	10	0	25	25	10	80	96	70	56	60	69	78.6
Oxide Analysis -to calculate thermal coefficient of expansion	50	50	50	10	10	10	20	20	10	100	98	70	56	60	69	80.6
Compression Test to -measure elastic modulus	45	45	50	5	5	10	10	25	10	90	98	60	48	55	63	76
Dew Point Indicator -to calculate relative humidity	40	50	50	30	10	0	20	20	10	90	98	90	83	50	59	85.7
Drop Test -to measure mixture mobility	25	30	50	30	10	20	20	20	20	55	30	90	83	80	70	53.9
Joint Sealant Materials																
Tensile Bond Strength Between Sealant Material and Concrete	40	50	50	5	5	15	15	10	15	90	98	60	48	55	63	76
Relaxation Test for Joint Sealant Materials	45	45	50	5	5	10	10	10	10	90	98	60	48	40	48	73

APPENDIX E

EVALUATION OF CURRENT TxDOT AND RELATED ASTM TEST PROCEDURES AND PRACTICES

The purpose of this appendix is to evaluate current TxDOT and related ASTM tests that are relevant to assessment of structural criteria related to the design of concrete pavement systems described in Chapter 1. While Chapter 3 focuses on new development, each TxDOT test method relevant to the scope of this project is evaluated on its value and its worth to the design process of concrete pavements. This evaluation is divided into three sections. The first section centers on soils and subgrade materials that is concerned with tests that measure the material properties or parameters of soils, bases, and stabilized bases. The next section centers on cement, aggregates, and concrete materials and is concerned with testing the properties of aggregates and cement used in concrete and concrete in its plastic and hardened states. The third section considers joint sealant material tests.

SOILS AND SUBGRADE MATERIALS

Tex-103-E Determination of Moisture Content in Soil Materials

The moisture content of soils is defined as the percentage of the mass of water in the soil to the mass of the solids in the soil. This test is performed by weighing a sample of the soil at its field condition and then weighing it dry. The moisture content is the weight of water lost divided by the dry weight. The moisture content for soils greatly affects its load supporting capabilities.

Performance

Moisture content is a very important material property of soils. The moisture content affects the expansion and contraction of soils. It also determines the soil's load carrying capabilities.

Nature of Test

This test measures the moisture content directly by measuring the difference in mass between standard and dry conditions. This test must be performed in a materials lab because the sample must be dried in a drying oven. This procedure requires a sample of the soil.

Test Equipment

This procedure utilizes equipment that can be found in any materials lab. The test is easy to perform but takes some time since the sample needs to be dried. The accuracy of this test is very high since all measurements are determined from a balance. No special training is required to perform this test.

Tex-104-E Determination of Liquid Limit of Soils

The liquid limit of soils is the moisture content at which the soil stops behaving as a plastic solid and starts behaving as a liquid. Water is mixed with the soil until the sample becomes a paste. The sample is then placed in a mechanical liquid limit device that will agitate the sample. The sample is smoothed, and a groove is put through the sample. The sample is agitated, and the number of blows necessary to close the groove is recorded. The moisture content is changed several times, and the test is repeated for each new moisture content. The results are plotted, and a best-fit line is calculated. The liquid limit of the soil is defined as the moisture content at which 25 blows will close the gap.

Performance

The liquid limit is an important material property. The liquid limit is an important design consideration for subbases. When a soil reaches the liquid limit, the soil will deform continuously with an applied load.

Nature of Test

This procedure measures the amount of blows needed to close the gap for given moisture contents. The liquid limit is then calculated from a graph of these results. This test must be performed in a materials lab because the sample must be dried several times. This test requires a sample of the soil.

Test Equipment

This procedure uses equipment that can be found in most material labs. The test takes a long time to perform because the samples must be oven dried. The accuracy of this procedure is low because it is dependent on the manner in which the technician forms the sample in the mechanical liquid limit device. This test does not require a significant amount of technician training.

Tex-105-E Determination of Plastic Limit of Soils

This test procedure determines the moisture content at which the soil changes from the semi-solid state to the plastic state. The sample is rolled into a thin thread until the surface of the thread begins to crack. The moisture content of the sample is then measured. This value is the plastic limit of the soil.

Performance

The plastic limit of soils is an important material property. When a soil reaches the plastic limit, its load-supporting capabilities are significantly reduced.

Nature of Test

This test measures the plastic limit of soils directly. This procedure must be done in a materials lab because the sample must be oven dried. This procedure requires a soil sample.

Test Equipment

The equipment needed for this procedure can be found in a standard materials lab. The test is simple to perform but depends on the skill of the technician. The accuracy of this procedure is dependent upon the technician's ability to accurately determine when the soil has reached its plastic limit. No significant amount of training is required to perform this test.

Tex-108-E Determination of Specific Gravity of Soils

The specific gravity of soils is determined by the weight of the sample in air and in water. From these weights, the specific gravity can be calculated. When obtaining the soil weight in water, the sample must be de-aired by boiling or by a partial vacuum. The specific gravity gives a useful volume to weight relationship for the soil sample.

Performance

The specific gravity is an important material property of soils. The specific gravity is an important value that is needed for many calculations of soil properties, such as voids ratio and saturation ratio.

Nature of Test

This procedure directly measures the specific gravity of soil samples. This test must be performed in a materials lab because the sample must be subjected to a partial vacuum. A soil sample is needed to perform this procedure.

Test Equipment

This test procedure uses equipment that can be found in any standard materials lab. It is simple to run and requires very little training. If the procedure is properly performed, this test is a very accurate measure of the specific gravity of a soil sample.

Tex-110-E Determination of Particle Size Analysis of Soils

Two procedures for determining the particle size distribution are detailed in this test standard. The first method uses sieve analysis to determine particle size distribution. The second method uses a hydrometer and Stoke's Law to determine the particle size distribution. The second method is based on the assumption that different particle sizes will settle out of solution at different rates. The hydrometer measures the amount of soil in solution at any given time.

Performance

Particle size distribution is a very important material property of soils. Particle size distribution has a significant impact on the load-supporting capability of a soil. The particle size distribution also changes the effect added water has in the soil properties.

Nature of Test

Sieve analysis directly measures the particle size distribution. The hydrometer indirectly measures particle size distribution by measuring the density of water with soil in suspension. This procedure must be performed in a materials lab. This test requires a sample of the soil.

Test Equipment

The equipment required to perform this test can be found in any standard materials lab. Sieve analysis is very simple to run but requires the sample to be oven dried. Determining the particle size distribution by using the hydrometer takes 1440 minutes and requires a properly prepared solution. Both tests are accurate if run properly. No special training is required to accurately run this test.

Tex-111-E Determination of the Amount of Minus No. 200 Sieve Materials in Soil

The percent of a soil that passes the No. 200 sieve is determined by measuring the weight of an oven dried sample and weighing the amount of that sample retained on the No. 200 sieve. The weight of the soil that passed the No. 200 sieve can be calculated by subtracting the weight of soil retained from the total weight of the soil. The percentage of the soil that passes the No. 200 sieve is calculated by dividing the weight of soil passing the No. 200 by the total weight of the sample.

Performance

The percentage of soil that passes the No. 200 sieve is a material property that has an effect on many soil properties. Compressibility increases as the percentage of particles passing increases. The hydraulic conductivity is greatly reduced when the percentage of soil passing the No. 200 sieve increases because these small particles fill the gaps and prevent water from flowing freely. The amount of soil passing the No. 200 sieve has a significant impact on the ability of a subbase to prevent pumping action at joints, cracks, and pavement edges.

Nature of Test

This test directly measures the amount of soil that will pass the No. 200 sieve by weighing those soil particles. This procedure must be performed in a materials lab because the soil sample must be oven dried. This test requires a sample of the soil.

Test Equipment

This procedure uses equipment that can be found in a standard materials lab. The test is easy to perform and does not take any significant amount of training. The accuracy of this experiment is a function of the technician's ability to properly agitate the soil so that all the smaller particles pass the No. 200 sieve. If performed properly, the accuracy of this procedure is very high.

Tex-114-E Compaction Ratio Method for Selection of Density of Soils and Base Materials in-Place

This test method determines the desirable density and moisture at which a soil will have adequate strength to support design loads. Cement, lime, fly ash, and asphalt stabilized soils can be used in this experiment. This test procedure determines the loose density. The loose density is used to calculate the compaction ratio. The actual desired density is calculated from the compaction ratio.

Performance

The compaction ratio is an important material property. It is used to calculate the desired density of soils and bases. The desired density must be known so that the base material can be compacted for optimum performance. If the soil is not placed at desired density, the soil will not have the strength to support the design loads.

Nature of Test

This test indirectly determines the desired density from calculations based on the compaction ratio. This test must be performed in a materials lab and requires a soil or base sample.

Test Equipment

This procedure utilizes equipment that can be found in a standard materials lab. The determination of the desired density is based on calculations and points determined from graphs of the moisture and density relationships. The results of this procedure should be considered an approximation. This procedure does not require any special training but does require the technician to be familiar with the calculations and required graphs.

Tex-115-E Field Method for Determination of In-Place Density of Soils and Base Materials

This procedure determines the in-place density of a compacted soil in a roadway or in a natural state in a cut site. The density is expressed as pounds of dry soil per cubic foot of volume. A volume of soil sample is removed from the location, and its moisture and weight are determined. The volume of the sample occupied is determined by a volumeter. The purpose of this test method is to determine the degree of compaction.

Performance

The in-place density of a soil or base material is an important material property. The density and percent compaction have a significant effect on the strength characteristics of the soil. The percent compaction determines the ultimate amount a soil can consolidate once a load is placed on it.

Nature of Test

This test directly measures the density by weighing the amount of soil that is removed from a volume. This volume is directly determined using the volumeter. The soil sample must be obtained from the site for which data are needed. The test must be performed in a materials lab because the soil sample must be oven dried.

Test Equipment

This procedure utilizes equipment that can be found in a standard materials lab. The test is easy to perform and is relatively accurate. No special training is required to accurately perform the test procedure.

Tex-117-E Triaxial Compression Tests for Disturbed Soils and Base Materials

This test method determines shearing resistance, water absorption, and expansion of soils. An axial load is applied to a specimen that also has a lateral applied pressure from zero to 20 psi. The loading blocks are lowered at a constant rate to apply the axial force. The test is over when the sample fails or the loading block travels 15 mm (0.60 in). Once the sample fails, it is removed, and the dry weight of the sample is determined. The volumetric swell can be calculated from the volume of the specimen as molded and the volume after capillary swell.

Performance

The shearing resistance, water absorption, and expansion of soils are important material properties. Shearing resistance determines the ability of a soil to resist design loads. Expansion of soils is an important design consideration if the soil expands a significant amount with added moisture.

Nature of Test

The shearing resistance and water absorption are determined directly. The expansion of the soil is calculated from measured volumes. This test procedure must be performed in a materials lab. This test requires a soil sample.

Test Equipment

The equipment needed to run this test could be found in most materials labs. This procedure is difficult to perform. It takes a long time and requires significant training to perform properly. The shearing resistance and the expansion should be used as an approximate value. The moisture content of the soil is accurately determined.

Tex-118-E Triaxial Compression Test for Undisturbed Soils

This procedure measures the undrained compressive strength of undisturbed cohesive soils. The cylindrical specimen is subjected to a confining pressure in a triaxial chamber. This procedure provides data useful for determining the strength characteristics and the stress-strain relationship of the soil. The size of the specimen is not specified. This procedure can be performed on a sample greater that 71 mm (2.8 in) in diameter and having at least a 2 to 3 ratio between the height and the diameter.

Performance

The undrained compressive strength of undisturbed cohesive soils is an important material property for most pavement systems. The undrained compressive strength of cohesive soils gives a good indication of the compressive strength of in-place soils and base materials. This compression strength is the actual value that will support the designed loads.

Nature of Test

This procedure directly measures the compressive strength of soils by applying a compressive load to a confined sample. This test must be performed in a materials lab because the test requires a triaxial chamber and a compressive tester. This procedure requires a soil sample.

Test Equipment

This test utilizes equipment that can be found in most materials labs. This procedure is difficult to perform. It takes a long time and requires significant training to perform properly. The compressive strength determined from this procedure should be used as an approximate value.

Tex-120-E Soil-Cement Compressive Strength Test

This procedure measures the compressive strength of soil samples combined with 6 percent cement by weight. The optimum water content is determined, and water is added to achieve this value. The sample is compacted with 50 blows of a 10 lb hammer for each 50 mm (2 in) of depth. The sample is cured in a moisture room for seven days. After seven days, the sample is tested with a compressive load.

Performance

The compressive strength of cement stabilized soil is an important material property when cement stabilization is being used. The compressive strength of the cement-soil mixture predicts the maximum load the soil can resist without failure.

Nature of Test

This test directly measures the compressive strength of a cement-stabilized soil by applying an increasing compressive load until failure. This procedure must be performed in a materials lab because the sample must be cured in a moisture room, and it must be tested on a compressive tester. This test requires a soil sample to be destructively loaded.

Test Equipment

The equipment needed for this procedure can be found in any standard materials lab. Sample preparation takes time and precise measurements, but the actual test is very quick and simple. The compressive strength value obtained should be used as an approximate value. No special training is required to perform this test.

Tex-120-E Soil-Lime Compressive Strength Test

This procedure measures the compressive strength of soil samples combined with lime. The unconfined compressive strength is an indicator of the effectiveness of the hydrated lime treatment. As the effectiveness of the hydrated lime increases, the strength characteristics of the base or subgrade materials improve.

Performance

The compressive strength of lime-stabilized soil is an important material property when lime stabilization is being used. The compressive strength of the lime-soil mixture predicts the maximum load the soil can resist without failure. It also gives an indication of how effective the hydrated lime is at improving the strength characteristics of the material.

Nature of Test

This test directly measures the compressive strength of a lime-stabilized soil by applying an increasing compressive load until failure. This procedure must be performed in a materials lab because the sample must be tested on a compressive tester. This test requires a soil sample to be destructively loaded.

Test Equipment

The equipment needed for this procedure can be found in any standard materials lab. Sample preparation takes time and precise measurements, but the actual test is very quick and simple. The compressive strength value obtained should be used as an approximate value. No special training is required to perform this test.

Tex-122-E Cohesiometer Test Methods for Stabilized Mixtures of Soil-Asphalt, Soil-Lime, or Soil-Cement

This test determines a cohesiometer value for samples molded 150 mm (6 in) in diameter and 50 mm (2 in) in height. The soil samples are compacted and then tested in the cohesiometer. Round metal shot is dropped on the sample until the sample fails or deforms excessively. The cohesiometer value is calculated from the total weight of shot dropped and the dimensions of the sample.

Performance

The cohesiometer value for a soil is not a direct material property. This value is an indication of the resistance to a bending moment. The resistance to a bending moment must be considered for any application where the soil would experience any amount of bending moment.

Nature of Test

This procedure indirectly measures the resistance to a bending moment by determining a cohesiometer value. This procedure must be performed in a materials lab because it requires sample compaction, and it must be tested on the cohesiometer. This test requires a sample to be destructively loaded.

Test Equipment

The cohesiometer can be found in any materials lab with standard equipment. The sample preparation is often time consuming and difficult, but the actual test on the cohesiometer is simple and quick. The cohesiometer value should be used as an approximate indicator of the resistance to bending. No special training is required to perform this test procedure.

Tex-127-E Fly Ash Compressive Strength Test Methods

This procedure measures the compressive strength of soil samples combined with fly ash. The optimum water content is determined, and water is added to achieve this value.

The sample is compacted with 50 blows of a 10 lb hammer four times. The compressive strength is an indication of the effectiveness of the fly ash in improving the strength characteristics of the soil.

Performance

The compressive strength of fly ash stabilized soil is an important material property when fly ash stabilization is being used. The compressive strength of the fly ash-soil mixture predicts the maximum load the soil can resist without failure. It also gives an indication of the effectiveness of the fly ash in improving the strength characteristics of the soil or base.

Nature of Test

This test directly measures the compressive strength of a fly ash stabilized soil by applying an increasing compressive load until failure. This procedure must be performed in a materials lab because the sample must be tested on a compressive tester. This test requires a soil sample to be destructively loaded.

Test Equipment

The equipment needed for this procedure can be found in any standard materials lab. Sample preparation takes time and precise measurements, but the actual test is very quick and simple. The compressive strength value obtained should be used as an approximate value. No special training is required to perform this test.

CEMENT, AGGREGATE, AND CONCRETE MATERIALS

Tex-302-D Time of Setting of Hydraulic Cement by Gillmore Needles

The time of setting of hydraulic cement is performed with a previously determined water to cement ratio. This water-to-cement ratio is experimentally found as the amount of mixing water needed to yield a paste of desired consistency. The time of setting is defined as the amount of time it takes for the paste to harden to a consistency that will allow the

Gillmore needle to penetrate a specific distance. The time of setting of hydraulic cement is greatly influenced by temperature. It is essential that this test be performed at the prescribed temperature.

Performance

Time of setting is a material property of hydraulic cement. The time of setting for hydraulic cement has a significant impact on the setting time of portland cement concrete. The setting of portland cement concrete is an important mix design consideration in extreme temperatures.

Nature of Test

This test measures the time of setting directly by measuring the amount of time it takes for a sample to harden. This test must be performed in a lab so that a constant temperature can be maintained. This test requires a sample of the hydraulic cement.

Test Equipment

The Gillmore needle assembly can be found in some materials labs but is not considered standard equipment. This test takes a long time to perform because the technician must wait for the cement to set. The cement sample must be mixed with the proper amount of water to get it to the desired consistency. If the paste is not at the proper consistency, the accuracy of the experiment will be compromised. The test must also be performed at a constant, predetermined temperature. Any variation in temperature will also compromise the accuracy of the test. The technician must be trained to mix the paste properly and to determine when the sample has set.

Tex-303-D Time of Setting of Hydraulic Cement by Vicat Needles

The time of setting of hydraulic cement is performed with a previously determined water-to-cement ratio. This water-to-cement ratio is experimentally found as the amount of mixing water needed to yield a paste of desired consistency. The time of setting is defined as the amount of time it takes for the paste to harden to a consistency that will allow the Vicat needle to penetrate a specific distance. The time of setting of hydraulic cement is greatly influenced by temperature. It is essential that this test be performed at the prescribed temperature.

Performance

Time of setting is a material property of hydraulic cement. The time of setting for hydraulic cement has a significant impact on the setting time of portland cement concrete. The setting of portland cement concrete is an important mix design consideration in extreme temperatures.

Nature of Test

This test measures the time of setting directly by measuring the amount of time it takes for a sample to harden. This test must be performed in a lab so that a constant temperature can be maintained. This test requires a sample of the hydraulic cement.

Test Equipment

The Vicat needle assembly can be found in some materials labs but is not considered standard equipment. This test takes a long time to perform because the technician must wait for the cement to set. The cement sample must be mixed with the proper amount of water to get it to the desired consistency. If the paste is not at the proper consistency, the accuracy of the experiment will be compromised. The test must also be performed at a constant, predetermined temperature. Any variation in temperature will also compromise the accuracy of the test. The technician must be trained to mix the paste properly and to determine when the sample has set.

Tex-304-D Tensile Strength of Hydraulic Cement Mortars

This test is performed on small, bone-shaped specimens. The specimens are loaded in tension until failure. This test is no longer used as the routine acceptance test for determining the strength of cement mortars.

Performance

This test measures the tensile strength of a hydraulic cement mortar molded in a bone shape. The tensile strength of the hydraulic cement mortar has a significant impact on the tensile strength of portland cement concrete. The tensile strength of portland cement concrete is an important design consideration for concrete pavements and many concrete structures.

Nature of Test

The tensile strength of the hydraulic cement mortar specimens is determined directly by applying a tensile load at the ends. This test must be performed in a materials lab because a tensile tester is required. This procedure requires a sample of the hydraulic cement mortar that is destructively tested.

Test Equipment

This test requires a tensile tester that can be found in most materials labs and requires bone-shaped molds that are not common in a standard materials lab. This test requires the samples be made very carefully since the results are greatly influenced by the shape of the specimen. There is a high degree of variability between samples. The results should be used as an approximation of the tensile strength and not as an exact value.

Tex-307-D Compressive Strength of Hydraulic Cement Mortars

This test is performed on 50 mm (2 in) cube specimens. The cubes are loaded on a compressive tester until failure. This test must be performed on a cement mortar at a specified consistency. This test is usually used as the routine acceptance test for determining the strength of cement mortars.

Performance

This test measures the compressive strength of hydraulic cement mortar cubes. The compressive strength of the hydraulic cement mortars has a direct impact on the compressive strength of portland cement concrete. Compressive strength is an important design consideration for most concrete structures.

Nature of Test

This test directly measures the compressive strength of the hydraulic cement mortar cube. This test must be performed in a materials lab because a compressive tester is required. This test requires a sample of hydraulic cement that is destructively tested.

Test Equipment

This test uses only equipment that can be found in a standard materials lab. The test is easy to perform and produces an accurate result for any given mix. This procedure does not require any special training.

Tex-310-D Fineness of Portland Cement by the Turbidimeter

This test uses the Wagner turbidimeter to determine the fineness of portland cement. The fineness of portland cement is expressed as the surface area of cement in cm^2 per gram of cement. Aged linseed oil mixed with kerosene is used to separate the cement particles.

Performance

The fineness of portland cement concrete is a material property that is a function of the amount the cement is ground during production. The fineness of portland cement concrete has a significant impact on portland cement concrete. Fine cements react more rapidly with water during hydration, producing a higher heat of hydration. Concrete made using fine cement has a high early strength but lower final strength. Fine cement also increases the amount of plastic shrinkage in portland cement concrete.

Nature of Test

This test indirectly measures the fineness of portland cement by determining the surface area per gram of cement. This test must be performed in a materials lab. This test requires a sample of portland cement.

Test Equipment

The Wagner turbidimeter can be found in some materials labs but is not standard equipment. The test is very difficult to perform. The results obtained using this procedure should be used as an approximation and not an exact value. Technicians must be thoroughly trained to run this test properly.

Tex-401-A Sieve Analysis of Fine and Coarse Aggregate

Sieve analysis is the mechanical shaking of an oven-dried aggregate sample through a set of standard sieves. The sieves with the aggregate are weighed, and the amount retained on each sieve is calculated. The percent passing can then be calculated for each sieve. A plot is then prepared with the log of the particle size on the x-axis and the percent passing on the y-axis. The coarse aggregate can then be classified as densely graded or open graded. Open-graded aggregates are primarily one size and have very few smaller particles to fill in the gaps. The high amount of empty voids between aggregate pieces allows for a high mortar demand. The particle size distribution of fine aggregate can have a significant impact on the concrete. A large proportion of particles passing the No. 200 sieve causes an increase in water demand and an increase in shrinkage.

Performance

The particle size distribution of both fine and coarse aggregate is a very important material property. Sieve analysis measures this property directly. The particle size distribution of fine aggregate has a significant impact on the performance of concrete.

Nature of Test

Sieve analysis directly measures the particle size distribution by weighing the mass retained on each sieve. This test is confined to a lab since a mechanical sieve shaker must be used, and the sample must be oven dried. This test requires a sample of the aggregate.

Test Equipment

Most material labs contain a set of standard sieves, a mechanical sieve shaker, and a drying oven. This test is easy to run, but does take some preparation since the sample must be oven dried. When performed properly, sieve analysis is a very accurate test that relies only on a balance for the readings. No special training is required to perform this test.

Tex-403-A Saturated Surface-Dry Specific Gravity and Absorption of Aggregates

This test determines the saturated surface-dry specific gravity of aggregates by using a pycnometer. The specific gravity does not have an impact on any performance or failure mechanisms but is essential for the mix design process. The absorption of aggregates is determined by comparing the saturated surface-dry weight of the aggregate to its dry weight. The absorption of aggregates impacts the amount of mixing water needed.

Performance

Specific gravity and absorption are both important material properties of aggregates. Both these values are important to the mix design procedure. Specific gravity relates mass to volume, allowing easy mix proportioning. The absorption of aggregates must be considered when determining the amount of water to add. High absorption may result in significant water loss, causing early set times and drying shrinkage.

Nature of Test

This test measures both specific gravity and absorption directly. The test is confined to a materials lab because the sample must be oven dried after being brought to the saturated surface-dry condition. This test requires a sample of the aggregate.

Test Equipment

All of the necessary equipment for this test is found in most materials labs. This is an easy test to perform but requires some time since the aggregate must be soaked until saturation and then oven dried. This test is relatively accurate as a balance determines all measurements. There is some human subjectivity since the technician must decide when the aggregate is at the saturated surface-dry condition.

Tex-404-A Determination for Unit Weight of Aggregates

The unit weight of aggregates is determined by simply filling a unit weight bucket of known volume with the aggregate that is saturated surface-dry and determining the weight of the aggregate. The unit weight is then calculated by dividing the weight by the volume of the unit weight bucket.

Performance

This test measures the unit weight of aggregates directly. The unit weight of aggregates has no significant impact on any performance or distress mechanisms. The unit weight of the aggregate has an impact on the unit weight of concrete.

Nature of Test

This test directly measures the unit weight of aggregates. The test can be performed both in the field and in the lab. This test is a non-destructive test.

Test Equipment

The equipment required for this test can be found in most materials labs. This is a very simple procedure that does not require any special training to perform. This test has only moderate accuracy since it depends on the technician's rodding and leveling off the surface.

Tex-406-A Materials Finer Than No. 200 Sieve in Materials Aggregate

The amount of materials in aggregate passing the No. 200 sieve is determined by finding the dry weight of the aggregate and then washing all the particles passing the No. 200 sieve off the aggregate. The dry weight of the aggregate remaining and the aggregate retained on the No. 200 sieve is subtracted from the original dry weight to calculate the amount of the aggregate that will pass the No. 200 sieve. The inclusion of high amounts of these small particles increases water demand and shrinkage.

Performance

This test measures the amount of material in aggregate that will pass the No. 200 sieve. A large quantity of less than No. 200 particles can have adverse effects on concrete in both the plastic and hardened phases. The presence of a large percentage of particles passing the No. 200 sieve increases water demand and increases plastic shrinkage.

Nature of Test

This procedure directly measures the mass of aggregate passing the No. 200 sieve by washing the aggregate and determining the amount washed away. This test requires the sample to be oven dried twice and, thus, must be carried out in a materials lab. This test requires a sample but is non-destructive.

Test Equipment

This test uses only equipment that will be found in a standard materials lab. The procedure requires the sample to be oven dried twice and takes several days to conduct.

The accuracy of this test is low since the amount washed off the aggregate depends on the amount of agitation provided by the technician. No special training is required to perform this test.

Tex-409-A Free Moisture and Water Absorption in Aggregate for Concrete

Free moisture in aggregates is determined by weighing a sample at present conditions and then dry. The percent moisture is then subtracted from the predetermined water absorption of the aggregate. If this value is positive, mixing water has to be added to account for the water that will be absorbed by the aggregate. If this value is negative, mixing water must be subtracted to account for the free moisture in the aggregate.

Performance

This test measures the amount of free moisture and the amount of water absorbed by the aggregate. These properties do not affect the performance or failure mechanisms. These values are necessary in order to use the desired amount of mixing water.

Nature of Test

This procedure measures the free moisture and water absorption directly. This test is performed in a materials lab and is non-destructive in nature.

Test Equipment

This test only uses equipment normally found in a materials lab. The procedure is simple but is subjective since the technician must use judgment to determine when the aggregate has reached the saturated surface-dry condition. No special training is required to perform this procedure.

Tex-417-A Weight per Cubic Foot and Yield of Concrete

The weight per cubic foot of freshly mixed concrete is determined by weighing a sample in a bucket of known volume and weight. The unit weight is then the weight of the sample divided by the volume of the bucket. From the unit weight, the yield can then be determined by dividing the total batch weight by the unit weight. This gives the volume of concrete for that batch.

Performance

This test determines the weight of plastic concrete per cubic foot. This property is important when the weight of the structure is a concern. The yield of concrete is a good check to ensure the mix design is yielding the designed volume of concrete. The utility of this test would be higher if it was applicable to the in-place density since this is important in terms of the quality of placement and the existence of rock pockets.

Nature of Test

This test measures the unit weight of concrete directly, and the yield can then be determined indirectly. This test can be performed in a lab or in the field. This procedure requires a sample of freshly mixed concrete.

Test Equipment

This test uses only a unit weight bucket, which can be found in any materials lab. It is very simple to run and requires very little training to achieve accurate results.

Tex-418-A Compressive Strength of Cylindrical Concrete Specimens

The compressive strength of concrete can be determined by using cast specimens or drilled cores. The samples are cured in a moisture room under a constant temperature at 100 percent humidity. An axial load is applied at a constant rate until the specimen fails. The compressive strength is expressed as a load per unit area. The compressive strength is, thus, the total load divided by the area of the specimen.

Performance

Compressive strength is an important material property but is only indirectly related to most distress types in concrete pavements on both performance and failure mechanisms. It can be used to calculate the modulus of elasticity of concrete.

Nature of Test

This test directly measures compressive strength. The samples may be cast in the lab or the field but must be broken in a materials lab. This test requires a sample of freshly mixed concrete but the sample will be destroyed during the test.

Test Equipment

This test is a standard procedure, and all necessary equipment can be found in a standard materials lab. The accuracy of the test is greatly influenced by sample preparation and curing. Relative moisture and temperature during curing can greatly influence test results. Any technician with little training can properly perform this procedure.

Tex-420-A Flexural Strength of Concrete

The flexural strength of concrete is determined by breaking a simply supported concrete beam with a center point load. From the maximum load, the modulus of rupture can be calculated.

Performance

Flexural strength is an important material property. The flexural strength of concrete has a significant impact on the performance of concrete pavement or any member in tension.

Nature of Test

This procedure measures the flexural strength of concrete beams directly. The samples for this test may be cast in the field or a lab, and the beams must be broken in a materials lab. This test requires a sample of freshly mixed concrete, but the sample will be destroyed during the test.

Test Equipment

Most materials labs contain the necessary equipment to perform this procedure. The accuracy of the test is greatly influenced by sample preparation and curing. Any technician with little training can properly perform this procedure.

Tex-421-A Determination of Modulus of Elasticity of Concrete

The modulus is determined by measuring the amount a concrete cylinder specimen deflects under known loads. The cross-sectional area and the length of the cylinder must be measured. The modulus can then be calculated from these values.

Performance

The modulus of elasticity of hardened concrete is an important material property. The modulus of elasticity gives the relationship between applied loads and corresponding deflections.

Nature of Test

This test measures the modulus of elasticity of hardened concrete directly. This test must be performed in a materials lab because a compressive tester and a compressometer are needed. This test requires a sample of the concrete molded into a 150 × 300 mm (6 × 12 in) cylinder.

Test Equipment

The equipment needed for this test procedure will not be found in most materials labs. The compressometer must be adjusted correctly, which makes the test difficult to perform. Measurements are obtained using the gauge on the compressive tester and the dial gauges on the compressometer. The results should be used as a good approximation and not an exact value. This test requires a significant amount of training to perform accurately.

Tex-422-A Linear Shrinkage of Portland Cement Concrete

The linear shrinkage of portland cement concrete is determined by casting a beam specimen that has a cross section that is 75 mm × 75 mm (3 in × 3 in) and is 286 mm (11¼ in) in length. The pieces of aggregate larger than 25 mm (1 in) should be removed. The sample is then cured in a moisture room. The length of the specimen is measured in seven-day increments by using a high-grade micrometer. The readings are taken from the ends of the sample. If the readings are not taken from the exact same location on the sample, the readings will have significant errors. Shrinkage is greatly affected by temperature and moisture. This test must be performed at a constant temperature.

Performance

Lineal shrinkage is a very important material property in concrete pavements and structures. Shrinkage is the primary cause of transverse cracking in concrete pavements. Shrinkage is also the primary source for tensile load on the reinforcing steel.

Nature of Test

This test procedure measures the lineal shrinkage of concrete by directly measuring the amount a specimen shrinks. This test must be performed in a lab because it requires that the specimen lay undisturbed for a significant period of time so accurate readings can be obtained. This test is a non-destructive test that requires a sample of freshly mixed concrete.

Test Equipment

This test requires a standard beam mold that can be found in any materials lab and a high-grade dial micrometer that is usually not standard in most materials labs. This test requires the specimen to be stored in a curing room for 28 days with readings obtained every seven days. The dial gauge can be read in 0.0001 in units. The accuracy of this procedure greatly depends on the ability to acquire readings at precisely the same location on the sample. Results should be used as an approximation and not an accurate value. This procedure requires the technician to be familiar with this method and aware of the potential sources of error so that they can be minimized.

Tex-612-J Acid Insoluble Residue for Fine Aggregate

This test is used to detect the amount of $CaCO_3$ in a sample of fine aggregate by means of the percent of hydrochloric acid insoluble residue that is present. The percentage is determined as a ratio of the weight of residue to the weight of original sample in an oven-dried condition. A sample of sand is subjected to a solution of hydrochloric acid prepared at a ratio of 1:3. During the soaking period, $CaCO_3$ is dissolved and removed from the sample.

Performance

The amount of fine $CaCO_3$ dust in the fine aggregate may affect performance if the content is more than 20 percent, but current specifications hold the percentages to less than 3 percent. The primary effect of high fines content in concrete is on the degree of drying shrinkage and the water demand of the mixture during placing operations. At contents greater than 20 percent, a loss in strength may occur.

Nature of Test

The test is used to detect the buildup of excessive limestone fines in a limestone stock pile that has been subjected to construction traffic during the placing of the stockpile. The test is destructive since the sample of sand is discarded after the test.

Test Equipment

The test can be conducted in a field laboratory and uses equipment that is available in most materials labs. Training is required to conduct this test since it involves the use of hazardous chemicals.

JOINT SEALANT MATERIALS

Tex-613-J Testing of Preformed Joint Seals (Class 6)

Joint seals are an important component in pavement performance. They provide a cushion between pavement interfaces and can also be used to allow failure to occur in a predetermined location. Preformed joint seals are manufactured and delivered to the site for installation. The joint is designed to fit a specific need. Factors that must be considered are precise dimensions of the joint, weather conditions the joint material will be subjected to, and strength properties required of the joint material. This test examines the lateral pressure exerted by the seal on the joint faces when the seal is subjected to compression and also examines the change in area of contact between the seal and the joint faces.

Performance

When designing a pavement, the type of joint seal must be designed as well if it is to be preformed. It is important to know the strengths of the joint seal material to ensure that the seal will not fail due to physical alterations of the pavement. The joint seal should behave as a cushion between the joint faces under any normal weather and loading conditions.

Nature of Test

The test procedure requires accurate measurements and calibrations. It is recommended that a qualified technician conduct the test and record the data. The time in which this test can be performed is relatively short depending on the material being tested. It is estimated that the entire test should not exceed two hours. The test procedure must be conducted in a lab that can maintain standard laboratory test conditions.

Test Equipment

The apparatus for this test is assumed to be equipment already owned by the Texas Department of Transportation and can be readily available to perform this test procedure.

Tex-525-C Tests for Asphalt and Concrete Joint Sealers

This test method yields several important material characteristics that are necessary in designing a joint sealer. The test separates materials into the following classes; Class 1 and 2 are to be two component synthetic polymers; Class 3 is hot poured rubber; Classes 4, 5, and 7 will be low modulus silicone sealant; Class 6 is a preformed joint seal and is discussed in Tex-613-J.

Performance

Class 1 is a cold extruded sealant, and Class 2 is a self-leveling sealant. By following test method ASTM D 1851, the bond strength, resistance to penetration, and flow capacity can be determined. The bond strength is a property that represents the amount of tensile load, caused by shrinkage of the pavement, that the sealant material can support. The flow capacity will assist in predicting how the sealant will behave under constant loading. Also, aged and un-aged resilience of a sealant can be determined using the ASTM D 3407 test method. In knowing the aged and un-aged resilience of the joint sealant, its performance in the field after being subjected to heating and cooling cycles can be estimated.

For Class 3, the sealant bond strength, resistance to penetration, flow capacity, and resilience can all be determined using test method ASTM D 3407. The importance of these material properties is discussed in the previous paragraph.

For Classes 4, 5, and 7, test procedures to determine the flow, extrusion rate, tack free time, and non-volatile content are outlined by the TxDOT Manual of Testing Procedures. Class 4 is a low modulus silicone that is non-sag. Class 5 is a low modulus silicone that is self-leveling. Finally, Class 7 is a low modulus silicone that is rapid curing and self-leveling.

Nature of Test

The test measures are direct and non-destructive and must be performed in a lab by a qualified technician. The purpose of these tests is to aid in estimating a sealant's performance during use and after being subjected to weather cycles. These tests will require repetition of test procedures and conditioning of the sealant material to properly model actual conditions the joint sealant will be subjected to in the field.

Test Equipment

The test equipment required to perform these tests can be found in any standard materials lab. If the procedures are followed precisely and care is taken in recording data, this test method can provide accurate property values of the joint sealant material.

Summary

Using a threshold utility of 80, very few of the current TxDOT tests would qualify for use in the assessment of structural design criteria, as noted in Appendix B. However, some of the tests have a performance utility near 90, which warrants some consideration. The tests that meet that criteria are: soil moisture content and basic soil properties that relate to swell potential, soil strength, soil k-value (field test), cement fineness and tensile strength, aggregate gradation, concrete compressive, modulus of elasticity, and flexural strength. These tests provide valuable information in terms of supporting data that are useful in interpreting the results of field tests directly related to structural criteria.