Analytically Based Asphalt Pavement Design and Rehabilitation: Theory to Practice, 1962–1992

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INTRODUCTION

The subject of this lecture is the development of analytically based asphalt pavement design and rehabilitation during the 30-year period from 1962 to date, development that received impetus from the First International Conference on the Structural Design of Asphalt Pavements, held at the University of Michigan in 1962.

Why this subject, other than the fact that this has been my area of engineering research, at least for this 30-year period? When one considers the amount of money expended for pavements in general and asphalt mixes in particular, the importance of research in this general area becomes apparent. Consider, for example, a 1-mi stretch of freeway consisting of three lanes in each direction with shoulders; the cost for an 8-in.-thick layer of asphalt concrete alone would be of the order of $3 million. Considering then the existing street and highway network as well as airfield pavements, parking facilities, and so on, it is possible to understand why expenditures for asphalt mixes are of the order of $10 billion to $12 billion per year. If research could save 1 percent of these costs, the 5-year, $50 million asphalt research program on which the Strategic Highway Research Program (SHRP) is now embarked would be paid for in approximately 4 months.

Add to the asphalt mix costs those for other pavement components as well as the potential savings in user costs resulting from improved pavement performance, and one develops an appreciation for the necessity of continued research on pavements.

The perspective presented herein has been influenced strongly by research at the University of California at Berkeley during this period, research performed by many who have contributed significantly to the field. Moreover, the interrelation of asphalt pavement design and rehabilitation and asphalt-aggregate mix design is emphasized; they must be considered together to develop optimally performing pavement structures, whether new or rehabilitated.

Although 1962 has been selected as the starting point for analytically based design as we know it, four developments before this time had a significant influence: the early analytical work of Burmister (*1*), the development of a deflection-measuring device (the Benkelman beam) during the WASHO Road Test (*2*), the research by Hveem on pavement deflections and fatigue failures (*3*), and the AASHO Road Test (*4*).

A brief summary is given of available analysis procedures that have been developed during this period, analysis procedures made possible by the advent of the electronic computer. Included are references to available multilayer elastic and viscoelastic analyses using closed-form solutions and finite-element idealizations. Although the majority of these solutions are based on so-called static load response, a recently developed computer solution permits treating the load and pavement response dynamically.

A simplified framework for pavement analysis and design is shown in Figure 1. Some aspects of this process will be discussed, as outlined in the following paragraphs.

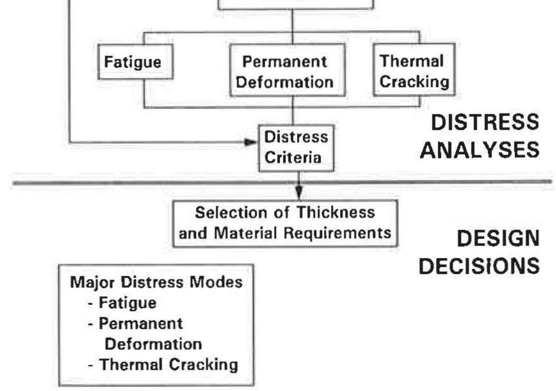

FIGURE 1 Simplified framework for pavement analysis and design.

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Materials characterization, so necessary to supply the requisite input information for analytically based design and rehabilitation, is reviewed. A summary of constitutive relationships for stiffness (modulus) characteristics that can be used in the various analysis procedures is presented for fine-grained (subgrade) soils, untreated granular materials, asphalt- or modified-binder-bound materials and portland-cement-stabilized materials. Included are the effects of environment and stress on material characteristics.

The necessity for proper specimen preparation is emphasized, and some recommendations are included to ensure that the stress-strain characteristics of laboratory-prepared specimens will be representative of the materials as they exist in the pavement structure.

Fatigue, permanent deformation, and *thermal cracking* are the three major modes of distress that lead to a reduction in the serviceability of asphalt concrete pavements. So that the potential for these forms of distress can be analyzed within the framework of Figure 1, prediction methodologies as well as distress criteria are required. Methodologies associated with each of the three distress modes are discussed.

A number of design procedures have been developed that incorporate aspects of the various analyses and materials evaluation procedures described in this paper. Some of these are briefly summarized to illustrate the efficacy of this approach. In effect, the intent of the analysis and design process is to simulate, in advance, the expected performance of the asphalt pavement so that the optimum thicknesses of the various components can be selected and the available materials can be used effectively. Thus, it is possible for an engineer to use the information of the type presented and, interacting with a computer work station, to carry out for either new or rehabilitated pavements designs that range from relatively simple to complex, depending on the significance (and cost) of the particular project. Moreover, through this process, general guidelines and catalogues of information can be developed for future reference. Updating and modifications are possible as further research provides additional information. It must be recognized that pavement design and rehabilitation processes are not static, but must be amenable to improvements as research-based developments provide better ways to do the job.

In a discussion of this type, in which past is prologue, I have also included recommendations for what might be done in the next few years to expand our capabilities for pavement design and rehabilitation. One person can never provide an all-encompassing view; rather, suggestions like those included here together with recommendations from others provide a framework by means of which substantial advances can be made. It is my intent that the material included here be presented in that context.

BACKGROUND AND FOUNDATIONS

Although there was considerable development in the pavement field before 1962, four studies from this period, in my opinion, have affected the development of analytically based design methodology.

A key development was the work of Burmister in the early 1940s, that is, his solutions for the response of two- and three-layer elastic systems to representative loading conditions (*1*). Although these solutions were limited to conditions at layer interfaces and the results were generally presented in graphical form, they nevertheless introduced the engineering community to the important concept of treating the pavement as a layered system. Comprehensive use of these solutions would have to wait approximately 15 years for the advent of the electronic computer.

A second important development occurred during the WASHO Road Test when Benkelman introduced the Benkelman beam, which permitted pavement deflections to be measured under slow-moving wheel loads (*2*). The Benkelman beam facilitated rapid measurement of pavement response, thus providing an early indication of future performance and a comparative measure against which to check calculated pavement response. It also provided an important tool for improved design of overlay pavements.

A third important development occurred in California. Using a General Electric travel gauge, Hveem had been investigating pavement deflections for a number of years before the WASHO Road Test. Publication of his research in 1955 (*3*), which is one of the most important papers in the pavement field, provided a strong link between pavement deflections and fatigue failures in the asphalt-bound portion of pavement sections. Hveem's work had, in my judgment, a most significant impact on the development of procedures to predict fatigue cracking using analytically based methodologies.

The AASHO Road Test, completed in 1961, is the fourth important development (*4*). Funded in the 1956 Interstate Highway Act, its cost of $29 million corresponds to the current cost of the SHRP program. It sparked a renewed interest in improved pavement design and provided the impetus for the development of many of the current analytically based design procedures. Under the excellent leadership of W. N. Carey, Jr., the AASHO Road Test provided another important contribution to the engineering community, since well-documented performance data were assembled and stored, permitting future researchers to have access to them. Performance predictions by the new analytically based procedures could be compared with actual field performance; reasonable comparisons confirmed the "engineering reasonableness" of the methodologies.

PAVEMENT ANALYSIS

The use of multilayered analysis to represent pavement response, although developed by Burmister in the 1940s (*1*), did not receive widespread attention until the First International Conference on the Structural Design of Asphalt Pavements in 1962. Although some agencies utilized solutions for two- and three-layered elastic solids in their design methodologies [e.g., the U.S. Navy (*5*)], the use of these solutions was both limited and cumbersome.

At the 1962 conference, however, important contributions were made by Whiffin and Lister (*6*), Skok and Finn (*7*), Peattie (*8*), and Dormon (*9*). Both Whiffin and Lister and Skok and Finn illustrated how layered-elastic analysis could be used to analyze pavement distress. Peattie and Dormon presented a number of concepts based on such analyses, which would later become a part of the Shell pavement design methodology (and that of other organizations as well).

A number of general solutions for determination of stresses and deformations in multilayer elastic solids also were presented at the 1962 conference. Additional related work was presented in 1967 at the Second International Conference. These general solutions, coupled with the rapidly advancing computer technology, fostered the development of the current generation of multilayer elastic and viscoelastic computer programs. Some of the most commonly used programs are given in Table 1. The widely used ELSYM program, developed at University of California at Berkeley by Ahlborn (*12*), most certainly benefitted from the 1962 and 1967 conference papers. [Although it never appeared in the published literature, the work of the Chevron researchers (*11*) must be acknowledged, because they presented the first computer solution for a five-layer system (CHEV5L) in 1963.]

In the late 1960s finite-element analyses to represent pavement response were developed by researchers such as Duncan et al. (*17*). Increasingly the finite-element method has been used to model pavement response, particularly to describe the nonlinear aspects of materials behavior. The significant work of Dehlen (*18*) and Hicks (*19*) illustrated how the nonlinear response of granular materials could be reasonably accounted for in pavement analyses. The program ILLIPAVE (*20*) incorporated many of the developments by Duncan et al. (*17*), Dehlen (*18*), and Hicks (*19*).

Current finite-element methodology has some advantages over layered-elastic and viscoelastic solutions because it provides greater flexibility in realistically modeling the nonlinear response characteristics of all the materials that make up the pavement section.

Although pavement engineers have recognized the importance of dynamic loading, it is only recently that such effects could be treated analytically. Lysmer and others (*21a*, *21b*) have developed a menu-driven program (SAPSI) for a

TABLE 1 Examples of Multilayer Elastic Analysis Computer Programs

Program	Number of layers (max.)	Number of loads	Continuity conditions at interface	Probalistic considerations	Program source
BISAR (*10*)	10	10	full continuity to frictionless	no	Shell International Petroleum Co., Ltd., London, England
Remarks:	• Comparatively long running time since complete set of stresses and strains provided for each point. • Considers horizontal as well as vertical loads.				
CHEV (*11*)	5	2	full continuity	no	Chevron Research Company
Remarks:	• Nonlinear response of granular materials accounted for in DAMA program of the Asphalt Institute which makes use of CHEV program.				
ELSYM (*12*)	10	100	full continuity to frictionless	no	University of California at Berkeley
Remarks:	• Short running time for particular point.				
PDMAP (PSAD) (*13*)	5	2	full continuity	yes	National Cooperative Highway Research Program (Project 1-10B)
Remarks:	• Running time is long for degrees of reliability other than 50-percent (the deterministic mode). • Iterative process used to arrive at moduli for untreated granular materials.				
VESYS (*14*)	5	2	full continuity	yes	FHWA-US DOT
Remarks:	• Running time is long in probabilistic mode. • Program considers materials both as time independent (elastic) and time dependent (viscoelastic).				
CHEVIT (*15*)	5	12	full continuity	yes	U.S. Army CE Waterways Experiment Station
Remarks:	• Modification of CHEV program. • Includes provision for stress sensitivity of granular layers.				
CIRCLY (*16*)	5+	10+	full continuity to frictionless	no	MINCAB Systems, Canterbury, Australia (for Australian Road Research Board)
Remarks:	• Permits consideration of horizontal and vertical loads; in particular permits consideration of radially directed horizontal forces. • Can consider orthropic material behavior. • Permits consideration of strain energy.				

viscoelastic-layered system subjected to dynamic loads. This program may be run on a microcomputer and incorporates material properties that can be varied with the excitation frequencies of the load. The SAPSI program also permits the calculation of dissipated energy at any point in the asphalt-bound layer. This capability may prove extremely useful in the prediction of fatigue response, as will be seen in the discussion of the SHRP program research activities.

With improved microcomputer capabilities, it is now possible to simulate materials response to both load and environmental factors more accurately. The use of finite-element idealizations need not be limited to research applications. Rather they should be an integral part of routine pavement analysis and design.

MATERIALS CHARACTERIZATION

An integral part of the development of analytically based methodologies has been the evolution of procedures to define requisite materials characteristics. For example, the solutions for stresses, strains, and deflections on which the analyses discussed in the previous section depend require a measure of the elastic or viscoelastic properties of the pavement materials. The solutions summarized in Table 1 are based on the assumption of *linear* response. [In some of the solutions, for example, PDMAP (PSAD) (*13*), an ad hoc representation of the nonlinear response of granular materials is utilized.] In reality, the majority of the materials used in pavement structures do not satisfy such an assumption. Accordingly, ad hoc simplifications of materials response must be used.

To define pavement materials response characteristics properly, one must consider the following service conditions: stress state (associated with loading), environmental conditions (moisture and temperature), and construction conditions (including water content and dry density for untreated materials). To ensure that materials evaluation is accomplished with reasonable cost, these service conditions must be carefully selected for use in laboratory testing.

Many of the existing pavement design procedures do not provide materials parameters in a form that can be used in the analysis methodologies described earlier. Certainly the California bearing ratio (CBR), the stabilometer *R*- and *S*-values, and the Marshall stability are not compatible with the analytically based procedures. Fortunately, there have been developments that have remedied these shortcomings. Although these developments have required simplifications, they generally have passed the test of engineering reasonableness, at least in my judgment.

One such simplification has been to describe the materials response in terms of the relationship between applied stress and recoverable strain measured in a repeated load test. Introduced by Seed (*22*), the term *resilient modulus* was used to describe this relationship and was based on his work with fine-grained soils. It has had, I believe, a significant impact on the development of analytically based design procedures and has been incorporated into the 1986 version of the *AASHTO Guide for Design of Pavement Structures* (*23*).

Research results of Seed and his colleagues (and of my colleagues as well), together with research on the resilient and dynamic stiffness properties of other paving materials, will be discussed in this section. Although this discussion focuses primarily on developments at the University of California at Berkeley, it also includes research by other organizations.

To determine the stresses, strains, and deflections in the various systems described above, it is necessary to have a measure of the stiffness characteristics of the various pavement components.

Although there has been considerable research on the stiffness characteristics of fine-grained soils and granular materials, impetus for these efforts was provided by the research of Seed and his associates, particularly Chan, Lee, and Mitry (*22, 24, 25*). In addition, the research endeavors of Hicks (*19*) and Dehlen (*18*), which followed from those efforts, have supplied very useful information for design purposes.

The research at Berkeley by Secor (*26*), Alexander (*27*), Terrel (*28*), Epps (*29*), Sousa (*30*), and Tayebali (*31*) has provided useful information on the stiffness characteristics of asphalt-aggregate mixtures.

Similarly the studies on cement-stabilized materials by Mitchell and those associated with him, including Fossberg (*32*), Shen (*33*), and Wang (*34*), as well as the work of Pretorius (*35*) and Raad (*36*), have provided useful data on the stiffness characteristics of those materials as well.

Fine-Grained Soils

The stiffness characteristics of fine-grained soils are dependent on dry density, water content, soil structure, and stress level. For a particular condition, the resilient modulus M_R (one measure of stiffness) is dependent on the applied stress; that is,

$$M_R = F(\sigma_d) \quad (1)$$

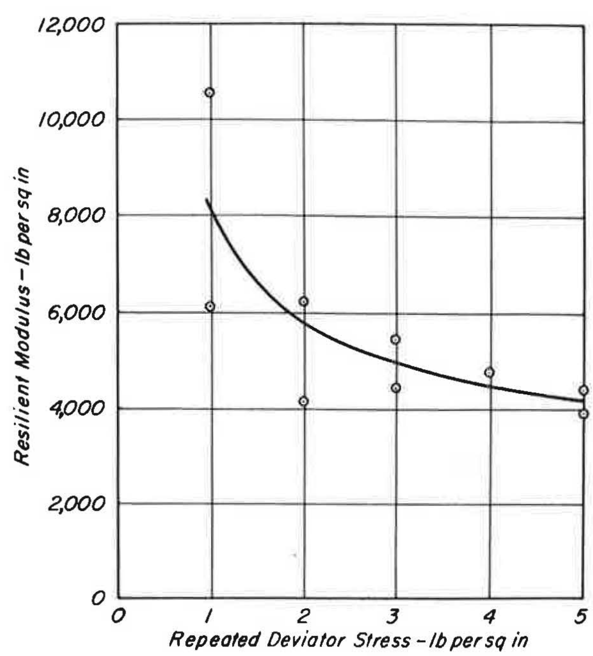

FIGURE 2 Results of repeated load test, subgrade soil.

where $F(\ )$ represents function of and σ_d is the repeatedly applied deviator stress in a triaxial compression test.

Figure 2 provides an example of this dependency, and Figure 3 shows, for a particular stress state and number of load repetitions, the dependence of M_R on water content and dry density (and presumably soil structure as well) for a wide range of potential service conditions.

For partially saturated soils (a condition representative of many subgrades worldwide), stiffness is dependent on the negative pore-water pressure (soil moisture section) as shown in Figure 4 (*18*). Data shown in Figure 5 suggest that laboratory-prepared specimens exhibit essentially the same stiffness as "undisturbed" specimens for comparable suction values (*18*).

Freeze-thaw action also influences the stiffness of fine-grained soils. When the soil is frozen, its stiffness increases; when thawing occurs, the stiffness is reduced substantially, as shown in Figure 6 (*37*), even though its water content may remain constant. This was originally suggested by Sauer (*38*). Such variations should be incorporated into the design process where appropriate.

To ensure that fine-grained soils tested in the laboratory for pavement design purposes are properly conditioned requires an understanding of soil compaction, particularly the relationship among water content, dry density, soil structure, and method of compaction (*39*). At water contents dry of optimum for a particular compactive effort, clay particles are arranged in a random array termed a "flocculated" structure.

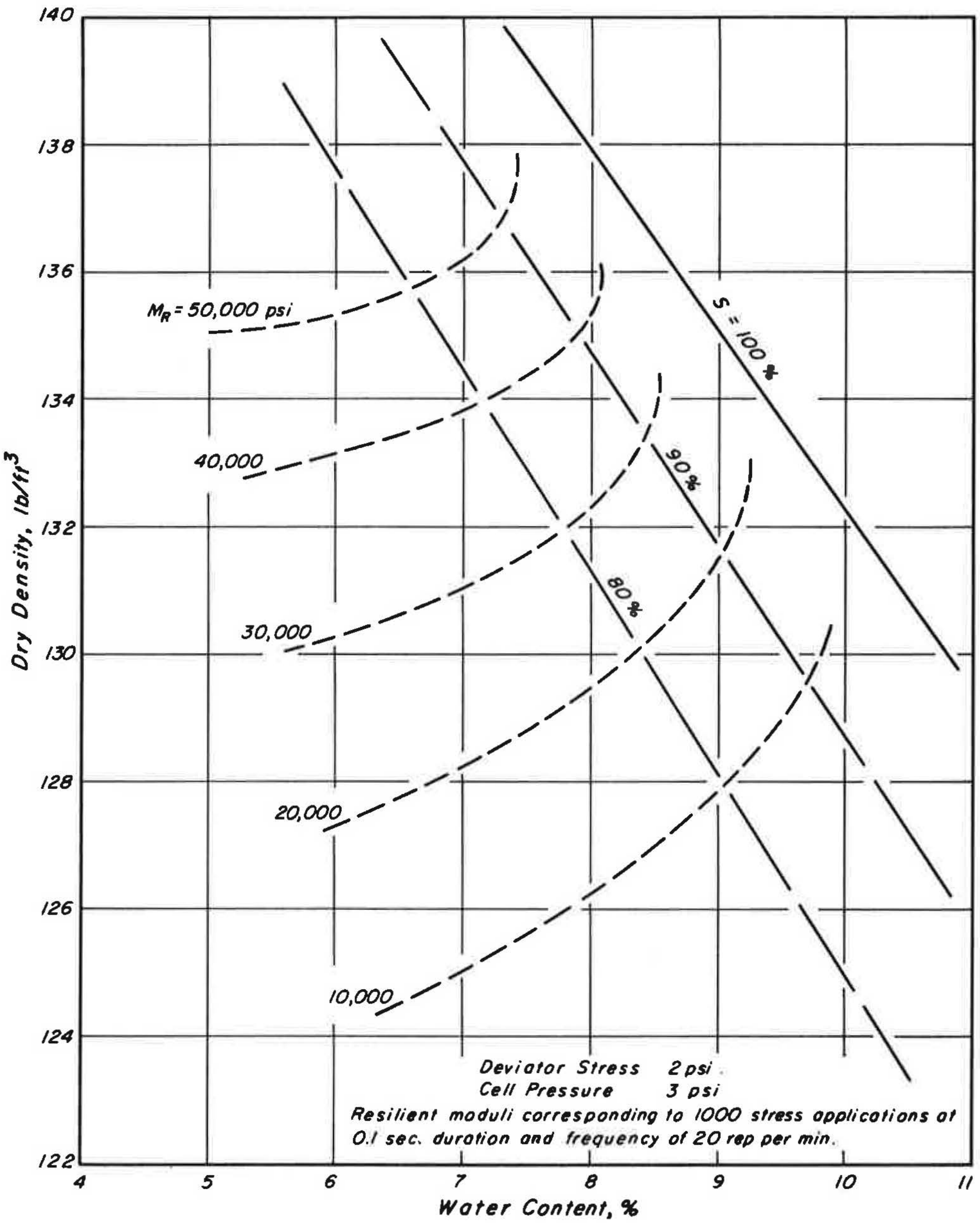

FIGURE 3 Water content–dry density–modulus relationship for subgrade soil.

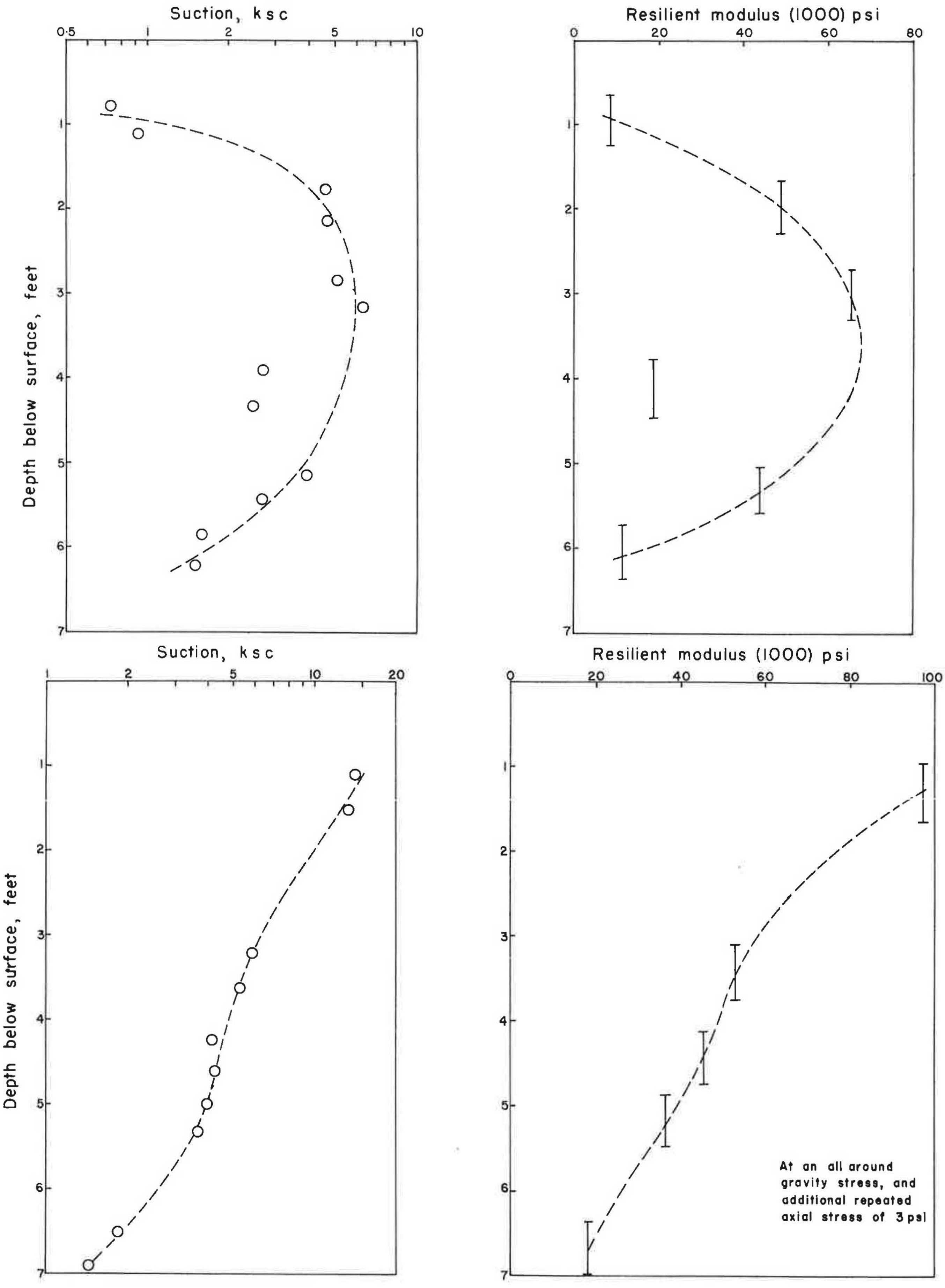

FIGURE 4 Relationships between suction and resilient modulus (*18*).

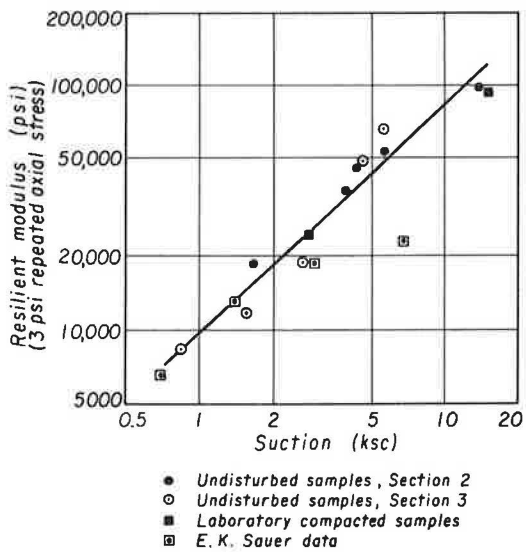

FIGURE 5 Relationship between resilient modulus and suction, subgrade soil (*18*).

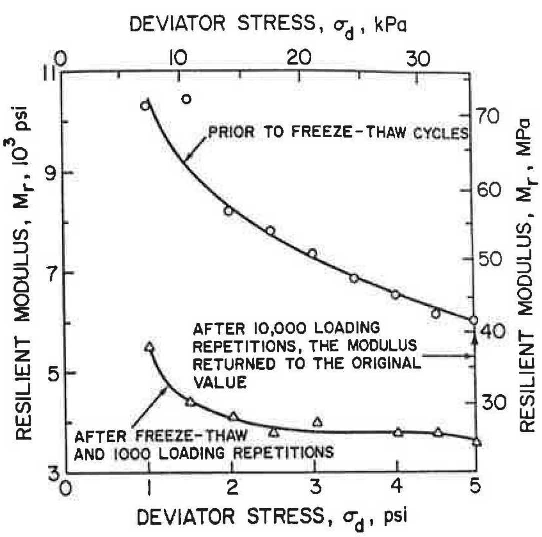

FIGURE 6 Resilient modulus test results before and after freeze-thaw for undisturbed Regina clay (*37*).

At water contents wet of optimum (provided shearing deformation is induced during compaction), particles are oriented in a parallel fashion, often termed "dispersed." These dispersed and flocculated compacted soil structures can lead to significant differences in mechanical properties for specimens assumed to be at the same water content and dry density.

To illustrate, consider a sample prepared by kneading compaction and soaked to a condition representative of that expected at some time subsequent to placement. The resilient response is shown in Figure 7 (H. B. Seed, unpublished data). If the designer were to compact the sample to the same initial condition by kneading compaction to save time in the laboratory (since it takes considerable time for a fine-grained material to become saturated), a different result would be obtained. On the other hand, if the soil were prepared by static compaction to the same condition, essentially the same result would be obtained as for the situation in which the sample is prepared "dry" by kneading compaction and soaked to the particular state. In this case, static compaction wet of the line of optimums creates essentially the same structure as kneading dry of the line of optimums.

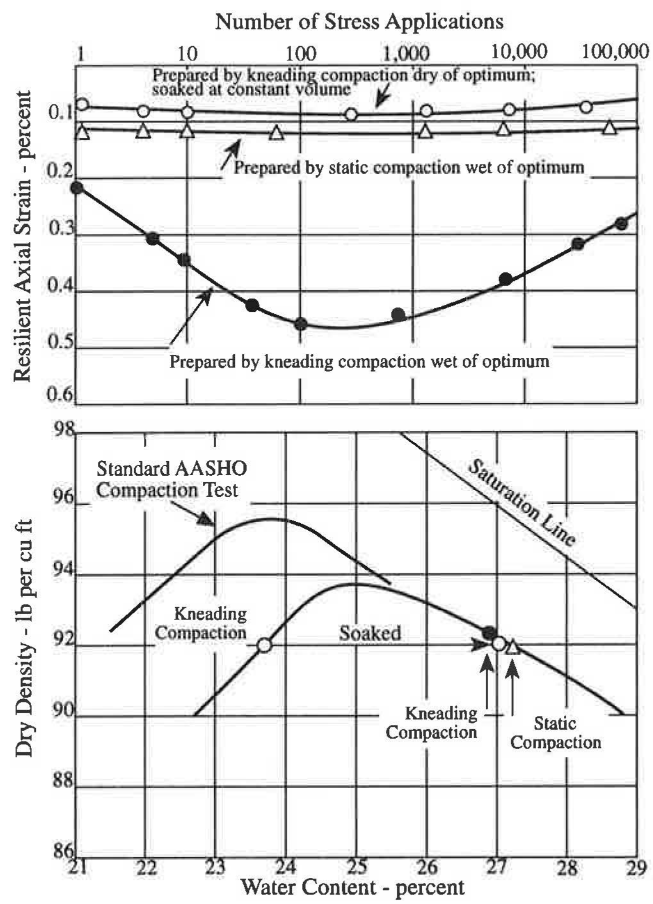

FIGURE 7 Influence of soil structure on resilient response (H.B. Seed, unpublished data).

Thus, it is important that the designer understand these principles and utilize them in the selection of conditions for specimen preparation for testing. Guidelines based on such considerations are available (*40*).

Untreated Granular Materials

The stiffness characteristics of untreated granular materials are dependent on the applied stresses. This stress dependency can be expressed in several different ways (*18, 19, 25, 41a, 41b*):

$$M_R = K\sigma_3^n \tag{2}$$

$$M_R = k_1\theta^{k_2} \tag{3}$$

$$M_R = F(p,q) \tag{4}$$

where

σ_d, σ_3 = deviator stress and confining pressure in a triaxial compression test, respectively;
θ = sum of principal stresses, in triaxial compression ($\sigma_d + 3\sigma_3$);
q = σ_d in a triaxial compression test;
p = mean normal stress ($\sigma_d + 3\sigma_3$)/3; and
K,n,k_1,k_2 = experimentally determined coefficients.

The work of Dehlen, in which a granular material was characterized as a non-linear-elastic material, suggests that Equation 3 is a reasonable way to represent materials response. This form can be used in an ad hoc manner in layered elastic analyses (*42, 13*) and in finite-element idealizations (*17*). The work of Hicks (*19*) clearly demonstrated the efficacy of this latter approach.

Figure 8 shows the response represented by Equation 3. Table 2 contains a summary of aggregate responses representative of the behavior depicted by Equation 3 and Table 3, a summary of design moduli used by some agencies (*44*).

Although method of compaction is important for fine-grained soils because of soil structure considerations, the primary factors affecting the stiffness characteristics of granular materials are water content (degree of saturation) and dry density (*18, 19, 45*). Accordingly, any method of compaction (e.g., vibratory) that produces the desired dry density is considered suitable for laboratory preparation of specimens for testing.

Asphalt-Aggregate Mixtures

The stiffness characteristics of asphalt-aggregate mixtures are dependent on the time of loading and temperature:

$$S_{\text{mix}} = \frac{\sigma}{\varepsilon}(t,T) \tag{5}$$

where

S_{mix} = mixture stiffness;
σ,ε = stress and strain, respectively;
t = time of loading; and
T = temperature.

At temperatures above 25°C it is likely that the stress state has an influence on the stiffness characteristics of these materials, becoming more pronounced as the binder becomes less stiff. Figure 9 shows the dependence of mixture stiffness on both time of loading and temperature, and Figure 10 provides an indication of the range in stiffness that might be expected under moving wheel loads in different environments in the United States (*46*).

For some engineering applications, asphalt-aggregate mixtures can be treated as linear-viscoelastic materials, as demonstrated by Secor (*26*). The interchangeability of time and temperature can be considered applicable (i.e., the material can be assumed to be rheologically simple) as shown by Alex-

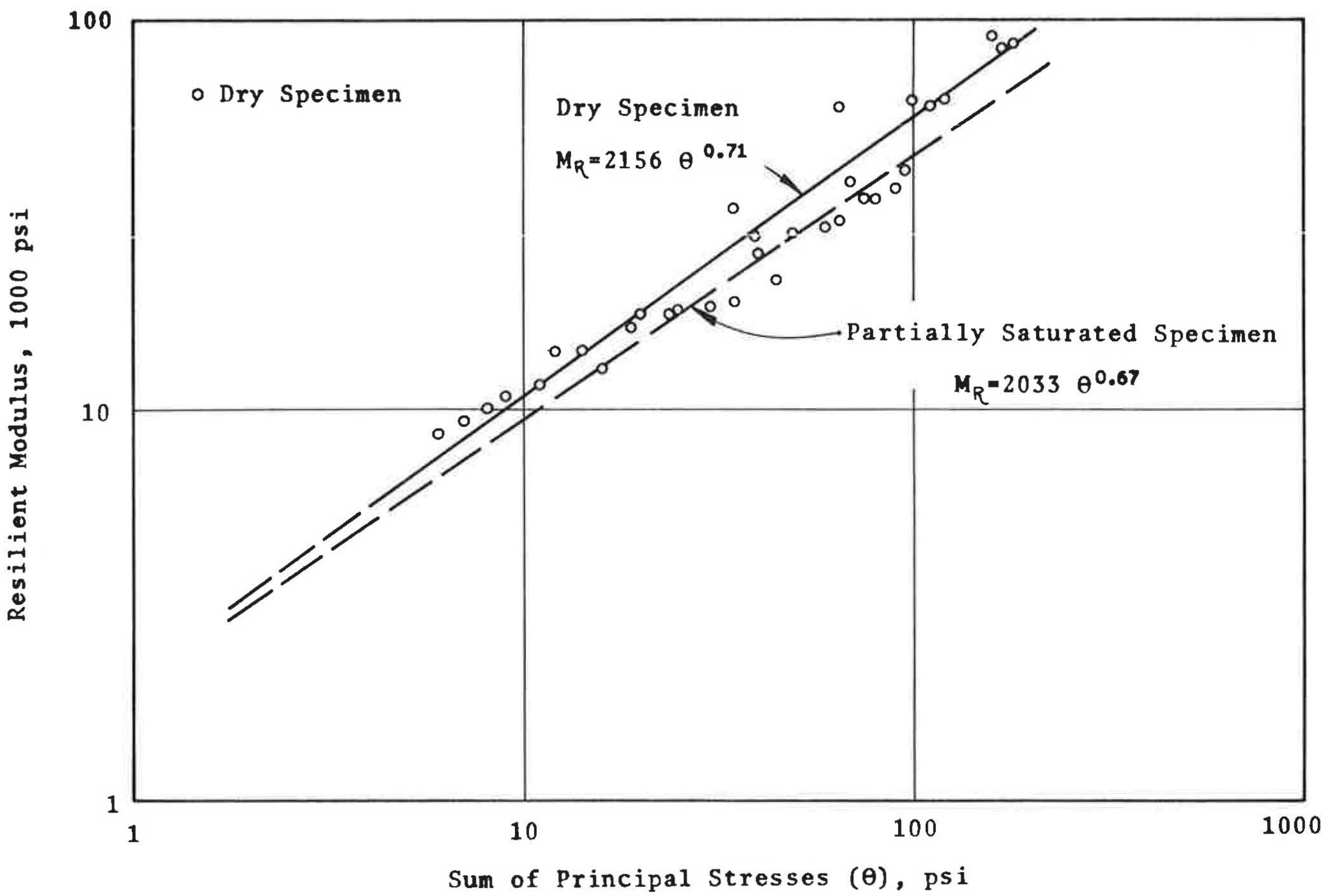

FIGURE 8 Resilient modulus versus sum of principal stresses (σ), untreated aggregate base (*19*).

TABLE 2 Summary of Representative Repeated Load Triaxial Compression Test Data for Untreated Granular Materials

Material	K_1	K_2	Reference
Partially crushed gravel; crushed rock	1,600 — 5,000	0.57 — 0.73	(*19*)
Crushed stone	4,000 — 9,000	0.46 — 0.64	(*43*)
Well-graded crushed limestone	8,000	0.67	(*41*)

ander (*27*) and others (*47–49*). For example, when the propensity of a mix for fatigue cracking is evaluated, mix stiffness used to calculate the critical stresses or strains can be determined using the above assumptions at a specific temperature and at a rate of loading corresponding to that of a rapidly moving vehicle (e.g., 0.02 sec). Use of this approach has been discussed elsewhere (*46*).

For permanent deformation evaluation, particularly at temperatures of 40°C or above, mixtures can no longer be treated as linear-viscoelastic. Under these circumstances research suggests that the material should be defined by nonlinear materials characteristics in order to properly model observed behavior like stress hardening and dilatancy (*50*). One approach by which this can be accomplished is shown in Figure

TABLE 3 Representative Moduli for Untreated Granular Materials

Organization	Material	Modulus, ksi	
Belgium	Stone base	72.5	
	Subbase	29.0	
Czechoslovakia	Subbase	21.8	
Italy	Granular material	36.3	
U.S.A., FHWA	AASHO Base:		
	Spring	30.0	
	Other seasons	40.0	
South Africa, NITRR	AASHO Subbase:		
	Spring	15.0	
	Other	20.0	
	Overlaying Cement Stabilized Layer		
	High quality crushed stone	Range	36 - 130
		Design value	65
	Crushed stone/natural gravel	Range	29 - 116
		Design value	51
	Gravel base	Range	25 - 102
		Design value	51
	Gravel subbase	Range	21 - 65
		Design value	36
	Overlaying Untreated or Cracked Stabilized Layer		
	High quality crushed stone	Range	25 - 87
		Design value	29[a]
	Crushed stone/natural gravel	Range	15 - 65
		Design value	29[a]
	Gravel base	Range	15 - 65
		Design value	29[a]
	Gravel subbase	Range	11 - 58
		Design value	29[a]
	Gravel subbase (lower quality)	Range	7 - 44
		Design value	21[a]

[a] The values shown are for bases or subbases under asphalt concrete. For base courses directly under surface treatments, higher values are used; e.g., in the case of the crushed stone base, a design modulus of 36 ksi (versus 29 ksi) is recommended [Reference (*44*)].

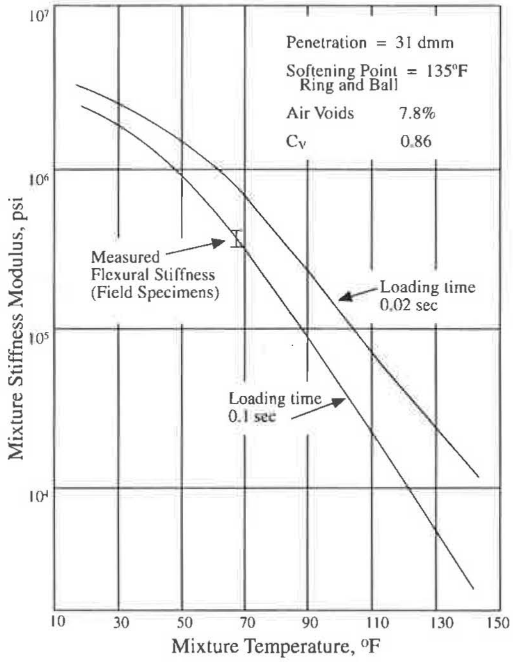

FIGURE 9 Computed relationship between mix stiffness and asphalt concrete.

11, in which the material (asphalt concrete) is treated as a nonlinear-viscoelastic system containing at least five Maxwell elements. In this model nonlinear-elastic response characteristics (defined by the *E*'s) can be determined from a simple shear test (Figure 12). The linear-viscoelastic response (defined by the η's in Figure 11) can be obtained from interpretations of the results of dynamic stiffness (or creep) testing over a range of frequencies (and temperatures).

When the response characteristics of an asphalt concrete mixture are measured to define its propensity for permanent deformation, it is important that the mixture be prepared by

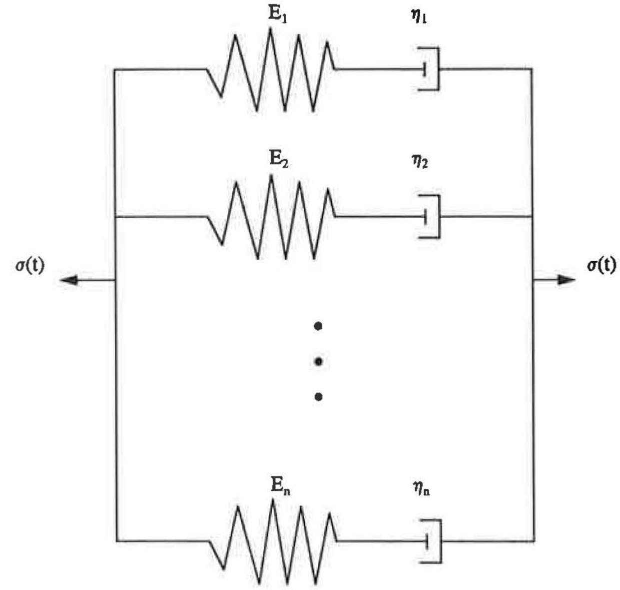

FIGURE 11 Nonlinear viscoelastic representation for asphalt concrete.

a compaction procedure that will reproduce an aggregate structure similar to that obtained in situ, including the effects of both the initial compaction process and repeated trafficking. Available evidence from Sousa et al. (*51*) and the Permanent International Association of Road Congresses (PIARC) (October 1990) suggests that a form of rolling wheel compaction is the method most likely to achieve these representative conditions.

In general, it is possible to define the stiffness characteristics of asphalt concrete in dynamic (sinusoidal), creep, or repeated loading. With today's equipment capabilities, dynamic loading over a range of frequencies (and temperatures) is the recommended procedure. If repeated loading in the diametral mode is used, it is suggested that the test be performed at

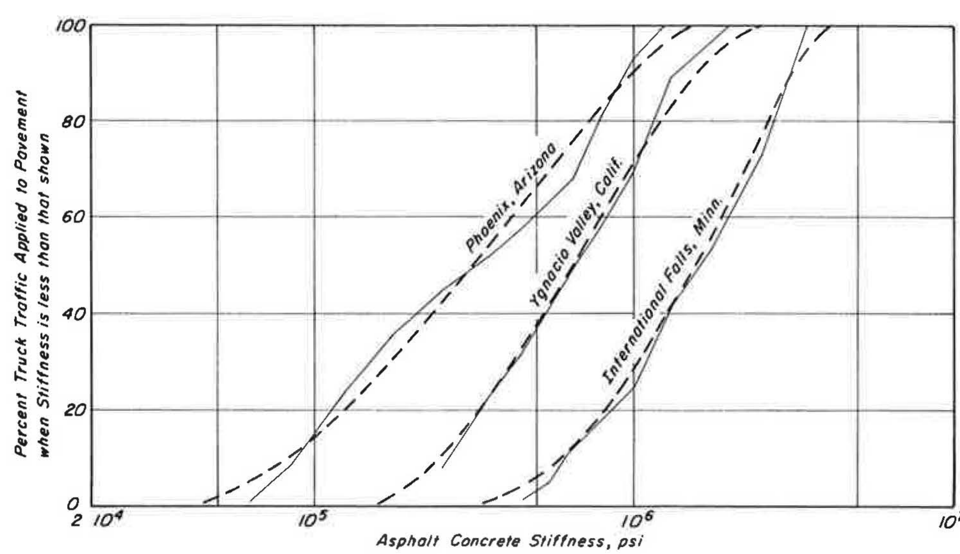

FIGURE 10 Stiffness variation with traffic application, 12-in.-thick asphalt concrete layer.

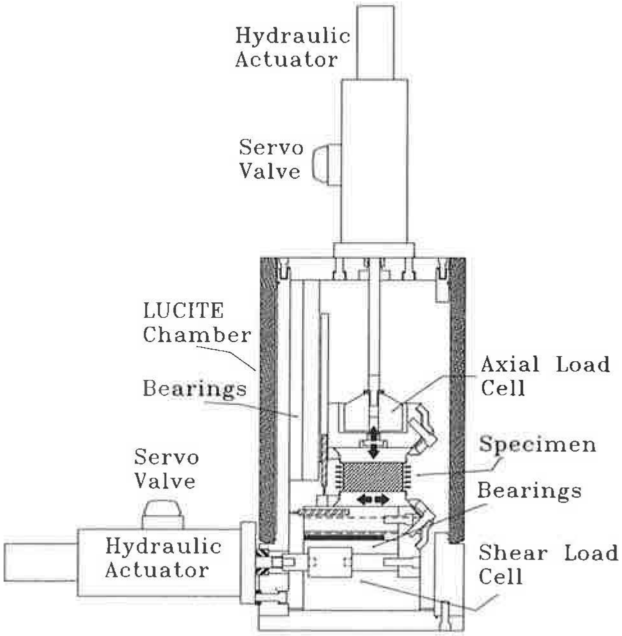

FIGURE 12 Schematic representation of simple shear test equipment.

temperatures equal to or less than about 25°C with only the horizontal deformations being measured to define the stiffness modulus (*52*).

Asphalt-Emulsion-Treated Aggregate Mixtures

For aggregate mixtures treated with asphalt emulsion, the influence of curing on stiffness also must be evaluated. Terrel has presented a procedure whereby the influence of curing could be evaluated in the design process (*28*). Other investigators have incorporated these considerations into formal pavement design methodologies (*53, 54*). For example, both the Chevron and the Asphalt Institute procedures include a provision for damage development in the early life of pavements containing emulsified asphalt bases that are partially cured.

Portland-Cement-Stabilized Mixtures

Studies of the stiffness characteristics of portland-cement-stabilized materials (*32–36, 55, 56*) indicate that stiffness moduli may range from approximately 10,000 to several million pounds per square inch, depending on soil type, treatment level, curing time, water content, and test conditions.

The research of Mitchell and his colleagues, some of which is summarized elsewhere (*55*), has developed useful relationships between the stiffness characteristics of cement-stabilized materials and various parameters such as unconfined compressive strength and flexural strength. These parameters have been used by other researchers as well and a summary of such values is included in Table 4 (*44*).

ASPHALT CONCRETE DISTRESS CONSIDERATIONS

Three major modes of distress considered in the design of asphalt concrete pavements are *fatigue cracking*, *permanent deformation*, and *thermal cracking*. Distress criteria as well as prediction methodologies that can be used in the analysis and design process are briefly discussed for each of the three distress modes.

Fatigue Cracking

When an asphalt-bound pavement layer is resting on an untreated aggregate base, the passage of a wheel load causes the pavement to deflect. The work of Hveem (*3*) demonstrated that the larger this deflection is and the higher the frequency of its occurrence, the greater the propensity for fatigue cracking. Hveem's work had, I'm certain, an impact on the development of laboratory fatigue tests on asphalt-aggregate mixtures to define this response. The resulting research has demonstrated that the fatigue response of asphalt concrete to repetitive loading can be defined by relationships of the following form (*46, 57*):

$$N = A\left(\frac{1}{\varepsilon_t}\right)^b \quad \text{or} \quad N = C\left(\frac{1}{\sigma_t}\right)^d \tag{6}$$

where

N = number of repetitions to failure,
ε_t = magnitude of the tensile strain repeatedly applied,
σ_t = magnitude of the tensile stress repeatedly applied, and
A,b,C,d = experimentally determined coefficients.

The work of Deacon (*58*), Epps (*29*), and others [such as that by Pell and his coworkers at Nottingham (*57, 59*)] has contributed significantly to our ability to design pavements to minimize fatigue cracking.

A design relationship utilized today by a number of organizations is based on strain and uses an equation of the form

$$N = K\left(\frac{1}{\varepsilon_t}\right)^a\left(\frac{1}{S_{\text{mix}}}\right)^b \tag{7}$$

which may involve a factor that recognizes the influence of asphalt content and degree of compaction and that is proportional to the following expression:

$$\frac{V_{\text{asp}}}{V_{\text{asp}} + V_{\text{air}}} \tag{8}$$

where V_{asp} is the volume of asphalt and V_{air} is the volume of air. Data developed by the researchers at Nottingham (*59*) and by Epps (*29*) have permitted the quantification of Equation 8, for example, in the Asphalt Institute design procedure (*60*).

Equation 7 is used in the Shell (*61, 62*) and Asphalt Institute (*63*) procedures with the coefficients set according to the amount

TABLE 4 Stiffness Characteristics of Portland-Cement-Stabilized Materials

Source	Material	Unconfined Compression Stress at 7 days (psi)	Modulus of Rupture at 18 days (psi)	Stiffness Modulus (psi)	Poisson's Ratio
United Kingdom (dynamic loading)	Lean concrete		225 - 250	3.75 to 5.5 × 10^6	
	Cement-treated granular material		175	2.0 to 3.75 × 10^6	
	Soil cement		175	0.5 to 3.0 × 10^6	
Belgium	Lean concrete		175	2.2 × 10^6	
Netherlands	Sand cement		220		0.25
France	Cement-treated granular material			2.9 × 10^6	0.25
	Sand cement			1.75 × 10^6	0.25
South Africa	Pre-cracked phase				
	Cement-treated:				
	Crushed stone	870 - 1740		2.0 × 10^6	0.35
	Crushed gravel	435 - 870		1.2 × 10^6	0.35
	Gravel subbase	110 - 215		0.5 × 10^6	0.35
	Post-cracked phase a) under treated (bound layer)				
	Crushed stone			0.22 × 10^6	
	Crushed gravel			0.14 × 10^6	
	Gravel subbase			0.073 × 10^6	
	b) under untreated layer				
	Crushed stone			0.17 × 10^6	
	Crushed gravel			0.11 × 10^6	
	Gravel subbase			0.044 × 10^6	

of cracking considered tolerable, the type of mixture that might be used, and the thickness of the asphalt-bound layer.

In the pavement structure the asphalt mix is subjected to a range of strains caused by a range of both wheel loads and temperatures. To determine the response under these conditions requires a cumulative damage hypothesis. A reasonable hypothesis to use [as demonstrated by Deacon (*58*)] is the linear summation of cycle ratios (sometimes referred to as Miner's hypothesis), which is stated as

$$\sum_{i=1}^{n} \frac{n_i}{N_i} \leq 1 \tag{9}$$

where n_i is the number of actual traffic load applications at strain level i and N_i is the number of allowable traffic load applications to failure at strain level i. This equation indicates that fatigue life prediction for the range of loads and temperatures anticipated becomes a determination of the total number of applications at which the sum reaches unity.

Thus, prediction of fatigue life requires that tensile strains on the underside of the asphalt-concrete layer be computed for the range of traffic loads and materials and environmental conditions anticipated [e.g., as shown in the paper by Monismith et al. presented at the Sixth International Conference on the Structural Design of Asphalt Pavements (*64*)]. With knowledge of the applied traffic for each of the above conditions, Equation 9 can be used to estimate the propensity of the particular structure for cracking.

An alternative approach is to utilize the concept of dissipated energy suggested by Chomton and Valayer (*65*) and van Dijk (*66*). Current work in the SHRP asphalt research program (*67*) suggests that the relationship presented by the aforementioned researchers is mix specific, potentially "capturing" the effects of mode of loading, rest periods, temperature, and specimen configuration test type (in flexure). That relationship is

$$W_D = AN^z \tag{10}$$

where

W_D = total dissipated energy to fatigue failure,
N = number of load repetitions to failure, and
A, z = experimentally determined coefficients.

Moreover, it is possible to compute the dissipated energy in a pavement structure by using a program like SAPSI (*21a, 21b*). Thus it is possible to check the adequacy of a specific pavement section (and asphalt mixture) if an estimate can be made of the total dissipated energy expended for a prescribed amount of traffic.

Permanent Deformation and Rutting

Rutting in paving materials develops gradually with increasing numbers of load applications, usually appearing as longitudinal depressions in the wheel paths accompanied by small upheavals to the sides. It is caused by a combination of densification (decrease in volume and hence increase in density) and shear deformation and may occur in any or all pavement layers, including the subgrade. Available information suggests that shear deformation rather than densification is the primary rutting mechanism (*68*).

From a pavement design standpoint two approaches have evolved to consider rutting. In the first, the vertical compressive strain at the subgrade surface is limited to a value associated with a specific number of load repetitions, this strain being computed by means of a layered-elastic analysis. The logic of this approach, first suggested by the Shell researchers [e.g, see the paper by Dormon (*9*)], is based on the observation that, for materials used in the pavement structure, permanent strains are proportional to elastic strains. Limiting the elastic strain to some prescribed value will also limit the plastic strain. Integration of the permanent strains over the depth of the pavement section provides an indication of the rut depth. By controlling the magnitude of the elastic strain at the subgrade surface, the magnitude of the rut is controlled.

The second procedure attempts to predict the surface rutting resulting from contributions of permanent deformations in each of the pavement components. Although this procedure is appealing from an engineering standpoint, it is more complex than the first. Only this latter approach will be discussed here and the discussion will be limited to rutting estimations in the asphalt-bound layer.

A number of researchers [originally Barksdale (*69*) and then, for example, McLean (*70*) and Freeme (*71*)] have presented procedures that use elastic analyses to compute stresses within the asphalt-bound layer and constitutive relationships that relate the stresses so determined to permanent strain for specific numbers of stress repetitions (termed the layered-strain procedure). Integration or summation of these strains over the layer depth provides a measure of the rutting that could develop.

One version of this approach was developed by the Shell researchers and has been used in modified form to evaluate specific pavement sections (*61, 62*). In this methodology, creep test results are incorporated into the following expression to estimate rutting:

$$\Delta h_1 = C_M \sum_{i=1}^{n} \left[h_{1-i} \cdot \frac{(\sigma_{\text{ave}})_{1-i}}{S_{\text{mix}_{1-i}}} \right] \tag{11}$$

where

Δh_1 = permanent deformation in the asphalt-bound layer,
h_{1-i} = thickness of sublayer of asphalt-bound layer with thickness h_1,
$(\sigma_{\text{ave}})_{1-i}$ = average vertical stress in layer h_{1-i}, and
$S_{\text{mix}_{1-i}}$ = mix stiffness for layer h_{1-i} for specific temperature and time of loading (obtained by summing the individual times of loading of the moving vehicles passing over that layer at the specific temperature).

Although this procedure is not sufficiently precise to predict the actual rutting profile due to repeated trafficking, it provides an indication of the relative performance of different mixes containing conventional asphalt cements. {In special projects [e.g., as described by Monismith et al. (*64*)], field documentation may provide a reasonable measure of C_M for use in estimation of performance of pavements containing comparable mixes.} If it is planned to use mixes containing modified binders, creep test data within the framework of Equation 11 will not provide correct estimates of mix performance since mixtures containing these binders behave differently under loading representative of traffic as compared with their response in creep. Data suggest that the use of creep test data may overpredict rutting for mixes containing some modified binders.

To predict the development of rutting and the lateral movement that may lead to upheavals adjacent to the wheel tracks, a more complex analysis is required (*50*). One such methodology is being developed within the SHRP research program wherein the constitutive relationship is defined by a model like that shown in Figure 11 that combines non-linear-elastic response with linear-viscous response. This relationship is then used in a finite-element idealization [based on FEAP (*72*)] of the pavement system to permit calculation of the accumulation of permanent deformation with repeated trafficking. Such an approach has the potential for improved rutting prediction since it incorporates some of the mix factors that cannot be considered in the layer-strain procedure.

Thermal Cracking

Thermal cracking is a mode of distress generally manifested by transverse cracks at the pavement surface. In qualitative terms, cracking is developed as follows. As the temperature at the pavement surface drops, a temperature gradient develops through the depth of the layer, since time is required for the cold to be conducted into the system. The surface of the pavement attempts to contract, but this contraction is restrained by the lower portions of the pavement. Tensile stresses will develop because of this restraint. Initially the stresses are small since the stiffness of the mix is relatively low. However, as the temperature decreases, the tendency to deform increases, but the lower portions of the pavement still prevent the deformation from occurring. Mix stiffness is also increased at lower temperatures; this increased stiffness, coupled with the propensity for increased contraction, eventually leads to tensile stresses at the surface that exceed the fracture (tensile) strength of the asphalt concrete and result, in turn, in surface cracking (*73*).

Assessment of the low-temperature response of asphalt pavements thus requires a knowledge of mix stiffness characteristics at longer times of loading and the fracture (tensile) strength characteristics, both of which must be defined at the low temperatures expected in pavement structures.

Like mix stiffness, fracture strength is dependent on both time of loading and temperature. Both Epps (*29*) and Salam (*74*) have presented data on the tensile strength of asphalt-aggregate mixtures that support the significant work of Heukelom (*75*), which permits the tensile strength of mixes to be defined with minimal testing.

Although there are a number of approaches that address the prediction of the potential for low-temperature (thermal) cracking, that suggested by Christison et al. (*76*) is considered most suitable at this time since it accounts for the significant factors contributing to this mode of distress in a framework that is readily analyzed. In this procedure the asphalt concrete is considered as a pseudoelastic beam and the stresses resulting from the restraint of temperature-induced strains are determined from

$$\sigma_x(t) = \int_{t_0}^{t} S_{mix}(\Delta t, T)\alpha(T)dT(t) \quad (12)$$

where

S_{mix} = mix stiffness dependent on Δt, T,
$\sigma_x(t)$ = thermal stress, and
$\alpha(T)$ = coefficient of thermal contraction.

With input of actual temperature data, thermal stresses can be determined near the surface of the asphalt-bound layer according to Equation 12. By comparing these stresses with the tensile strength of the asphalt concrete, the propensity for fracture can be determined. This is shown schematically in Figure 13 (*77*).

Within the SHRP research program, a direct determination of the fracture temperature has been developed. The Thermal Stress Restrained Specimen Test (TSRST) attempts to simulate conditions analogous to those represented by Equation 12. In the TSRST the thermal stress is developed at a specific rate of cooling as shown schematically in Figure 14 (*78*). When the thermal stress reaches the fracture strength of the mix (for the particular conditions), the specimen fractures. This should correspond to the development of thermal cracks in the pavement. With the TSRST it is possible to evaluate mixes in advance of construction by ensuring that the temperature at which fracture occurs in the test is less than that anticipated in situ.

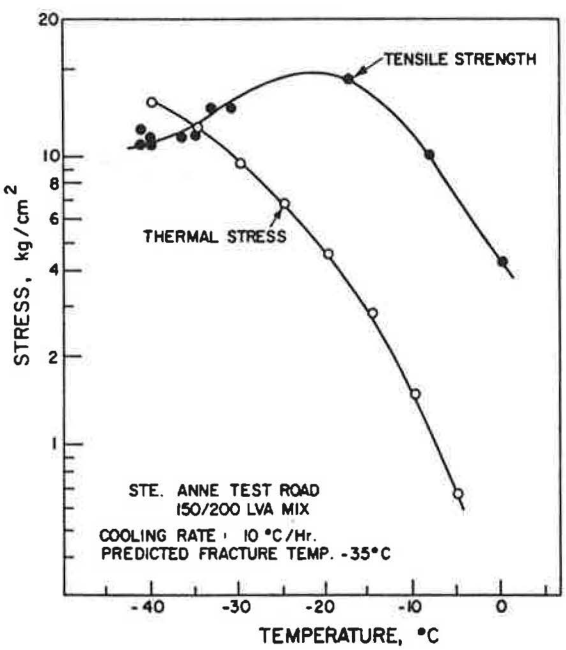

FIGURE 13 Prediction of fracture temperature for a restrained strip of asphalt concrete (*77*).

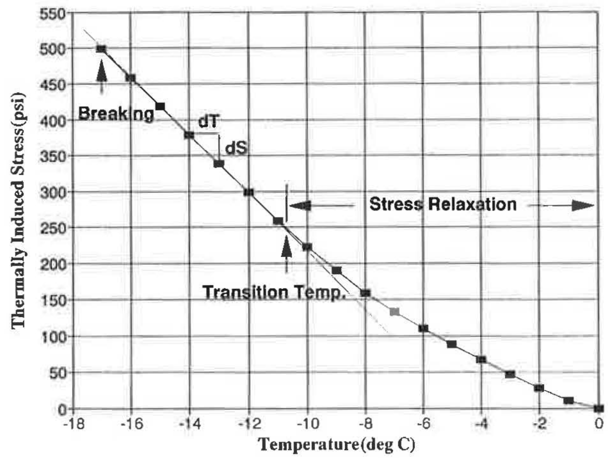

FIGURE 14 Stress-temperature relationship in TSRST.

PAVEMENT DESIGN AND REHABILITATION

A number of pavement design and rehabilitation procedures using analytically based (mechanistic-empirical) methodologies are now in place, having received impetus from presentations and discussions at the First International Conference on the Structural Design of Asphalt Pavements in 1962 as noted earlier. These design procedures, some of which are briefly summarized in Table 5, use the type of research described in the previous sections. Generally, they follow the framework given in Figure 1 and have been utilized for the design of both highway and airfield pavements. Criteria used in some of these methodologies have been developed from analyses of the AASHO Road Test data [e.g., work by Finn et al. (*13*)]. Moreover, the results of the AASHO Road Test provided the data base against which to check the thickness-selection process associated with some of these methodologies. For example, the work by Witczak to validate the current Asphalt Institute procedure [described in Asphalt Institute Research Report 82-2 (*80*)] provides an excellent example of the use of this well-documented information.

General Approach to Pavement Design

Analytically based design is possible because of the advances made in computer solutions used to represent pavement structures and developments in materials characterization that have evolved during the past 30 years. Although pavement re-

TABLE 5 Examples of Analytically Based Design Procedures

Organization	Pavement representation	Distress modes	Environmental effects	Pavement materials	Design format
Shell International Petroleum Co., Ltd., London, England *(61,62,79)*	Multilayer elastic solid	Fatigue in treated layers Rutting: • subgrade strain • estimate in asphalt bound layer	Temperature	Asphalt concrete, untreated aggregate cement-stabilized aggregate	Design charts; computer program: BISAR
Remarks:	Reference *(61,62)* is for highways. Procedure can be used for airfield pavements and BISAR is recommended for analyses of stresses and strains.				
The Asphalt Institute, Lexington, KY (MS-1) *(60,63,80)*	Multilayer elastic solid	Fatigue in asphalt treated layers Rutting: • subgrade strain	Temperature, freezing and thawing	Asphalt concrete, asphalt emulsion treated bases, untreated aggregate	Design charts; computer program: DAMA
Remarks:	Applicable to highway pavements.				
National Institute for Transport and Road Research (NITRR) South Africa *(81,82)*	Multilayer elastic solid	Fatigue in treated layers Rutting: • subgrade strain • shear in granular layers	Temperature	Gap-graded asphalt mix, asphalt concrete, cement-stabilized aggregate, untreated aggregate	Catalogue of designs; computer program
Remarks:	Applicable to highway pavements				
Federal Highway Administration U.S. DOT, Washington, D.C. *(84)*	Multilayer elastic or viscoelastic solid	Fatigue in treated layers Rutting: • estimate at surface Serviceability (as measured by PSI)	Temperature	Asphalt concrete, cement-stabilized aggregate, untreated aggregate, sulphur-treated materials	Computer program: VESYS
Remarks:	Applicable to highway pavements.				
University of Nottingham, Great Britain *(85,86)*	Multilayer elastic solid	Fatigue in treated layers Rutting: • subgrade strain	Temperature	Hot rolled asphalt (gap-graded mix), dense bituminous macadam (continuous graded asphalt concrete), untreated aggregate	Design charts; computer program
Remarks:	Applicable to highway pavements.				

(continued on next page)

sponse is typically computed using some form of elastic analysis, the material properties utilized must necessarily be tempered with engineering judgment since the materials that make up pavement structures do not exhibit linear-elastic behavior characteristics, as noted in previous sections.

Although specific design procedures are available, examples of which are shown in Table 5, it may be desirable for some projects, either highways or airfields, to consider a more general framework, such as that shown in Figure 15. Such an approach is not likely to be incorporated into a single computer program. Rather, it requires that the designer interact with the computer, making preliminary judgments regarding specific materials and thicknesses, performing some desk calculations to ensure that sections and conditions are representative, and then using a work station for detailed computations of stress, strain, and damage.

An example of this approach has been described by Monismith et al. (*64*), following the format in Figure 16. For the example, the computer program ELSA (an updated version of ELSYM5) was utilized. The necessity for a work station is apparent since computations are made for the complete state of stress and strain at several locations in the pavement section (Figure 17). These computations permit the evaluation of fatigue in the asphalt concrete, rutting at the pavement surface by controlling the subgrade strain, and permanent deformation within the asphalt-bound layer using the modification to the Shell procedure described earlier. For fatigue, aircraft wander could also be considered, as shown in Figure 18. If such computations were performed for a series of aircraft using the facility, damage at a number of locations transverse to the direction of traffic could be obtained by using Equation 9, permitting identification of the critical location.

TABLE 5 (*continued*)

Organization	Pavement representation	Distress modes	Environmental effects	Pavement materials	Design format
Laboratoire Central de Ponts et Chaussees (LCPC), France (*87*)	Multilayer elastic solid	Fatigue in treated layers Rutting	Temperature	Asphalt concrete, asphalt-treated bases, cement stabilized aggregates, untreated aggregates	Catalogue of designs; computer program
Remarks:	Applicable to highway pavements.				
Centre de Recherches Routieres, Belgium (*88*)	Multilayer elastic solid	Fatigue in treated layers Rutting	Temperature	Asphalt concrete, asphalt stabilized bases, untreated aggregates	Design charts; computer program
Remarks:	Applicable to highway pavements.				
National Cooperative Highway Research Program (NCHRP) Project 1-10B Procedure (AASHTO) (*13*)	Multilayer elastic solid	Fatigue in treated layers Rutting	Temperature	Asphalt concrete, asphalt stabilized bases, untreated aggregates	Design charts; computer program
Remarks:	Includes consideration of variability; applicable to highway pavements.				
National Cooperative Highway Research Program (NCHRP) Project 1-26 Procedure (AASHTO) (*89*)	Finite element idealization Multilayer elastic solid	Fatigue in asphalt concrete Rutting: • subgrade strain	Temperature	Asphalt concrete, untreated aggregates	ILLI-PAVE; elastic layer programs; e.g., ELSYM
Remarks:	Applicable to highway pavements.				

Overlay Pavement Design

Like the design methodologies for new pavements using an analytically based approach, design procedures for overlay pavements have effectively made use of the research results of the last 30 years as well. A general framework for overlay design is presented in Figure 19 (*90*). The same types of analyses as those used for new pavements to define propensity for fatigue and rutting are also applicable to overlay design, that is, the use of elastic analysis and material characteristics of the type discussed earlier.

One of the key elements in overlay design is the nondestructive evaluation of the existing pavement (Figure 19). The development of the Benkelman beam has played a key role in the overlay design process and today still provides a comparatively inexpensive device for pavement evaluation. It should be noted, however, that the falling weight deflectometer (FWD) has become the most widely used device to define the characteristics of the existing pavement.

For overlay thicknesses to minimize fatigue, there are two alternatives, one in which the existing surface is considered intact and remaining life considerations allow selection of an overlay thickness. This thickness may be less than that for the second alternative, in which the existing asphalt concrete is no longer intact. In this latter situation a reduced stiffness of the existing asphalt-bound layer must be used.

For rutting, on the other hand, it can be assumed that the rut in the existing pavement, if any, will be filled. The thickness of the overlay will be that required to control the development of rutting and will only be a function of the additional traffic to be applied on the "new" pavement structure with the overlay. NCHRP Synthesis 116 (*90*) provides a summary of a number of the procedures utilized.

McCullough was one of the first to apply analytically based methodology to the design of asphalt concrete overlays on portland cement concrete pavements (*91*). Later, through finite-element analyses, Coetzee demonstrated the applicability of stress-absorbing membrane interlayers (SAMIs) to mitigate reflection cracking in asphalt concrete overlays on jointed (undoweled) portland cement concrete pavement (*92*).

ASPHALT-AGGREGATE MIXTURE DESIGN

Asphalt mix design involves the selection of mix components and their relative proportions and requires a knowledge of the significant properties and performance characteristics of

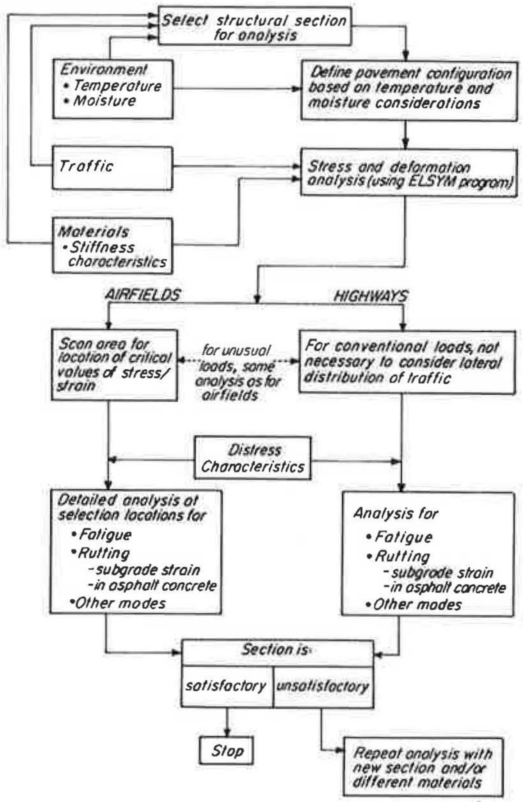

FIGURE 15 General design methodology.

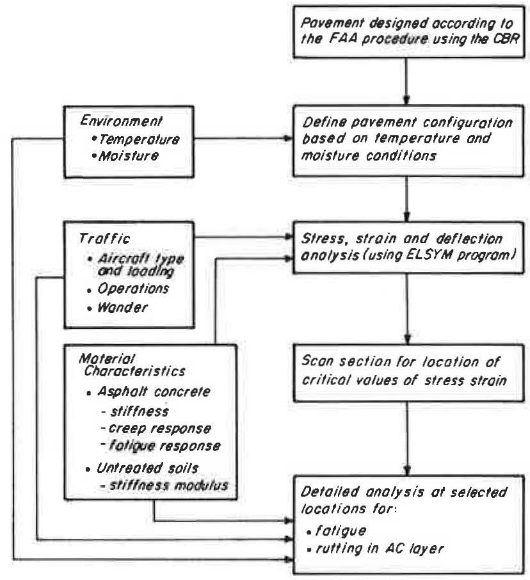

FIGURE 16 Analysis procedure.

asphalt paving mixtures and how they are influenced by the mix components.

It is desirable to select the components to achieve a reasonable balance in mix properties for the specific pavement application. Selection of the components and their relative proportions is also influenced by the pavement structural section into which the mix will be incorporated. Thus, the mix designer must be cognizant of the fact that mix design and pavement design are interrelated and must be considered together.

In general terms, mix design consists of the following basic steps: selection of the type and gradation of the aggregate; selection of the type and grade of the asphalt binder, with or without modification; and selection of the binder content. These steps have been incorporated into a general framework for design, as shown in Figure 20 (*93, 94*).

In the comprehensive design system of Figure 20, it will be noted that the system consists of a series of subsystems in which the mix components, asphalt (or binder) and aggregate, and their relative proportions are selected in a step-by-step procedure to produce a mix that can then be tested and evaluated to ensure that it will attain the desired level of performance in the specific pavement section in which it is to function. The influence of environmental factors, the effects of traffic loading, and the consequence of the pavement structural section design at the selected site are also included in this evaluation.

It is important to note in Figure 20 that an evaluation for water sensitivity of the mix is scheduled in the trial design

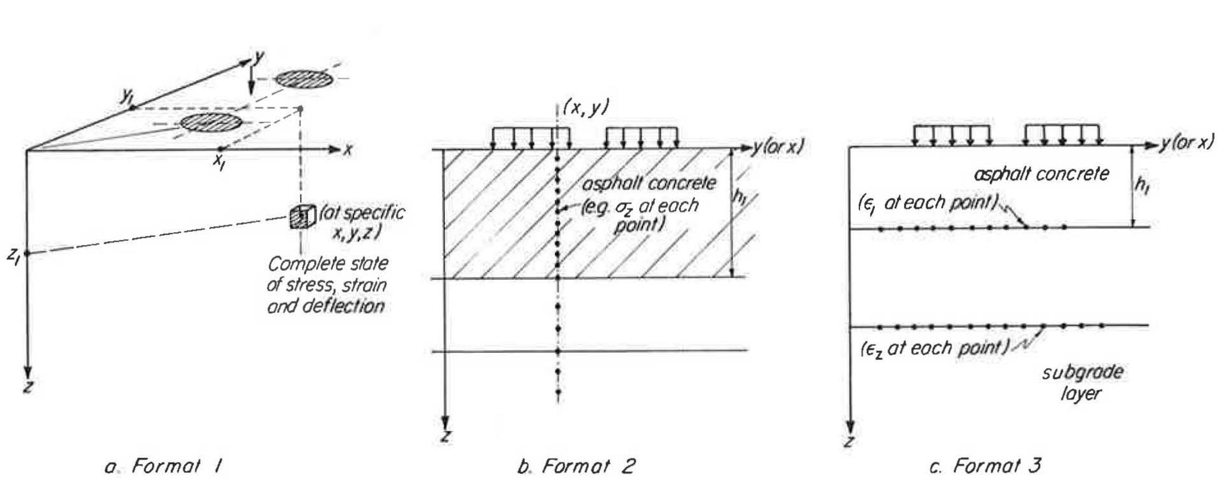

FIGURE 17 Different formats for ELSA.

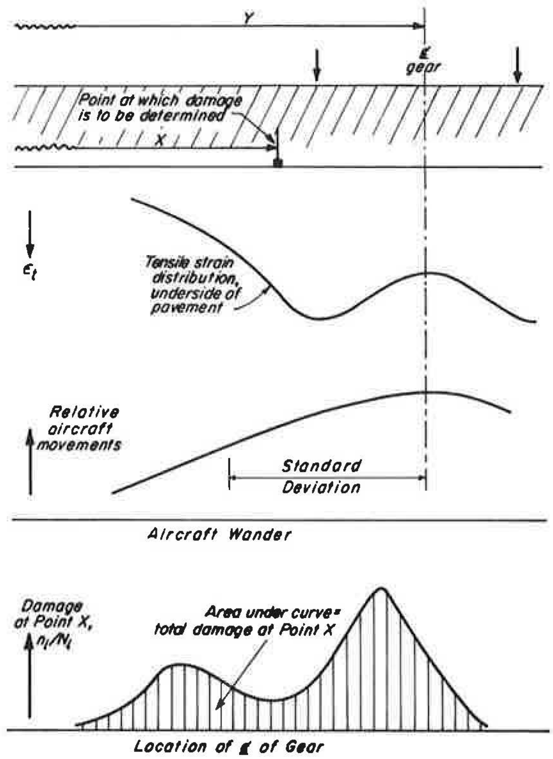

FIGURE 18 Fatigue damage at a point on the underside of the pavement, taking aircraft wander into account.

subsystem. Satisfactory resolution of the water sensitivity problem before examination of the response of the trial mix to the three modes of distress shown in Figure 20 (fatigue, rutting, and thermal cracking) will allow full concentration on these evaluations.

Depending on the climatic conditions and loading factors to which the specific pavement is subjected, any or all of the distress modes may be evaluated. For example, in a hot, dry climate, it may not be necessary to examine the potential for thermal cracking, whereas because of the potential for fatigue, rutting, and surface raveling associated with reduced stiffness and asphalt embrittlement, it would be essential to evaluate these latter three modes.

Although satisfactory resolution of the water sensitivity problem is desirable in the initial design phase, it may not always be possible to completely preclude the deleterious influence of water or water vapor, or both. Accordingly, provision is also included in the distress evaluation phase for defining the characteristics of mixes that reasonably reflect the influence of this factor. In addition, the effects of long-term mixture aging must be considered. For example, as the mixture ages, its stiffness increases, leading in turn to increased propensity for thermal cracking. Both considerations are shown in Figure 20 as input at the appropriate point in the mixture-design process.

IMPLICATIONS AND FUTURE DIRECTION

The developments discussed afford the engineering community an opportunity to expand its capabilities to improve both the design and rehabilitation procedures for heavily trafficked pavements.

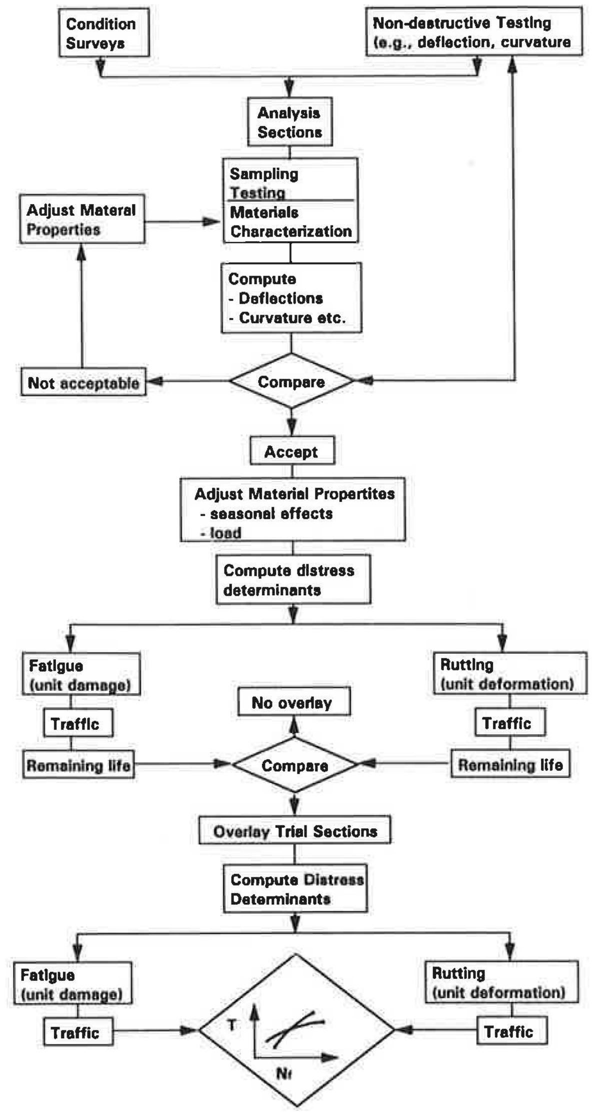

FIGURE 19 Overlay design procedure using elastic layer theory to represent pavement response.

The SHRP research program is developing improved procedures to measure the stiffness (as a function of both frequency-time and temperature), permanent deformation, fatigue, thermal cracking, aging, and water sensitivity characteristics of asphalt-aggregate mixes. Material properties determined from these tests can be used in performance-prediction models to estimate, as part of the design process and in advance of construction, the expected performance of the mix in a specific structural pavement section in a particular environment and for anticipated traffic loading.

Although some of the test procedures (including the method of compaction) appear to be more complex than those widely used today, it is my belief that we should not settle for something simplistic in the interest of expediency. It is important that technical merit rather than simplicity and ease of implementation drive the selection of test methods and analysis techniques. In the past 20 years we have all too often chosen

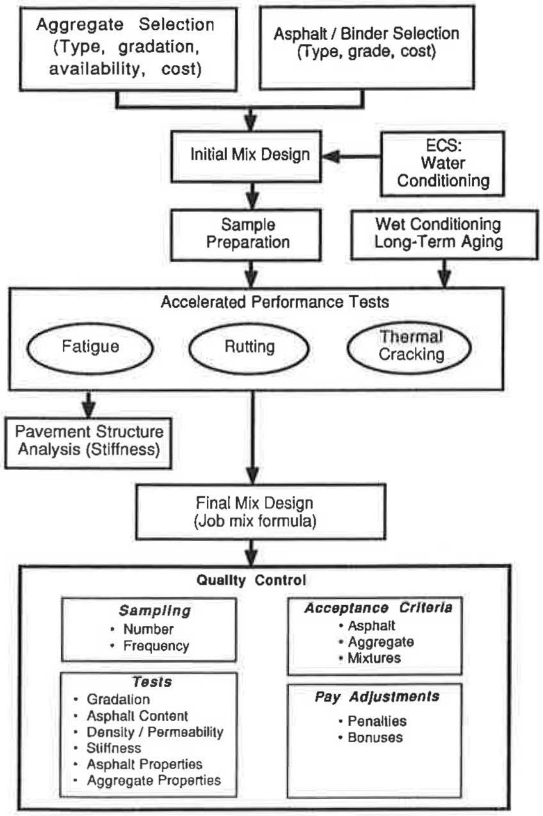

FIGURE 20 Comprehensive mix design and analysis system.

the latter course and, in effect, have let implementation considerations drive the selection process. Moreover, at times it has driven the research as well. Although it appears that we may be taking a chance, it really is not that much of a gamble and the results to be gained certainly appear worthwhile (e.g., improved performance and reliability). As Bernstein has recently stated,

> While our university research capabilities are unmatched by any other country, we have been unable to commercialize or capitalize on that strength. Other countries are quick to monitor our research activities, invest in them, take the results, and quickly move from the laboratory to the marketplace while we are still evaluating the risk and costs associated with trying something new. (*95*)

The comments from the participants in the 1990 European asphalt study tour (June 1991) clearly illustrate the point made in the previous paragraph. The group appeared to be enamored with European technology. In reality, the Europeans are implementing what was available in both the United States and Europe at about the same time. The Europeans in the transportation community have chosen to implement the technology, whereas those in the United States have not. Highway engineers and managers, including some of the those who were a part of the study tour, are responsible for this disparity. Let us not make the same mistake with the SHRP program: we must not permit simplicity and ease of implementation to dictate the outcome of the SHRP endeavor.

In the field of asphalt technology we must get away from what is sometimes termed the "Marshall" mindset. One way of doing this initially is to develop regional test centers where the new test methodologies can be implemented and some applied research can be accomplished as well. [The Laboratoire Central des Ponts et Chaussées (LCPC) has such a system in place in France.] This would allow the user agencies to take advantage of economies of scale and the pooled funding of resources. Until greater confidence in the new methodologies is more widely established, those who wish to participate can have their mix and pavement designs accomplished at these centers by skilled and knowledgeable personnel and obtain training in these new methodologies as well.

Although the SHRP program, as discussed here, is related to the asphalt technology aspects, there are a number of other areas toward which pavement engineers should direct their efforts. Examples are given in the following paragraphs.

The interaction between the vehicle (e.g., truck, aircraft) and the pavement has considerable potential for payoff in improved pavement performance and vehicle (suspension) design, which can benefit the population as a whole through reduced costs associated with the movement of goods. Research directed toward improved (dynamic) analysis capabilities for pavements, vehicle suspension designs, parametric studies of truck and pavement variables, development of new and improved dynamic load measuring systems, and development of an instrumented truck-trailer as a device to measure pavement response for pavement management activities is indicative of the types of investigations that can be accomplished. Increased interactions among the pavement engineers, the truck (and bus) manufacturing industry, and aircraft design groups are a prerequisite to successful activities in this area. Assessments must be made of the influence of the magnitude and type of aircraft and truck loadings on pavements (including the effects of load magnitude, gear and axle configurations, and contact pressures). The Turner Truck Study (*96*) recently completed by TRB can be considered a forerunner of the more detailed types of studies implied by the two research activities just described.

The development of new materials as well as the effective utilization of recycled materials must be accompanied by improved characterization and prediction techniques to ensure their proper use. Cooperation between engineers and engineering mechanicians and materials scientists is critical to the successful completion of such activities. Examples of this approach have been included in the SHRP program.

Consideration should be given to new design and rehabilitation techniques. So long as the materials to be utilized can be characterized and the proposed systems analyzed, analyses like those described here can establish their feasibility.

An important step in ensuring implementation of new materials and construction-rehabilitation procedures is the use of accelerated load testing devices. Such devices have been used extensively by European engineers but are virtually nonexistent in the United States. The accelerated loading facility (ALF) is a large-scale example; however, smaller, more versatile and faster laboratory-scale models could also be developed in the United States to accelerate evaluation of asphalt mix performance. Such devices should be considered as an essential part of the regional centers described above and could be part of the applied research activity referred to earlier.

Finally the importance of continued observation and documentation of performance cannot be overemphasized. At the conclusion of the AASHO Road Test, the Highway Research Board (HRB) (now the Transportation Research Board) prepared guidelines for implementing such a program (*97*). Unfortunately, these recommendations were not followed, and it was not until the Long-Term Pavement Performance (LTPP) Program of SHRP was implemented that the HRB recommendations came to fruition. We must ensure that the activities instituted through the SHRP program continue if we are to continue to improve pavement technology.

I would like to conclude on a more philosophical note by drawing on observations by W. R. Hudson relative to the elements of successful research. They include the following: (*a*) an overall plan with top-level commitment and sufficient and continuous funding assured; (*b*) a research environment, including personnel and facilities, that fosters flexibility and innovation; (*c*) interaction between researchers and practitioners; and (*d*) dissemination and implementation of the research results.

My comments will be directed toward some of these elements. Naturally, there must be a person or persons with the desire and capabilities to solve the problem at hand. Top-level commitment and support must be provided and there must be continuity of funding, since innovation doesn't occur on schedule. In providing the funding there must be, on the part of the funding agency, a willingness to take some risk, since all research is not successful. Moreover, there must be freedom for innovation. An excellent example of this was provided by W. N. Carey, Jr., the former Executive Director of TRB. As project engineer for the AASHO Road Test, he carefully weighed the comments of various advisory groups. Although he often accepted their advice, he protected his researchers from costly and nonproductive suggestions, allowing the staff the freedom to explore their innovative ideas.

Finally, we must recognize the need for intermediate and long-term research. There has been in the last 20 years too much emphasis on poorly coordinated and short-term research, and, as noted earlier, although implementation is important, it should not drive the research as it seems to have done. Implementation will come if the benefits can be demonstrated.

In conclusion, I would like to acknowledge again both the U.S. and the international pavement research communities. Though not delineated in detail, the results of their research efforts permeate this discussion. The friendships developed with Peter Pell, Stephen Brown, Jacques Bonnot, W. Heukelom, L. Nijboer, A. Klomp, K. Wester, J. Verstraeten, Charles Freeme, Neil Walker, John Yeaman, as well as with others of the international community, are treasured.

I indeed have been fortunate to have been in a research environment where some of the requisite factors discussed here were present, including

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