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16. Abstract

This report presents an overview of the state-of-the-art on rutting in asphalt concrete pavements. Items addressed include: 1) mechanism on rutting, 2) test methods used to characterize asphalt mixtures; and 3) models for predicting rutting.

A companion report titled "Wheel Track Rutting Due to Studded Tires" was also completed as a part of this project.

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STATE-OF-THE-ART ON

RUTTING IN ASPHALT CONCRETE

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DISCLAIMER

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1.0 INTRODUCTION

Since the 1960's considerable research effort has been concerned with solving the problems of rutting in asphalt pavements. Research work has been published by the Transportation Research Board (TRB), Association of Asphalt Pavement Technologists (AAPT), and in the International Conferences on Structural Design of Asphalt Pavements (the Ann Arbor Conferences). All the works presented in these prestigious journals have, more or less, paralleled one another. This report therefore has relied heavily on information presented at the International Conferences and has been supplemented, where necessary, with works presented at TRB, AAPT, and elsewhere.

Rutting in asphalt pavements is the result of several factors including:

1) Deformation within the stabilized layers.

2) Deformation in the unstabilized layers--both granular and fine-grained materials.

3) Surface wear--due primarily to studded tires and/or tire chains.

This report deals primarily with methods of controlling the deformation in the stabilized asphalt layers. Many of the concepts are also application for evaluating deformation in unstabilized materials. A companion report titles "Wheel Track Rutting Due to Studded Tires" deals with the problem associated with surface wear.

1.1 Background

Prior to the First International Conference on Structural Design of Asphalt Pavements in 1962, little formal work had been done either to predict or limit the amount of rutting due to traffic loading. During this period, most engineers felt that conventional techniques such as the Marshall and Hveem tests, CBR, R-value or static triaxial compression tests could be designed to minimize rutting. In 1962, the Shell Oil Company [1] presented the first pavement design approach which considered both fatigue and rutting as mechanisms of distress. As a part of this design method, Dorman and Metcalf [2] developed a relationship between vertical compressive strain in the subgrade and number of load repetitions which could be used to limit rutting. For over ten years after this initial work, practitioners and researchers alike frequently assumed that rutting could be limited using the Shell approach or

through conventional mix design. During this same period, fatigue distress often became less important due to a trend toward thicker asphalt surfaces and higher asphalt contents. This, together with gradual increases in allowable axle loads, tire pressures, and the applied numbers of repetition, resulted in a need for an improved approach to predict rutting, particularly in the upper 10 to 12 inches of the pavement.

The Third International Conference (1972) called attention to the need for technology developments related to the occurrence of rutting in flexible pavements. Papers presented by Barksdale [3] and Romain [4] outlined what is referred to as the layer strain approach for predicting the amount of rutting due to traffic loads. Since these early efforts, considerable additional work has been undertaken and completed which deals with various methods for predicting rutting using laboratory tests, and subsequent verification of the predicted values with results from test tracks or roadways. These design approaches utilize fundamental properties of the materials in the pavement section, and account in varying ways for the effects of variations in loading and environmental conditions (e.g., moisture and temperature) on the amount of rutting.

At the Fourth International Conference (1977), papers were presented on design methods which were capable of minimizing the occurrence of rutting. The procedures discussed concerned limiting rutting in one of the following ways:

1) statistical techniques based on observed rutting performance,
2) limiting subgrade strain approaches,
3) methods using the creep test, and
4) linear viscoelastic methods.

A wide variation is present in the degree of sophistication in these methods. Finn et al. [5] used stepwise regression techniques to relate rutting to stress, surface deflection, and number of load repetitions. This was done for both conventional and full-depth asphalt pavements using data from the AASHO Road Test. Claessen et al. [6], modified the original Shell vertical compressive subgrade strain criteria slightly. In the Claessen et al. approach, the final design is checked for rutting in the bituminous layers using the creep test approach developed by Van de Loo [7] and others [8,9]. Kenis [10] related plastic strain to stress, temperature, loading time, and moisture content; he used a linear quasi-viscoelastic theory to compute rut depth.

In the Fifth International Conference on Asphalt Pavements (1982), the common method of coping with rutting was to limit vertical compressive strain on the subgrade. However, only a limited amount of work was presented which dealt specifically with verification of these methods. Further, only one of six sessions dealt with materials characterization and this offered little new information on test methods or prediction procedures for permanent deformation.

Since the Fifth International Conference (1982), there has been renewed interest in rutting. Some of the reasons given for this are listed in Table 1.1. From 1982 to the present, there has been a continuous series of papers published regarding the occurrence and prediction of rutting in flexible pavements, together with information concerning wheel load and tire pressure effects on stress and strain within the pavement layers. References 14-28 provide a listing of research efforts directed at characterizing materials and developing models to predict rutting and other forms of distress associated with asphalt pavements. These reports range from empirical, e.g., Uzan and Lytton [15], to highly theoretical, e.g., Abdulshafi [20,27].

At the Sixth International Conference (1987), there were only a few papers concerned with rutting. Eckmann [53] presented a study that utilized the results of the dynamic creep test and the layer strain approach to predict rutting in full-scale test pavements. The predictor models showed good agreement with actual field measurements. Eisenmann and Hilmer [54] studied the influences of wheel loading and tire pressure on the magnitude of the rutting in asphalt pavements. Tests were performed using a full-scale test facility using various wheel loads, inflation pressures, and wheel arrangements. The rutting development was measured directly and the effects of the varying test conditions were analyzed using regression analysis. All the factors were shown to have a significant influence on rut depth.

Since the Sixth International Conference, considerable interest has continued in identifying ways of preventing rutting which include:

1) development of improved test methods,

2) use of modified asphalt binders, and

3) use of large stones in asphalt mixtures.

Table 1.1. Reasons for renewed interest in pavement rutting.

Reason	Consequences
Increased Tire Pressure and Truck Weight	Causes compaction or shear deformation of the surface layer.
Increased Use of Additives	May soften the asphalt cement.
Drum Mixers	Less hardening of the asphalt cement than anticipated.
Field Compaction Procedures	Lack of initial compaction results in increased rutting.
Increased Channelization	Increasing passes accelerates deformation.
Enforcement Procedures	Extended use of studded tires increases wheel track ruts. Excessive contact pressures and axle weights accelerates deformation.

A major effort is now underway as part of the Strategic Highway Research Program to develop improved methods for evaluating asphalt-aggregate mixtures to prevent rutting.

1.2 Mechanism of Rutting

Rutting in pavement material develops gradually with increasing wheel load applications, and usually appears as a longitudinal depression in the wheel path with a small shoulder to the sides. This rutting is caused by a combination of densification (decrease in volume and, hence, increase in density) and shear deformation (plastic flow). Trenching studies performed at the AASHO Road Test [11] and also test track studies reported in the Third International Conference in 1972 by Hofstra and Klomp [12] indicated that shear deformation rather than densification in the pavement layers was the primary rutting mechanism. In addition, it was pointed out that placing the material at a high density is important to minimize shear deformation.

Rutting is the accumulation of plastic (permanent) strain in all pavement layers. The variation of plastic strain with depth beneath the pavement surface, however, has not yet been clearly established. Theoretical approaches based on the layer strain method generally show that the largest plastic strain occurs in the tensile zone of the stabilized layer near the bottom; however, measurements made by Hofstra and Klomp [12], and Brown and Bell [13] suggest that the distribution may be closer to uniform. Since more resistance to plastic flow should be encountered at the greater depths beneath the wheel load, the occurrence of large amounts of plastic strain near the bottom of the layer could be questioned. Recent work by Eisenmann and Hilmer [54] also indicated that rutting was mainly caused by deformation flow without volume changes.

1.3 Purpose of Report

The purpose of this report is to present an overview of the state of the art on rutting in asphalt concrete pavements. Specifically, it presents the following:

1) tests used to evaluate rutting in the laboratory, and

2) methods available to predict or limit rutting in full scale pavements.

Chapter 2 emphasizes the importance of testing materials at appropriate stress conditions, the types of tests currently used, sample preparation, advantages and disadvantages of each test, and a discussion of typical test results. Chapter 3 presents the various methods available to predict permanent deformation and a brief discussion on the verification of each. Particular emphasis is made to indicate where information gaps still exist, as well as what needs to be done to improve the current state of knowledge and its implementation. Chapter 4 illustrates additional activity (since 1987) in each of these areas to cope with the problem of rutting.

As indicated earlier, a companion report title "Wheel Track Rutting Due to Studded Tires" deals with the other potential cause of rutting in Alaska, surface wear.

2.0 MATERIALS CHARACTERIZATION

The development of predictive methods or models requires that suitable techniques be developed not only for calculating the response of the pavement to load, but also for realistically characterizing the materials. Use of a suitable mathematical model of the pavement system and realistic material properties are closely interrelated; methods for predicting rutting must be developed with this in mind.

The overall objective of materials testing should be to reproduce as closely as practical the in situ pavement conditions that include the general stress state, temperature, moisture, and general condition of the material. The difficulties in duplicating the stress state are carefully considered by Brown and Bell [13]. They point out that Barksdale [3] and Romain [4], in the Third International Conference, related permanent strain to vertical and horizontal stresses. Brown and Bell [13] suggest the use of stress invariants as the most appropriate method of representing the correct stress state for materials characterization. The use of stress invariants is particularly advantageous in the tension zone in the bottom of bituminous layers, and also for predicting rutting away (off-axis) from the axis of symmetry of loading. Following this approach, the stress conditions at any point can be characterized by the mean normal stresses, p, and the octahedral shear stress, τ_{oct}, where:

$$p = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \tag{1}$$

$$\tau_{oct} = \frac{1}{3}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{1/2} \tag{2}$$

where σ_1, σ_2, and σ_3 are the principal stresses existing at the point under consideration. For simplicity, the shear stress term, q, can be defined as

$$q = \frac{3}{\sqrt{2}}(\tau_{oct}) \tag{3}$$

Similarly, the strain invariants corresponding to p and q are volumetric strain (v) and shear strain (e), defined as:

$$v = \epsilon_1 + \epsilon_2 + \epsilon_3 \tag{4}$$

$$e = \frac{2}{3}(\epsilon_1 - \epsilon_3) \text{ for the special condition where } \epsilon_2 = \epsilon_3 \left(\begin{array}{c}\text{assumed in the} \\ \text{triaxial test}\end{array}\right) \tag{5}$$

where ϵ_1, ϵ_2, and ϵ_3 are the principal strains at the point under consideration. The above representations for stress and strain were made since in situ plastic strain develops as a result of the combination of volume change and shear distortion. Volume change is associated with poor compaction, and shear strain is associated with high shear stresses in the pavement. The advantage of using the p and q stress invariants representation is that tensile and off-axis principal stresses cannot always be directly reproduced in the triaxial test, but the corresponding values of p and q can. Brown and Bell also point out that off-axis plastic strain (ϵ_p) is a function of the number of load repetitions, temperature, time, p, and q. The values of p and q can be calculated from the elastic layered theory or finite element programs.

Brown and Bell found that substantial errors in both p and q (and, hence, plastic strain) develop if shear stresses are ignored, and this can result in an underestimation of the plastic strain by as much as 40 percent. This emphasizes the importance of testing materials over the entire range of stresses expected to exist in the field.

Using the generalized layer strain approach, the amount of laboratory testing associated with predicting a rut depth can be considerable. Therefore, from the point of view of implementation, use of an average stress condition within the layer is highly desirable for implementing a practical rutting subsystem and would involve a single test. An approximate theoretical average stress in a layer can be estimated using the "Z" function approach [8,29]. The Z-function is defined as the ratio of the average vertical elastic strain occurring in the layer to the vertical plastic strain measured in the unconfined compression test. This function is dependent upon the pavement structure, geometry, and wheel load spectrum. Use of the Z-function, which is based on elastic theory, gives a preliminary indication of the average stress state within a layer suitable for use in laboratory testing to evaluate rutting characteristics. Specific stress conditions, however, should be determined by correlating laboratory test results with measured values of rut depth from actual pavements.

2.1 Types of Tests

The types of tests presently used to characterize the rutting behavior of pavement materials consist of the following two general testing approaches:

1) Repeated load tests;
   a) triaxial condition with confinement and
   b) split tension (diametral) stress condition.
2) Static creep tests (with or without confinement);

These tests have been designed to evaluate the elastic, viscoelastic, plastic, and shear strength parameters of asphalt concrete. In addition, wheel tracking tests (on slabs or actual pavements) have been used for determining which types of mixtures are more prone to rutting.

Triaxial Repeated Load Tests

A variety of test systems have been used, ranging from relatively simple mechanical or pneumatic systems to more complex electro-hydraulic systems. Pneumatic test systems such as shown in Figure 2.1 have been the most widely used. More sophisticated systems include a testing chamber similar to that shown in Figures 2.2 and 2.3. Such equipment permits careful control of temperature during long-term tests as well as the application of repeated load confining pressure that can be coordinated with the vertical repeated load. For example, the equipment shown in Figures 2.2 and 2.3 is capable of the following test options:

1) applying repeated axial and lateral stress pulses of any desired shape, in phase with one another, with pulses ranging from 0.01 to 1.0 seconds;
2) applying the axial stress as either tension or compression;
3) incorporating rest periods between stress pulses, ranging from zero to several seconds; and
4) controlling temperature conditions within a tolerance of 0.5°F.

The vertical and horizontal permanent strains or deformations at any desired number of load applications on a sample can be easily obtained. This is accomplished by using LVDT's on the axial ram and lateral deformation gauges mounted on the specimen.

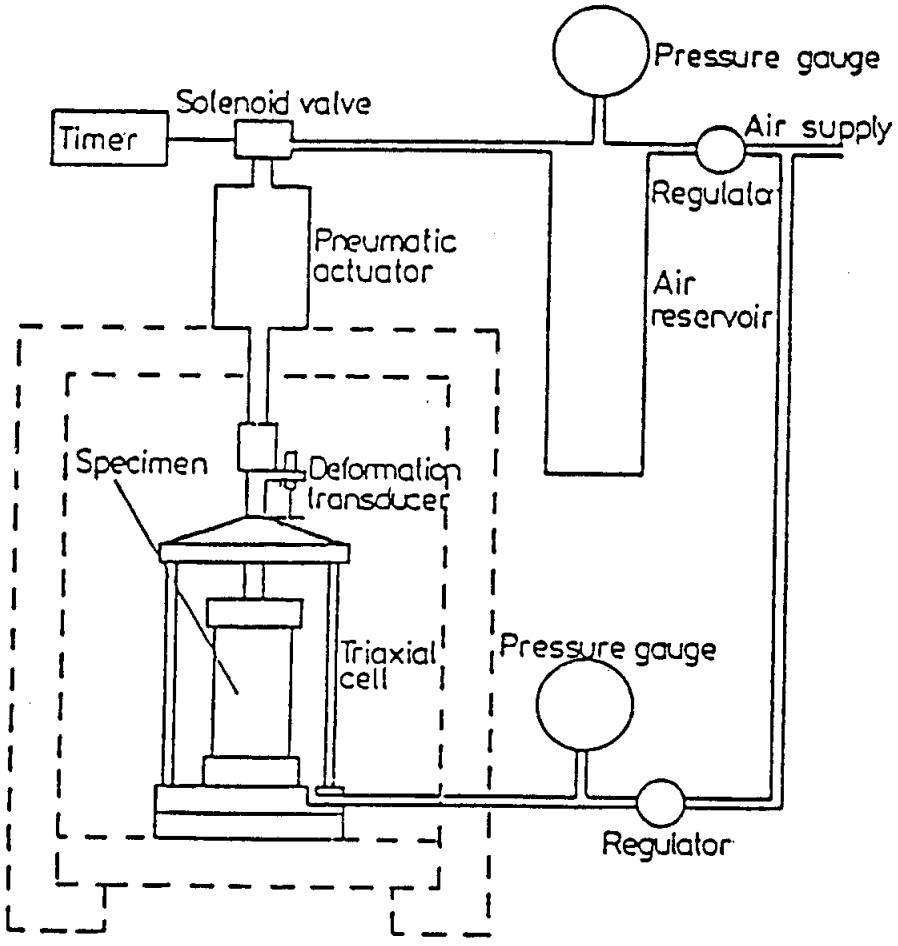


Figure 2.1. Schematic of pneumatic test system.

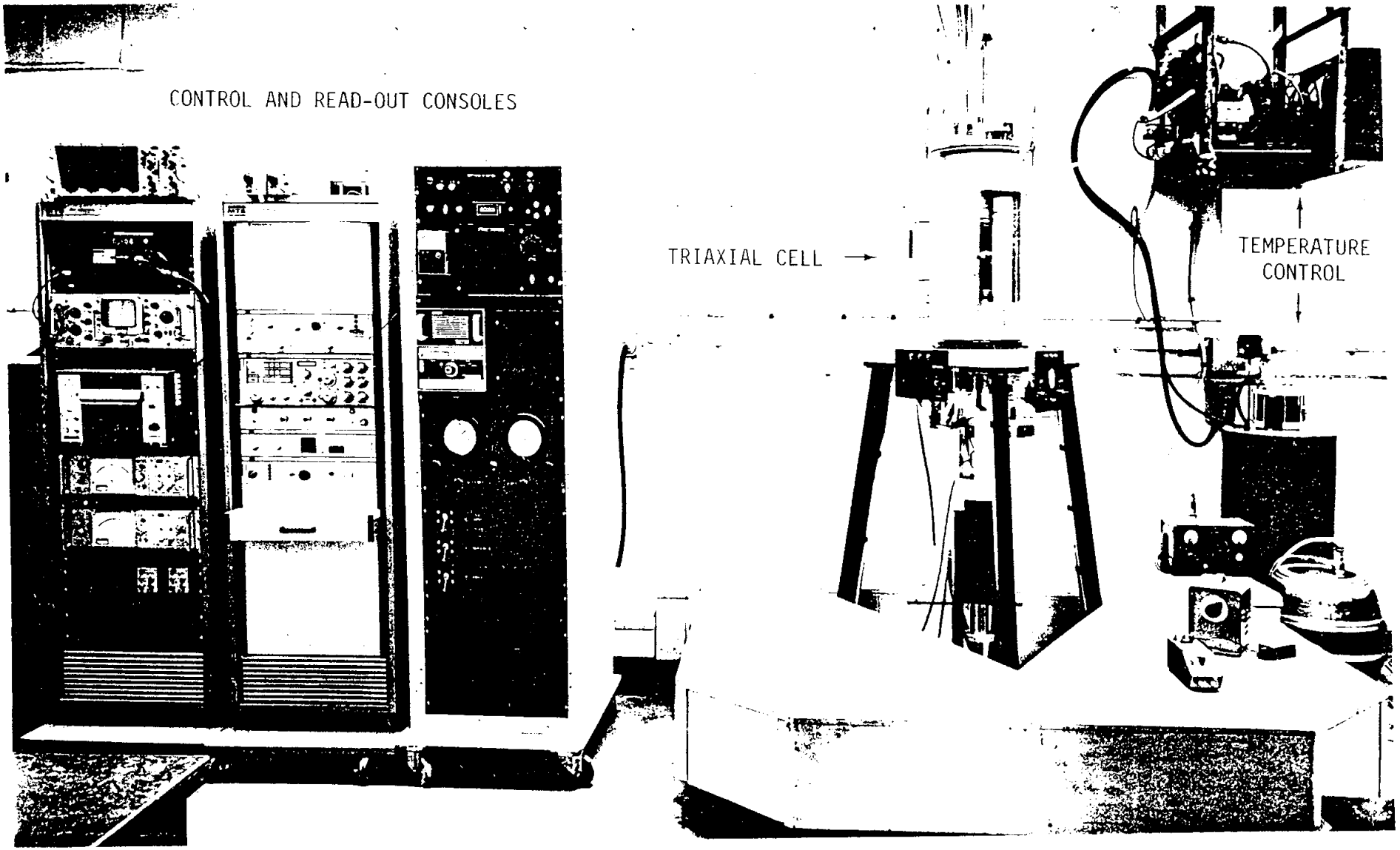


Figure 2.2. Overall view of electro-hydraulic test system.

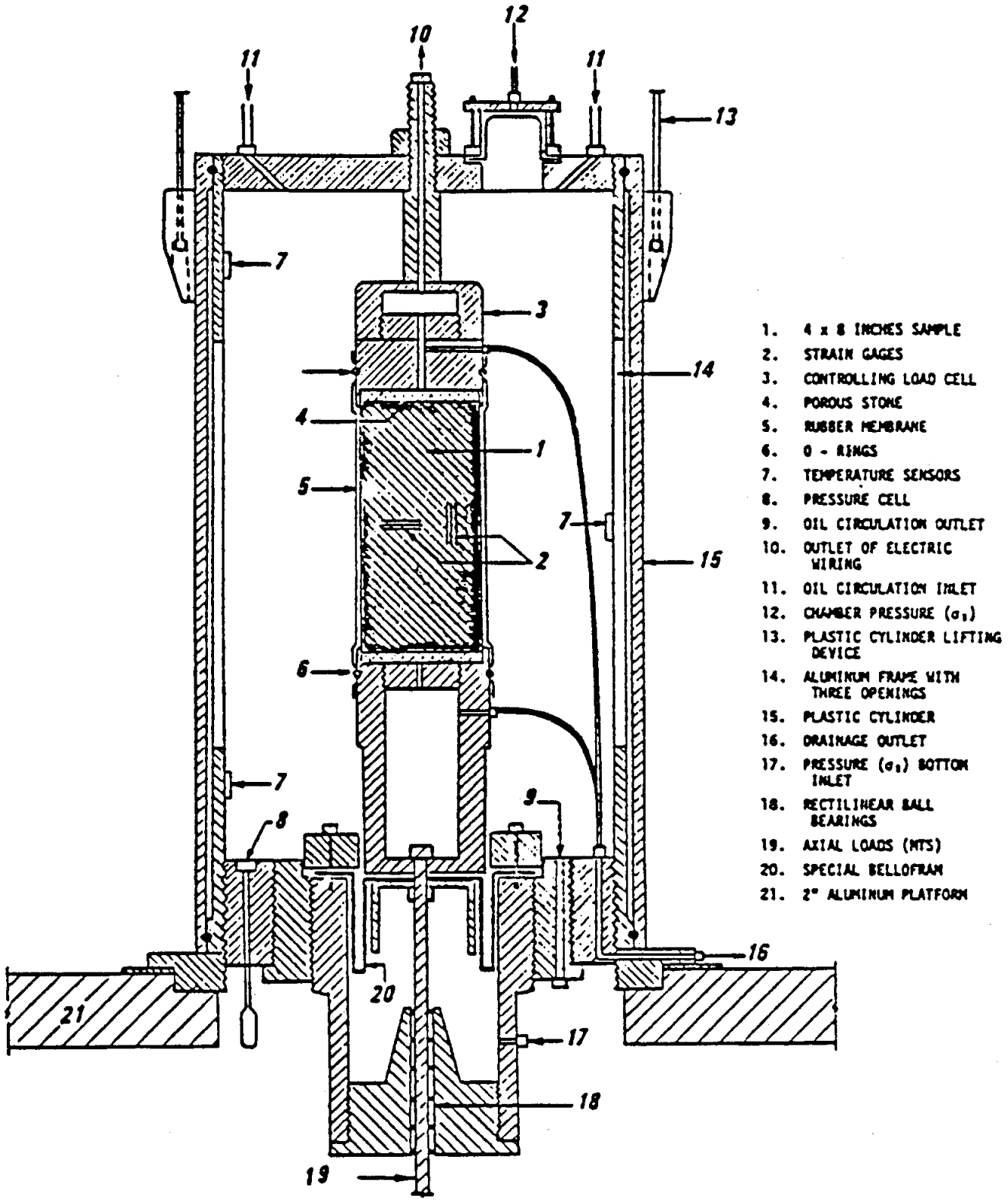


Figure 2.3. Cross section of triaxial cell for dynamic testing of pavement materials.

The important point to remember is that the pulse shape and duration should duplicate as closely as possible that which will exist in the actual pavement. Pulse duration and shape will vary with vehicle speed and depth within the pavement and can be estimated from available charts [30]. The pulse shape and duration can greatly influence the resulting predicted deformation.

It should be noted that repeated load tests appear to be more sensitive to mix variables than static creep tests. For example, Barksdale and Miller [8] reported that, when using a creep test, an increase in asphalt content from 4.5 to 5.5% did not have a significant effect on plastic deformation. However, use of repeated load tests on the same mixtures indicated a significant increase in plastic deformation.

Similar conclusions were drawn by Monismith and Tayebali [56] for tests on modified asphalt mixtures. For static creep tests, there was little difference between the different mixtures, while for repeated load tests, significant differences in mix behavior was found.

Diametral Tension Load Tests

A popular and practical method of measuring stiffness of asphalt bound materials is the diametral modulus originally described by Schmidt [31]. Several versions of this device have been used, but all operate in a manner similar to that shown in Figure 2.4. With this test system, most of the specimen is in tension along the vertical diameter in line with the load. Thus, the stiffness or resistance to load is largely within the asphalt binder and the aggregate has less influence than in the triaxial mode. Thus, this test method is much more suited to short repeated load duration during measurements for modulus than for creep loading. Without confinement, larger static loads tend to deform the specimen (becomes noncircular) and if the stress is too high, creep deformation may actually accelerate with time. Khosla and Omer [22] compared diametral test procedures with uniaxial compression and reported that the diametral test gave overestimates of field measured ruts.

Diametral testing does not seem promising for permanent deformation characterization for two major reasons:

1) The state of stress is nonuniform and strongly dependent on the shape of the specimen. At high temperatures or large loads, permanent deformation

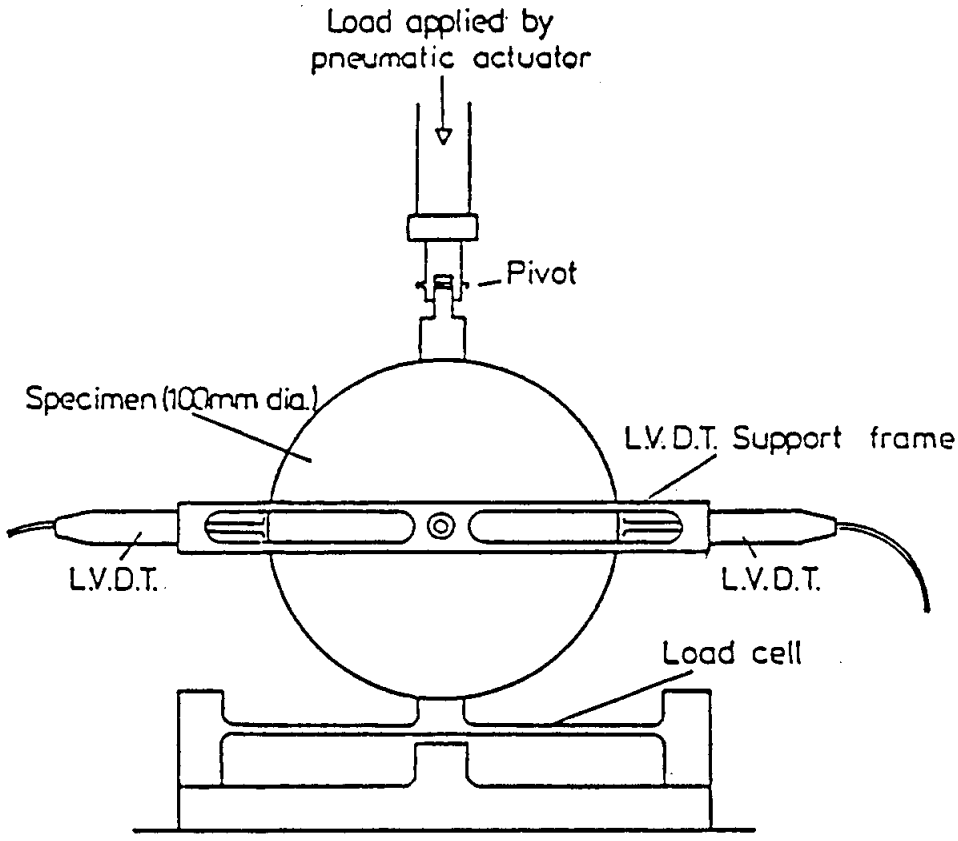


Figure 2.4. Schematic of repeated load diametral test.

produces changes in the specimen shape that significantly affect both the state of stress and test measurements.

2) During the test, the only relatively uniform state of stress is tension along the vertical diameter of the specimen. All other states of stress are distinctly nonuniform. It has been recognized that shear stresses contribute significantly to rutting and that laboratory tests must duplicate in-situ conditions. Further, shear stresses cause nonlinear behavior in the permanent deformation response of asphalt concrete. Because a nonuniform field of shear stresses is present in diametral specimens, deformation measurements cannot be related to a specific stress level.

Creep Tests

The creep test (unconfined or confined) has been used to determine material characteristics that are used with the viscoelastic theory to predict rutting. Variations of the creep test which incorporate limited cyclic loads have been used by Kenis [10] and Huschek [32]. However, there appear to be considerable differences in the results, as shown in Figure 2.5.

A detailed description of the constant-load creep compression test for asphalt mixes has been given by Van de Loo [33]. In short, an asphalt specimen with flat and parallel ends is placed between two hardened steel platens, one of which is fixed and the other movable. A constant load is placed on the movable platen and the deformation of the specimen is measured by means of electrical strain gauges as a function of time. The test temperature is kept constant. A system for static creep testing is shown in Figure 2.6.

The results of the creep test, when expressed as relative deformation (measured change in height divided by the original height) are independent of the shape of the specimen and of the ratio of height to diameter, provided that the specimen's ends are parallel, flat, and well lubricated. Van de Loo [33] states that lubrication is necessary to prevent the platens from exerting lateral constraint during the deformation process, to keep a uniform stress distribution, and to prevent barrelling (bulging of the specimen sides). In the creep test, the strain in the mix is measured as a function of the loading time (t) at a fixed test temperature (T).

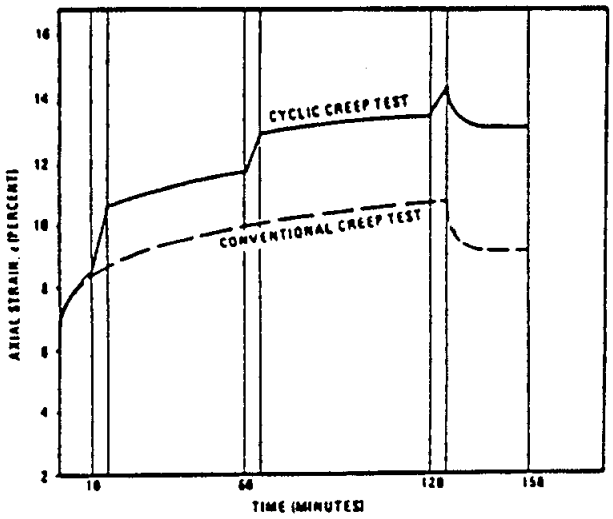


Figure 2.5. Comparison between the conventional stepload creep test and cyclic-loading creep tests (after Ref. 32).

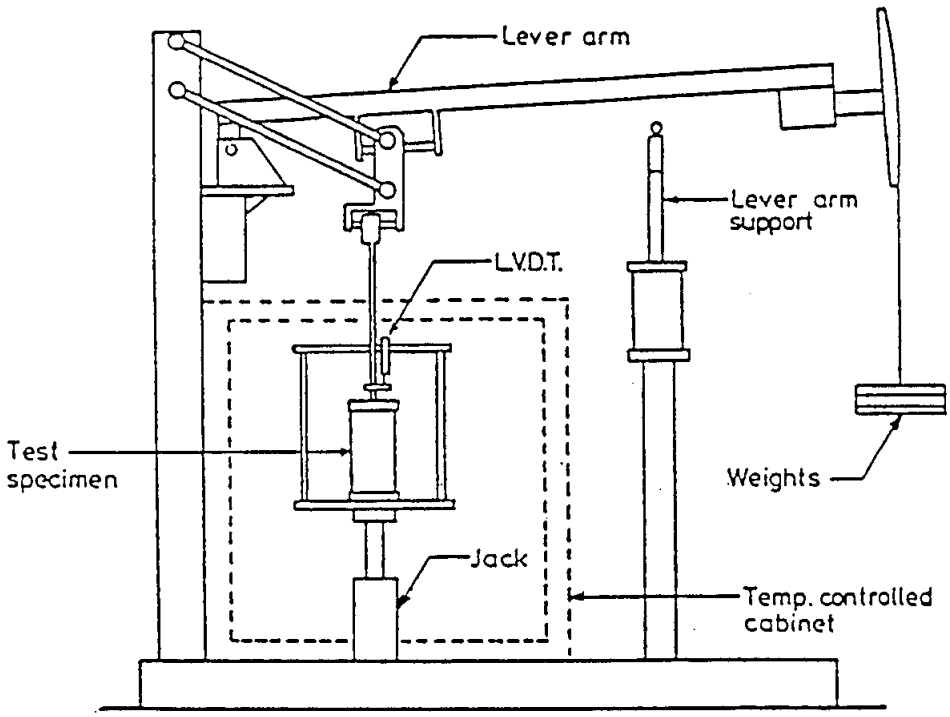


Figure 2.6. Example of static creep test system.

Wheel-Track Tests

All proposed methods for estimating rutting need further field and test-track validation. A complete mechanistic validation should include determining whether the correct plastic strain profile, both vertical and lateral, can be estimated. Bonnot (1986) has described procedures used by the Laboratoire Central des Ponts et Chausses (LCPC) for practical mixture design. He has emphasized that, for design applications, laboratory simulation of rutting must duplicate stress conditions in actual pavements. In the LCPC design procedure, a wheel-track test (Figure 2.7) is used for measuring ruts created by the repeated passage of a wheel over prismatic asphalt concrete specimens. Each specimen is a plate measuring 500 by 150 mm and is 100 mm thick. It is placed in a metal frame and rests on a steel base plate. The specimen can be removed from an actual pavement but generally is compacted in the laboratory with a pneumatic-tired compactor.

Rutting is measured by the relative reduction in the thickness of asphalt concrete in the wheel path. The test is terminated after 10^4 cycles, unless the rut depth exceeds 15 percent prior to this time. Generally rut depths are measured by stopping the test at 30, 100, 300, 1000, 3000, and 10,000 cycles. Tests are executed over the temperature range of 50° to 60°C to reproduce the most unfavorable pavement conditions expected in France. The tire passes over the center of the specimen twice each second, and the loading time at the center is approximately 0.1 seconds.

The Nottingham Pavement Test Facility (Figure 2.8) allows instrumented pavement sections, 16 ft long and 8 ft wide, to be constructed in a 5 ft deep test pit. Testing is carried out under controlled temperatures with a rolling tire, loaded to a maximum of 2 tons and inflated to 73 psi contact pressure, traveling at speeds up to 10 mph. The facility enables the collection of detailed pavement performance data under carefully controlled conditions.

Full-scale instrumented circular facilities have also been developed in Nantes, France. While circular test tracks may be useful for studying fatigue, there is some concern about their ability to study realistically the development of permanent deformation under repeated trafficking. This concern stems in part from the state of stress imposed by the tire in this circular loading path as compared to the stress state which develops from tires following a straight trajectory.

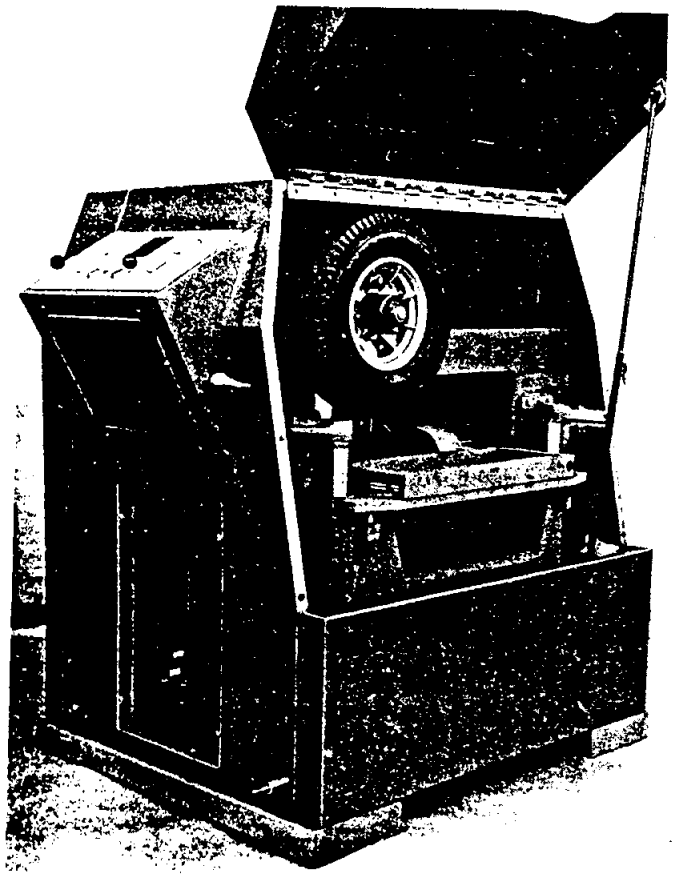


Figure 2.7. LCPC wheel-tracking rutting-test machine (after Bonnot, 1986).

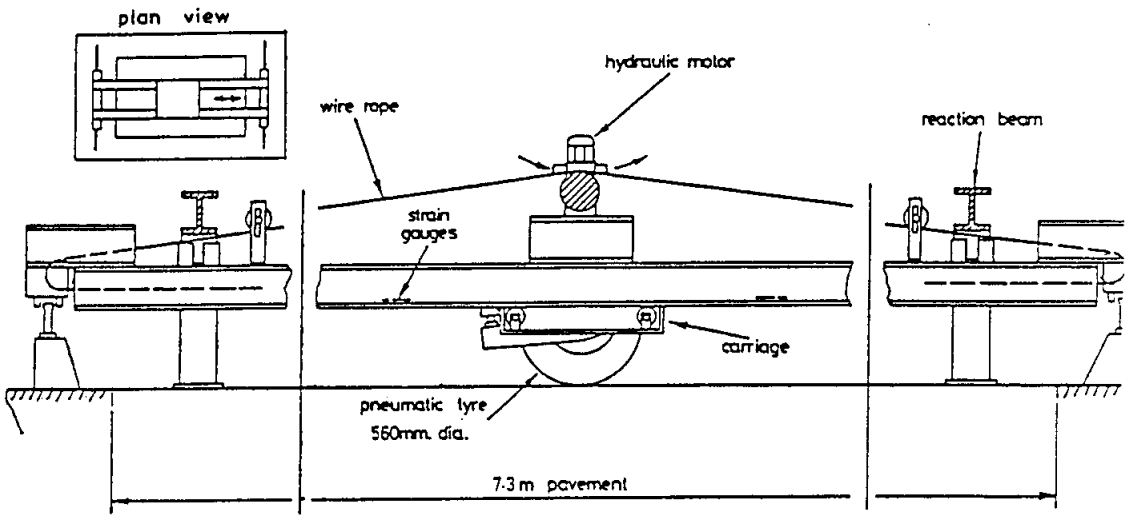


Figure 2.8. Side view of Nottingham pavement testing facility (after Brown and Bell, 1979).

Field test sections on existing roads have also been used to study pavement response. The major advantage of studies of this type is that they are representative of the response under real traffic patterns and environment conditions. Their major disadvantage is the confounding nature of uncontrollable elements that may affect the experiment and complicate its interpretation.

2.2 Sample Preparation

Usually, 4-inch diameter by 8-inch high specimens are used in repeated load testing of asphalt concrete and, in some cases, require using compaction procedures that are different from conventional methods. These samples can be tested either unconfined or confined. The diametral (or split tensile) test permits using existing sample preparation equipment to test for elastic and plastic behavior of all types of materials. Confining devices are now available to test materials in the diametral device. The simplicity of the test and use of small samples make the diametral test practical for routine testing. However, the nonuniform stress state developed in this test make the results suspect.

In a design situation, it is usually desirable to test material in the "as placed" state, which can be accomplished by obtaining cores from the pavement. However, in real life most specimens have to be prepared in the laboratory. Here, the method of mixing and compaction should be as realistic as possible and a correlation must be known between the mechanical properties obtained in the laboratory and those which will be obtained in the field. ASTM has published a standard method (D3496) for preparation of bituminous mixture specimens for dynamic testing which can be applied to axial creep testing as well. For the diametral test, samples can be prepared using either the conventional Marshall (ASTM D1559), Hveem (ASTM D1561), or Gyratory (ASTM D3387) methods. The Hveem (kneading compaction) or Gyratory method is preferred in order to better represent field conditions (Von Quintus, et al., 1990).

2.3 Typical Test Results

Brown and Snaith [34] have carried out an investigation on dense bitumen macadam made with nominally 100-pen. bitumen. They noted that increasing the stress level or temperature results in increasing the creep response (Figures 2.9 and 2.10). They also noted that at low stress levels, the

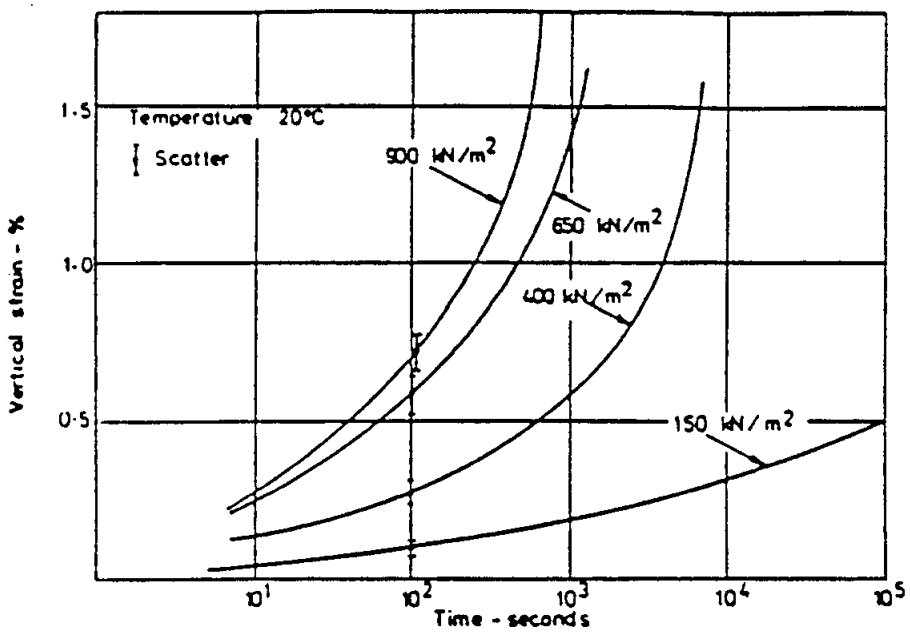


Figure 2.9. Creep tests - effect of stress level (after Ref. 34)

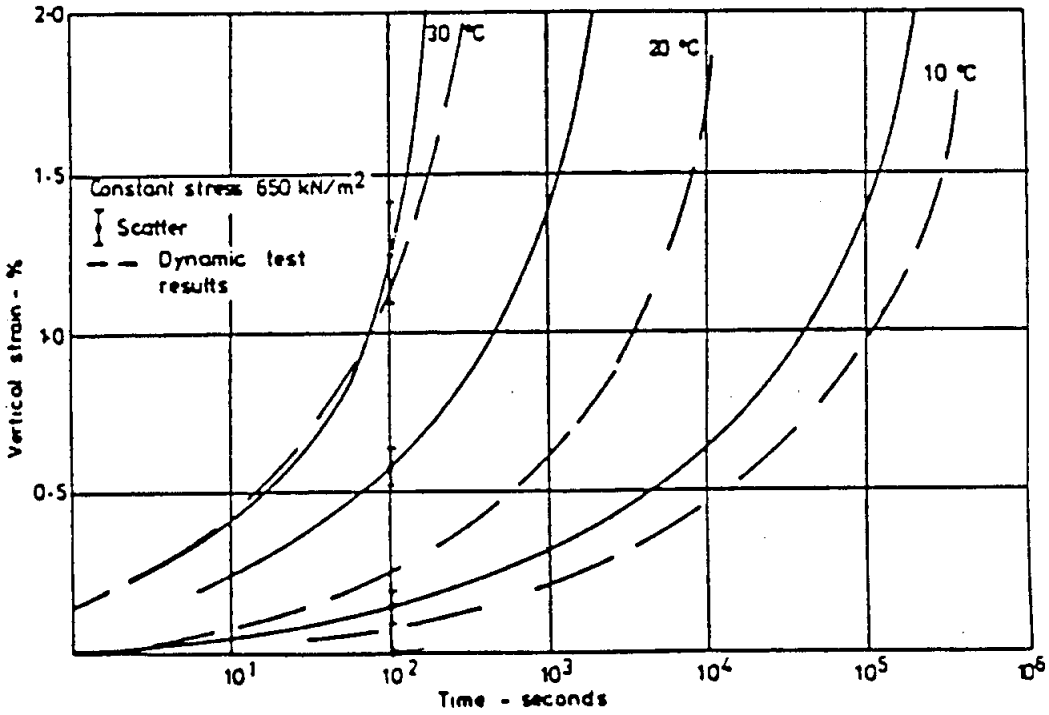


Figure 2.10. Creep tests - effect of temperature (after Ref. 34).

static and dynamic test results are similar. However, at higher stress levels a static stress of about 65 percent of dynamic value would be required to produce the same strain at a particular time. They also noted that decreasing confining stress, increasing the vertical stress, increasing temperature, or decreasing load frequency results in increasing the vertical strain of specimens tested in the triaxial test (Figures 2.11 to 2.14).

Akili and Monismith [35] tested cement-emulsion treated sand using the triaxial test. They noted that increasing deviator stress results in increasing deformation (Figure 2.15). Moreover, they noted that at short curing times rutting tends to decrease as the curing time increases (Figure 2.16).

McLean and Monismith [36] evaluated asphalt cement stress states at different positions in thick asphalt-bound layers by conducting the following triaxial tests:

1) tension tests - to represent the stress states near the surface,

2) compression tests - to represent the stress states near the center of the layer, and

3) tension tests - to represent the stress states near the bottom of the layer

The results of the tests are shown in Figure 2.17. Interestingly, the slopes of the rutting curves are similar regardless of the test type; extension and tension tests gave similar results.

In summary, there are a variety of test methods available for characterizing material properties for use with rutting models and that can be designed for use with fatigue and cold temperature prediction models. Criteria for selection of a particular procedure will depend on the analytical model to be used and the specific objective associated with the model. For research, it may be desirable to do testing which requires sophisticated equipment and procedures. For engineering applications, however, simplicity and productivity must be a major consideration.

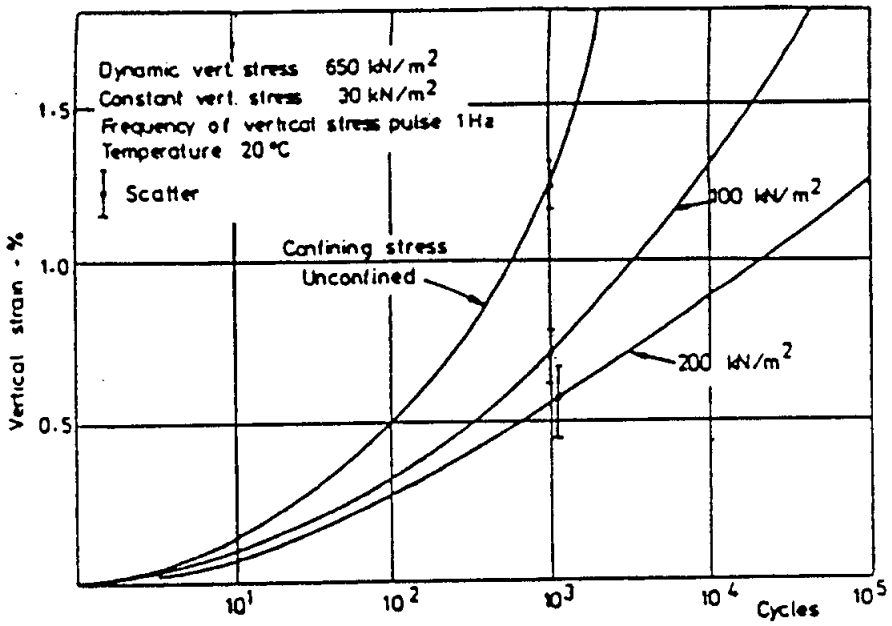


Figure 2.11. Influence of confining stress on vertical strain (after Ref. 34).

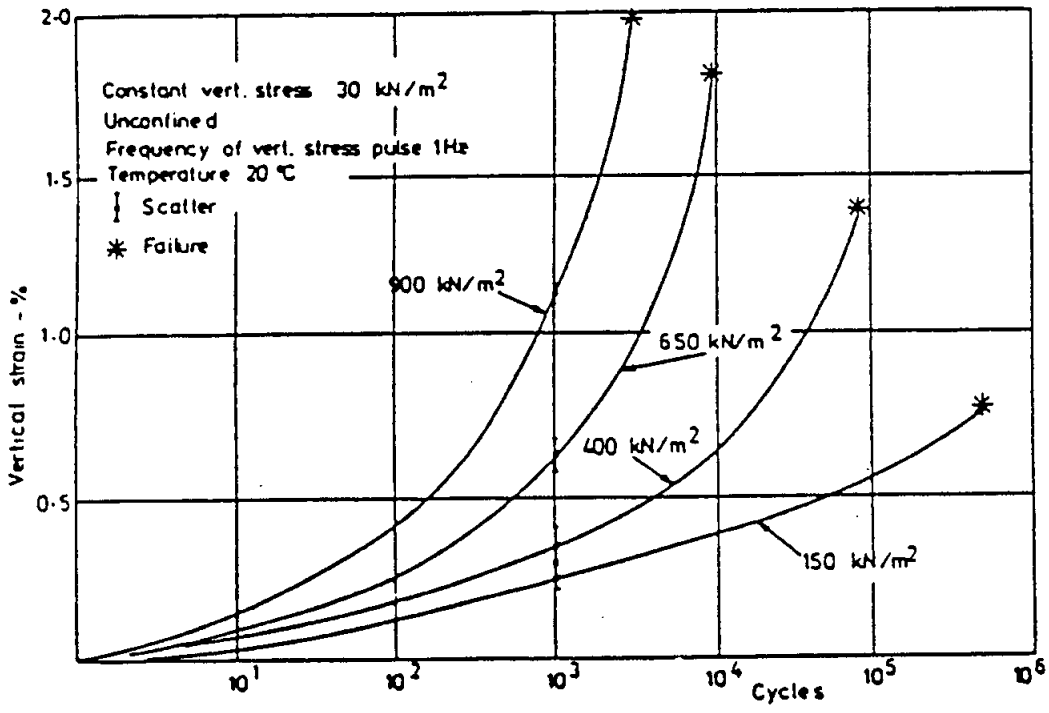


Figure 2.12. Influence of the magnitude of the vertical stress pulse on vertical strain (after Ref. 34).

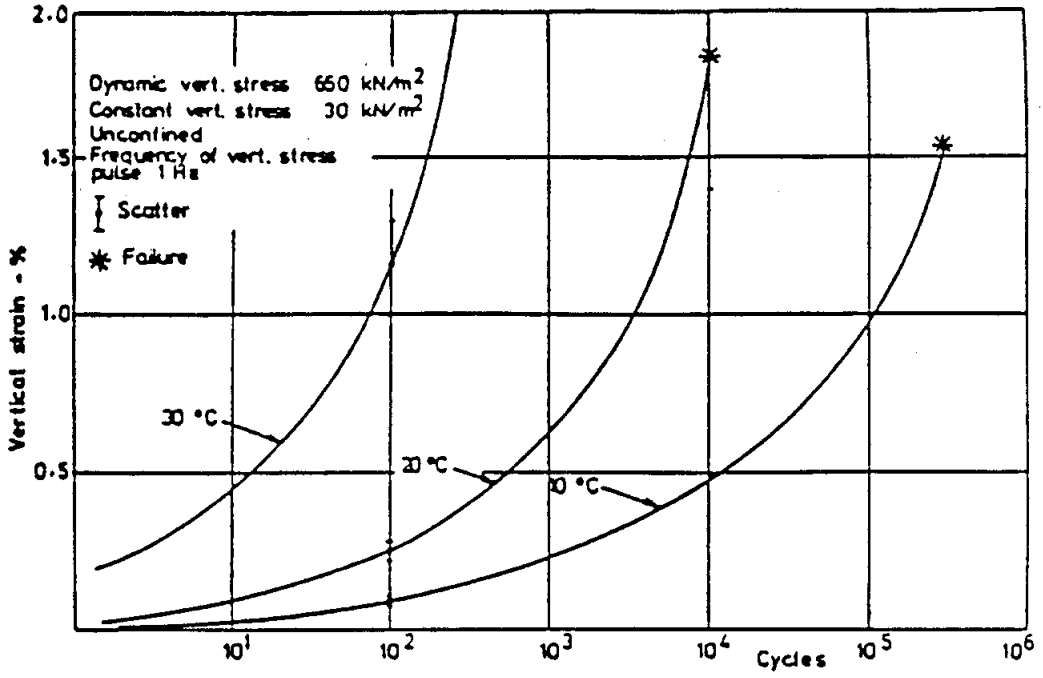


Figure 2.13. Influence of temperature on vertical strain (after Ref. 34).

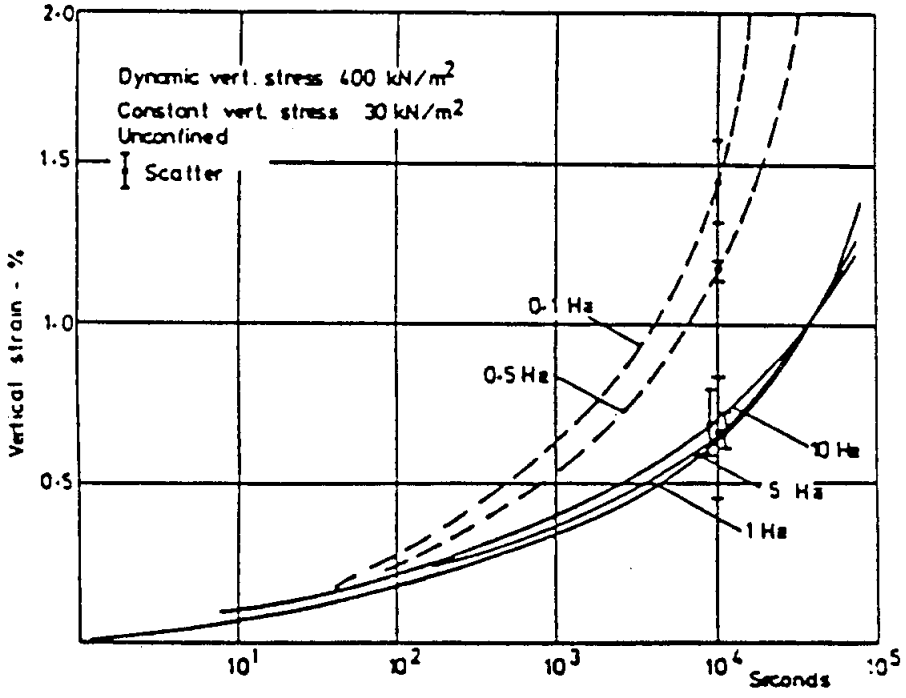


Figure 2.14. Influence of load frequency on vertical strain at 20°C (after Ref. 34).

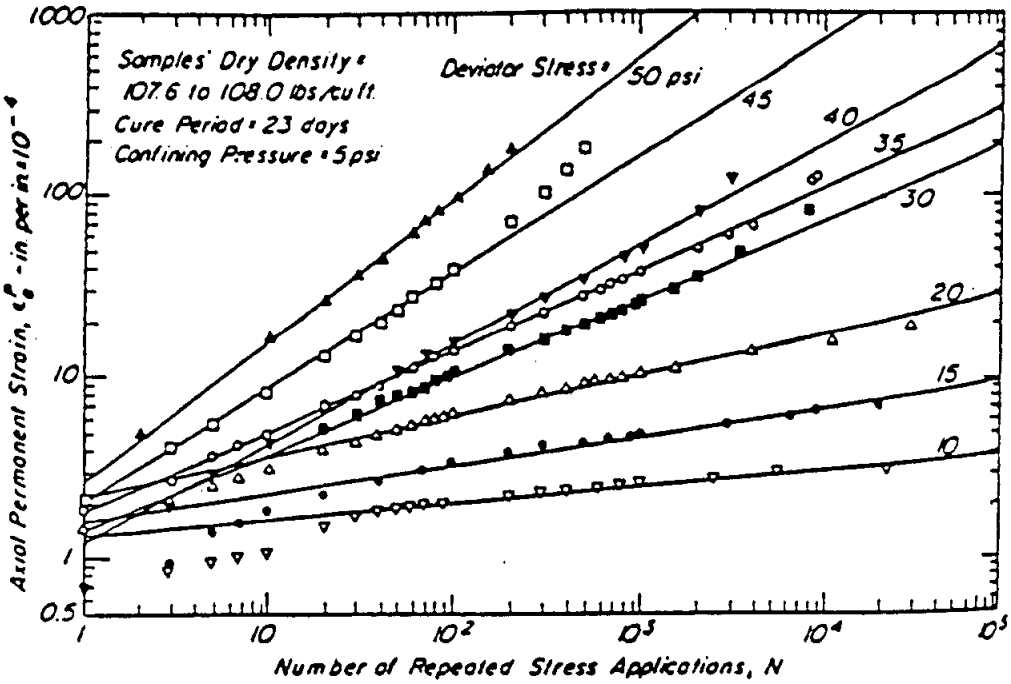


Figure 2.15. Axial permanent strain versus number of stress applications at different stress levels (after Ref. 35).

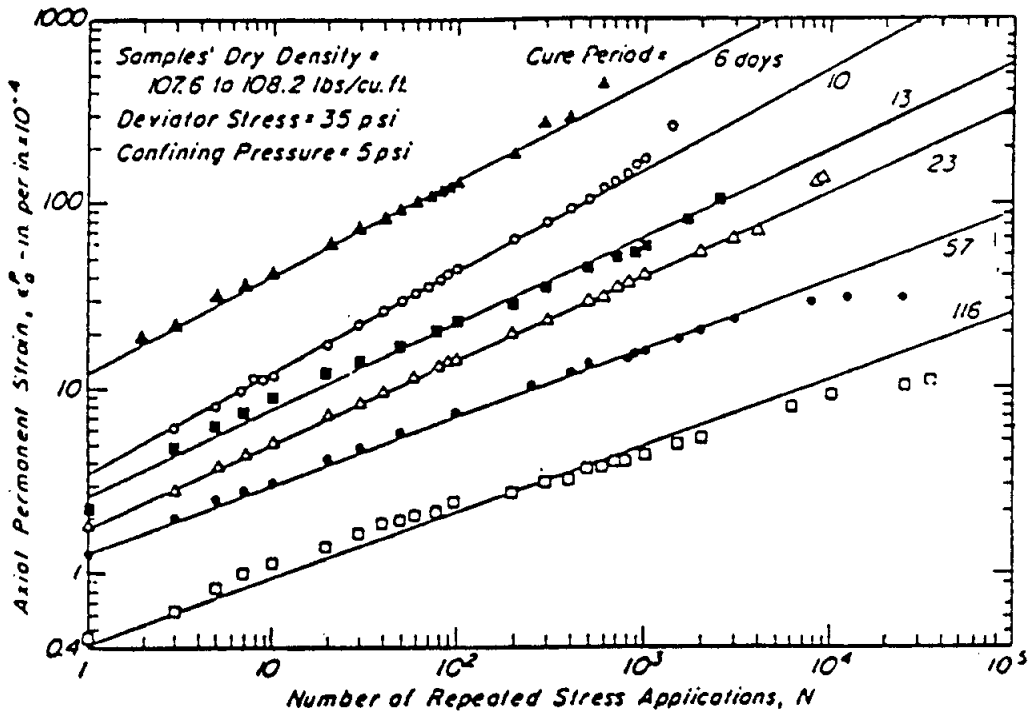
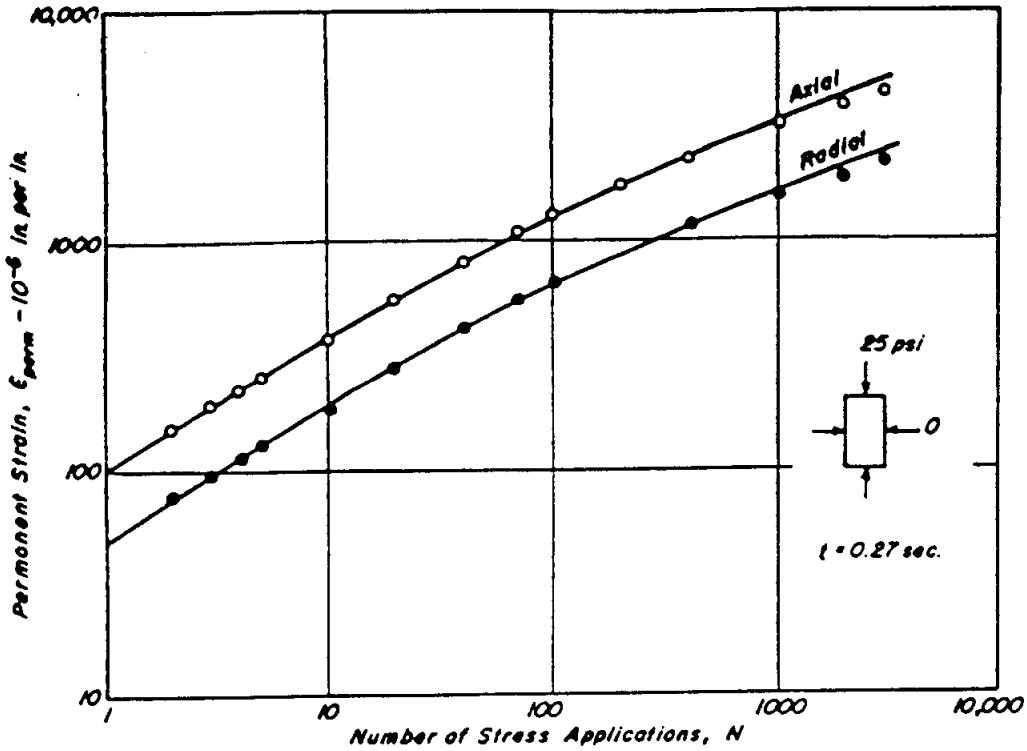
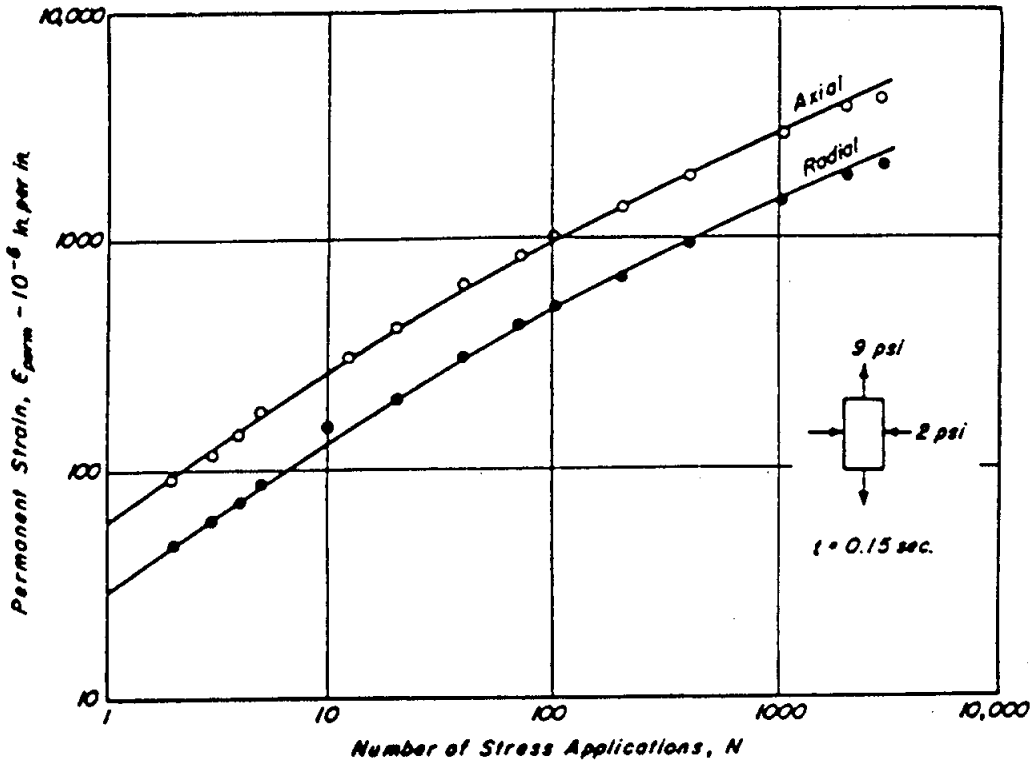


Figure 2.16. Axial permanent strain versus number of stress applications of samples tested at different cure periods and under constant repeated deviator stress (after Ref. 35).



a) Compression test



b) Tension test

Figure 2.17. Typical triaxial test results.

3.0 PREDICTION OF PERMANENT DEFORMATION

The need for reliable rut depth prediction methods has arisen primarily from the use of heavier wheel loads, higher tire inflation pressures, thicker asphalt concrete layers, and the more extensive use of marginal materials such as sand asphalt. At the present time, most pavement design systems utilize the simple subgrade strain criteria for limiting rutting in the pavement system (primarily in the subgrade layer). For example, the Kentucky Design Method [37], the original Shell Method [2], and the Asphalt Institute Method described by Shook et al. [38], all use limiting vertical strain criteria on the subgrade. None use the limiting strain on the base layer. However, the Shell Method, as presented by Claessen et al. [6], has been modified to include the a creep test for estimating rutting in the bituminous stabilized materials.

Hicks and Finn [39], Monismith [40], and Santucci [41] have also proposed vertical strain criteria for limiting rutting. Saraf et al. [42] proposed a rut deflection prediction model based on a surface deflection which worked well for the AASHO and Brampton Road Test projects but was not acceptable for the Chiefland Test Road in Florida. Barksdale [8] has suggested limiting vertical subgrade stress criteria. Limiting either subgrade strain, subgrade stress, or surface deflection is not likely to control rutting in the material above the subgrade. If the vertical strain criteria are developed for a given structural design and set of material properties, some justification can be presented for using this type of criteria. For varying conditions, however, a more general method is needed for limiting rutting in each layer. Two such methods include the layer strain and viscoelastic theoretical methods which are used presently for predicting pavement deformation by various investigators.

3.1 Layer Strain Method

The layer strain method consists of predicting rut depths using permanent deformation properties evaluated from laboratory or other tests together with either linear or nonlinear theory. This approach was first proposed by Barksdale [3] and Romain [4] in 1972. While nonlinear theory should provide more accurate results [13], its use has been limited because it is more complicated to apply.

To predict the amount of permanent deformation that would occur after a given number of wheel load applications, each layer of the pavement structure is divided into several fictitious sublayers and the

stress state is calculated using an appropriate theory at the center of each sublayer beneath the wheel load (Figure 3.1). Using the average stress state at the center of each sublayer, the axial plastic strain corresponding to that stress state can be readily interpreted from the results of laboratory tests corresponding to the desired number of load repetitions. The total rut depth beneath the wheel loading can then be obtained by summing up all of the products of the average plastic strains occurring at the center of each sublayer and the corresponding sublayer thickness [3] as shown in Figure 3.2:

$$\Delta_p = \sum_{i=1}^{N} [(\epsilon_{pi})(h_i)] \qquad (6)$$

where Δ_p = total rut depth, ϵ_{pi} = average plastic strain in the ith sublayer, h_i = thickness of the ith sublayer, and N = total number of sublayers.

Papers given by Brown and Bell [13], Kirwan et al. [43], Meyer and Haas [44], and Monismith et al. [45] all describe the layer strain approach. The Shell Method [6], in a generalized sense, can also be included in this category since it uses a fictitious layer and representative stress conditions.

An important advantage of using the layer strain method is its great flexibility which allows the use of either linear or nonlinear elastic theory. Also, material properties which are consistent with the existing stress state (at least according to theory) in each sublayer of the pavement system can be used. One disadvantage of this method is that repeated load triaxial tests generally should be performed to define the material properties.

3.2 Viscoelastic Methods

In basic concept, the viscoelastic methods offer the most realistic approach for predicting permanent deformations. In practice, however, linear theory for predicting structural response has always been used because of the mathematical complexities involved with using nonlinear viscoelastic theory [46,47]. Use of the linear stress distribution theory is a serious disadvantage to using viscoelastic approaches. The important advantage of using viscoelastic theory is that moving wheel loads can be directly considered. The use of a moving wheel load automatically causes the correct time-rate of loading to be applied to each material element, and results in realistic lateral plastic flow of material from

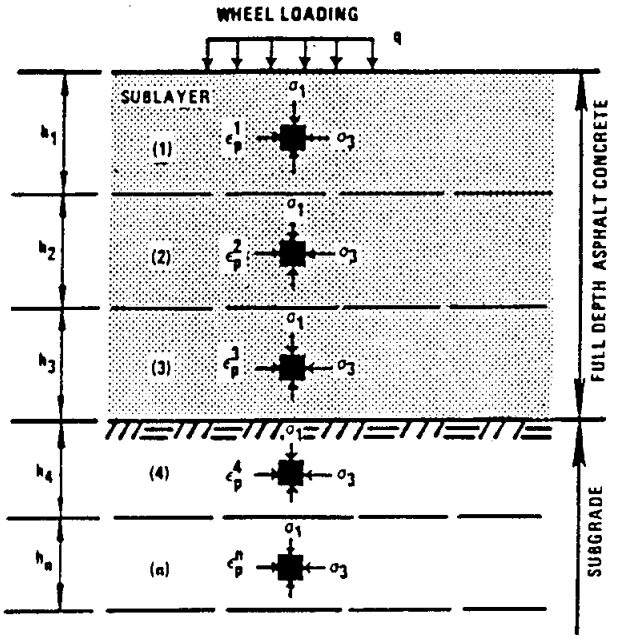


Figure 3.1. Layer strain method of calculating rut depth using sublayers.

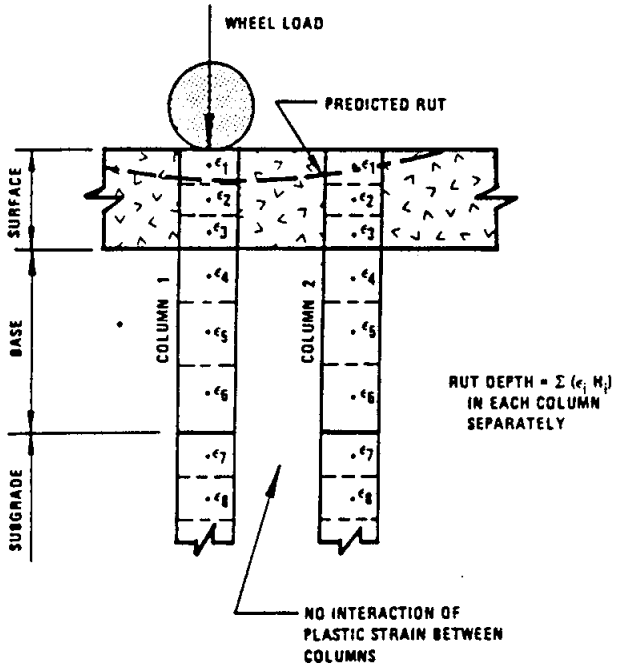


Figure 3.2. Idealized independent column assumption made in layer strain analysis.

beneath the wheel load. Because of the use of linear theory, the material properties within a given layer have been assumed to be the same throughout the layer regardless of whether the material is in tension or compression.

Papers presented by Battiato et al. [48], Huschek [32], and Thrower [49] all use linear viscoelastic layered theory for predicting permanent deformations. These methods use superposition to handle the effects of moving wheel loads. Power functions corresponding to a Maxwell model are used to characterize the viscoelastic behavior of the material.

3.3 Application of Layer Strain Methods

Brown and Bell [13] have compared theoretically-predicted rut depths using the layer strain approach with those actually measured in the Nottingham Test Track. The test track consists of a pavement about 15 feet long and 7.6 feet wide. A 3,600 lb. wheel load moving at a speed of 9 mph can be applied in the central portion of the test section. The testing facility has the capability of automatically positioning the wheel load in the lateral direction so that a semirandom lateral distribution of wheel passes can be applied. Material properties were predicted using the repeated load triaxial test. Appropriate stress states in the tensile zone of the pavement were carefully selected using the p-q approach previously described. Comparison between predicted and measured total displacements indicated good agreement using the layer strain method by Brown and Bell, as illustrated in Table 3.1. Reasonably good agreement was also found for the method proposed by Kirwan et al. [43], and also the Shell Method [6]. The paper by Brown and Bell [13] contains a considerable amount of fundamental information on rutting and pavement behavior and deserves careful study.

Kirwan et al. [43] present a subsystem for predicting permanent deformation that has been simplified for practical applications. This method makes use of the layer strain approach and a nonlinear finite element computer program. The properties of a glacial till subgrade are characterized from repeated load tests by a simple-to-use chart. For evaluating the dynamic properties of the asphalt concrete mix, the authors recommend that the properties of each material be evaluated by applying the root-mean-square of the dynamic pulse loading to a creep test specimen of bituminous material. For a sinusoidal loading, they recommend applying 61 percent of the peak-to-peak value of the dynamic load

Table 3.1. Measured and predicted rut depths at Nottingham test track.

Method	Meas. (mm)	Calc. (mm)
Brown & Bell	12.4	13.3
Snaith	12.4	17.0
Van de Loo	12.4	9.3

in the creep test. This approach offers a simple, practical method for evaluating dynamic characteristics of a material. To estimate rut development, the authors proposed a method for handling transverse distribution of loads based on the time-hardening concept first proposed by Monismith [40] and used by Van de Loo [29]. The approach used is illustrated in Figure 3.3 for two repetitions of load applied at offset r_1, then three repetitions of load applied at offset r_2, and finally four repetitions applied at the centerline of the wheel path. The approach consists of first calculating the permanent deformation as a function of number of wheel load repetitions at each specified offset distance from the load. As illustrated in Figure 3.3, the plastic strains are then continuously accumulated on each curve according to the past permanent deformation and number of repetitions applied corresponding to that curve. A comparison of the results of the method proposed by Kirwan et al., with the measured rut depths at Nottingham for the multi-track tests, shows the computed rut depths to be somewhat greater than measured values, but the comparison indicated still reasonably good agreement (Table 3.1).

Monismith et al. [45] also used the layer strain method for predicting deformation. The material properties are evaluated using the repeated load triaxial test, and the pavement response is calculated using the elastic layered computer program, ELSYM5. The method considers the distribution of traffic including axle loads and lateral distribution. The mean temperature of each sublayer for each month is calculated using the method proposed by Barber [50]. Consideration of temperature variation in the pavement throughout the year is certainly an important requirement for predicting rutting in asphalt concrete layers.

The authors presented the following expression relating permanent plastic strain to the stress state in the pavement:

$$\epsilon_p = R[\sigma_z - v(\sigma_x - \sigma_y)] \tag{7}$$

where

R = effective strain divided by effective plastic stress, $\bar{\epsilon}_p/\bar{\sigma}$.

v = Poisson's ratio, normally assumed = 0.5.

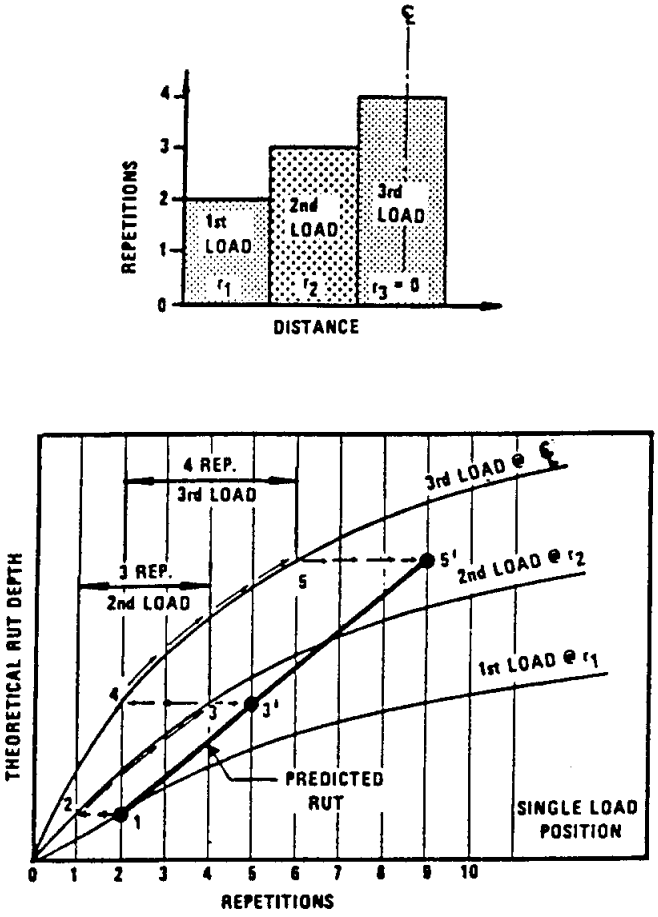


Figure 3.3. Rut depth prediction - time hardening rule (after Ref. 43).

For triaxial testing conditions, the constant R can be evaluated using:

$$\bar{\epsilon}_p = \frac{2}{3}(\epsilon_1 - \epsilon_3) \tag{8}$$

and

$$\bar{\sigma} = \sigma_1 - \sigma_3 \tag{9}$$

Equation (7) is modified from the theory of linear elasticity for use in predicting permanent deformations for any stress state. It should be pointed out that if one takes the axial and radial plastic strains from a typical repeated load triaxial test and substitutes them into this expression, the correct measured axial plastic strain is not given by the expressions, although the error for the cases checked is not great. Better results would probably be obtained if in Equation (7) the actual ratio of lateral to axial plastic strain (v) measured in the triaxial test was used rather than the assumed value of 0.5. Nevertheless, this expression appears to be quite useful for practical application. Simple relationships for R in Equation (7) are developed for each material characterized.

The paper by Meyer and Haas [44] presents a working subsystem currently used in Ontario, Canada, to estimate rutting in asphalt concrete pavements. The method was developed using primarily the observed rutting from the Brampton Test Road. Meyer and Haas originally used the layer strain method to predict the permanent deformation of flexible pavements. Material properties were measured using the repeated load triaxial tests and a statistically designed experiment. In the repeated load test, both the vertical and horizontal stresses were independently controlled. Statistically significant variables influencing permanent strain were found to be stress state, pavement temperature, density, air voids, and number of repetitions. Rut depths were calculated in a number of typical pavements using the layer strain approach. Finite element techniques were employed to calculate the stress state in the pavement. From these results, a statistical analysis indicated that the primary factors affecting rutting were the asphalt concrete thickness, modulus of both the asphalt concrete layer and subgrade, and number of wheel load repetitions. To handle rutting in granular bases, the granular base is converted to an "equivalent" thickness of asphalt concrete using a substitution ratio of 1 inch of asphalt concrete for 2 inches of stone. Extreme caution should be exercised in converting from one type section to another since the

equivalency ratios can vary greatly with density and level of stabilization. The Meyer and Haas theory also indicated an optimum bituminous layer thickness that gives a minimum depth of rutting. In an actual pavement, it is more likely that a limiting depth of bituminous surfacing exists beyond which additional rutting does not occur, as was found at the AASHO Road Test.

3.4 Shell Method of Predicting Rutting

The Shell Method of predicting permanent deformation [33,51] has been developed as a practical method for applying layer strain concepts to help predict rutting in asphalt pavements and deserves some special consideration. The method has been included as part of the overall design procedure used by Shell in Western Europe and Asia.

The Shell Method follows the layer strain approach and, therefore, utilizes Equation (6) to calculate the deformation. To arrive at a plastic strain to use as input in this equation requires detailed information on the mixture components, traffic, environment for the pavement, a layered elastic analysis, and data from a simple uniaxial creep test of the mixture on a representative laboratory sample. It is this last item that simplifies the procedure relative to methods requiring repeated load tests. The basic premise to the method is that the development of deformation in an asphalt pavement is closely related to that occurring in a laboratory creep test, as was observed in the development of the method by Shell researchers. They expressed the development of deformation in a normalized form which is independent of temperature, as shown in Figure 3.4. The mixture stiffness (S_{mix}) and bitumen stiffness (S_{bit}) are uniquely related, regardless of the temperature since S_{bit} is a function of both time of load and temperature. Mixture stiffness decreases during a creep test as loading time increases and is defined as follows:

$$S_{mix(t)} = \sigma_o / \epsilon_t \tag{10}$$

where σ_o = applied stress and $\epsilon_{(t)}$ = time dependent axial strain.

The applied stress is constant throughout the test; hence, measurement of the strain at regular intervals enables the mixture stiffness to be calculated. Similarly, the stiffness of the bitumen in the mixture decreases during the test, as loading time increases. Estimates of bitumen stiffness can be obtained using Van der Poel's nomograph. Prediction of mixture stiffness can be estimated from a master

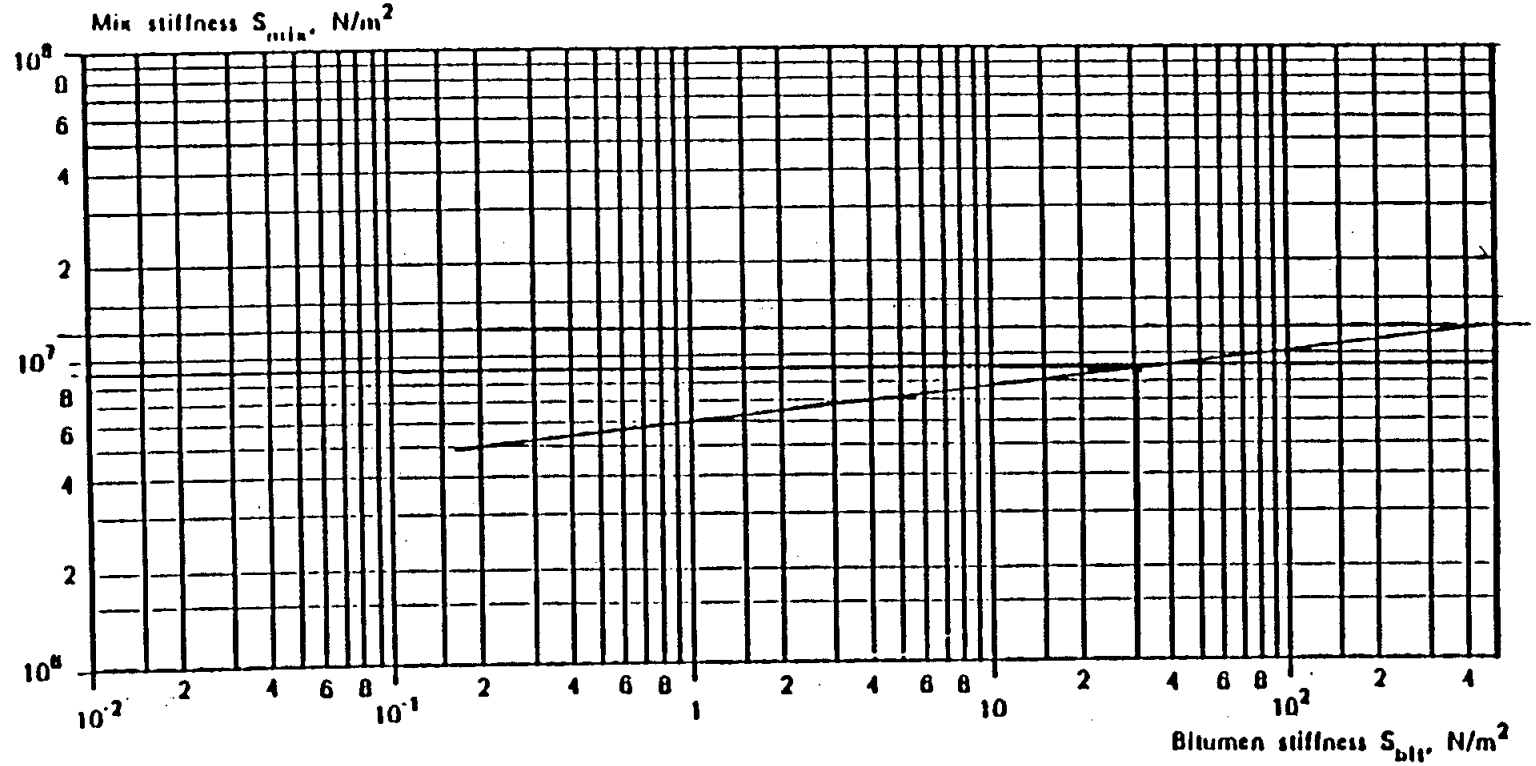


Figure 3.4. Hypothetical creep plot for asphalt concrete.

curve, such as Figure 3.4, which reflects the time of loading. In other words, if a value of S_{bit} can be found corresponding to the field conditions leading to deformation, the resulting S_{mix} can be found from the master curve, and:

$$\epsilon_{(t)} = \sigma_o / S_{mix} \tag{11}$$

Since deformation and strain are related, as indicated in Equation (6), we have completed the essential elements of the method. Van de Loo indicates that the required bitumen stiffness is the viscous component of the total stiffness ($S_{bit,visc}$) and this is found from:

$$S_{bit,visc} = 3\eta / N t_w \tag{12}$$

where N = total number of load applications, t_w = loading time for one load application (seconds), and η = viscosity of bitumen (Ns/m^2).

A nomograph, provided by Shell for estimating the viscosity, requires the temperature, penetration index, and softening point as input. Alternative procedures for use in the U.S. are discussed in the following paragraphs.

To estimate the field deformation, the following variation on Equation (6) is used:

$$\Delta h = C_M \cdot h \cdot \sigma_{av} / S_{mix} \tag{13}$$

where

σ_{av} = average stress in the bituminous layer,

$h, \Delta h$ = thickness and change in thickness, respectively, of the bituminous layer, and

C_M = correction factor.

The procedure for using Equation (13) in the Shell Design Manual [6] determines σ_{av} by applying a "Z" function to σ_o; however, users can employ their own analysis to find a representative σ_{av}. Also, the manual utilizes a method of dividing the bituminous layer(s) into three sublayers and calculates the deformation in each, which requires appropriate S_{mix} and σ_{av} values.

It must be emphasized, as stated in the Shell Manual, that considerable error could result if an inappropriate S_{mix} versus S_{bit} curve is used. The curve must either be developed from typical data, from a creep test on a core of material, or by correlations between laboratory specimens and field cores.

Finally, the method, as presented by Shell, requires bitumen (asphalt) consistency data using penetration and softening point. Such data are not readily available in the U.S.A. or other countries which use viscosity to characterize bitumens. However, the Bitumen Test Data Chart (BTDC, Figure 3.5) can be used to plot measured viscosities (and possibly the penetration), and to estimate the required inputs for Van der Poel's and the viscosity nomograph. Note the viscosities at 60°C and 135°C and penetration at 25°C are plotted on the BTDC for two asphalts, an AC-30 and AR-4000. Interpolation permits determination of the softening point (important for rutting). Extrapolation would permit the determination of the Fraas point (important for low temperature cracking).

An example of the Shell method of predicting deformation is given in Appendix A.

3.5 Application of Viscoelastic Methods

This section provides a brief summary of the linear viscoelastic methods proposed for predicting permanent deformation. Battiato et al. [48] developed a two-layer incompressible viscoelastic pavement system. Laboratory creep tests were used to evaluate the characteristics of the asphalt concrete surfacing material. The bituminous layer was characterized as a Maxwell model consisting of a spring and dashpot in series, and the subgrade was assumed to be elastic. The creep compliance was evaluated from unconfined creep tests. Verification of the proposed method by comparing calculated rut depths with observed values was not given; however, the interesting results obtained by both Battiato et al. [48], and Thrower [49] for static pulse loads and moving wheel loads will be discussed subsequently.

Huschek [32] proposed a linear viscoelastic theory for calculating rutting in a layered pavement system. A generalized Maxwell model is used with the viscosity of the dashpot increasing with the number of wheel load repetitions. Both conventional and cyclic unconfined creep tests were used to derive material characteristics. Huschek suggests that the specimens should be confined to better define the internal friction of the grain structure. The method considers the temperature distribution in the pavement, distribution of transverse traffic, and vehicle speed. Only the bituminous layers were considered to have time-dependent material properties.

The method proposed by Huschek was verified by comparing measured and calculated rut depths for a test road near Zürich consisting of five test sections. Creep tests were run on cores from

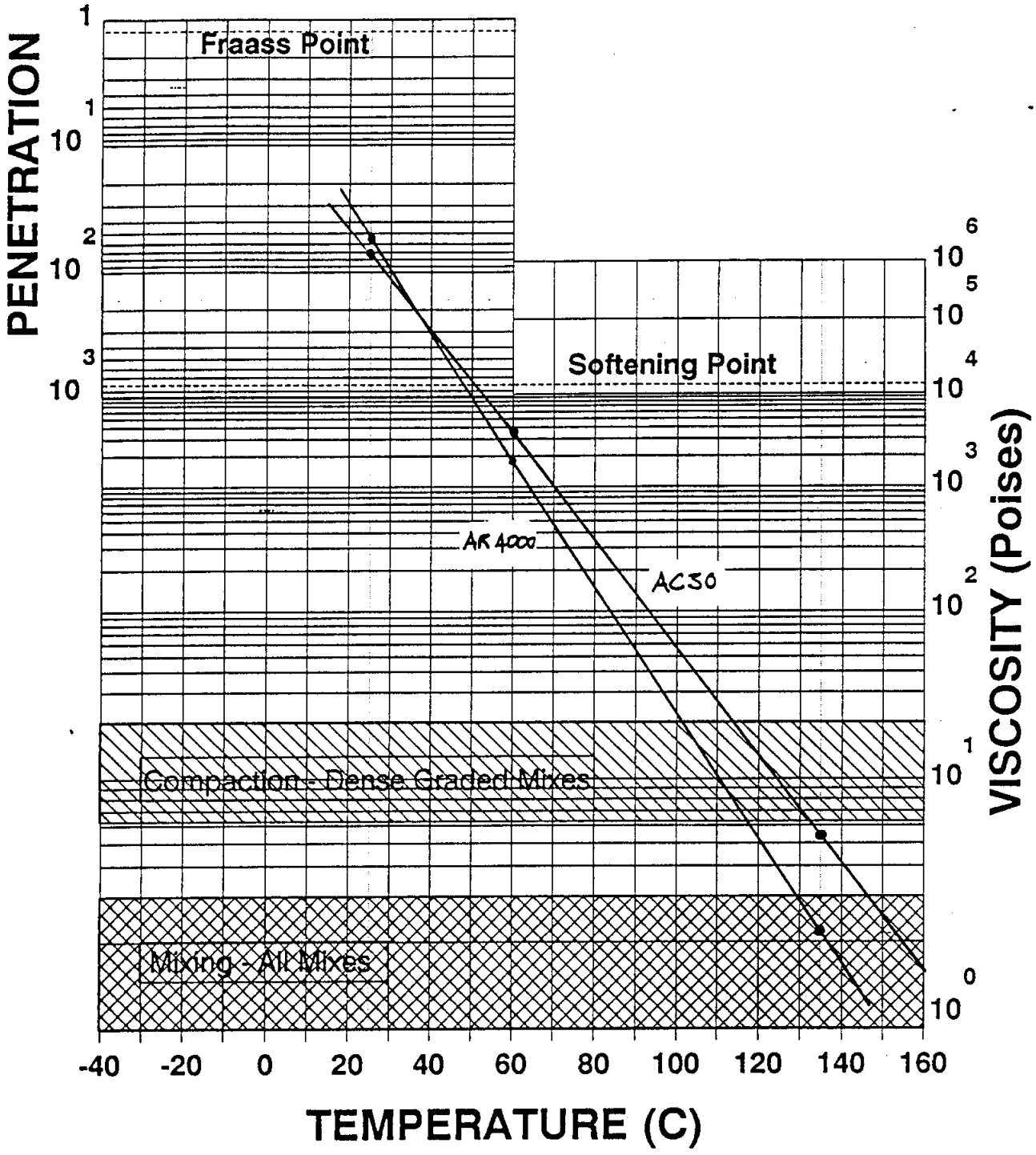


Figure 3.5. Bitumen test data chart with typical data.

each test section. A comparison of the measured and calculated rut depth values showed good agreement.

Thrower [49] developed a linear viscoelastic method for predicting permanent deformation which assumes that the elastic stress and strain distribution in the layered system is not significantly affected by permanent deformation. Thrower justified this assumption by observing that elastic deformation was large compared with the plastic deformation caused by a single wheel passage. After obtaining the stress distribution using elastic layered theory, the permanent deformation was put back into the viscoelastic theory. This method is called the "separative approach", and is analogous to the layer strain method.

3.6 Discussion of Prediction Methods

To predict rutting using theoretical methods, the permanent strain in pavement materials must be tested at a stress condition compatible to that which exists in the in-situ pavements. Brown and Bell [13] uses p-q plots for depicting the stress state in the pavement structure for selecting appropriate test conditions. The term "p" is the mean normal stress applied to an element of material, and "q" is equal to a constant times the octahedral shear stress. The mean normal stress, p, is associated with volume change whereas q is associated with shear distortion. Since, in general, shear distortion is the most important mechanism causing permanent deformation in a pavement structure, separating the stress state into p and q components is a rational and logical approach for selecting appropriate stress conditions for testing purposes. Both Brown and Bell [13] and Freeme [52] have found from repeated load triaxial testing that permanent deformation is primarily caused by shear stress q. The mean normal stress, p, was found not to contribute significantly to the accumulation of plastic strain.

Since permanent strain is primarily associated with q, its variation in the pavement structure is of great concern in selecting appropriate stress states. Brown and Bell [13] found that in determining the deformation beneath one wheel of a dual wheel assembly, the shear stress caused by the adjacent wheel must be included in determining the correct p-q stress state for testing. Shear stresses should also be included in measuring plastic strains for computing rutting off the axis of symmetry for a single wheel loading.

Brown and Bell [13] also found from their theoretical analysis that approximately the same amount of rutting was induced for distances up to 4.4 inches from the center of the wheel load. This result is apparently related to the importance of shear stress in causing permanent deformation. For pavement temperatures which cause rutting, Brown and Bell (Figure 3.6) conclude that a nonlinear stress analysis should be used to determine p and q. In contrast, Battiato et al. [48], conclude that linear viscoelastic theory can be used for predicting the response of the asphalt concrete layer in a two-layer system.

For a theoretical method to be mechanistically correct, it must predict the correct variation of permanent strain with depth in the bituminous layer. For thin sections and light wheel loadings, Hofstra and Klomp [12], as presented in the Second International Conference, found relatively little variation in permanent strain with depth in their small-scale test section.

Brown and Bell [13] have also measured the variation of permanent strain with depth in the Nottingham Test Track. A bituminous layer which rested directly on a silty clay subgrade was subjected to 100,000 repetitions of a 3,600 lb load. The measured variation in vertical permanent strain for the bituminous mix placed at 6 percent voids was parabolic in shape, being somewhat larger at the top and bottom with the smallest permanent strain occurring near the center of the layer (see Figure 3.7).

Meyer et al. [44] found from their layer strain analysis that rutting in the tensile zone of the bituminous layer was approximately three to four times the magnitude of rutting which occurred in the compression zone. Similar results have been obtained by McLean and Monismith [36]. In contrast, Battiato et al. [48] calculated a relatively uniform profile using viscoelastic theory.

Comparison of the predicted permanent strain profile with measured variations in test tracks indicate that, in many instances, layer strain theory, as presently applied, gives permanent strains in the tensile zone which are greater than those that apparently develop. As clearly pointed out by Brown and Bell [13], a better understanding of the distribution with depth of permanent plastic strain in the bituminous layer must be obtained before the existing theoretical approaches can be accurately assessed. Use of Bison strain coils, such as employed in the Nottingham Test Track, offer an accurate and reliable method for determining the variation of permanent plastic strain with depth in the bituminous layers.

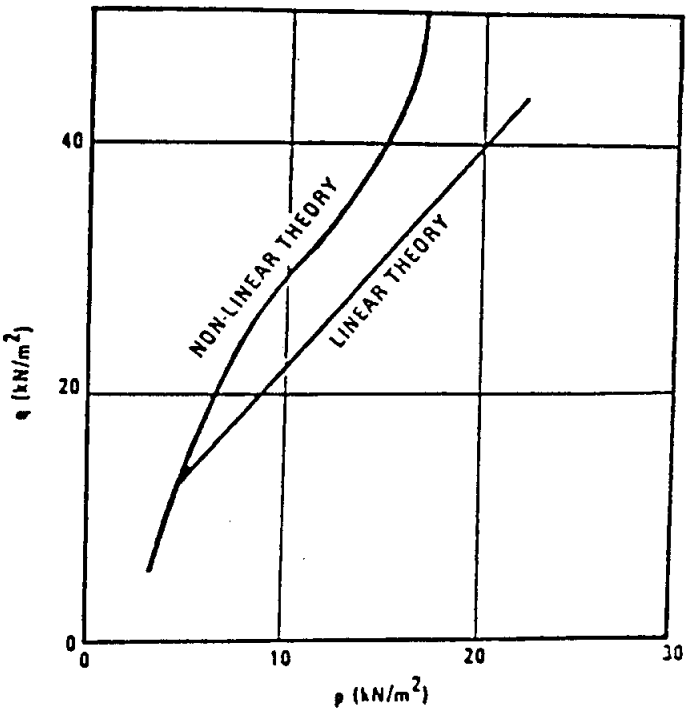


Figure 3.6. Comparison of p and q using linear and nonlinear layered theory (after Ref. 13).

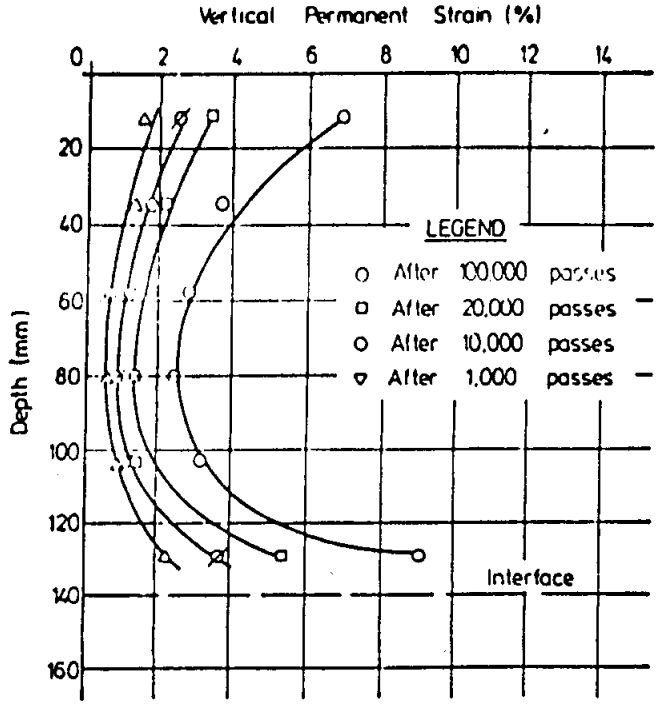


Figure 3.7. Measured pavement strains against depth (after Ref. 13).

Test track measurements of variation of plastic strain with depth have been made for pavements having a relatively thick bituminous concrete surfacing. The variation of permanent strain with depth, and hence the mechanism of rutting, is probably a function of the thickness of the bituminous layers. This is suggested by the fact that rutting at the AASHO Road Test was almost directly proportional to the thickness of the bituminous layer up to a certain threshold value. Above this value, the average plastic strain in the layer decreased. This result suggests that the plastic strain near the bottom of the layer may become very small for thick bituminous layers. With increasing depth, the resistance to plastic flow will become greater due to the presence of surrounding material. This effect is not considered in the layer strain method as presently applied. The variation of plastic strain with depth is also probably influenced by the magnitude of the wheel loading and perhaps even the number of load repetitions.

3.7 Implementation and Verification

Implementation

Practical subsystems which require little or no sophisticated laboratory testing are available for use. Methods based on limiting subgrade strain and regression equations can be placed in this category. These and similar methods, as previously illustrated, can be successfully used when applied to conditions similar to those for which the approach was developed. In general, similarity would be required of environment, stabilized mixes, bases and subbases, and also subgrade conditions. Obviously, the requirement of similar conditions would place important restrictions on the use of these methods. Nevertheless, for at least some user groups, this approach may suffice.

Presently, conditions are rapidly changing: the use of lower quality materials due to the depletion of existing supplies and rising asphalt prices, higher wheel loads, higher tire pressures, and greater volumes of heavy traffic. As time goes on, even greater changes are likely to occur. In this atmosphere of change, most transportation organizations will find it desirable to develop methods that are adaptable to these changing conditions. Such methods must rationally consider material properties which are fundamental to the problem of rutting. To accomplish this, a basic understanding of the rutting problem must first be developed. The end product should be a practical system which requires very few tests. In developing a method which will be routinely used for design, careful consideration should be given to

selecting an approach which requires a single test to characterize each layer. Such a test can very accurately characterize the rutting properties of a layer provided the "average" stress condition in that layer is used. The hardest part in developing an approach of this type will be in deriving criteria for selecting the average stress condition. The Z-function approach previously discussed can be used as a guide in this development.

The Shell Method [7] has found that the average stress state in the bituminous layer can be approximated by an unconfined creep test using a 15 psi axial load. The VESYS Method [10] uses an unconfined creep test and a cyclic axial loading. For the repeated load triaxial test, Barksdale and Miller [8] concluded that for a 10.5 inch layer, the average stress state was close to a confining pressure of 3.0 to 4.5 psi and a repeated axial deviator stress equal to that defined by the Z-function of 25 psi.

The above examples indicate that for practical design purposes, procedures exist for deriving average stress states for routine testing purposes. It should be kept in mind, however, that the method must be reasonably simple or design engineers simply will not use it.

Verification

All the proposed methods for estimating rutting need further field and test track verification. A complete mechanistic verification would include whether the method yields the correct plastic strain profile. Certainly, more test tracks, such as the one at Nottingham described by Brown and Bell [13], are needed to mechanistically verify proposed approaches. Also, considerably more verification of the methods is needed using measurements from actual roadways. In verifying a method, it is probably better to obtain rut depths from ten actual pavements with limited instrumentation than from one fully instrumented laboratory model. This type of verification is the key to developing a sound method. A practical method need not be completely correct mechanistically to work quite satisfactorily when used in the field. Nevertheless, it is important to know what the limitations of the method are so it is not incorrectly applied.

In summary, a significant amount of progress has been made; workable subsystems are available including statistical methods and methods based on the creep test for predicting rutting. In the future, emphasis should be placed on developing improved methods which are simplistic while at the

same time based on rationally evaluated material rutting properties. In evaluating the material properties for a design method, more use should be made of the concept of the average stress state in each layer. Finally, a considerable amount of carefully planned test track and field pavements are needed for verification of mechanistic pavement design methods in general, and rutting subsystems in specific.

4.0 DEVELOPMENTS SINCE 1987

It is clear that rutting is still an important nationwide problem as evidenced by the FHWA report on rutting and stripping published in 1987 [56]. However, the amount of progress made in solving the rutting problems are still limited. This section discusses recent developments in the areas of materials characterization and prediction models as well as work in minimizing the effects of rutting through changes in mix ingredients.

4.1 Materials Characterization

As part of the SHRP A-003A study, which began in 1989, considerable effort has been directed toward using a shear test to evaluate rutting characteristics of asphalt-aggregate mixtures. Simple shear tests have been widely used in the measurement of soil properties. Their increasing use stems from both a greater awareness of the importance of stress-strain anisotropy in geotechnical problems and the simplicity of simple shear testing relative to triaxial testing. The simple shear test can approximate field situations that are characterized by a pure shear stress state or one close to it. It is the simplest test that permits controlled rotation of the principal axes of strain and stress.

Though the simple shear test has not been extensively used for measuring asphalt-concrete properties, it appears suitable for investigating the rutting propensity of asphalt concrete because rutting is predominantly caused by plastic shear flow. The Laboratoire Central des Ponts et Chausses, LCPC [53] has used a simple shear test to determine fatigue characteristics of asphalt concrete (Figure 4.1). The French contend the stresses imparted to the specimen are more representative of those found in their AC layers. The test is performed under imposed strain amplitudes on almost rectangular specimens (Figure 4.2). In short, they are rectangular specimens with cores removed at the ends.

Monismith and Tayebali [57] employed the simple shear test to compare the response of cored specimens obtained from field pavements with the response of specimens compacted with the California kneading compactor. Although only creep response was measured, the apparatus used is also capable of applying repeated or dynamic loads over a range of frequencies for the determination of

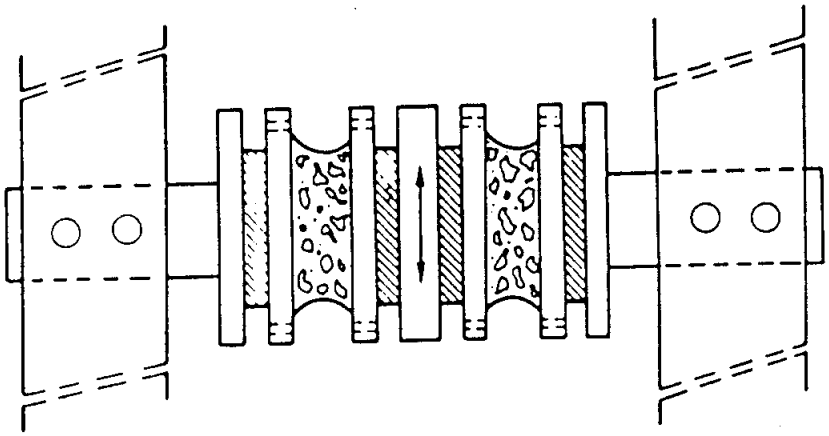


Figure 4.1. Principal of shear test machine (after Bonnot, 1986).

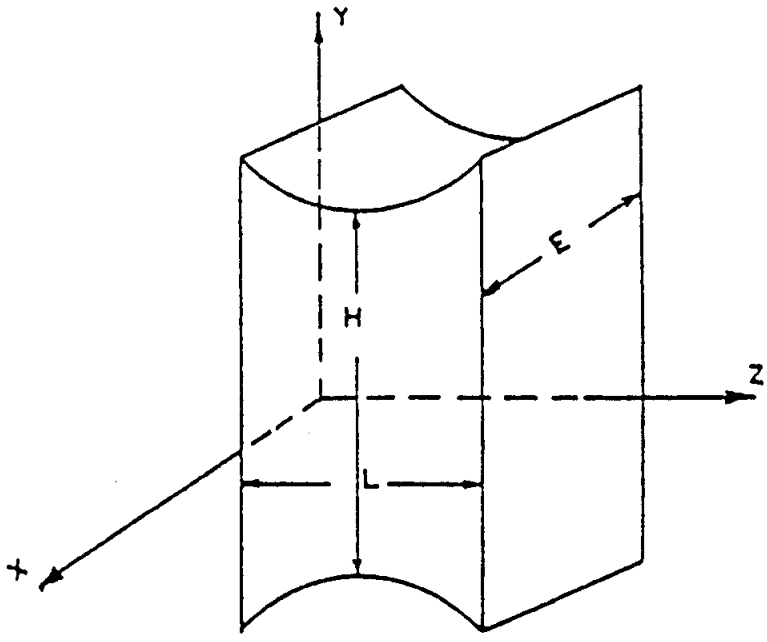


Figure 4.2. Test specimen configuration for shear test (after Bonnot, 1986).

resilient shear modulus, dynamic shear modulus, or shear damping response under stress or strain control and with or without stress reversal.

4.2 Prediction Models

Procedures for rutting prediction require that suitable techniques be developed not only for calculating the response of the pavement to load but also for characterizing the material in a realistic manner. Though a number of approaches have been developed (e.g. layer strain and viscoelastic), it is clear that a viable prediction model is still not available. What is needed is a predictive model which accounts for the shear stresses extending outward from the centerline of load to include the tire edges [63]. Though it may be possible to accomplish this with finite element techniques (using nonlinear viscoelastic methods), it has not yet been accomplished. This activity is being undertaken as a part of SHRP projects A-003A and A-005.

4.3 Effects of Mix Variables

In March 1988, the Federal Highway Administration used Technical Advisory T5040.27 titled "Asphalt Concrete Mix Design and Field Control." One of the intents of this document was to provide mix design guidelines to minimize the occurrence of rutting in asphalt pavements. Factors addressed were:

1) Aggregate quality, shape, and fracture and gradation.

2) Asphalt grade and characteristics.

3) Mix properties including stability, voids, VMA and moisture susceptibility.

Controlling these factors, they contend, will substantially reduce the problems with rutting. Alaska DOTPF implemented these guidelines in the summer of 1989. To date, there is not clear evidence as to the benefits of the new mix designs. Creep tests, which will be performed as a future task of this study should provide evidence as to the benefits of using the Technical Advisory.

Two other areas which have received considerable attention over the past few years: 1) use of modified asphalts, and 2) use of large stone mixes [59,60,61]. Both changes from conventional mixes have clearly reduced, in the laboratory, the propensity of mixes to rut.

Clearly, with modified binders, some form of repeated load is needed to show their benefit [57,61]. At present, only 6 in. Marshall tests and/or field installations have been used to evaluate the effect of stone size and gradation [60]. Work planned as a part of SHRP projects A-003A and A-004 is expected to provide additional information as to the benefits of these mix changes [63].

5.0 SUMMARY

This report has presented a state-of-the-knowledge on factors which affect deformation in asphalt-aggregate mixtures, laboratory test methods used to evaluate resistance to deformation, and methods for predicting deformation in the upper layers of a pavement structure. The primary applications of this research is in the areas of mixture and structural design. This concluding chapter summarizes the current use of the information in these two important areas.

5.1 Mix Design

Two of the most widely used mixture design methods are the Hveem Stabilometer and the Marshall methods which provide an empirical measure of plastic flow characteristics. Both methods provide useful information, but neither is able to predict the magnitude of permanent deformation under traffic. However, it has been proposed that if the S-value from the Hveem stabilometer is at least 35 in the asphalt layer or the Marshall stability is greater than 1800 lbs excessive permanent deformation in the asphalt layer will not be produced by traffic.

Current mix design methods do not always prevent rutting. To evaluate the effect of rutting on the mix, especially for hot areas or where traffic loading is excessive, it is recommended that a creep test (static or repeated) be employed. Such tests will help to select the best asphalt mixture to reduce rutting; this cannot be evaluated otherwise. An improved approach is also needed for design of asphalt mixtures. Such an approach would require mixtures to be selected to meet the specific conditions for which they will be used. In particular, the use of creep modulus at a specified temperature to evaluate the relative differences between mixes is suggested (see Table 5.1 for suggested guidelines).

5.2 Pavement Design

Several methods have been used for pavement layer designs. Some of these methods are empirical and some are fundamental where both fatigue and rutting are evaluated. Such methods offer a balanced design where fatigue and rutting life are utilized efficiently. Methods, such as limiting strain or stress criteria, are often used for pavement design. The basic assumption is that if the maximum

Table 5.1. Mix design criteria for creep modulus (after Ref. 57)

Reference	Limiting Mix Stiffness
Viljoen & Meadows (1981)	12,000 psi @ t = 100 mi, σ = 30 psi
Knonfuss et al. (1984)	7500-10,000 psi @ t = 60 min, σ = 15 psi
Finn et al. (1983)	20,000 psi @ t = 60 min, σ = 30 psi

compressive vertical strain or stress at the surface of the subgrade is less than a critical value, then excessive rutting will not occur for specified numbers of load applications to terminal serviceability of the pavement. Though this method is used, it only predicts rutting in subgrade and excludes pavement rutting. Therefore, it protects the subgrade material from rutting, but not the other pavement layers (e.g. asphalt surface and granular layers).

Cumulative rutting also can be calculated by using the layer strain concept which was used by various investigators. As was discussed before, the permanent strain in the sublayers can be calculated by relating the calculated stress or strain at the center of sublayer to laboratory results. Then, by summing the permanent strains, the total rut will be calculated.

The Shell method of predicting rutting can be considered a special case of layer strain approach. It requires an unconfined uniaxial creep test, which is simpler than triaxial test. The use of the layer strain and Shell method can be of great benefit when used in conjunction with limiting strain criteria.

Since pavement materials responses are time-dependent due to the fact that they have a viscous as well as an elastic component, a viscoelastic approach offers many advantages over elastic theory for the design or analysis of pavements. To predict or estimate the manner in which deformation accumulates, the environment, loads, and materials characteristics must be described in suitable form. These are then incorporated in a linear viscoelastic model or layer system such as VESYS.

In summary, several methods are available for the evaluation and prediction of pavement deformation. They offer the possibility of coping with different environmental conditions, material types, and loading conditions. They should be used together with fatigue evaluation methods for better pavement design.

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APPENDIX A

SHELL METHOD OF PREDICTING DEFORMATION

OUTLINE

1. Carry out a creep test on a small specimen of asphalt bound material (preferably a core) @ 40°C and 100 kPa - monitor δ with time.

2. Calculate strain on a log time scale (ϵ_t) and S_{mix}

$$S_{mix} = \frac{\sigma_o}{\epsilon_t} \quad (\sigma_o = 100 \text{ kPa})$$

3. Determine S_{bit} at the same values of t used in step 2, using Van der Poel's nomograph.

4. Plot S_{mix} v S_{bit} - see Fig. 1.

5. Determine the asphalt viscosity (N_s/m^2) at the mean annual air temperature (MAAT) for the asphalt layer.

6. Calculate the viscous component of asphalt stiffness,'

$$S_{bit,visc} = \frac{3\eta}{N.t_w}$$

where N is the total number of applications of loads of average duration t_w.

7. Input $S_{bit,visc}$ to the S_{mix} v S_{bit} plot (Fig. 1) and read off S_{mix}. (This S_{mix} corresponds to an ϵ_t that is anticipated in situ.)

8. Calculate the in-service deformation:

$$\delta H = C_M \times hx \frac{\sigma av}{S_{mix}}$$

where C_M is a correction factor (Table 1) and σ_{av} is the average stress in the asphalt layer (vertical).

9. Estimate the deformation in the other components of the structure and add to the above to give rut depth.

10. The procedure is summarized in Fig. 4.

Notes

a) This procedure is a modification of that presented in the Shell Design Manual.

b) The procedure relies on a knowledge of penetration and softening point for the asphalt--if these aren't known they can be estimated (Fig. 3) from viscosity data.

c) Aged properties of the asphalt should be used.

d) The temperature adopted requires careful selection.

Example

- **Layer Properties**

Asphalt layer: $E_1 = 11000$ $h_1 = 240$ mm

Gran layer: $E_2 = 125$ MPa, $h_2 = 240$ mm

Subgrade: $E_3 = 50$ MPa

- **Other Data**

Initial penetration of asphalt = 50

Design is for 20 msa

Design speed is 50 kph

Mean Annual Asphalt Temp = 14°C

The S_{mix} v S_{bit} plot is Fig. 1

- **Solution**

Estimated Aged Penetration (P_r) = .65 x 50 = 32.5

Estimated Aged Softening Point (SP_r) = 98.4 - 26.4 log P_r = 58.5°C

Estimated PI_r = (20-500A)/(1+50A)

where A = (log 32.5 - log 800)/(25 - 58.5)

$\therefore PI_r = -.25$

From Fig. 2, inputting PI, SP_r-T (58.5-14)

$\eta = 60 \times 10^6$ Ns/m^2

$$\therefore S_{bit,visc} = \frac{3 \times 60 \times 10^6}{20 \times 10^6 \times 0.02\ t_w} = 450\ N/m^2$$

$$\left(t_w \sim \frac{1}{v} = \frac{1}{50} = 0.02\ secs \right)$$

From Fig. 1: $S_{mix} = 12.5 \times 10^6$ N/m^2

From a Boussinesq analysis, $\sigma_{av} = 300$ kPa

For Asphalt Concrete, taking $C_M = 1.2$

$$\delta H = 1.2 \times 240 \times \frac{300 \times 10^3}{12.5 \times 10^6} \simeq \underline{6.9 \text{ mm}}$$

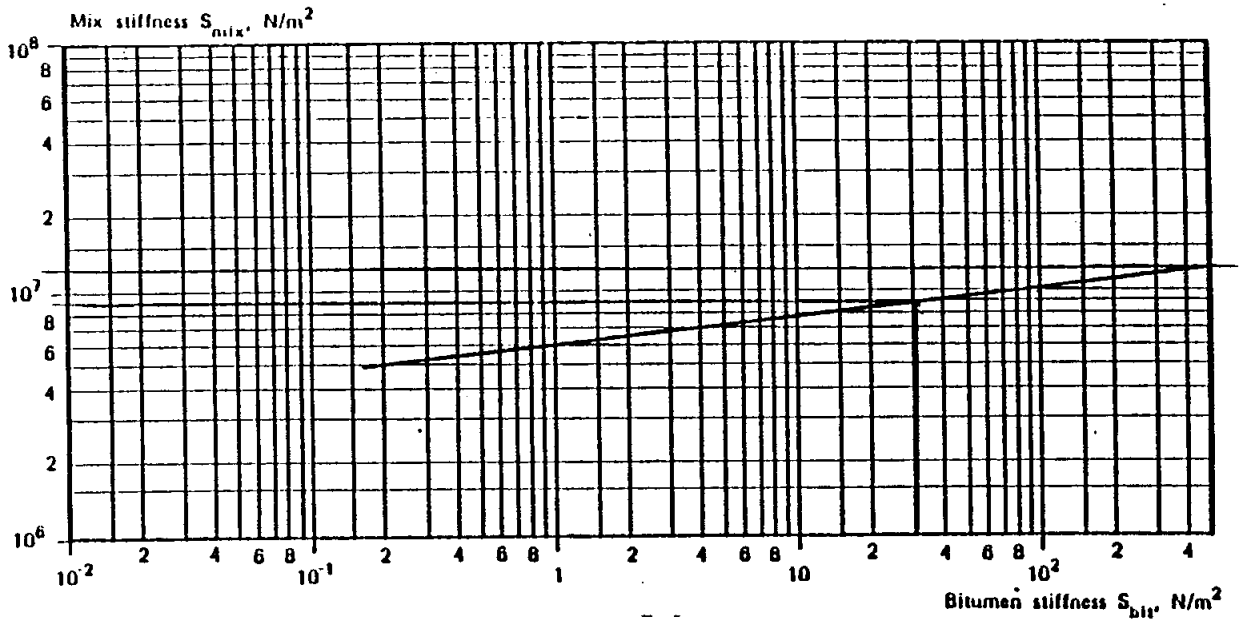

Figure 1. Hypothetical creep plot for HRA roadbase.

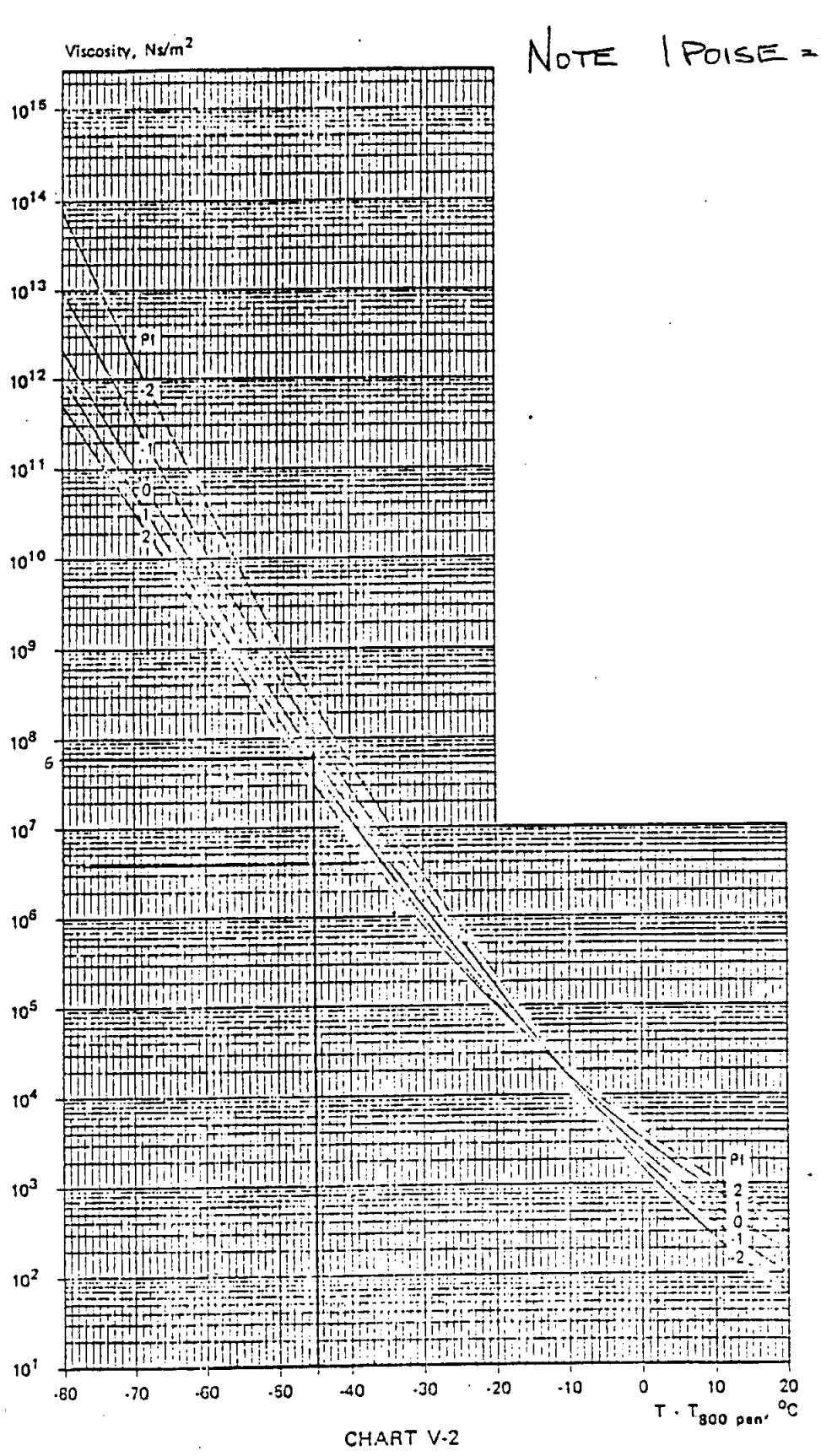

Figure 2. Viscosity as a function of the temperature difference $T-T_{800\ pen}$

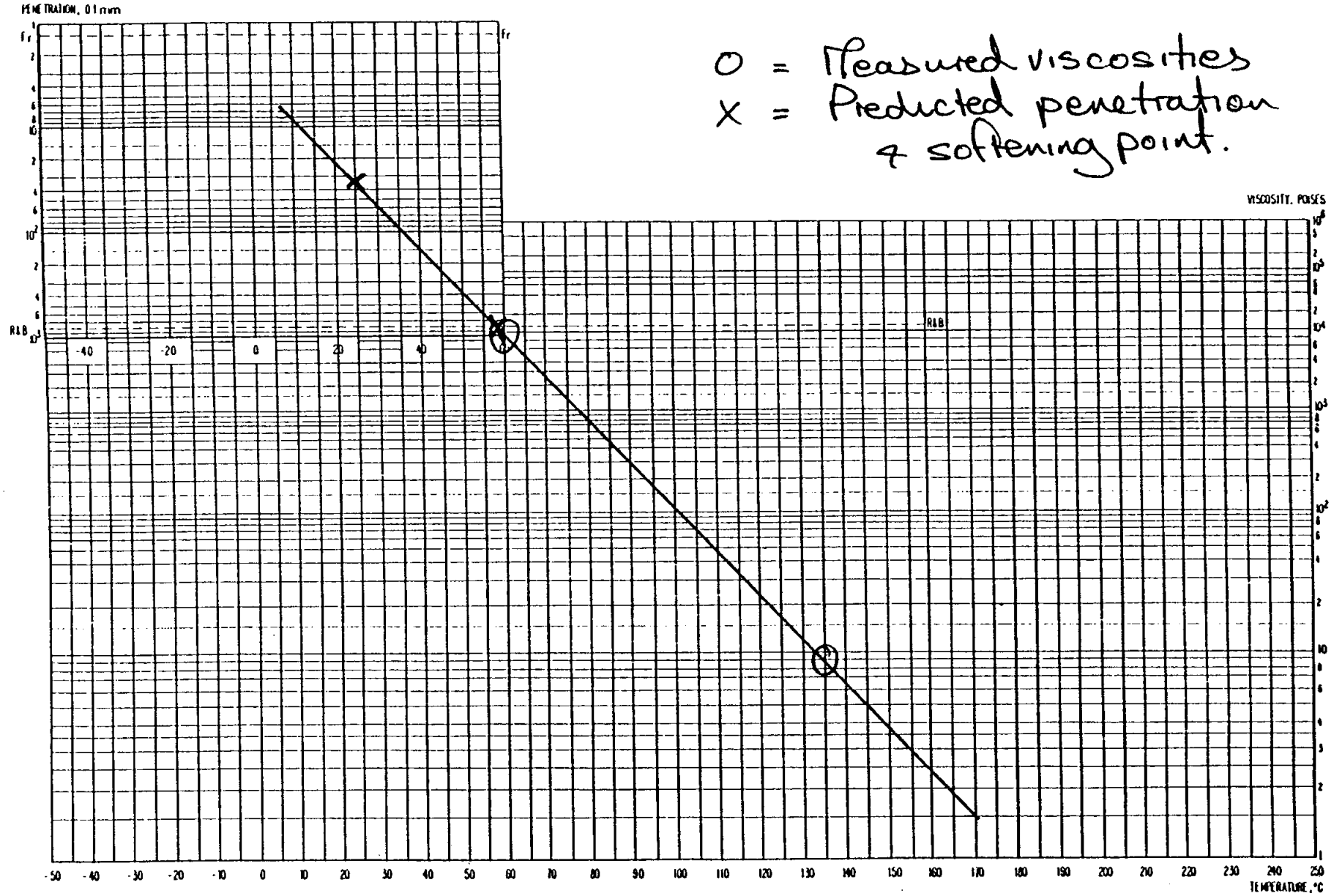

Figure 3. Bitumen test chart.

Table 1. Typical values of C_{m-i}, the correction factor for dynamic effects, for various mix types.

Mix type		C_{m-i}
Open	Sand sheet and lean sand mixes Lean open asphaltic concrete	1.6-2.0
	Lean bitumen macadam	1.5-1.8
	Asphaltic concrete Gravel sand asphalt Dense bitumen macadam	1.2-1.6
Dense	Mastic types Gußasphalt Hot rolled asphalt	1.0-1.3

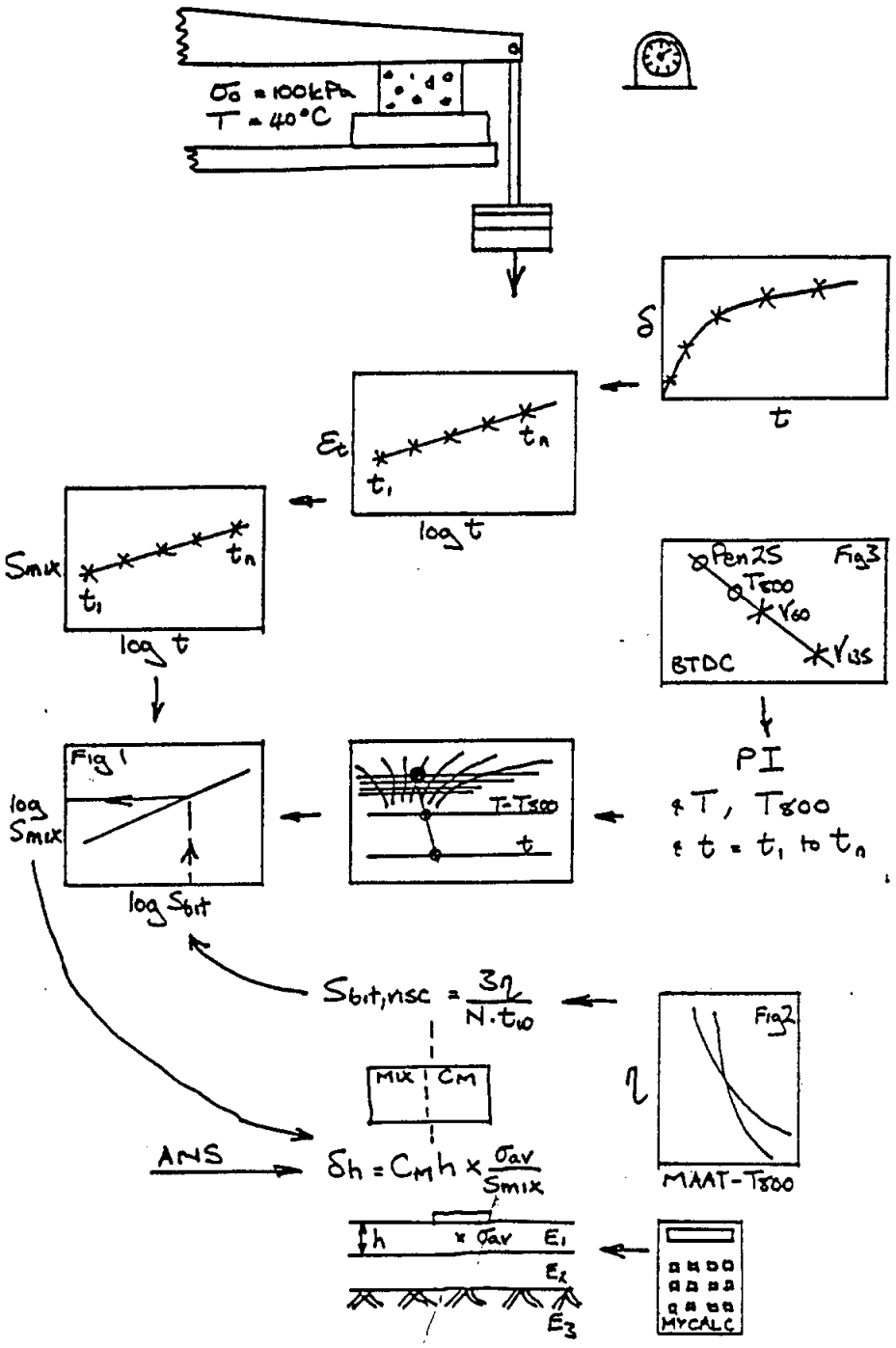

Figure 4. Summary of creep prediction.