OVERVIEW OF FLEXIBLE PAVEMENT DESIGN

by

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Early Road Building

History tells us that road building dates back to about 3500 B.C. which was soon after the discovery of the wheel. The Romans are usually considered as the first "scientific road builders". They began construction of the "Appian Way" in 312 B.C., this roadway is still in use and is a major tourist attraction. The invention of the automobile at about the beginning of the twentieth century (1900 A.D.) marks what is usually considered as the beginning of paved highways as they are known today. John MacAdam (1736-1836) is credited with what is known as "macadam construction". The "macadam construction" evolved into the following basic types:

(1) Traffic - bound macadam
(2) Water - bound macadam
(3) Bituminous - bound macadam
(4) Cement - bound macadam

The "macadam construction" was still moderately popular in the 1940's according to a report by the Bureau of Public Roads. The water-bound macadam and the bituminous-bound macadam were the most predominant of the macadam types in usage early flexible roadway construction in the United States. It appears likely that the water-bound macadam was the forerunner of flexible bases as they are used today. The bituminous bound macadam was also referred to as a penetration macadam. The macadam construction originally involved the use of a aggregate which was predominately one size or gradation. As the bituminous-bound macadam construction evolved it became a multi-layer procedure with the upper layers being smaller aggregate. It appears reasonable to think that surface treatments, seal coats, open graded friction courses and asphaltic concrete pavement may have all evolved from the bituminous bound macadam construction procedure.

ROAD TESTS AND FLEXIBLE PAVEMENTS

Road tests are usually performed to determine the effects of loads and repetitions of loads on various types of pavements. Over the years there have been several road tests that relate to flexible pavement, they are:

(1) Bates Road Test
(2) WASHO Road Test
(3) AASHTO Road Test
(4) Individual States
(5) Corps of Engineers

Probably the best known of these and possibly the most significant was the American Association of State Highway Officials (AASHO) Road Test in Ottawa, Illinois in 1958-1961.
DEFINITION OF PAVEMENT TYPES

The topic of this paper is "Overview of Flexible Pavement Design" but it appears desirable to define several other pavement types along with the flexible pavement. The various pavement types and their definition are:

(1) **Flexible Pavement**: The flexible pavement has been classically defined as a pavement that has an asphaltic concrete surface. Another well used flexible pavement definition is those pavements that are not made of Portland cement concrete. The true flexible pavement is one which consists of one or more unbound or unstabilized base courses resting on a natural subgrade and surfaced with an asphaltic material. In the flexible pavement the unbound base courses transmit the load to the natural subgrade by aggregate interlock or the contact between aggregates.

(2) **Semi-Rigid Pavement**: The semi-rigid pavement has the asphaltic surfacing but may have one or more base or subbase layers which are bound or cemented with material such as asphaltic or Portland Cement. The bound layers are assumed to have the ability to withstand tensile stress and/or tensile strains. These layers transmit load by slab action to the underlying layers or subgrade.

(3) **Rigid Pavement**: The classical definition of rigid pavement is a pavement that is bound by the use of Portland Cement. The rigid pavement exhibits a slab like distribution of load stresses to the subbase or natural subgrade.

(4) **Composite Pavement**: The composite pavement is a rigid pavement which has been overlaid with asphaltic concrete. Its behavior in distribution of the load stresses is essentially the same as the rigid pavement.

PAVEMENT DISTRESS TYPES

Generally distress in pavements can be divided into two categories, structural distress and functional distress.

Structural distress or load carrying capacity sometimes is referred to as the engineers distress. In the early stages of structural distress the effects may not be serious enough to affect the functional aspects of a pavement. Such things as minor cracking, excessive deflection.

Functional distress more nearly relates to the highway users perception of how the highway is serving their needs. A loss in ride comfort would likely be looked upon by the user as a functional distress or failure. Safety related items such as the skid resistance of the pavement would be considered as a function
skid resistance of the pavement would be considered as a function of distress if the skid resistance was causing a safety problem.

**SERVICEABILITY CONCEPT**

One of the major achievements of the AASHO Road Test was the development of the serviceability concept. The serviceability of a pavement is defined as the ability to serve high-speed, high-volume automobile and truck traffic. The rating scale which is known as the "Present Serviceability Index (PSI)" runs from 0 to 5.0. Quantitative description of scale value versus pavement performance is as follows:

5.0 - 4.0 Very Good
4.0 - 3.0 Good
3.0 - 2.0 Fair
2.0 - 1.0 Poor
1.0 - 0.0 Very Poor

The Present Serviceability Index concept is based on being able to correlate user opinion to some measure of pavement roughness.

**Present Serviceability Rating (PSR)** is the "rating" value given to a pavement by a panel of raters such as the group used at the AASHO Road Test. The panel of raters should reflect the opinion of a pavements serviceability in terms of the user public. Since it is not possible for "the panel" to go to all projects it becomes necessary to adopt some electro-mechanical means of measuring pavement roughness or smoothness. There are several definitions which are important with respect to pavements and their performance or serviceability. These definitions as defined by AASHTO are as follows:

Serviceability - the ability at time of observation of a pavement to serve high-speed high volume automobile and truck traffic.

Present Serviceability Rating (PSR) - the mean value of the independent subjective ratings by members of a special Panel for the AASHO Road Test as to the serviceability of a section of highway.

Pavement Serviceability Index (PSI) - a number derived by formula for estimating the serviceability rating from measurements of certain physical features of the pavement.

Pavement Performance - the trend of serviceability with load applications.
There are a number of devices which are capable of measuring road roughness. Some of these devices are:

1. U.S. Bureau of Public Roads roughometer (BPR)
2. CHLOE profilometer
3. Rolling straightedge
4. Surface dynamics profilometer
5. Portland Cement Association (PCA) road meter
6. Mays Road Meter
7. Precision leveling
8. SIOMETER (Walker)

In order for these devices to be able to measure Pavement Serviceability Index (PSR) it is necessary to calibrate them with a group of pavements which have been "panel" rated to determine their Present Serviceability Rating (PSR).

Measurements of pavement roughness on the various pavement test sections of the AASHO Road Test were made with the BPR roughometer and compared to the measurements made with the CHLOE profilometer which was developed at the Road Test.

In February of 1967, during the course of Research Project 73, the Texas State Department of Highways and Public Transportation (TSDHPT) then named Texas Highway Department (THD), took delivery of a new profilometer. This profilometer was called the Surface Dynamics (SD) Profilometer. Also in connection with Project 73 a panel rating was conducted on a group of pavements in and around the Austin, Texas area. Subsequently the new SD profilometer was used to profile the sections which previously been rated by the panel. Following these two steps, equations were developed which correlated the SD profilometer to the panel rating thus the SDHPT had a device available which could rapidly measure profile information which could then be reduced to a Pavement Serviceability Index (PSI) value.

In 1967 the Mays Ride Meter was designed by Ivan K. Mays and is fabricated and sold by the Rainhart Company. The Mays Road Meter has become the SDHPT's principal pavement roughness inventory tool. Calibration roadway sections are maintained in and around Austin, Texas. Periodically profile of each section is determined by use of the SD Profilometer. Subsequently these same sections are profiled by the Mays Road Meters which results in a calibration of the Mays Road Meter.

In January, 1982 SDHPT purchased a new profilometer which is designated as the 690D Surface Dynamics Profilometer. The acquisition of the new profilometer and its calibration are a part of Research Project 251. As a part of Project 251 a new users panel was formed and sections of roadway were rated so that the new profilometer could be calibrated. The new raters panel rode in automobiles which reflect current production models. This should allow SDHPT to calibrate all profile measuring
equipment to the current user opinions on roughness or smoothness of pavements.

ELEMENTS OF THICKNESS DESIGN

At mid-twentieth century when the author was in engineering college there were three elements of pavement thickness design which were in general usage. These elements are:

1. Magnitude and method of application of wheel loads
2. Function of pavement and base in transmitting the load to the subgrade
3. Measure of subgrade support

Terminology or pavement jargon change with time and new pavement experts enter the scene, but these three basic elements of pavement thickness design appear to still be applicable. If the pavement is to function or perform satisfactorily the wheel loads and repetitions thereof must be accommodated. Also the pavement surface base and subbase layers must be of sufficient thickness and quality to transmit the loads into the subgrade without causing either a catastrophic failure due to one large wheel load or the accumulated failure due to repeated loads of lesser magnitude.

In subsequent sections of this report these three elements of thickness design will be discussed. An understanding of the loads applied to a pavement, the resulting stresses and an understanding of flexible pavement design methodologies will allow the designer to select a flexible pavement design which will provide a pavement that has satisfactory functional and structural characteristics.

DESIGN WHEEL LOADS

Pavement structure design must consider two wheel load concepts, the static wheel load and repetitions of wheel load. The findings of the various road tests indicated that the effects of wheel loads are accumulative many small wheel loads can cause the same damage that fewer repetitions of a larger wheel load.

The need to consider the static wheel load in flexible pavement is based on the fact that pavements for city streets, farm roads and other light duty pavements will usually have a very small truck traffic component in their traffic mix, but some of these trucks may have very large wheel loads. It is possible for some light duty pavements to suffer extensive pavement damage due to the passage of only one very heavily loaded truck. Its this one very large wheel load that must be accounted for by use of a static wheel load pavement design concept. This will be further discussed under design methodologies.
Another of the very important results of the AASHTO Road Test was the development of a procedure for converting mixed traffic equivalent 18-kip single-axle loads. The use of 18-kip single-axle equivalents as a traffic variable has been widely accepted in both flexible and rigid pavement design. Basically the procedure allows the conversion traffic with various axle loads to an equivalent 18-kip single-axle load. It was possible to determine the equivalency factor for various axle loads based on the relative damage to the AASHO Road Test sections. The Road Test had test loops that contained various pavement designs. For each loop the trucks were all loaded to a constant axle-load. Also some of the loops contained replicate pavement sections of other loops. With this information it was possible to determine the equivalency factors based on damage to the pavement.

The equivalent 18-kip single-axle load concept is used by a majority of the states in their pavement design processes. Additional discussion of 18-kip single-axle equivalents will be made in the section on design methodologies.

**FUNCTION OF PAVEMENT (SURFACE) AND BASE IN TRANSMITTING THE LOAD TO THE SUBGRADE**

Figure 1, Simple Flexible Pavement Section, and Figure 2, Complex Flexible Pavement Section, are an indication of the variation in flexible pavement designs. In the simple flexible pavement section the surfacing would likely be a surface treatment or a thin asphaltic concrete. The flexible base in this type of construction would typically be unbound. The flexible base would be placed directly on the natural subgrade. The basic function of the surfacing is to act as a wearing course or to protect the base course from the wearing action of the wheel loads. The surfacing also protects the base course from the intrusion of surface moisture which would tend to soften the base and reduce its load carrying or spreading capability. The function of the base course is to transfer the load into the subgrade without causing compressive or shear failures of the subgrade. The base course depends on aggregate interlock to spread the load and thereby reducing its unit pressure to an acceptable level before they are transferred to the subgrade.

Figure 3, Load Distribution In Flexible Pavements, is a somewhat crude concept of how loads were distributed in flexible pavements. This concept seemed to be in vogue in the early 1950's. The concept of spreading the load to the subgrade doesn’t appear to be quite this simple, but it does illustrate the role that the surfacing and base material must play if the load magnitude is to be reduced to a level which will not fail the subgrade in compression. It was and is assumed that the wheel load (P) is distributed over a circular area as follows:

\[
\text{Tire Pressure} = \frac{\text{Wheel Load}}{\text{Contact Area}}
\]

By knowing the tire pressure and design wheel load and by assuming that the contact area was circular the contact area
radius \( (a) \) could be computed. If some assumption or
determination of the load spreading angle \((\theta)\) could be made then
stresses could be calculated at any depth in the pavement
structure. If allowable compressive stresses to the subgrade
were known then the thickness of base material could be
calculated. From this it would appear that base materials with
good load spreading capability would allow a lesser thickness
then those of lesser load spreading ability. This good load
spreading capability is a function of how well the base material
is graded, how hard or abrasion resistant the aggregate is and
how well the material retains these quantities when exposed to
high moisture levels.

The pavement structure diagrammed in Figure 2, Complex Flexible
Pavement Structure Section, cannot be explained in the simple
terms of the true flexible pavement shown in Figure 1 and
discussed above. The discussion of the pavement structure shown
in Figure 2 will be deferred to the section of this paper which
discusses pavement design methodologies.

**MEASURES OF SUBGRADE SUPPORT**

The measurement of subgrade support is just one facet of the
larger picture which is materials characterization in general.
For determination of subgrade support for flexible pavements the
following is a partial listing of methods:

1. Plate loading
2. Triaxial
3. California Bearing Ratio (CBR)
4. Resilient modulus

The above noted measures of subgrade support for flexible
pavements are only a sample of the methods available. In Texas
the SDHPT uses two basic methods of quantifying subgrade support
for flexible pavements, they are:

1. Texas Triaxial (Tex-117-E)
2. Dynaflect stiffness coefficients

If the Texas SDHPT elects to use the flexible pavement design
procedures proposed in the new AASHTO Guide for Design of
Pavements (July 15 1985) then it will be necessary to quantify
the resilient modulus of the subgrade because it is an input to
the AASHTO procedure.

The quantification of subgrade support is one of the major
factors in flexible pavement design. The subgrade must support
the pavement structure and the pavement structure transmits the
wheel loads to the subgrade. If the support value of the
subgrade is not evaluated correctly the pavement layers thickness
and strength will most likely be either under designed or over
designed. If the pavement is under designed because the subgrade
support was rated too high the end result will be a failure of
both the pavement and the subgrade. On the opposite side of the
picture, an under evaluation of the subgrade will lead to pavement thickness greater than needed which will be uneconomical.

**STRESSES, STRAINS AND DEFLECTIONS IN FLEXIBLE PAVEMENTS**

Layered elastic theory or a multilayered elastic system is a good analysis procedure which will allow an understanding of the stresses, strains, deflections (deformations) which occur in a multilayered pavement structure such as was pictured in Figure 2, Complex Pavement Structure Section.

Figure 4, Generalized Multilayered Elastic System, illustrates the general concept of a multilayered elastic system. For each pavement layer the thickness, the elastic modulus and Poisson’s Ratio must be input to the calculation procedure. For the subgrade layer the thickness is omitted because the procedure assume that it is infinite in thickness. Linear elastic theory has been available since 1885 when Boussinesq presented his one layer elastic concept. In the 1940’s Burmister expanded the theory to a two layer system. It took the advent of the high speed electronic computer to make layered elastic theory a practical design and analysis tool. The computer made it possible to economically solve for stresses, strains and deformations in a multilayered elastic system.

Most computer programs for multilayered elastic systems allow multiple loads to be applied to the system. Usually the loads may be input as a "load and radius" combination or a "unit stress (tire pressure) and radius" combination. Figure 5, Coordinate System for Multilayered Elastic Systems is one of the means by which some programs define the location of the loads and the points at which stress, strain or deflections are to be made.

**DEFLECTIONS IN FLEXIBLE PAVEMENT STRUCTURES**

Figure 6, Typical Flexible Pavement Deflection Basin, depicts the deflection basin or bowl that is expected to occur in a linear elastic flexible pavement structure as a result of a single applied load. As load is applied to a multilayered elastic pavement system each layer is compressed to a degree depending on its thickness, elastic modulus of the material and Poisson’s Ratio. If a summation of vertical compressive strains for each layer was made at successive vertical planes normal to the "X" axis the deflective pavement surface shows in Figure 6 could be computed.

The deflections basin under a given load or loads can also be measured directly by general devices, three of which are:

1. Benkelman Beam
2. Dynaflect
3. Falling Weigh Deflectometer
The Dynaflect is a very popular device for measuring deflections in existing flexible pavements. Figure 7, Dynaflect Loading and Measurement Layout, is a schematic of the loading and measurement procedure.

When measured deflections are available they can be used to characterize the elastic layer properties of existing pavement structures. The procedure requires that elastic moduli values be assumed for each of the pavement layers and then multilayered theory (computer program) is used to calculate a deflection basin. The calculated basis is compared with the measured deflection basin and the process is iterated until there is good agreement between measured and calculated basins.

When deflections are taken on an existing pavement at some equal or known distance along the roadway the deflections themselves as well as computed moduli of the layers can be used to generate a profile that characterizes either pavement structure condition or subgrade condition along the project.

**FLEXIBLE PAVEMENT DESIGN METHODS**

There appear to be about as many flexible pavement methods as there are self-professed flexible pavement design experts. Some of the more widely recognized flexible pavement design methodologies are:

1. AASHTO Flexible-Pavement Design Procedure
2. Multilayer Elastic Analysis
3. The Asphalt Institute Design Procedure
4. Texas Flexible Pavement Design System (FPS)
5. Texas Triaxial Design (Tex-117-E).

The above is just a small sampling of the known methods of flexible pavement design.

The AASHTO Flexible Pavement Design Procedure was a development of the AASHO Road Test. As noted earlier, the AASHO road Test took place in 1958-1961. During the time since the end of the Road Test and the present time the AASHTO procedures for pavement design have been labeled as "interim". Webster's dictionary defines the adjective "interim" as temporary. This temporary procedure has been around for some 24-25 years. Over the last several years the AASHTO Joint Task Force on Pavements has been working with a consultant group under NCHRP Project 20-7/24 to revise the "interim" guide. One of the giant steps in this revision will be the removal of the word "interim". It is expected that the "AASHTO Guide for Design of Pavement Structures" will be published sometime in 1986.
Texas has not used the AASHTO Flexible Pavement Procedures, but has a related procedure known as the Flexible Pavement Design System (FPS) which will be discussed later.

The Multilayer elastic analysis procedure was discussed earlier in the report. The procedure is based on the theory of elasticity. The concept dates back many years, but the recent usage and acceptance of the procedure is made possible by the use of high speed electronic computers. For elastic theory to apply the material of each layer must conform to the following:

1. Material properties of each layer are homogeneous.
2. Each layer except for the bottom layer is of a finite thickness and all are infinite in the lateral direction.
3. Each layer is isotropic.
4. Full friction is developed between layers at each interface.
5. Surface shearing forces are not present at the surface.
6. Stress solutions are characterized by two material properties for each layer, the Poisson’s ratio and the elastic modulus.

Some of the current day computer programs allow a varying friction at the interfaces and also allow the input of shear forces to the face of the pavement. One of the major difficulties with the use of multilayer elastic analysis centers about the assumption that typical pavement materials act linearly due to the stress applications which large wheel loads apply. Tests indicate that cohesive soils are non-linear in their reaction to load. The standard triaxial test at various confining pressures verifies the non-linearity of the cohesive soils. Multilayer elastic systems can be used for design and analysis, but basically the design is an iterative procedure, a structure is assumed (input) and calculations of stress and strain are made and compared to limiting values. When the assumed structure stresses/strains meet the limiting criteria it is assumed that that particular strategy is satisfactory.

The Asphalt Institute published their new thickness procedure in 1981. This procedure is titled "Thickness Design - Asphalt Pavements For Highways and Streets", Manual Series No. 1 (MS-1), September 1981. The procedure is based on the use of elastic theory. The Asphalt Institute procedure can be done by use of the charts and tables published in MS-1 or by the use of the DAMA computer program. The manual presents a structural thickness design procedure for pavements utilizing asphalt cement or emulsified asphalt in all, or in part of the pavement structure.
Guidelines are offered for defining subgrade properties, materials properties, and traffic values. Also there are procedures for stage construction design and economic analysis.

The Texas Flexible Pavement Design System (FPS) is the principal flexible pavement design procedure used in the Texas SDHPT at this time. The FPS procedure is sponsored by the Highway Design Division of the Texas SDHPT. The FPS procedure will be presented in more detail in a later section of this report.

The Texas Triaxial Design procedure is defined in the File D-9 Manual of Testing Procedures and is Designated as Test Method-Tex-117-E, Triaxial Compression Tests For Disturbed Soils and Base Materials. Test Method Tex-117-E may be divided into two very general areas, a classification procedure for base and subgrade materials and a base thickness design procedure. The Texas Triaxial Design procedure is sponsored by the Materials and Test Division (File D-9) of the Texas SDHPT. As a design tool, this procedure is most useful for thickness design of flexible pavements which utilize the thin surfacing and unstabilized base concept. The Texas Triaxial Design procedure uses the design wheel load (static load) as its basic traffic data input. Because of this feature the procedure is most applicable for those projects such as farm-to-market roads or light urban streets where the number of 18-KSA equivalents is low, but a few excessively heavy loads exist in the traffic mix.

THE TEXAS FLEXIBLE PAVEMENT DESIGN SYSTEM (FPS)

As previously noted, the Highway Design Division, of the Texas SDHPT sponsors the Texas Flexible Pavement Design System (FPS). The official User’s Manual for FPS is titled as follows:


FPS consists of three computer programs:

1. FPS-11 (Principal program)
2. Stiffness Coefficient Program
3. Profile Analysis Program

The purpose of the FPS system is to provide, from available materials, a pavement that can be maintained above a specified level of serviceability, over a specified period of time, with a specified reliability, at a minimum overall total cost.

The FPS-11 Program has the capability of designing a new flexible pavement (or rehabilitation of an existing pavement structure) or an Asphalt Concrete Pavement overlay for an existing flexible pavement.
The FPS system objective of providing a pavement design "at a minimum overall total cost" is the backbone of the program. The optimization procedure is an optimization of total cost for a given analysis period. Items considered in the total cost optimization are:

1. Initial construction cost,
2. Overlay construction,
3. User cost (delay),
4. Routine maintenance cost, and
5. Salvage value.

Sixty-six inputs to the system are provided by the FPS-11 program. These inputs are in ten categories listed below. The parenthetical numbers indicate the inputs on each card or category.

<table>
<thead>
<tr>
<th>Card No.</th>
<th>Category</th>
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<tbody>
<tr>
<td>1</td>
<td>Project Identification (8)</td>
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<td>2</td>
<td>Project Comments (1)</td>
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<td>3</td>
<td>Basic Design Criteria (6)</td>
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<td>4</td>
<td>Program Controls and Constraints (5)</td>
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<tr>
<td>5</td>
<td>Traffic Data (8)</td>
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<td>6</td>
<td>Environmental and Subgrade (5)</td>
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<td>7</td>
<td>Construction and Maintenance Data (9)</td>
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<tr>
<td>8</td>
<td>Detour Design for Overlays (7)</td>
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<tr>
<td>9</td>
<td>Existing Pavement and Proposed ACP (8)</td>
</tr>
<tr>
<td>10</td>
<td>Paving Materials Information (9)</td>
</tr>
</tbody>
</table>

A very important feature in training a flexible-pavement designer in the use of the FPS system is the understanding or recognition of the major inputs to FPS. Stated in another way, What are the most sensitive inputs? If pavement design performance is the major objective, then the input items contained in the FPS performance equation should be examined. The performance equation input items are:

1. Serviceability Index
   a. Initial serviceability
b. Serviceability after ACP overlay

c. Terminal serviceability

2. Materials Stiffness Coefficients
   (or Surface Curvature Index)

3. Traffic (18-KSA applications)

4. Temperature Constant

5. Swelling Clay Properties

**FPS Design Process**

The FPS design process can be divided into the following basic steps:

1. Develop Input Data
   
   (a) Measure Field Data
   (b) Select Materials Properties
   (c) Secure Traffic Data

2. Compute with the FPS Program

3. Select best pavement design strategy.

Field data for use in FPS consists of Dynafl ect deflections of existing pavements. From the Dynafl ect deflections stiffness coefficients for the composite pavement structure and the subgrade can be calculated. In the "new" pavement design mode, the strength of the subgrade and the proposed pavement layers are input in terms of stiffness coefficients. The FPS program uses the stiffness coefficients and layer thicknesses to determine the anticipated Dynafl ect deflection basin for the design strategy in question. The shape of this basin is used by the program to compute a Surface Curvature Index (SCI) value. The SCI value represents the bending strength for the design in question. The SCI value is one of the prime inputs to the FPS performance equation. When the FPS program is to be operated in the ACP Overlay mode, the input to FPS which represents the strength of the existing pavement structure is the measured SCI value and a corresponding standard deviation of SCI.

The stiffness coefficient computer program is used to process the Dynafl ect data and compute properties such as the composite pavement stiffness coefficient (AP2), subgrade stiffness coefficient (AS2), Dynafl ect basin deflections and Surface Curvature Index (SCI) which is part of the "select materials properties" phase of the data development phase.

Another very important part of the data development process is the securing of traffic projections for input to FPS. Traffic
data is secured from the Transportation Planning Division, D-10. If possible the request should be made to D-10 in writing as far in advance of the need as possible. D-10 should be advised of any unusual circumstances expected on the project within the design period such as new developments, proposed highway reroutings, materials hauls, any other items which might affect traffic projections. When requesting traffic for use in FPS it should be based on a 20 year projection period. If the design analysis period is to be shorter or longer than 20 years the FPS program will make the necessary traffic adjustments. The beginning of the 20 year projection period should be based on the pavement designers' best judgement as to when the project will be completed and opened to traffic.

Computing with FPS consists of coding the FPS data sheets, keying in the data and submitting the job for execution. Appendix A, Coding of Example Design Problem, is a typical example problem for the new pavement design mode. After coding the input data the designer must either key the inputs to "ROSCOE" or have this done by automation personnel, subsequently the coded data is submitted for execution.

Appendix B, Computer Output for Example Design Problem, is the end result of the FPS design process, all that remains is the selection of a design strategy.

When the FPS printout is returned to the designer, their first step should be a careful proofreading of the first two pages. The first two pages of output are an echo print of the input data. This check must be made to assure that the intent of the designer has been achieved.

Reviewing the FPS output will reveal that FPS will use the building block principal to design the pavement. FPS will increment through the first layer plus subgrade in an attempt to find designs meeting design criteria. Next FPS will increment through the first two layers plus subgrade looking for designs. This step process will follow until all layers are included in the design process. The designer will note that FPS prints out the optimum (lowest total cost) design in each group. Finally FPS will provide a summary listing of designs by layer code in order of least total cost.

The design selection process will involve reviewing the FPS output and selecting the design strategy which best meets the designers criteria. This final selection may not always be the least cost design. The designer is encouraged to document his reasons for selecting a given strategy.

The use of the ACP Overlay feature of FPS-11 differs from the new pavement mode in one major respect. In the new pavement mode the designer submits information on the cost, stiffness coefficient, and allowable thickness range for each material layer proposed for the design. With the ACP Overlay procedure there is an existing pavement structure in place which is to receive the
overlay. The strength of the existing structure is input to FPS as the average Surface Curvature Index (SCI) value for the design section and the standard deviation of the SCI. All other coding is essentially the same for both design modes.

PAVEMENT DESIGN ASSISTANCE

The Pavement Design Section of the Highway Design Division (File D-8) offers both pavement design training and consultative assistance in the area of pavement design and performance.

SUMMARY

It is hoped that the very brief look at flexible pavement design will give the pavement designer and the potential pavement designers a brief idea on what a flexible pavement consists of and the design procedures which can be used to successfully design a flexible pavement. To fully appreciate the area of pavement design a person needs to be aware that the Texas SDHPT spends approximately fifty percent of its construction funds for the items which are typically noted as pavement items. Since such a large percentage of our funds are spent on pavement items it is apparent that the Department should be making a design effort which is in keeping with the funds spent if the taxpayer is expected to get his "money's worth".

To get full worth for the money spent it is obvious that pavement designs must be optimized against performance. All will agree with the optimization concept, but it is seldom achieved or practiced. The timeliness of a pavement design has a lot to do with optimization. If the proper or optimum pavement design is not available to the engineer responsible for programs when program funds are set for a project it appears that the likelihood of programming the proper amount of funds will not occur. Most likely there will be an inadequate amount of funding available to the project and the actual design at some future date will be short of optimum. An overprogramming of funds on the other hand will give a satisfactory pavement design, but the over usage of funds will be reflected in other projects.

It must be concluded that pavement design is a very important area of highway design. With the importance of pavement design established it becomes evident that both administrative and design personnel must be willing to increase material and personnel allocations to achieve the overall objective of better performing highways at lesser unit costs.
FIGURE 1
SIMPLE FLEXIBLE PAVEMENT STRUCTURE SECTION

FIGURE 2
COMPLEX FLEXIBLE PAVEMENT STRUCTURE SECTION
FIGURE 3
LOAD DISTRIBUTION
IN FLEXIBLE PAVEMENTS
FIGURE 4

GENERALIZED MULTILAYERED ELASTIC SYSTEM

\[ h = \text{LAYER THICKNESS} \]
\[ E = \text{ELASTIC MODULUS OF MATERIAL} \]
\[ u = \text{POISSON'S RATIO} \]
\[ A_i, \text{etc} = \text{CALCULATION LOCATIONS} \]
FIGURE 5

Coordinate System For
Multilayer Elastic Systems
FIGURE 6
TYPICAL FLEXIBLE PAVEMENT DEFLECTION BASIN
FIGURE 7
Dynaflect Loading and Measurement Layout
APPENDIX A

Coding of Example Design Problem
| 1.0 Card type | 01 12 |
| 1.1 Problem number | X-1 3 4 5 |
| 1.2 District | 48 6 7 |
| 1.3 County | SOFTNMET 8 9 0 1 2 3 4 5 6 7 8 9 20 21 |
| 1.4 Control | 00 8 0 22 23 24 25 |
| 1.5 Section | 07 26 27 |
| 1.6 Highway | BUMPY 1 26 29 30 31 32 33 34 35 36 37 |
| 1.7 Date | 09-13-85 38 39 40 41 42 43 44 45 |
| 1.8 IPE | 46 47 48 49 |
NEW PAVEMENT DESIGN EXAMPLE FOR THE PAP

ER TITLED "OVERVIEW OF FLEXIBLE

PAVEMENT DESIGN" WHICH IS TO BE PRESENT

ED AT THE FIFTY NINTH ANNUAL HIGHWAY

AND TRANSPORTATION SHORT COURSE, OCTOBER

R 23, 1985 AT TEXAS A&M UNIVERSITY,

COLLEGE STATION, TEXAS

PREPARED BY: ROBERT L. MIKULIN, TEX-AN

823-8104
TEXAS HIGHWAY DEPARTMENT  
FLEXIBLE PAVEMENT DESIGN SYSTEM  
FPS - 11  

BASIC DESIGN CRITERIA

3.0 Card type

3.1 Length of analysis period (years)

3.2 Minimum time to first overlay (years)

3.3 Minimum time between overlay (years)

3.4 Minimum serviceability index

3.5 Design confidence level

3.6 Interest rate (%)

PROGRAM CONTROLS AND CONSTRAINTS

4.0 Card type

4.1 Problem type: 1 = new pavt. const., 2 = ACP overlay

4.2 Number of summary output pages (8 designs/page)

4.3 Max. funds available per S.Y. for initial const. ($)

4.4 Maximum total thickness of initial construction (inches)

4.5 Maximum total thickness of all overlays (inches)
TEXAS HIGHWAY DEPARTMENT
FLEXIBLE PAVEMENT DESIGN SYSTEM
FPS - 11

TRAFFIC DATA

5.0 Card type ........................................... 05 12

5.1 ADT at the beginning of the analysis period (veh./day) .......... 16080
5 6 7 8 9 10 11

5.2 ADT at the end of 20 years (veh./day) ................................ 34000
15 16 17 18 19 20 21

5.3 One-direction cumulative 18 KSA at the end of 20 years .......... 264000000
23 24 25 26 27 28 29 30 31

5.4 Avg. approach speed to the overlay zone (mph) ................. 60
34 35

5.5 Avg. speed through overlay zone (overlay direction) (mph) ... 20
39 40

5.6 Avg. speed through overlay zone (non-overlay direction) (mph) .. 60
44 45

5.7 Percent of ADT arriving ea. hr. of construction ................ 60
49 50 51

5.8 Percent trucks in ADT .................................. 20
54 55

ENVIRONMENT AND SUBGRADE

6.0 Card type ........................................... 06 12

6.1 District temperature constant .................................. 28
4 5

6.2 Swelling probability ...................................... 0 0 0 0
9 10 11 12

6.3 Potential vertical rise (inches) ................................ 0 0
13 14 15 16

6.4 Swelling rate constant ..................................... 0 0 0 0
19 20 21 22

6.5 Subgrade stiffness coefficient ................................ 0 2 2
24 25 26 27

A-4
## CONSTRUCTION AND MAINTENANCE DATA

<table>
<thead>
<tr>
<th>Column</th>
<th>Description</th>
<th>Value</th>
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<tr>
<td>7.0</td>
<td>Card type</td>
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<tr>
<td>7.1</td>
<td>Initial serviceability index</td>
<td>4.4</td>
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<tr>
<td>7.2</td>
<td>Serviceability index after overlaying</td>
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</tr>
<tr>
<td>7.3</td>
<td>Minimum overlay thickness (inches)</td>
<td>1.5</td>
</tr>
<tr>
<td>7.4</td>
<td>Overlay construction time (hrs/day)</td>
<td>8</td>
</tr>
<tr>
<td>7.5</td>
<td>Asph. conc. compacted density (tons/C.Y.)</td>
<td>1.80</td>
</tr>
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<td>7.6</td>
<td>Asph. conc. production rate (tons/hr)</td>
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<tr>
<td>7.7</td>
<td>Width of each lane (feet)</td>
<td>12</td>
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<tr>
<td>7.8</td>
<td>First year cost of routine maintenance (dollars/lane - mile)</td>
<td>120.00</td>
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<tr>
<td>7.9</td>
<td>Annual incremental increase in maintenance cost (dollars/lane - mile)</td>
<td>74.00</td>
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### DETOUR DESIGN FOR OVERLAYS

<table>
<thead>
<tr>
<th>8.0 Card type</th>
<th>08 12</th>
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<tbody>
<tr>
<td>8.1 Detour model used during overlaying</td>
<td>3 4</td>
</tr>
<tr>
<td>8.2 Total number of lanes of the facility</td>
<td>4 5 6</td>
</tr>
<tr>
<td>8.3 Number of lanes open in the overlay direction</td>
<td>1 8</td>
</tr>
<tr>
<td>8.4 Number of lanes open in the non-overlay direction</td>
<td>2 0</td>
</tr>
<tr>
<td>8.5 Distance traffic is slowed (overlay direction) (miles)</td>
<td>1 0 12 14</td>
</tr>
<tr>
<td>8.6 Distance traffic is slowed (non-overlay direction) (miles)</td>
<td>1 0 17 18 19</td>
</tr>
<tr>
<td>8.7 Detour distance around the overlay zone (miles)</td>
<td>0 0 22 23 24</td>
</tr>
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</table>
### PAVING MATERIAL INFORMATION

<table>
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<th>Column</th>
<th>Data</th>
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<tr>
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<tr>
<td>10.1</td>
<td>Layer designation number ______________________</td>
</tr>
<tr>
<td>10.2</td>
<td>Letter code of material ______________________</td>
</tr>
<tr>
<td>10.3</td>
<td>Name of material ______________________________</td>
</tr>
<tr>
<td>10.4</td>
<td>In-place cost/comp. - C.Y. ($) ______________</td>
</tr>
<tr>
<td>10.5</td>
<td>Stiffness coefficient ______________________</td>
</tr>
<tr>
<td>10.6</td>
<td>Min. allowable thickness of initial const. (inches)</td>
</tr>
<tr>
<td>10.7</td>
<td>Max. allowable thickness of initial const. (inches)</td>
</tr>
<tr>
<td>10.8</td>
<td>Material's salvage value as % of original cost</td>
</tr>
<tr>
<td>10.9</td>
<td>Check* ________________________________</td>
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<tr>
<td>Card Type</td>
<td>Layer Designation Number</td>
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<td>--------------------------</td>
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## PAVING MATERIAL INFORMATION

### 10.0 Card type

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### 10.1 Layer designation number

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### 10.2 Letter code of material

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### 10.3 Name of material

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### 10.4 In-place cost/comp. - C.Y. ($)  

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<th>10.4</th>
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### 10.5 Stiffness coefficient

<table>
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<tr>
<th>10.5</th>
<th>92</th>
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### 10.6 Min. allowable thickness of initial const. (inches)

<table>
<thead>
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<th>10.6</th>
<th>4 50</th>
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### 10.7 Max. allowable thickness of initial const. (inches)

<table>
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<th>16 00</th>
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### 10.8 Material's salvage value as % of original cost

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### 10.9 Check*

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*Check*
### PAVING MATERIAL INFORMATION

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<th>Card type</th>
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<td>10.2</td>
<td>Letter code of material</td>
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<tr>
<td>10.3</td>
<td>Name of material</td>
<td>FLEXIBLE BASE</td>
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<tr>
<td>10.4</td>
<td>In-place cost/comp. - C.Y. ($)</td>
<td>24.50</td>
</tr>
<tr>
<td>10.5</td>
<td>Stiffness coefficient</td>
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<td>10.6</td>
<td>Min. allowable thickness of initial const. (inches)</td>
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<tr>
<td>10.7</td>
<td>Max. allowable thickness of initial const. (inches)</td>
<td>16.00</td>
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<td>10.8</td>
<td>Material's salvage value as % of original cost</td>
<td>75</td>
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<td>Check*</td>
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</table>
TEXAS HIGHWAY DEPARTMENT
FLEXIBLE PAVEMENT DESIGN SYSTEM
FPS - 11

PAVING MATERIAL INFORMATION

10.0 Card type

10.1 Layer designation number

10.2 Letter code of material

10.3 Name of material

10.4 In-place cost/comp. - C.Y. ($)

10.5 Stiffness coefficient

10.6 Min. allowable thickness of initial const. (inches)

10.7 Max. allowable thickness of initial const. (inches)

10.8 Material's salvage value as % of original cost

10.9 Check*
APPENDIX B

Computer Output for Example Design Problem
NEW PAVEMENT DESIGN EXAMPLE FOR THE PAPER TITLED "OVERVIEW OF FLEXIBLE PAVEMENT DESIGN" WHICH IS TO BE PRESENTED AT THE FIFTY NINTH ANNUAL HIGHWAY AND TRANSPORTATION SHORT COURSE, OCTOBER 23, 1985 AT TEXAS A&M UNIVERSITY, COLLEGE STATION, TEXAS.

PREPARED BY: ROBERT L. MIKULIN TEX-AN 823-8104

BASIC DESIGN CRITERIA

LENGTH OF THE ANALYSIS PERIOD (YEARS) 20.0
MINIMUM TIME TO FIRST OVERLAY (YEARS) 10.0
MINIMUM TIME BETWEEN OVERLAYS (YEARS) 8.0
MINIMUM SERVICEABILITY INDEX P2 3.0
DESIGN CONFIDENCE LEVEL D
INTEREST RATE OR TIME VALUE OF MONEY (PERCENT) 8.0

PROGRAM CONTROLS AND CONSTRAINTS

NUMBER OF SUMMARY OUTPUT PAGES DESIRED ( 8 DESIGNS/PAGE) 3
MAX FUNDS AVAILABLE PER SQ.YD. FOR INITIAL DESIGN (DOLLARS) 40.00
MAXIMUM ALLOWED THICKNESS OF INITIAL CONSTRUCTION (INCHES) 46.0
ACCUMULATED MAX DEPTH OF ALL OVERLAYS (INCHES) (EXCLUDING LEVEL-UP) 4.0

TRAFFIC DATA

ADT AT BEGINNING OF ANALYSIS PERIOD (VEHICLES/DAY) 16080.
ADT AT END OF TWENTY YEARS (VEHICLES/DAY) 34000.
ONE-DIRECTION 20.-YEAR ACCUMULATED NO. OF EQUIVALENT 18-KSA 26400000.
AVERAGE APPROACH SPEED TO THE OVERLAY ZONE(MPH) 60.0
AVERAGE SPEED THROUGH OVERLAY ZONE (OVERLAY DIRECTION) (MPH) 20.0
AVERAGE SPEED THROUGH OVERLAY ZONE (NON-OVERLAY DIRECTION) (MPH) 60.0
PROPORTION OF ADT ARRIVING EACH HOUR OF CONSTRUCTION (PERCENT) 6.0
PERCENT TRUCKS IN ADT 20.0

ENVIRONMENT AND SUBGRADE

DISTRICT TEMPERATURE CONSTANT 28.0
SWELLING PROBABILITY 0.00
POTENTIAL VERTICAL RISE (INCHES) 0.00
SWELLING RATE CONSTANT 0.00
SUBGRADE STIFFNESS COEFFICIENT 0.22
CONSTRUCTION AND MAINTENANCE DATA

SERVICEABILITY INDEX OF THE INITIAL STRUCTURE 4.4
SERVICEABILITY INDEX P1 AFTER AN OVERLAY 4.4
MINIMUM OVERLAY THICKNESS (INCHES) 1.5
OVERLAY CONSTRUCTION TIME (HOURS/DAY) 8.0
ASPHALTIC CONCRETE COMPACTED DENSITY (TONS/C.Y.) 1.80
ASPHALTIC CONCRETE PRODUCTION RATE (TONS/HOUR) 175.0
WIDTH OF EACH LANE (FEET) 12.0
FIRST YEAR COST OF ROUTINE MAINTENANCE (DOLLARS/LANE-MILE) 120.00
ANNUAL INCREMENTAL INCREASE IN MAINTENANCE COST (DOLLARS/LANE-MILE) 74.00

DETOUR DESIGN FOR OVERLAYS

TRAFFIC MODEL USED DURING OVERLAYING 3
TOTAL NUMBER OF LANES OF THE FACILITY 4
NUMBER OF OPEN LANES IN RESTRICTED ZONE (OVERLAY DIRECTION) 1
NUMBER OF OPEN LANES IN RESTRICTED ZONE (NON-OVERLAY DIRECTION) 2
DISTANCE TRAFFIC IS SLOWED (OVERLAY DIRECTION) (MILES) 1.00
DISTANCE TRAFFIC IS SLOWED (NON-OVERLAY DIRECTION) (MILES) 1.00
DETOUR DISTANCE AROUND THE OVERLAY ZONE (MILES) 0.00

PAVING MATERIALS INFORMATION

<table>
<thead>
<tr>
<th>LAYER CODE</th>
<th>MATERIALS</th>
<th>COST</th>
<th>STR.</th>
<th>MIN.</th>
<th>MAX.</th>
<th>SALVAGE,</th>
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<tbody>
<tr>
<td>1</td>
<td>ASPH CONC PVT TY D</td>
<td>64.00</td>
<td>0.96</td>
<td>1.50</td>
<td>1.50</td>
<td>30.00</td>
</tr>
<tr>
<td>2</td>
<td>ASPH CONC PVT TY C</td>
<td>60.00</td>
<td>0.96</td>
<td>2.00</td>
<td>2.00</td>
<td>40.00</td>
</tr>
<tr>
<td>3</td>
<td>ASPH CONC PVT TY A</td>
<td>58.00</td>
<td>0.92</td>
<td>4.50</td>
<td>16.00</td>
<td>40.00</td>
</tr>
<tr>
<td>4</td>
<td>FLEXIBLE BASE</td>
<td>24.50</td>
<td>0.55</td>
<td>6.00</td>
<td>16.00</td>
<td>75.00</td>
</tr>
<tr>
<td>5</td>
<td>LIME TRTD SUBGRADE</td>
<td>10.70</td>
<td>0.32</td>
<td>8.00</td>
<td>8.00</td>
<td>90.00</td>
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</table>
PROB DIST. COUNTY CONT. SECT. HIGHWAY DATE IPE PAGE
X-1 48 SOFTNWET 0080 07 BUMPY 1 09-13-85 3
FOR THE 1 LAYER DESIGN WITH THE FOLLOWING MATERIALS--
MATERIALS COST STR. MIN. MAX. SALVAGE
LAYER CODE NAME PER CY COEFF. DEPTH DEPTH PCT.
1 A ASPH CONC PVT TY D 64.00 0.96 1.50 1.50 30.00
SUBGRADE 0.22

THE CONSTRUCTION RESTRICTIONS ARE TOO BINDING TO OBTAIN A STRUCTURE
THAT WILL MEET THE MINIMUM TIME TO THE FIRST OVERLAY RESTRICTION.
<table>
<thead>
<tr>
<th>Layer Code</th>
<th>Name</th>
<th>Cost/Per CY</th>
<th>Str. Coeff.</th>
<th>Min. Depth</th>
<th>Max. Depth</th>
<th>Salvage Rate</th>
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<tbody>
<tr>
<td>1</td>
<td>ASPH CONC PVT TY D</td>
<td>64.00</td>
<td>0.96</td>
<td>1.50</td>
<td>1.50</td>
<td>30.00</td>
</tr>
<tr>
<td>2</td>
<td>ASPH CONC PVT TY C</td>
<td>60.00</td>
<td>0.96</td>
<td>2.00</td>
<td>2.00</td>
<td>40.00</td>
</tr>
</tbody>
</table>

Subgrade: 0.22

The construction restrictions are too binding to obtain a structure that will meet the minimum time to the first overlay restriction.
FOR THE 3 LAYER DESIGN WITH THE FOLLOWING MATERIALS--

<table>
<thead>
<tr>
<th>LAYER CODE</th>
<th>NAME</th>
<th>MATERIALS</th>
<th>COST</th>
<th>STR.</th>
<th>MIN.</th>
<th>MAX.</th>
<th>SALVAGE</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>A ASPH CONC PVT TY D</td>
<td>64.00</td>
<td>0.96</td>
<td>1.50</td>
<td>1.50</td>
<td>30.00</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>B ASPH CONC PVT TY C</td>
<td>60.00</td>
<td>0.96</td>
<td>2.00</td>
<td>2.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>C ASPH CONC PVT TY A</td>
<td>58.00</td>
<td>0.92</td>
<td>4.50</td>
<td>16.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SUBGRADE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.22</td>
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</table>

THE OPTIMAL DESIGN FOR THE MATERIALS UNDER CONSIDERATION--

FOR INITIAL CONSTRUCTION THE DEPTHS SHOULD BE
- ASPH CONC PVT TY D 1.50 INCHES
- ASPH CONC PVT TY C 2.00 INCHES
- ASPH CONC PVT TY A 14.50 INCHES

THE LIFE OF THE INITIAL STRUCTURE = 12. YEARS

THE OVERLAY SCHEDULE IS
- 2.00 (INCH(E(S) (INCLUDING 0.5 INCH LEVEL-UP) AFTER 12. YEARS.

TOTAL LIFE = 21. YEARS

SERVICEABILITY LOSS DUE TO SWELLING CLAY IN EACH PERFORMANCE PERIOD IS
- (1) 0.000
- (2) 0.000

THE TOTAL COSTS PER SQ. YD. FOR THESE CONSIDERATIONS ARE
- INITIAL CONSTRUCTION COST 29.361
- TOTAL ROUTINE MAINTENANCE COST 0.654
- TOTAL OVERLAY CONSTRUCTION COST 1.412
- TOTAL USER COST DURING OVERLAY CONSTRUCTION 0.097
- SALVAGE VALUE -2.634
- TOTAL OVERALL COST 28.890

NUMBER OF FEASIBLE DESIGNS EXAMINED FOR THIS SET -- 6

AT THE OPTIMAL SOLUTION, THE FOLLOWING
BOUNDARY RESTRICTIONS ARE ACTIVE--
- 1. THE MINIMUM DEPTH OF LAYER 1
- 2. THE MAXIMUM DEPTH OF LAYER 1
- 3. THE MINIMUM DEPTH OF LAYER 2
- 4. THE MAXIMUM DEPTH OF LAYER 2
TEXAS DEPARTMENT OF HIGHWAYS AND PUBLIC TRANSPORTATION

FPSll FLEXIBLE PAVEMENT DESIGN - 227001 VER 3.1 JUN 85

PROB DIST. COUNTY CONT. SECT. HIGHWAY DATE IPE PAGE
X-1 48 SOFTNWT 0080 07 BUMPY 1 09-13-85 6

FOR THE 4 LAYER DESIGN WITH THE FOLLOWING MATERIALS--

<table>
<thead>
<tr>
<th>MATERIALS</th>
<th>COST</th>
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<th>MAX.</th>
<th>SALVAGE</th>
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<tbody>
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<td></td>
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THE OPTIMAL DESIGN FOR THE MATERIALS UNDER CONSIDERATION--

FOR INITIAL CONSTRUCTION THE DEPTHS SHOULD BE
- ASPH CONC PVT TY D 1.50 INCHES
- ASPH CONC PVT TY C 2.00 INCHES
- ASPH CONC PVT TY A 5.50 INCHES
- FLEXIBLE BASE 16.00 INCHES

THE LIFE OF THE INITIAL STRUCTURE = 12. YEARS
THE OVERLAY SCHEDULE IS 2.00 (INCH(ES) (INCLUDING 0.5 INCH LEVEL-UP) AFTER 12. YEARS.

TOTAL LIFE = 21. YEARS
SERVICEABILITY LOSS DUE TO SWELLING CLAY IN EACH PERFORMANCE PERIOD IS
(1) 0.000
(2) 0.000

THE TOTAL COSTS PER SQ. YD. FOR THESE CONSIDERATIONS ARE
- INITIAL CONSTRUCTION COST 25.750
- TOTAL ROUTINE MAINTENANCE COST 0.654
- TOTAL OVERLAY CONSTRUCTION COST 1.412
- TOTAL USER COST DURING OVERLAY CONSTRUCTION 0.095
- SALVAGE VALUE -3.142
- TOTAL OVERALL COST 24.770

NUMBER OF FEASIBLE DESIGNS EXAMINED FOR THIS SET -- 208

AT THE OPTIMAL SOLUTION, THE FOLLOWING BOUNDARY RESTRICTIONS ARE ACTIVE--
1. THE MINIMUM DEPTH OF LAYER 1
2. THE MAXIMUM DEPTH OF LAYER 1
3. THE MINIMUM DEPTH OF LAYER 2
4. THE MAXIMUM DEPTH OF LAYER 2
### Materials Details

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<th>Name</th>
<th>Cost per CY</th>
<th>Str. Coeff</th>
<th>Min. Depth</th>
<th>Max. Depth</th>
<th>Salvage Pct</th>
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<td>1.50</td>
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<td>2</td>
<td>ASPH CONC PVT TY C</td>
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<td>2.00</td>
<td>40.00</td>
</tr>
<tr>
<td>3</td>
<td>ASPH CONC PVT TY A</td>
<td>58.00</td>
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### Optimal Design

The optimal design for the materials under consideration:
- For initial construction, the depths should be:
  - ASPH CONC PVT TY D: 1.50 inches
  - ASPH CONC PVT TY C: 2.00 inches
  - ASPH CONC PVT TY A: 4.50 inches
  - FLEXIBLE BASE: 15.00 inches
  - LIME TRTD SUBGRADE: 8.00 inches

The life of the initial structure = 12. years.

The overlay schedule is 2.00 (inch(es)) (including 0.5 inch level-up) after 12. years.

Total life = 22. years.

### Serviceability Loss

Serviceability loss due to swelling clay in each performance period is:
1. 0.000
2. 0.000

### Total Costs

The total costs per sq. yd. for these considerations are:
- Initial construction cost: 25.836
- Total routine maintenance cost: 0.654
- Total overlay construction cost: 1.412
- Total user cost during overlay construction: 0.097
- Salvage value: -3.353
- Total overall cost: 24.646

### Number of Feasible Designs

Number of feasible designs examined for this set = 216

### Boundary Restrictions

At the optimal solution, the following boundary restrictions are active:
1. The minimum depth of Layer 1
2. The maximum depth of Layer 1
3. The minimum depth of Layer 2
4. The maximum depth of Layer 2
5. The minimum depth of Layer 3
6. The minimum depth of Layer 5
7. The maximum depth of Layer 5
## SUMMARY OF THE BEST DESIGN STRATEGIES

### IN ORDER OF INCREASING TOTAL COST

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### TOTAL COST


### NUMBER OF LAYERS

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### NO. OF PERF. PERIODS

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B-8
## SUMMARY OF THE BEST DESIGN STRATEGIES

IN ORDER OF INCREASING TOTAL COST

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TOTAL COST            | 25.06 | 25.10| 25.15| 25.16  | 25.23| 25.27| 25.32  |

NUMBER OF LAYERS      | 5     | 4    | 4    | 5      | 5    | 4    | 4      |

LAYER DEPTH (INCHES)  

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PERF. TIME (YEARS)    

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OVERLAY POLICY(INCH)  

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SWELLING CLAY LOSS    

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### SUMMARY OF THE BEST DESIGN STRATEGIES

**IN ORDER OF INCREASING TOTAL COST**

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**NUMBER OF LAYERS**

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**NO. OF PERF. PERIODS**

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**PERF. TIME (YEARS)**

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**OVERLAY POLICY (INCH)**

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**SWELLING CLAY LOSS**

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The total number of feasible designs considered was 430
APPENDIX C

Slides Used in Presentation
Overview

Of

Flexible Pavement Design
Early Road Building
"OLD SLIDE"
Hot Mix Construction
US 81 Near Temple
about 1930

SLIDE No. 4

BRICK STREET

SLIDE No. 5
“Macadam” Construction

- Traffic—Bound Macadam
- Water—Bound Macadam
- Bituminous—Bound Macadam
- Cement—Bound Macadam
Road Tests
And Flexible Pavement

(1) Bates Road Test
(2) WASHO Road Test
(3) Individual States
(4) FHWA
(5) Corps of Engineers
AASHTO Road Test
Pavement Types

- Flexible Pavement
- Semi-Rigid Pavement
- Rigid Pavement
- Composite Pavement
Types of Pavement Distress

- Structural
- Functional
AASHTO Definitions

• Serviceability
• Present Serviceability Rating (PSR)
• Present Serviceability Index (PSI)
• Pavement Performance
Present Serviceability Rating Scale
INITIAL SERVICEABILITY

SERVICEABILITY AFTER OVERLAY

TERMINAL SERVICEABILITY

TIME, YEARS

INITIAL PERFORMANCE PERIOD

ANALYSIS PERIOD

SERVICEABILITY INPUTS
Road Roughness/Smoothness Measurement Devices

- BPR Roughometer
- CHLOE Profilometer
- Rolling Straightedge
- Surface Dynamics Profilometer
- PCA Road Meter
- Mays Road Meter
- Precision Leveling
- SIOMETER (Walker)
Elements of Thickness Design

- Magnitude and Method of Application of Wheel Loads
- Function of Pavement and Base in Transmitting the Load to the Subgrade
- Measure of Subgrade Support
Wheel Loads

- Static Wheel Load
- Repetitive Wheel Loads
"SO-HIGH"
(Truck with big tires)

BUBBA & HOWARD
"Fun Car"

MIXED TRAFFIC
- Trucks
- Cars
- Motorcycle
- etc
Converting Mixed Traffic

- Equivalent 18-Kip Single Axle Loads
- Developed Concept at AASHTO Road Test
FIGURE 1
Simple Flexible Pavement Structure Section

FIGURE 2
Complex Flexible Pavement Structure Section
FIGURE 3
LOAD DISTRIBUTION
IN FLEXIBLE PAVEMENTS
Wheel Load Contact Area

\[
\text{Stress} = \frac{\text{Force}}{\text{Area}}
\]

\[
\text{Tire Pressure} = \frac{\text{Wheel Load}}{\pi \ a^2}
\]
Measures of Subgrade Support

- Plate Loading
- Triaxial
- California Bearing Ratio (CBR)
- Resilient Modulus
Measure of Subgrade Support Used By Texas

- Texas Triaxial
- Dynaflect Stiffness Coefficient
- Resilient Modulus
FIGURE 6

TYPICAL FLEXIBLE PAVEMENT
DEFLECTION BASIN
$P = \text{Applied Pressure}$

**Surface** 
$\Sigma \text{Strain} = \Delta_P$

**Base** 
$\Sigma \text{Strain} = \Delta_B$

**Subgrade** 
$\Sigma \text{Strain} = \Delta_S$

$\Delta_T = \Delta_P + \Delta_B + \Delta_S$

**Pavement Deflections**
Deflection Measuring Devices

- Benkelman Beam
- Dynaflect
- Falling Weight Deflectometer
Benkelman Beam

(Overall View)
DYNAFLECT: (Overall View)

SLIDE NO. 34

DYNAFLECT: On Load Wheels

SLIDE NO. 35

DYNAFLECT: (Interior View)

SLIDE NO. 36
FIGURE 7
DYNAFLECT LOADING AND MEASUREMENT LAYOUT
DYNAFLECT LOADS

Undeflected Surface

Mirror Image of Basin

Deflected Surface

$SCI = W_1 - W_2$

$SCI =$ SURFACE CURVATURE INDEX

FIGURE 4
DYNAFLECT DEFLECTION BASIN
Falling Weight Deflectometer
(Showing overall view)

Falling Weight Deflectometer
(Showing Load Plate)

Slide No. 39

Slide No. 40
Flexible Pavement Design Methods

- AASHTO Flexible-Pavement Design Procedure
- Multilayer Elastic Analysis
- Asphalt Institute Procedure
- Texas Flexible Pavement Design System (FPS)
- Texas Triaxial Design (Tex-117-E)
AASHTO
Flexible Pavement
Design Procedure
AASHTO: Flexible Design

\[ SN = A_1 D_1 + A_2 D_2 + \ldots + A_n D_n \]

\[ SN = \text{Structural Number} \]
\[ A_n = \text{Structural Layer Coefficient} \]
\[ D_n = \text{Layer Thickness} \]
AASHTO: FLEXIBLE DESIGN

\[ \log W_{18K} = 9.36 \log (SN+1) + 0.20 + \frac{\log \left[ \frac{4.2 - P_T}{4.2 - 1.5} \right]}{0.40 \left[ \frac{1094}{(SN+1)^{5.19}} \right]} \]

\( W_{18K} = 18\text{-Kip Single Axle Equivalents} \)

\( SN = \text{Structural Number} \)

\( P_T = \text{Terminal Serviceability} \)
Multilayer Elastic Analysis
4500 Lb. 4500 Lb. 12" c-c

Wheel   Wheel 80 PSI Tire Pressure

Asphaltic Concrete, $E = 400,000$, $\mu = 0.35$

Flexible Base, $E = 50,000$, $\mu = 0.40$

Subgrade, $E = 10,000$, $\mu = 0.45$
Asphaltic Concrete Fatigue Equation

\[ N_f = (9.7255 \times 10^{-15})(1/\varepsilon)^{5.16267} \]

From Report No. FHWA-RD-75-75
Asphalt Institute Procedure
THE ASPHALT INSTITUTE

- ELASTIC THEORY (MECHANISTIC)
- RESULTS OF RESEARCH
THE ASPHALT INSTITUTE

- DESIGN METHODS
  * CHARTS IN MANUAL
  * COMPUTER PROGRAM DAMA
    (Not Available to SDHPT)
Locations of strains considered in design procedure.
Texas Triaxial Design Procedure (TEX-117-E)
STANDARD

TEXAS TRIAXIAL DESIGN

SURFACING

STABILIZED BASE

UNSTABILIZED BASE

SUBBASE

SUBGRADE

TOTAL REQUIRED COVER

SLIDE NO. 53
DESIGN WHEEL LOAD in Thousands of Pounds

FLEXIBLE BASE DESIGN CHART

Figure 16
FLOWER

SLIDE No. 55
Texas Flexible Pavement Design System (FPS)
AASHO ROAD TEST
OTTAWA, ILL.
LATE 1950's AND EARLY 1960's

"SATELLITE PROJECTS"
TO
TRANSFER ROAD TEST FINDINGS

TEXAS
Figure 1
The Ten Participating Districts
Purpose of FPS System:

To provide, from available materials, a pavement that can be maintained above a specified level of serviceability, over a specified period of time, with a specified reliability, at a minimum overall total cost.
FPS Computer Programs

(1) FPS-11 (Principal Program)
(2) Stiffness Coefficient Program
(3) Profile Analysis Program
OPTIMIZATION

- State Level
- District Level
- Project Level
FPS System Optimization

- Total Cost for Analysis Period
  1. Initial Construction Cost,
  2. Overlay Construction Cost,
  3. User Cost (Delay),
  4. Routine Maintenance Cost, and
  5. Salvage Value.
66 Inputs to FPS

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<tr>
<th>Card No.</th>
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<tr>
<td>1</td>
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<td>Project Comments (1)</td>
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<td>Basic Design Criteria (6)</td>
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<td>4</td>
<td>Program Controls and Constraints (5)</td>
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<td>5</td>
<td>Traffic Data (8)</td>
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<td>6</td>
<td>Environment and Subgrade (5)</td>
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<td>7</td>
<td>Construction and Maintenance Data (9)</td>
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<td>8</td>
<td>Detour Designs for Overlays (7)</td>
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<tr>
<td>9</td>
<td>Existing Pavement and Proposed ACP (8)</td>
</tr>
<tr>
<td>10</td>
<td>Paving Materials Information (9)</td>
</tr>
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</table>
Performance Equation Inputs

1. Serviceability Index
   a. Initial Serviceability
   b. Serviceability After ACP Overlay
   c. Terminal Serviceability

2. Materials Stiffness Coefficients
   (or Surface Curvature Index)

3. Traffic (18-KSA Applications)

4. Temperature Constant

5. Swelling Clay Properties
FPS Design Process

• Develop Input Data
  — Measure Field Data
  — Select Materials Properties
  — Secure Traffic Data

• Compute with FPS Program

• Select Best Pavement Design Strategy
COLLECTION OF DATA:

- Dynaflect Data
- Traffic Data
- Existing Pavement
- Soils Survey
- Visual Condition Survey
"New" Pavement

Input:
- Stiffness Coefficient

ACP Overlay

Input:
- Surface Curvature Index
- Standard Deviation

Performance Equation
Traffic Data

- File D-10
  - 20 Year Data for FPS
  - Historical Traffic
  - Local Knowledge
Confidence Level

- Highway Capacity Within Analysis Period
  - Greater Than 50% Of Capacity
  - Less Than 50% Of Capacity
Confidence Level

- Highway Status During Analysis Period
  - Will Remain Rural
  - Is Or Will Become Urban
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<th>The Highway Will Remain Rural Throughout The Analysis Period</th>
<th>The Highway Is Or Will Become Urban Before The End Of The Analysis Period</th>
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</thead>
<tbody>
<tr>
<td>C Or D</td>
<td>C Or D</td>
<td>E</td>
</tr>
<tr>
<td>The Highway Will Be Operating At Less Than 50% Of Capacity Throughout The Analysis Period</td>
<td>The Highway Will Remain Rural Throughout The Analysis Period</td>
<td>The Highway Is Or Will Become Urban Before The End Of The Analysis Period</td>
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IDENTIFYING THE OPTIMUM RELIABILITY LEVEL FOR A GIVEN FACILITY
FLOWER
PAVEMENT DESIGN ASSISTANCE
The End