SHRP-P-655

SHRP's Layer Moduli Backcalculation Procedure

Strategic Highway Research Program
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ABSTRACT

Deflection basin measurements for the purpose of structural capacity evaluation are a key component of the SHRP's Long-Term Pavement Performance monitoring program. In the near term, SHRP will apply a backcalculation procedure to these deflection measurements in order to estimate the in situ elastic moduli of the pavement layer materials. Because a standard method for evaluating the structural capacity of flexible pavements from deflection data does not presently exist, SHRP has undertaken a study to develop a layer moduli backcalculation procedure for use in the initial analysis of the SHRP deflection data. This procedure covers not only the software but also the rules and guidelines used in applying the program. This report focuses on the standard procedure used to ensure that the LTPP deflection data analysis is as consistent, productive, and straightforward as possible. The procedure consists of a rigorous set of application rules used to generate data files for direct input into the backcalculation program -- modeling of pavement structure and layer moduli ranges or initial moduli. Additional rules address the subsequent evaluation of the backcalculation results.

INTRODUCTION

Since the Spring of 1988, SHRP has completed an initial round of deflection testing on nearly 800 in-service pavement test sections, and has begun a second round. Although the raw deflection data is the primary data to be stored for use by pavement researchers, the initial Long Term Pavement Performance (LTPP) data analyses require that SHRP derive estimates of the in-situ elastic moduli of the pavement layers from the deflection data. In order to do so, SHRP has developed a backcalculation procedure, consisting of an existing backcalculation program and a series of application "rules".

The development process for the SHRP backcalculation procedure involved four phases: (1) a literature review to identify backcalculation programs which might be used in the procedure; (2) the selection of a limited number of programs for detailed evaluation; (3) a detailed evaluation of those programs; and (4) the development of a procedure around the selected program. The first three stages of this endeavor are discussed in detail elsewhere (1). This report focuses on the standard backcalculation procedure developed around the selected program.

In general, backcalculation is a laborious process, requiring a high degree of skill, and the results are known to be moderately to highly dependent on the individual doing the backcalculation. This comes about for a number of reasons, including the lack of a consensus standard addressing all aspects of the backcalculation process. In order to ensure that the backcalculation process applied in the SHRP data analysis is as consistent, productive, and straight forward as possible, the SHRP backcalculation procedure combines an existing backcalculation program with a rigorous set of application rules. In addition, the initial backcalculation has been automated to a high degree, thus reducing opportunities for "operator" error, and between user inconsistencies.

The SHRP backcalculation rules rely on information stored in the LTPP data base to generate the input -- modeling of pavement structure, layer moduli ranges, Poisson's ratios, etc. -- for the backcalculation program. Data base queries are used to generate data files for input into the backcalculation program, and additional rules address the subsequent evaluation of the backcalculation results. It is anticipated that both the application rules and the evaluation rules will be refined as more is learned about the strengths, weaknesses, and requirements of the backcalculation procedure that SHRP has developed.

BACKCALCULATION SOFTWARE

The process by which SHRP pursued the selection of a backcalculation program for use in the LTPP data analysis involved the following steps:

1. Software identification;

2. Preliminary software selection;
4. Software evaluation; and
5. Final software selection.

A brief summary of these is presented next, while a more detailed description of the process is presented in Reference (1).

The first three steps in the process outlined above were quite straightforward. Software identification involved a review of the literature to identify a number of the programs available, and their pertinent features. The second step was accomplished through discussions at a meeting of SHRP's LTPP Expert Task Group (ETG) for Deflection Testing and Backcalculation in November, 1990. Based on ETG recommended criteria, six programs were selected for further evaluation. ELCON and ILLI-BACK were selected for rigid pavements, and ISSEM4, MODCOMP3, MODULUS, and WESDEF for flexible pavements.

The purpose of SHRP's backcalculation software evaluation exercise was twofold: (1) to provide a basis for selecting a program for use in the SHRP backcalculation; and (2) to provide a basis for development of the procedures to be used with that software. For this endeavor a group composed of ETG members, the software developers, and SHRP contractors was assembled. Backcalculation results were evaluated on the basis of reasonableness, robustness and stability, goodness of fit, and general suitability for SHRP's purposes.

Based on the results of the evaluation exercise, it was concluded that MODCOMP3, MODULUS, and WESDEF are useful tools for backcalculation, which can produce good results. The programs, however, were found to have different strengths and weaknesses. MODCOMP3 produced results which match the measured deflection basins quite well, were reasonably independent of the user, and were generally "reasonable". In addition, it was the most flexible of the programs evaluated. MODULUS did a slightly better job of matching the measured deflections basins, was slightly more independent of the user, and also produced results which were generally "reasonable". However, the lower degree of user dependence of MODULUS, as compared to MODCOMP3, comes about as a result of fewer options with respect to modelling of the pavement structure (i.e., less flexibility). The performance of WESDEF was similar to that of MODCOMP3 (i.e., not quite as good as MODULUS), with respect to the ability to match measured deflection basins. However, the results were somewhat less independent of the user, and were subjectively judged to be slightly less "reasonable" for the sections evaluated.

Overall, it was concluded from the results of the evaluation exercise that the performance of MODULUS was somewhat superior to that of the other programs, although one or both of the other programs may be better for an individual section. Thus, MODULUS was selected as the primary backcalculation program to be used in the initial analysis of the SHRP deflection data.

BACKCALCULATION RULES

As indicated earlier, backcalculation is a laborious process, requiring a high degree of skill, and the results are known to be moderately to highly dependent on the individual doing the backcalculation. In order to ensure that backcalculation process applied in the SHRP data analysis is as consistent, productive, and straightforward as possible, a standard procedure (i.e., rigorous set of applications rules) was developed around the MODULUS program. This procedure relies on the wealth of information stored in the LTPP data base -- deflection, pavement structure and materials, and surface layer temperature data -- to generate the input for MODULUS. In addition, the procedure has been automated to a high degree, thus reducing opportunities for operator error or inconsistency.

The SHRP backcalculation rules address three major areas: definition of layer moduli ranges, modeling of the pavement structure, and evaluation of the analysis results. The first group of rules focuses on the definition of the moduli ranges required to run the MODULUS program, the second set of rules addresses the modeling of the pavement structure for purposes of backcalculation, and the third and final set of rules focuses on the evaluation of the backcalculation results. A step-by-step discussion of these rules is presented next. In addition, new rules or modifications to the existing ones based on preliminary LTPP data analysis results are discussed in a later section.

Definition of Layer Moduli Ranges

The MODULUS program requires that an estimate of the "expected" range of moduli be specified for each pavement layer, except the subgrade where only an estimate of the initial modulus is required. In the SHRP backcalculation procedure, predictive equations that rely on material property and field temperature data stored in the LTPP data base are used to establish the moduli range for asphaltic concrete (AC) layers -- the specific algorithm used depends on the available information. Moduli ranges for portland cement concrete (PCC) layers and other stabilized materials are determined based on available laboratory test results, or assumed. Similarly, moduli ranges for unbound granular base and subbase layers are estimated on the basis of material type. Outer deflection readings and Boussinesq's one-layer deflection equation are used to estimate the initial subgrade modulus.

Asphalt Concrete Layers

The following rules are used to arrive at the modulus range for asphalt concrete layers:

1. Determine Mid-Depth Temperature of AC Layer(s)

Using the surface layer temperature gradient versus time data stored in the LTPP data base, the mid-depth temperature for each AC layer in the pavement structure at the time of testing is determined (extrapolated or interpolated).

2. Compute Initial Modulus of AC Layer(s)

If mix data -- aggregate grading, maximum and bulk specific gravity of mix, and asphalt content -- are available from the LTPP data base, the following equation is used to estimate the initial modulus of AC layers (2):

$$\begin{aligned}\log_{10}[E^*] = {} & 2.250053 - 0.091756*V_{be} - 0.027949*V_a - 0.096881*p_{200} + \\ & 0.250094*p_{abs} - 0.006447*t_p + 0.060612*f - 0.00007404*t_p^2 + \\ & 0.00191539*V_{be}^2 + 0.0082813*p_{200}^2 - 0.0010225*p_{3/4}^2 + \\ & 0.0001909*p_{3/8}^2 - 0.0801155*p_{abs}^2 + 0.0148592*\eta_{70,10^6}^2 - 0.0024159*f^2 \\ & + 0.00094015*p_{3/8}*V_{be} + 0.00084534*p_{3/4}*V_{be} + 0.0004965*p_{3/4}*p_4 - \\ & 0.00034328*p_{3/8}*p_4 - 0.00316297*p_{3/8}*p_{abs} \qquad (1)\end{aligned}$$

where E^* = AC modulus, in 10^5 psi; V_{be} = effective asphalt content, by volume percentage; V_a = percent air voids in mix; p_{200} = percent aggregate weight passing the No. 200 sieve; p_{abs} = percent asphalt absorption, by weight of aggregate; f = test frequency of load wave, in Hz (assume 16 Hz in all cases); t_p = test temperature, in Fahrenheit (from Step No. 1); p_4, $p_{3/8}$, and $p_{3/4}$ = percent aggregate weight retained in the No. 4, 3/8" and 3/4" sieves, respectively; and $\eta_{70,10^6}$ = asphalt viscosity at 70°F, in 10^6 Poises.

The effective asphalt content (V_{be}), by volume percentage, is determined by means of the following equation (3):

$$V_{be} = [(p_{ac} - p_{abs} - p_{abs}*p_{ac}/100)*G_{mb}] / G_b \qquad (2)$$

where p_{ac} = percent asphalt content by weight of mix; p_{abs} = percent asphalt absorption by weight of aggregate; G_{mb} = maximum specific gravity of mix; and G_b = specific gravity of bitumen. If the specific gravity of the bitumen is not stored in the LTPP data base, a value of 1.010 is assumed.

If aggregate (effective and bulk) and bitumen specific gravities are stored in the LTPP data base, the following equation is use to determine the percent asphalt absorption (p_{abs}) by weight of aggregate (3):

$$p_{abs} = 100*[(G_{se} - G_{sb})/(G_{sb}*G_{se})]*G_b \qquad (3)$$

where G_{se} = effective specific gravity of aggregate; G_{sb} = bulk specific gravity of aggregate; and, G_b = specific gravity of asphalt. Otherwise, it is assumed that p_{abs} = 0.5% for crushed stone, gravel and sand mixtures and 1.5% for slag.

The percentage of voids in the mix, V_a, is determined from the following relationship (3):

$$V_a = [100*(G_{mm}-G_{mb})]/G_{mm} \quad (4)$$

where G_{mm} = maximum specific gravity of compacted mix and G_{mb} = bulk specific gravity of compacted mix.

The asphalt viscosity at 70°F ($\eta_{70,10^\wedge 6}$) can be determined in one of three ways. If measured absolute (140°F, in poises) and kinematic (275°F, in centistoke) viscosities are stored in the LTPP data base, a log(log(viscosity)) versus log(temperature) correlation is first established and then extrapolated to 70°F (2). Figure 1 graphically illustrates the computation of $\eta_{70,10^\wedge 6}$ from known viscosity and temperature data. When using this procedure, special care must be taken to ensure that viscosity data have been converted into centipoise and temperatures into degrees Rankine, prior to the development of the correlation.

If viscosity data is not available but a penetration value at 77°F (Pen_{77}) is known, the following relationship between asphalt viscosity at 70°F and penetration at 77°F is recommended (3):

$$\eta_{70,10^\wedge 6} = 475{,}300*Pen_{77}^{-2.93} \quad (5)$$

Finally, if the only information known about the asphalt consistency is the general grade, either viscosity or penetration grade, the values shown in Table 1 are used. In the event that asphalt consistency data are not available, viscosity values are assumed on a state-by-state basis; e.g., $2.5*10^6$ poises (AC-20) for the State of Maryland.

It has been assumed that a certain minimum amount of data -- aggregate grading, maximum and bulk specific gravity of mix, and asphalt content -- are available for the computation of the initial modulus for each AC layer in the pavement structure. In those cases where this information is not available from the LTPP data base, the initial modulus is computed using the following equation (3):

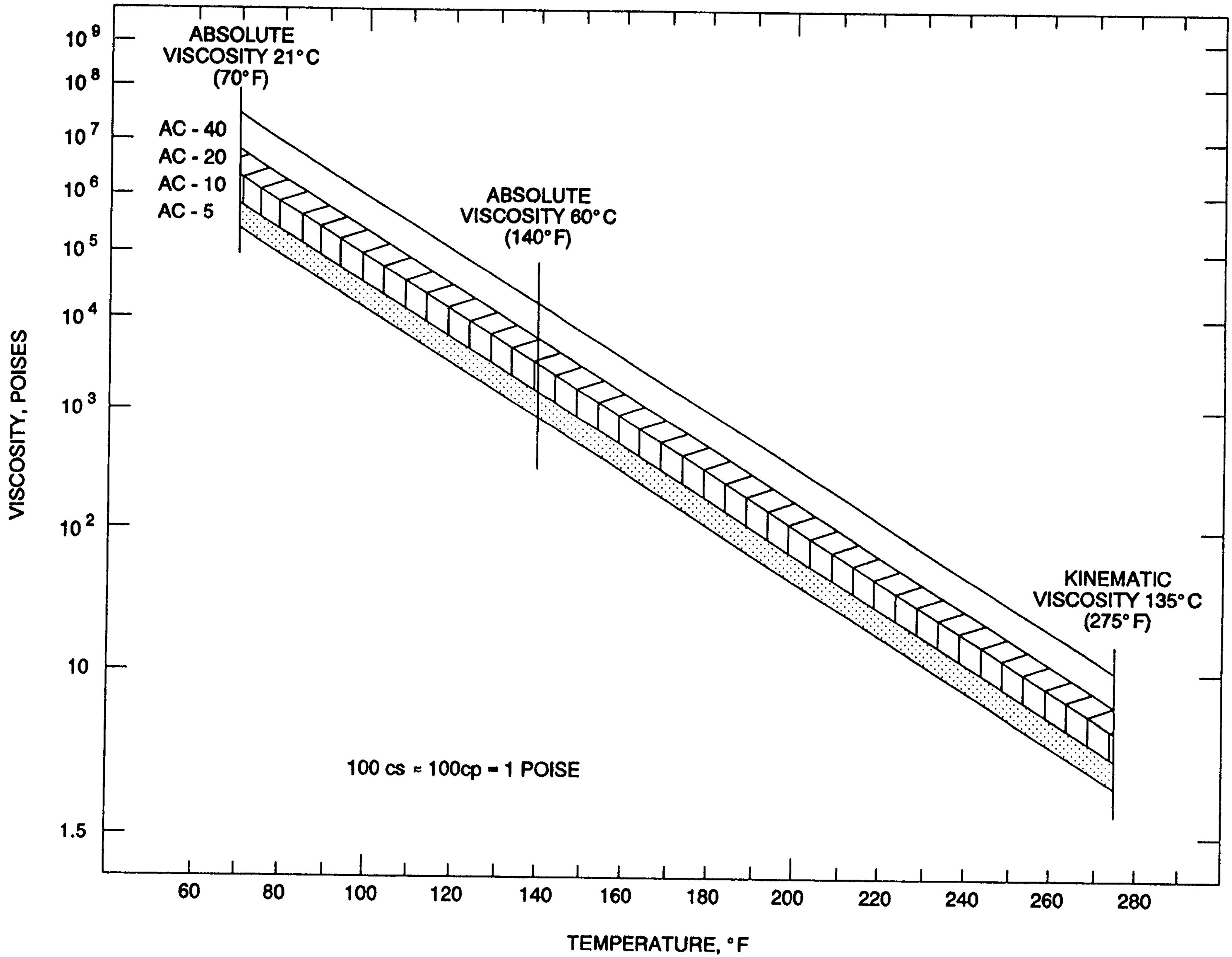

FIGURE 1. Typical Viscosity - Temperature Relationships.

Table 1 - Asphalt Viscosity at 70°F Based on Grade

Basis for Grade	Grade	Viscosity (70°F, 10^6 poises)
Viscosity	AC-5	0.3
	AC-10	1.0
	AC-20	2.5
	AC-40	5.0
Penetration	60-70	2.5
	85-100	1.0
	100-120	0.5
	150-200	0.25
After Residue (AR)[1]	10	0.08
	20	0.3
	40	1.0
	80	2.5
	160	5.0

Note: [1]Viscosity values were established for both viscosity and penetration grade asphalts based on recommendations provided in Reference 2; AASHTO M-226-80 correlations were used to establish viscosity values for the AR grades of asphalt.

$$\log_{10}[E^*] = 0.553833 + 0.028829*p_{200}*f^{-0.17033} - 0.03476*V_a + 0.070377*\eta_{70,10^6} + 0.000005*[t_p^{(1.3 + 0.49825\log(f))}*p_{ac}^{0.5}] - 0.00189[t_p^{(1.3 + 0.49825\log(f))}* p_{ac}^{0.5}*f^{1.1}] + 0.931757f^{-0.02774} \quad (6)$$

where E^* = AC modulus, in 10^5 psi; V_a = percent air voids in mix; f = test frequency of load wave, in Hz (assume 16 Hz in all cases); t_p = test temperature; in Fahrenheit (from Step No. 1); p_{200} = percent aggregate weight passing the No. 200 sieve; p_{ac} = percent asphalt content by weight of mix; and, $\eta_{70,10^6}$ = asphalt viscosity at 70 F, in 10^6 Poises.

If the information contained in the LTPP data base is not sufficient to define one or more of the variables in Equation 6, the following default values are recommended:

- Percent air voids in mix, V_a: 4% for surface courses, 5% for binder courses, and 7% for base courses.
- Percent asphalt content by weight of mix, p_{ac}: 6% for surface courses, 5% for binder courses, and 4% for base courses; 8% for all sand asphalt mixtures.
- Percent aggregate weight passing the No. 200 sieve, p_{200}: 6% for surface courses, 5% for binder courses, and 4% for base courses; 6% for all sand asphalt mixtures.

The asphalt viscosity at 70°F ($\eta_{70,10^6}$) can be determined using any of the three procedures described earlier for the definition of this variable in Equation 1. If none of the required grade information is present in the data base, viscosity values are assumed on a state-by-state basis.

3. Combine AC layers of Same Construction Age

In general, backcalculation procedures are unable to handle individual AC construction lifts separately. As a consequence, in the SHRP backcalculation procedure, AC layers having the same construction age are combined into a single layer -- e.g., binder and surface course for an overlay or original surface layer are combined into one layer. The specific rules for combining AC layers are as follows:

- Add thicknesses of all AC layers having the same construction age, including any surface treatments:

$$h_{composite} = h(\text{surface treatment}) + h(\text{surface course}) + h(\text{binder}) + \ldots \quad (7)$$

- Find initial composite modulus for the combination of AC layers having the same construction age:

$$E_{composite} = \Sigma[(h_i/h_{composite}) * E_i^{(1/3)}]^3 \quad (8)$$

where h_i = thickness of the "i"th layer; E_i = modulus of the "i"th layer (from Step No. 2); and i = 1 to n, where n is the number of AC layers having the same construction age. For example, if during construction, a 2 inch AC surface course (modulus of 1,000,000 psi) is placed over a 3 inch AC binder course (modulus of 500,000 psi), the composite modulus for the combined 5 inch AC layer is 673,000 psi. When surface treatments are present, their thickness should be included in the total surface thickness, but their presence should be ignored when determining the composite modulus value.

4. Define Modulus Range for AC Layer(s)

   Once the initial or composite modulus of each AC layer has been defined, the range of moduli is determined as follows:

$$\text{Range} = 0.25*E(\text{initial or composite}) \text{ to } 3.00*E(\text{initial or composite}) \qquad (9)$$

   The upper limit of the AC layer modulus range defined by the above relationship is not to exceed 3,000,000 psi.

Portland Cement Concrete Layers

The procedure to define the modulus range for portland cement concrete layers is considerably simpler than that for asphalt concrete layers. One reason for this is that more strength tests are being performed on PCC layer materials (static modulus, compressive strength, and splitting tensile strength). Most of this testing has been completed and is now stored in the LTPP data base. The other reason is that PCC moduli are not as temperature dependent as those for AC materials, thus the anticipated range of values can be more easily approximated in the absence of any information.

The specific set of rules used to define the range of moduli for PCC layers is as follows:

1. Determine Initial Modulus of PCC Layer(s)

   Depending on the type of laboratory strength data available, the initial PCC modulus is determined in the following priority order:

   - If static modulus (E) test results are available, these values are used directly in the definition of the layer moduli range.

   - If static modulus data are not available but compressive strength results are, the following equation is used to determine the initial modulus value (5):

$$E = 57{,}000 * (f_c')^{0.5} \qquad (10)$$

where E = PCC modulus, in psi, and f_c' = 28-day compressive strength, in psi.

- If neither static modulus or compressive strength data are available but splitting tensile strength results are, the following equation is used (6):

$$f_c' = 12.53 * \text{Splitting tensile strength} - 1{,}275 \qquad (11)$$

where the splitting tensile strength is in units of "psi". The value generated from this relationship is the entered into Equation 10 to estimate the initial PCC modulus value.

- If laboratory strength test data are not available, an initial modulus value of E = 4,000,000 psi is used.

2. Define Modulus Range for PCC Layer(s)

As with AC layers, once the initial modulus of each PCC layer has been established, the range of moduli is determined as follows:

$$\text{Range} = 0.25*E(\text{initial}) \text{ to } 3.00*E(\text{initial}) \qquad (12)$$

Also, the upper limit of the PCC layer moduli range defined by the above relationship is not to exceed 9,000,000 psi.

Base and Subbase Layers

Although many models for estimating the modulus of unbound and stabilized base and subbase materials are available in the current literature, a somewhat simplistic approach is used in the SHRP backcalculation procedure to estimate the initial modulus and modulus ranges for these material types. One reason for taking this approach is that existing models do not cover the full range of material types encountered in the SHRP pavement test sections. Another reason is that many of the material parameters required by these models are not yet available from the LTPP data base, though eventually, many of them will be. For now, however, the following rules are used:

- For unbound granular base and subbase materials, the initial modulus and range of moduli are determined on the basis of material type as shown in Table 2. If the lower bound of the modulus range is greater than the initial subgrade modulus (discussed in the next section), use the latter as the lower bound instead of the above guidelines.

Table 2 - Initial Modulus and Moduli Range for Unbound Base and Subbase Materials

Material Type	Initial Modulus (ksi)	Moduli Range (ksi)
Crushed Stone, Gravel or Slag		
Bases	50.0	10.0 to 150.0
Subbases	30.0	10.0 to 100.0
Gravel or Soil-Agg. Mix, Coarse		
Bases	30.0	10.0 to 100.0
Subbases	20.0	5.0 to 80.0
Sand		
Bases	20.0	5.0 to 80.0
Subbases	15.0	5.0 to 60.0
Gravel or Soil-Agg. Mix, Fine		
Bases	20.0	5.0 to 80.0
Subbases	15.0	5.0 to 60.0

- For stabilized base and subbase layers, estimates of the initial modulus and range of moduli are based on unconfined compressive strength data, which are generally available from the LTPP data base. The recommended values are summarized in Table 3, according to the stabilizing agent used. If unconfined compressive strength data is lacking, a value of 400 psi is assumed for lime stabilized layers, 700 psi for asphalt stabilized layers, and 1000 psi for cement stabilized materials for input into Table 3.

Subgrade Layers

The concept used to estimate the initial subgrade modulus from the measured deflections is illustrated in Figure 2, which shows a pavement structure being deflected under a load. As the test is conducted, the load applied to the surface is distributed through the depth of the pavement system. The distribution of stresses, represented in this figure by the "Zone of Stress", is obviously dependent upon the stiffness or modulus of the material within each layer. As the stiffness of the material increases, the stress is spread over a much larger area.

Figure 2 also shows a radial distance ($r = a_{3e}$) in which the stress zone intersects the interface of the subbase and subgrade layers. When the deflection basin is measured, any surface deflection obtained at or beyond the a_{3e} distance are due only to stresses, and hence deformations, within the subgrade itself. Thus, the outer readings of the deflection basin reflect the in-situ modulus of the subgrade soil.

Using this concept, the initial subgrade modulus is estimated from the composite moduli predicted for radial distances greater than the effective radius, a_{3e}, of the stress bulb at the pavement-subgrade interface; as indicated by the horizontal dashed line in Figure 3 for linearly elastic subgrades or by the upward trend for non-linear (stress dependent) subgrades. The composite modulus is a single value representation of the overall pavement stiffness, at a given radial distance, that combines the modulus of elasticity of all layers present in the pavement.

The specific set of rules used in the SHRP backcalculation procedure involves the following steps (4):

Table 3 - Initial Modulus and Moduli Range for Stabilized Base and Subbase Materials

Material Type	**Unconf. Comp. Strength (psi)**	**Initial Modulus (ksi)**	**Modulus Range (ksi)**
Lime Stabilized	< 250 250-500 > 500	30.0 50.0 70.0	5.0 to 100.0 10.0 to 150.0 15.0 to 200.0
Asphalt Stabilized	< 300 300-800 > 800	100.0 150.0 200.0	10.0 to 300.0 25.0 to 800.0 50.0 to 1500.0
Cement Stabilized	< 750 750-1250 > 1250	400.0 1000.0 1500.0	50.0 to 1500.0 100.0 to 3000.0 150.0 to 4000.0
Fractured PCC	-----	500.0	100.0 to 3000.0
Others	-----	50.0	10.0 to 150.0

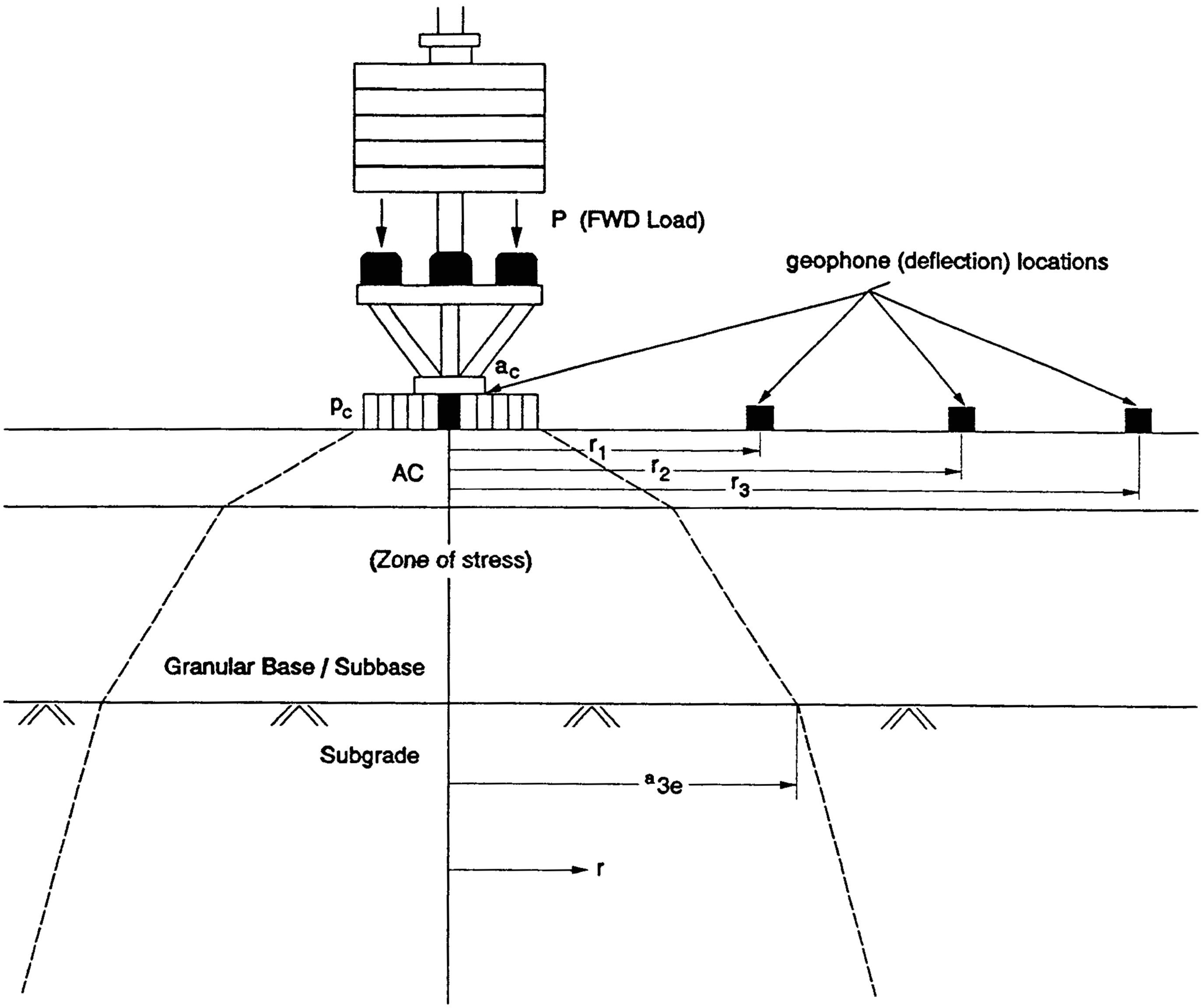

FIGURE 2. Schematic of stress zone within pavement structure under FWD load.

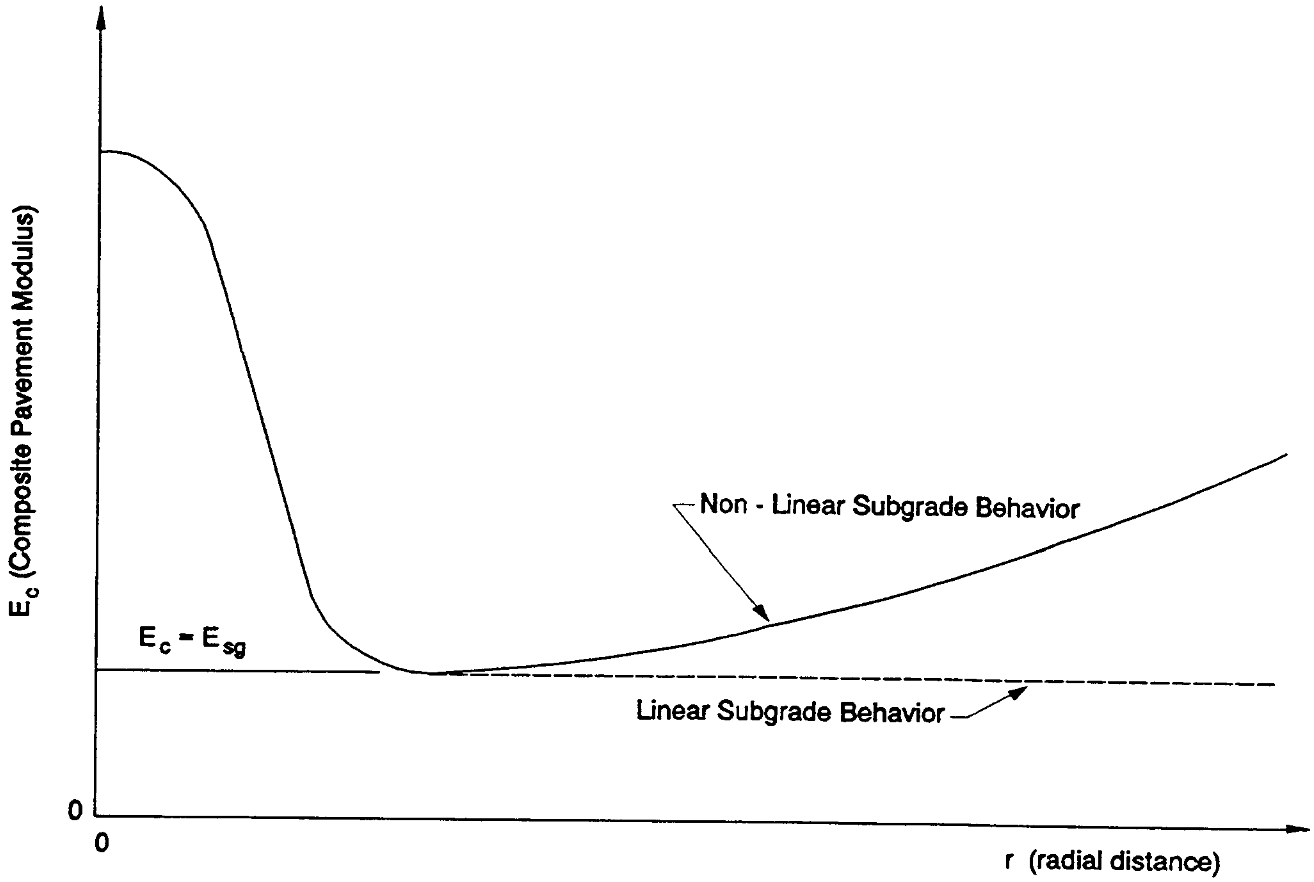

FIGURE 3. Composite modulus vs. radial distance plot.

- Calculate the composite modulus of the pavement at each radial distance beyond 5.91 in. (i.e., 8, 12, 18, 24, 36, and 60 in.) using the measured deflection data as input into Boussinesq's one-layer deflection equation:

(13)

$$E(comp) = \frac{p_c * a_c^2 * (1 - u^2) * C}{def * r}$$

where E(comp) = pavement composite modulus; p_c = contact pressure applied by FWD, from data base; a_c = load plate radius, from data base (5.91 in.); u = Poisson's ratio of subgrade, assume to be 0.4; def = measured deflection at given radial distance "r", from data base; r = radial distance for deflection in question; and C = deflection constant equal to:

$$C = 1.1 log\left(\frac{r}{a_c}\right) + 1.15$$

- Assume that the initial subgrade modulus is equal to the minimum composite pavement modulus:

$$E(subgrade) = E(comp)_{minimum} \qquad (15)$$

Note that the MODULUS program requires only an initial modulus value for the subgrade, not a range of modulus.

Modeling of Pavement Structure

Along with known layer thicknesses, the layer moduli derived from the SHRP backcalculation rules will provide much of the information required to run the MODULUS program, but not all. Because the MODULUS program is limited to a maximum of 4 unknown layers, prioritized guidelines are required for combining two or more layers in pavement structures with more than 4 layers. Likewise, rules for fixing layer moduli in complex pavement structures, thin asphalt concrete layers, and treated subgrade soils are also required. Another item that must be covered by these rules is the assignment of a Poisson's ratio for each pavement layer.

The specific set of rules used by the SHRP procedure for modeling of pavement structures in backcalculation analyses is as follows:

Subgrade Layers

- Lime, asphalt (mixed in place), or cement stabilized subgrade is treated as a subbase layer.

- If shoulder boring data or other similar information indicates that a rigid layer is present within 20 feet of the surface, then the subgrade thickness is defined in accordance with this information. Otherwise, the MODULUS option to calculate the depth to an effective rigid layer is used; i.e., to look for rigid layer effects at depths of up to 50 feet. If no rigid layer is found within this range, then the depth to rigid layer defaults to 50 feet.

- When analyzing a three-layer pavement system, the subgrade is modeled as two layers and the thickness of the top subgrade layer is assumed to be equal to 36 inches. This is done to account for possible changes in subgrade modulus with depth due to such factors as the stress sensitivity of the subgrade soil, varying moisture conditions, etc. However, if the total subgrade thickness is less than 72 inches (due to presence of rigid layer) a single subgrade layer is used.

Thin Layers

- If the total thickness of the AC layer is less than 3 inches, fix the modulus of this layer equal to that derived from Equation 1 or 6.

- If a thin layer ($\leq$ 2 inches) exists beneath portland cement concrete, neglect the modulus of this layer and combine its thickness with that of the underlying layer.

Pavement Structure

As indicated earlier, the maximum number of layers (with known or unknown modulus) that can be modeled in the MODULUS program is 4, exclusive of the effective rigid layer. If more than 4 layers are present, the prioritized list of rules given below are used to reduce the number of layers included in the backcalculation analysis.

1. Combine adjacent granular base and subbase layers, if more than one is present and material types are similar (e.g., crushed stone base and crushed gravel subbase not crushed stone base and sand subbase). The total thickness for the composite layer is equal to the sum of the thicknesses for the adjacent layers, while the modulus range is defined by the combined range of the layers (i.e., largest maximum, smallest minimum).

2. Combine adjacent AC layers of different construction dates, if more than one is present (e.g., overlay plus original surface). Use Equations 7, 8 and 9 to determine the total thickness and moduli range for the composite layer. If the total thickness is still less than 3 inches, fix the modulus of this composite layer as that generated from Equation 8.

3. Combine adjacent stabilized base and subbase layers, if more than one is present and material types are similar (e.g., cement stabilized base and subbase, not cement stabilized base and lime stabilized subgrade, which is treated as a subbase). The total thickness and modulus range for the composite layer is determined in the same fashion as in Item 1 above.

4. Combine adjacent granular base and subbase layers, if more than one is present; material types do not have to be similar; e.g., crushed stone base and sand subbase. The total thickness and moduli range for the composite layer is determined in the same fashion as in Item 1 above.

5. Combine adjacent subbase and subgrade layers, if material types are similar; e.g., sand subbase over sandy subgrade. If this done, the initial subgrade modulus should be used in the backcalculation analysis. The thickness of this combined layer will depend on whether or not a rigid layer (actual or effective) exists below the subgrade.

6. Combine adjacent AC and asphalt treated layers, if more than one is present; e.g., original surface plus asphalt treated base. Use Equations 7, 8 and 9 to determine the total thickness and moduli range for the composite layer.

7. Combine adjacent cement-stabilized and lime-stabilized base/subbase layers, if more than one is present; e.g., cement stabilized base and lime stabilized subgrade (treated as subbase). The total thickness and moduli range for the composite layer is determined in the same fashion as in Item 1 above.

Poisson's Ratio

Recommendations for assigning Poisson's ratios as a function of material type abound in the literature. Based on this information and recommendations by the Deflection Testing and Backcalculation ETG, the values shown in Table 4 have been selected for use in the SHRP backcalculation procedure.

Table 4 - Poisson's Ratio as a Function of Material Type

Material Type	**Poisson's Ratio**
Asphalt Concrete	
E > 500 ksi	0.30
E < 500 ksi	0.35
Portland Cement Concrete	0.15
Stabilized Base/Subbase	
Lime	0.20
Cement	0.20
Asphalt	0.35
Other (stabilized subgrade)	0.35
Other (fractured PCC)	0.30
Granular Base/Subbase	0.35
Cohesive Subgrade	0.45
Cohesionless Subgrade	0.35

Evaluation of Analysis Results

The third and final set of rules focus on the evaluation of the backcalculation results. Maximum allowable deflection matching error limits are established, both for the individual sensors as well as all sensors combined. Guidelines for checking the reasonableness of the results are also provided in these rules, along with procedures to be followed in case of bad or questionable data.

The specific rules for the evaluation of the results are as follows:

- All backcalculation results must be carefully reviewed by an engineer familiar with the backcalculation process.

- If the results fail the convexity test, the range of moduli must be widened (reduce lower bound by 50% and increase upper bound by 100%), and the backcalculation rerun. If the results are similar to those from the first run, they should be accepted whether they pass the convexity test or not. If the results from the second run differ from those from the first run, but pass the convexity test, they should be accepted. Otherwise, they are not considered valid.

- Results having an average absolute arithmetic error in excess of 2% are not valid. This corresponds to a total sum of absolute error of 14% when all seven sensors are used in the back-calculation; 10% when only five sensors are used, and so on.

- Predicted moduli which hit the boundaries provided as input into the backcalculation are not considered valid.

- When the deflection errors fail to meet the 2% tolerance, the modulus results hit an upper or lower bound, or the results are considered "unreasonable" in the judgement of the reviewer, the engineer must look for obvious problems, by verifying the input data, comparing the results with laboratory data, and checking the distress film. In the absence of obvious errors, unacceptable results will be set aside for further evaluation.

Other Considerations

Despite all of the above rules, the evolving nature of the science (or art) of backcalculation makes it likely that early experience with this procedure will bring to light areas where further refinement is needed. Hence, it is anticipated that the initial release of the SHRP backcalculation procedure will be followed up, as we learn more about the strengths, weaknesses, and requirements of the process.

While the initial analysis of the LTPP deflection data has not been completed, it is anticipated that new rules will likely be added to the existing SHRP backcalculation procedure and/or that existing ones may be modified. For example, based on preliminary analysis results, it is possible that the following rules will be implemented in the SHRP backcalculation procedure:

- Using the same rules described earlier in the report, fix the modulus of AC layers having thicknesses of 6 inches or less and constructed on portland cement concrete or other stiff materials (e.g., cement treated bases).

- In the case of portland cement concrete pavements, combine adjacent unbound base and subbase layers underneath the PCC slab. The total thickness for the composite layer is equal to the sum of the thicknesses for the adjacent layers, while the moduli range is defined by the combined range of the layers.

- In addition to AC layers, combine other "thin" material layers placed below PCC slabs with other adjacent base, subbase or subgrade layer.

- As more laboratory modulus test results become available (i.e., stored in the LTPP data base), these data will be used to estimate the initial value and range of moduli for the various material types.

SUMMARY AND CONCLUSIONS

This report focused on a standard backcalculation procedure, developed around the MODULUS program , to ensure that the backcalculation process applied in the LTPP deflection data analysis is as consistent, productive, and straightforward as possible. The procedure consists of a rigorous set of application rules which rely on the wealth of information stored in the LTPP data base to generate the input -- modeling of pavement structure, layer moduli ranges, Poisson's ratios, etc. -- for the backcalculation program.

In conjunction with data base queries, the SHRP backcalculation rules are used to generate data files for direct input into the backcalculation program. As detailed in the report, these rules are used to model the pavement structure and to establish initial moduli or moduli ranges for use in conjunction with measured deflections and loads in the backcalculation analysis. Additional rules address the subsequent evaluation of the backcalculation results.

Despite these rules, the evolving nature of the science (or art) of backcalculation makes it likely that early experience with this procedure will bring to light areas where further refinement is needed. Hence, it is anticipated that the initial release of the SHRP backcalculation procedure will be followed up, as we learn more about the strengths, weaknesses, and requirements of the process. Already, preliminary analysis results seem to indicate that new rules will need to be added to the SHRP backcalculation procedure and/or that some of the existing ones may have to be modified.

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