Implementation of Backcalculation in Pavement Evaluation and Overlay Design in Oregon

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The implementation of the BOUSDEF backcalculation program with emphasis on the comparison between the laboratory-tested and backcalculated moduli and in using the backcalculated moduli in overlay design is presented. In doing so, two projects, both conventional flexible pavement structures, were evaluated for overlay design requirement. The deflections were measured with a KUAB falling weight deflectometer, and pavement temperature was measured during the deflection tests. The laboratory tests included determination of modulus for asphalt concrete (AC) cores and base materials. For the AC cores, the diametral test procedure (ASTM D4123) was followed. The cores were tested at three temperatures—42°F, 73°F, and 95°F—to determine the AC modulus-temperature relationship. For the base material, the triaxial test procedure (AASHTO T-274) was used. The comparison showed that for the AC materials, the backcalculated moduli are generally lower than those that are laboratory tested and also seemed to be less susceptible to temperature variations. For the base material, the backcalculated modulus slope (k_2) is slightly higher than that determined from laboratory testing. However, in the range in which pavement stresses generally fall, a satisfactory comparison is observed. On the basis of the backcalculated and the laboratory results, inputs were developed for pavement overlay design using a mechanistic approach. The overlay design recommendation on these two projects were also compared with those from the ODOT (Oregon Department of Transportation) standard overlay design procedure. The results from both the mechanistic approach and the ODOT procedure were very close, implying that the backcalculated moduli provided a reasonable estimate of the existing pavement properties.

Using backcalculation techniques to determine pavement layer moduli has received increasing interest among the pavement engineering community. To date, a number of computer programs have been developed that use various algorithms. Oregon Department of Transportation (ODOT) has been using a backcalculation program, BOUSDEF, developed at Oregon State University (*1*). The BOUSDEF program is based on the method of equivalent thicknesses together with Boussinesq's theory. The program, because of its extremely fast computing speed and capability of determining nonlinearity of granular base and fine subgrade, has been used to assist ODOT pavement engineers in evaluating existing pavement structural properties and in developing inputs for pavement or overlay design using a mechanistic approach. The BOUSDEF program was initially evaluated by three approaches: (a) comparing the backcalculated moduli with theoretical moduli, (b) comparing the backcalculated moduli with results from other developed backcalculation programs,and (c) comparing backcalculated moduli with those from the laboratory tests. The evaluation indicated that the moduli backcalculated using the BOUSDEF program compared very well with the theoretical moduli and also are very similar to those from other developed programs. The moduli determined from the backcalculation and the laboratory tests were also compared on a limited scale and the results were promising.

This paper presents the implementation of the BOUSDEF program with emphasis on the comparison between the laboratory-tested and backcalculated moduli for asphalt concrete (AC) and base materials and the use of the backcalculated moduli in overlay design. Two projects, both conventional flexible pavement structures, were selected for this purpose. To verify the backcalculated results, pavement materials were obtained and tested in the laboratory for determining resilient modulus. On the basis of the backcalculated and laboratory-tested values, a set of design inputs was developed and used in a mechanistic approach for the development of overlay thickness. The overlay thickness was then compared with that from the standard procedure currently used in Oregon. The procedures used in this study are as follows:

1. Select project sites for evaluation.
2. For selected sites, perform pavement condition survey and deflection test.
3. Backcalculate pavement layer moduli from deflection basin data.
4. Obtain samples from same road section where deflections were measured.
5. Perform laboratory tests on samples.
6. Compare results from backcalculated and laboratory tests.
7. Determine pavement layer moduli and other inputs for overlay design.
8. Perform overlay design using a mechanistic approach and the ODOT procedure.

BACKCALCULATION AND LABORATORY TESTING PROGRAM

Project Descriptions

Two project sites were selected for this study. These two projects are typical conventional pavement structures con-

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sisting of an asphalt concrete surface layer over an aggregate base and subgrade. Project 1 is located by the Columbia River, in northern Oregon. The pavement was constructed in 1969 and has an average thickness of 6.8 in. of AC and 18 in. of aggregate base on the subgrade. In 1989 a pavement condition survey was conducted. The pavement had moderate rutting, extensive cracking, and apparent delamination and was rated fair to poor. The subgrade was identified in the field as sandy gravel, brown in color, nonplastic, damp, and very dense. Project 2 is situated at the south end of the Willamette Valley in western Oregon. The pavement was constructed in 1967 and has 4 in. of AC and 16 in. of aggregate base on the subgrade. The condition survey results showed that the pavement had light to moderate alligator cracking and moderate transverse cracking. The pavement was rated fair to poor. The subgrade is fine-coarse sandy gravel and dense.

Deflection Test

Deflection tests were performed in both travel directions of the selected projects using KUAB falling weight deflectometer (FWD). The impulse force is created by dropping a set of two weights from various heights. By varying the drop height, the load at the pavement surface was varied from approximately 3,000 to 15,000 lb. A smooth load pulse similar to that created by a moving wheel load is generated by using the two-mass system (*2,3*). Surface deflections were measured with seismic transducers that are lowered automatically with the loading plate. The sensor locations may be adjusted for the project requirement. For Project 1, the sensors were set at distances of 0, 8, 12, 24, 36, and 58 in. For Project 2, the sensors were set at distances of 0, 12, 24, 36, 60, and 99 in. Although the sensor settings were arbitrary for this study, it is important to have one sensor that is far enough away from the load to obtain the pavement response from the subgrade. For these projects, this distance is approximately 36 in. from the load.

Project 1 is approximately 1 mi long. The deflections were measured at 250-ft intervals in both travel directions. Three FWD load levels, ranging from approximately 3,000 to 12,000 lb, were applied at each test spot. There were 45 test spots for this project. Deflections were automatically recorded with a personal computer. Pavement surface temperatures were measured immediately before the deflection testing was performed. Eastbound, the measured pavement surface temperature was 66°F. Westbound, the measured pavement surface temperature was 78°F.

Project 2 is approximately 1.3 mi long. The deflections were measured at 200-ft intervals. At each test location, two load levels were applied ranging from 8,000 to 14,000 lb. There were 70 test locations for this project. Recorded data at each test location included pavement surface temperature, load applied, and deflection at each sensor location. For this project, the pavement surface temperatures were measured during the deflection testing with a thermometer mounted on the FWD. The pavement surface temperature varied from 50°F to 92°F.

Backcalculation of Layer Moduli

The BOUSDEF program was used to backcalculate the modulus for each pavement layer from the deflection data. All raw data, without correcting for temperature, were used to calculate the pavement moduli at the time of testing. This was intended to obtain a whole picture of pavement layer properties for the project. During backcalculation, typical modulus range and initial modulus values for AC, aggregate base, and subgrade were used. Poisson's ratios for AC, aggregate base, and subgrade were set at 0.35, 0.4, and 0.45, respectively. Deflections measured at various load levels were used to backcalculate layer moduli at various stress levels to determine nonlinearity of the base and subgrade materials. Table 1 presents the summary of the backcalculated results. The backcalculated results show that the base material is stress sensitive whereas the subgrade material appears not to be.

Materials Sampling

Pavement materials sampled at both project sites included asphalt concrete cores and base aggregates. Subgrade soil was not obtained because of difficulties in getting undisturbed soil samples.

For each project, eight 4-in.-diameter asphalt concrete cores were obtained for the determination of resilient modulus. Bag samples of aggregate materials were also obtained for the modulus testing.

Laboratory Tests

Laboratory tests were performed on the pavement samples for resilient modulus. For the AC cores, the diametral test (ASTM D-4123) was followed. For the aggregate base ma-

TABLE 1 Summary of Backcalculated Modulus

Project	AC Modulus (ksi)	Base Modulus (psi)	Subgrade Modulus (ksi)
1	480[1] 221[2]	For westbound: $MR = 11{,}100*\theta^{0.33}$ For eastbound: $MR = 9{,}800*\theta^{0.29}$	21[1] 6[2]
2	678[3] 287[2]	For westbound: $MR = 5{,}100*\theta^{0.72}$ For eastbound: $MR = 9{,}700*\theta^{0.42}$	15[3] 5[2]

[1] Average modulus based on a total of 135 deflection readings

[2] Standard deviation

[3] Average modulus based on a total of 140 deflection readings

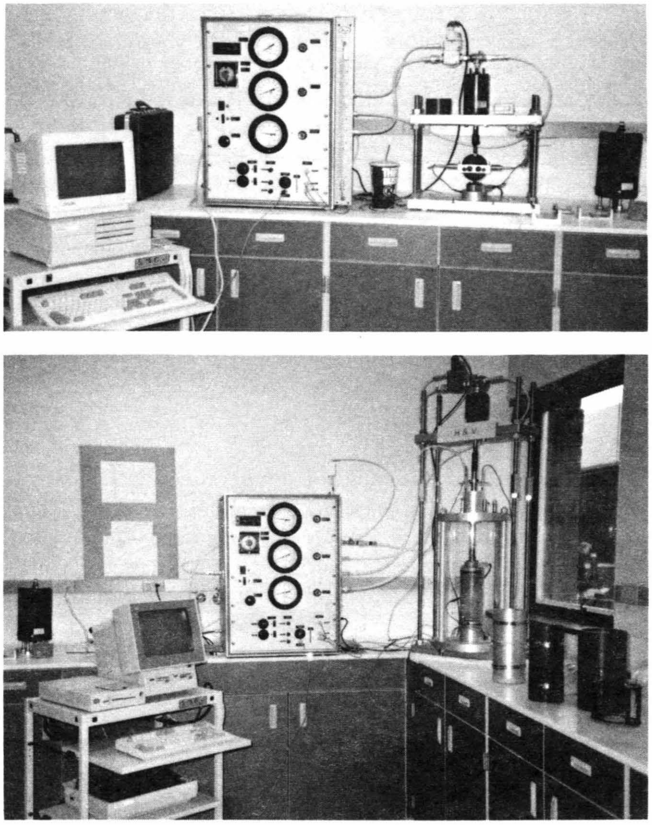

FIGURE 1 Resilient modulus testing system: *top*, diametral testing system; *bottom*, triaxial testing system.

terial, the triaxial test (AASHTO T-274) was used. The AC core samples for the purpose of testing were trimmed to a height of approximately 1.5 to 2.5 in., depending on the thickness of the surface lift. The resilient modulus test was then performed on the surface cores.

The AC cores were tested at three temperatures—42°F, 73°F, and 95°F—to determine the influence of the temperature on the modulus of the asphalt concrete. A diametral testing system was employed for the test (*4*). This testing system can be used for both diametral and triaxial resilient modulus test. The set up of the system is illustrated in Figure 1. For the diametral test, a temperature chamber was used for the control of the temperature. The data acquisition and modulus calculation were accomplished by a microcomputer that is connected to the testing system. Table 2 summarizes the test results for both projects. Actual temperatures at time of testing were recorded. The measured resilient modulus at 73°F and 95°F from Project 2 are much higher than those from Project 1 and also appear to be higher than those for conventional AC at the same temperature range. The cause of these higher moduli is not known. It is very likely that a stiff asphalt could have been used in this project.

The triaxial resilient modulus test on aggregate base material was performed by following AASHTO T-274. For Project 1, the moisture-density relationship for the aggregate base material was determined in accordance with the AASHTO T-99 Method C. The samples for the resilient modulus test were then prepared at the maximum density with the optimum moisture content. The actual moisture content at time of testing was slightly less than the optimum, indicating a slight loss of moisture during the testing. The density and actual mois-

TABLE 2 Summary of Laboratory-Tested AC Resilient Modulus

Project	Sample ID	Resilient Modulus (ksi)		
		42°F	73°F	95°F
1	1-1	2,521	477	183
	1-2	2,886	834	516
	1-3	3,563	728	538
	1-4	2,316	848	601
	1-5	2,733	624	262
	1-6	3,441	718	404
	1-7	2,536	811	560
	1-8	2,054	654	159
	Average	2,756	712	403
	STD	491	117	167
2	2-1	2,874	1,634	792
	2-2	2,673	1,296	469
	2-3	2,898	1,725	841
	2-4	2,262	1,373	515
	2-5	2,723	1,384	696
	2-6	2,369	1,482	602
	2-7	2,794	1,678	715
	2-8	2,794	1,754	752
	Average	2,674	1,541	673
	STD	219	167	124

ture content were measured right after the triaxial test and are summarized in Table 3. Resilient modulus test results for both samples are plotted in Figure 2. The test results from this project indicate that for the same material the resilient modulus values increase proportionally to the sample density.

For Project 2, the samples were prepared at the field moisture condition. The aggregate materials were delivered to the laboratory directly from the field, and samples were made immediately. Four samples were made and similar compaction efforts were applied to each sample. Table 4 presents the moisture content and density results that were measured immediately after the modulus testing, whereas the resilient modulus test results are summarized in Figure 3. The test results from this project seem to indicate that for the same material, when compacted with similar effects, the relationship between the modulus and bulk stress would be similar.

Comparison of Backcalculated and Laboratory-Tested Resilient Moduli

For AC material, comparisons between the backcalculated and laboratory-tested results are provided in Figures 4 and 5. The comparisons show that for asphalt concrete, the backcalculated moduli are generally lower than the laboratory-tested moduli and also seem to be less susceptible to tem-

TABLE 3 Density Results, Project 1

Sample ID	Optimum Moisture (%)	Maximum Dry Density (pcf)	Actual Moisture (%)	Actual Dry Density (pcf)	Relative to Max Density (%)
A	5.2	136.6	5.1	136.3	99.8
B	5.2	136.6	5.0	131.3	96.1

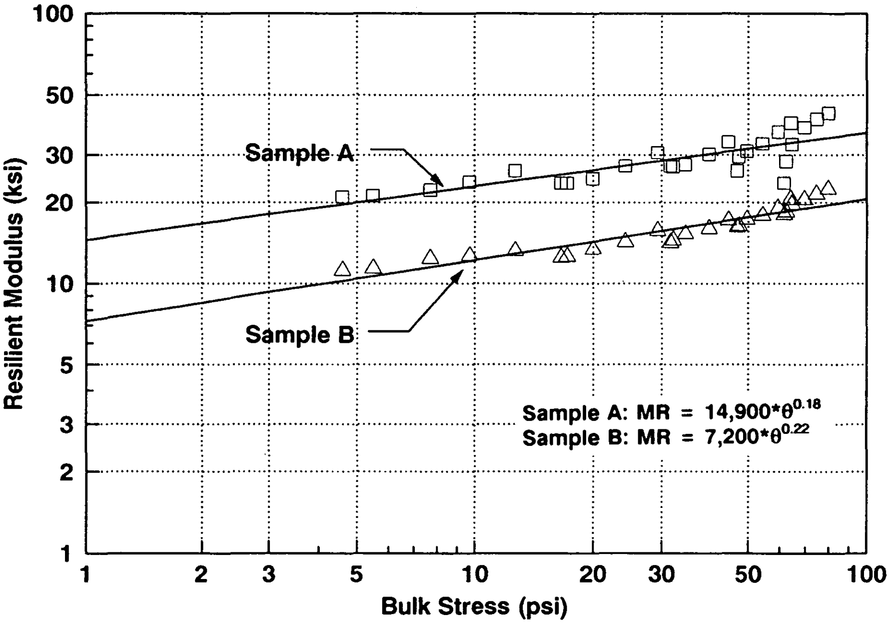

FIGURE 2 Laboratory-tested moduli for Project 1.

TABLE 4 Density Results, Project 2

Sample ID	Moisture Content (%)	Dry Density (pcf)
A	5.3	125.0
B	4.8	126.0
C	7.7	121.8
D	6.7	124.3

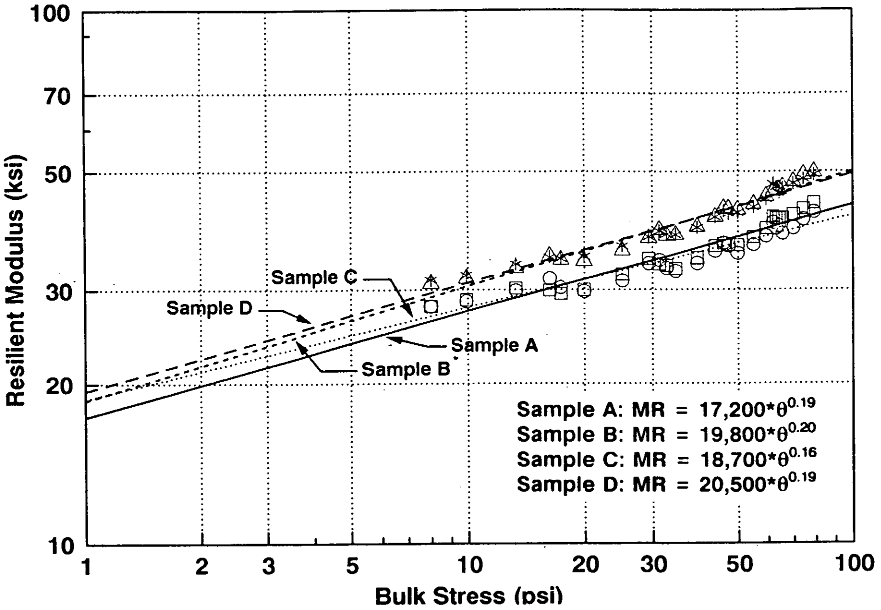

FIGURE 3 Laboratory-tested moduli for Project 2.

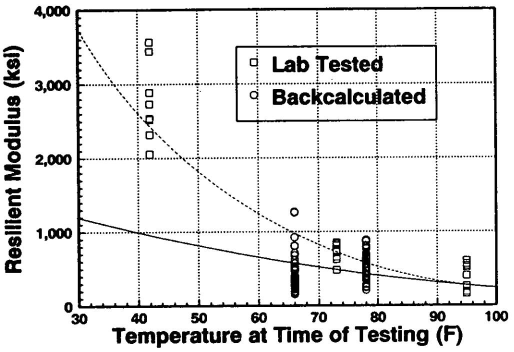

FIGURE 4 Comparison between laboratory-tested and backcalculated AC moduli, Project 1.

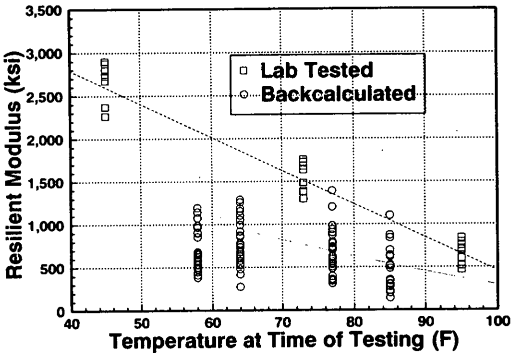

FIGURE 5 Comparison between laboratory-tested and backcalculated AC moduli, Project 2.

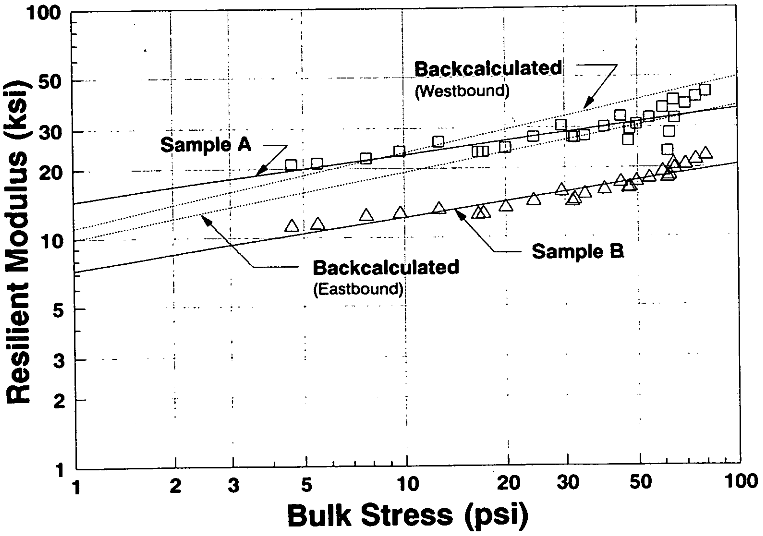

FIGURE 6 Comparison between laboratory-tested and backcalculated base moduli, Project 1.

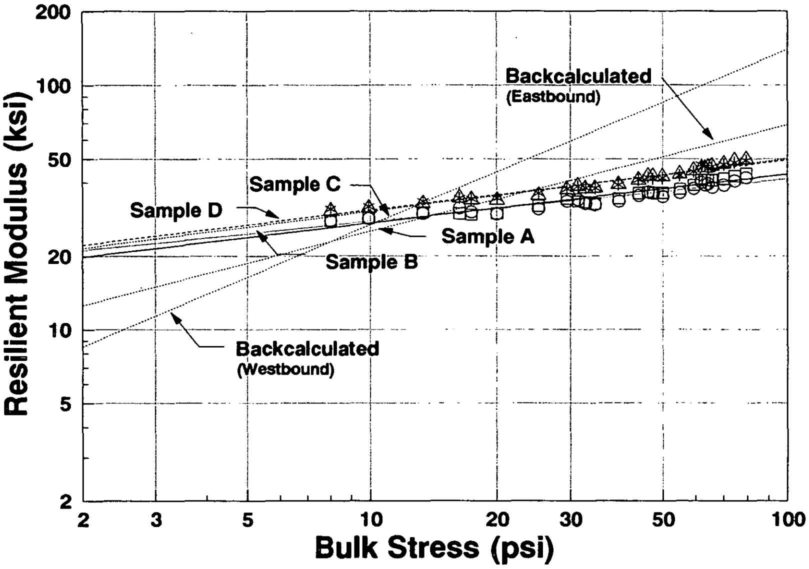

FIGURE 7 Comparison between laboratory-tested and backcalculated base moduli, Project 2.

perature variation. At the same temperature, the average difference can be expected to be 20 to 30 percent. The existing pavements had moderate to extensive cracking; these factors may contribute to the lower backcalculated AC moduli.

The difference may also result from the method used in moduli determination. The backcalculated AC moduli are more of a weighted average value for an entire layer, whereas the laboratory-tested moduli, which were measured on intact surface cores, are more representative of resilient modulus of the specimen. If the cores were taken from an uncracked portion of the AC layer and were of good quality, a higher resilient modulus would be expected. However, this may not truly reflect the entire AC layer material property. For the aggregate base material, the backcalculated modulus slope (k_2) is slightly higher than the laboratory-tested moduli, as can be seen in Figures 6 and 7. However, in the range of bulk stress in which actual pavement stresses generally fall (e.g., 5 to 20 lb/in.^{2}), a favorable comparison can be found.

DEVELOPMENT OF DESIGN INPUTS FOR OVERLAY DESIGN

Pavement Layer Moduli

The backcalculated moduli represent the pavement material properties corresponding to the temperature at the time of deflection testing. These modulus values may be converted to a standard design temperature or to other temperatures to consider temperature effects, similar to seasonal effects, on the pavement materials. For this study an attempt was made to consider environmental effects on the two projects. To do so, a representative temperature for each season was determined on the basis of local weather data. This representative temperature as used in this study was an average temperature for each season. The pavement temperatures used for characterizing the material properties within each season are presented in Table 5, along with modulus values corrected for

TABLE 5 Representative Temperature and Corresponding Modulus

Project	Description	Spring	Summer	Fall	Winter
1	Temperature (°F)	49	70	48	37
	AC modulus (ksi)	872 (0.50)[1]	436 (1.00)	908 (0.48)	1,282 (0.34)
	Base modulus (ksi)	20[2]	26	27[2]	20[2]
	Subgrade modulus (ksi)	15[2]	21	21[2]	15[2]
2	Temperature (°F)	50	64	49	42
	AC modulus (ksi)	1,240 (0.52)	777 (0.83)	1,290 (0.50)	1,573 (0.41)
	Base modulus (ksi)	44	50[2]	45[2]	40[2]
	Subgrade modulus (ksi)	15	20[2]	21[2]	16[2]

[1] Conversion Factor relative to 70°F (from Figure 6). For Project 1, modulus at 70°F is 436 ksi. For Project 2, modulus at 70°F is 645 ksi.

[2] Adjusted based on backcalculated results for considering seasonal effects.

temperature for the asphalt concrete. The resilient modulus for each season was determined by adjusting the backcalculated asphalt concrete modulus to the corresponding temperature, using a relationship shown in Figure 8. The modulus values at various temperatures may also be determined from either the laboratory-tested or the backcalculated results, as shown in Figures 4 and 5. For this study, the laboratory-tested moduli at the same temperatures appear to be high, whereas the backcalculated moduli are more close to those from using the relationship shown in Figure 8.

It should be noted that engineering judgment may be necessary to determine what moduli to be used in the overlay design. In this study, the base moduli were adjusted on the basis of the backcalculated modulus-bulk stress relationship and anticipated pavement stresses. For subgrade, because the soil is not stress sensitive, a single value determined from backcalculation was used. Variation of moisture content in base and subgrade was also a factor considered in developing the layer moduli for each season. In Oregon, summer and fall seasons are much dryer than winter and spring. It was assumed that moisture condition in the base and subgrade would be slightly dryer in summer and fall; therefore, slightly higher moduli were used. If the deflections were measured and moduli were backcalculated for each season, the resilient moduli determined could be directly used in overlay design.

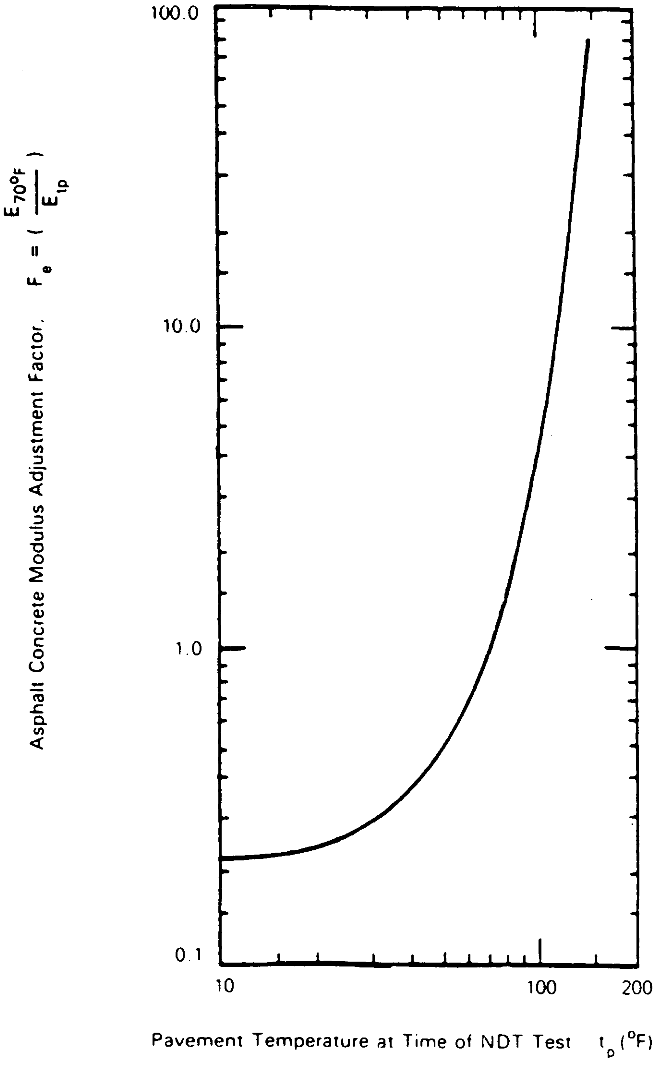

FIGURE 8 Asphalt modulus temperature adjustment factor.

Traffic Data

Projected traffic repetitions were expressed in terms of 18-kip equivalent axial loads (EALs). It is ideal if the historical traffic data are available. These data may help the designer evaluate the remaining life of an existing pavement before an overlay. However, the historic traffic data are usually difficult to obtain. In this study, the historic traffic applications were unknown; therefore, the remaining life of the pavements was not evaluated.

Traffic data for both projects was furnished by the Oregon State Highway Division (OSHD) traffic section. The data came from a 16-hr manual count taken in 1988 and projected for a 20-year design period. The traffic applications were then broken down for each season. The length of each season was determined on the basis of the location of the project.

Overlay Design Using Mechanistic Approach

After establishing the appropriate inputs for overlay design, a mechanistic design program, MECHOD (MECHanistic Overlay Design), was used to determine the thickness of overlay. The MECHOD program was developed at Oregon State University (*5*). The program uses ELSYM5 as its subroutine to calculate critical strains at the bottom of AC layer and on the top of subgrade (*6*). The strains were then used to evaluate fatigue and the subgrade rutting using the relationships developed by Finn and Monismith (*7*) and The Asphalt Institute (*8*), respectively. In MECHOD, pavement damage for each season is determined and the total pavement damage for all seasons in the analysis is summed. The inputs required to run MECHOD included design load, load radius, moduli, and Poisson ratios for each pavement layer, number of seasons in analysis, and historical and projected traffic applications for each season. The modulus value of overlay material and projected traffic applications for each season are presented in Table 6. The modulus values were determined using the representative temperature data shown in Table 5.

During calculation, the MECHOD program first uses the given data to evaluate the existing pavement. If an overlay is needed, on the basis of total pavement damage, the program would ask for the modulus of overlay material. For these two projects, an overlay modulus value of 450 ksi (at 70°F), was used.

The overlay thickness design is an iterative process. For practical purposes, an initial overlay thickness of 1 in. is used in the MECHOD program, with a ½-in. increment for each iteration. The process is repeated until the total pavement damage is less than unity. The design results for the two projects are summarized in Table 7. Total pavement damage for both fatigue and subgrade rutting is also presented in the table. These values indicate that after 20 years of service, the traffic loadings would consume a certain percentage of the

TABLE 6 Inputs for Overlay Design

Project	Description	Spring	Summer	Fall	Winter
1	Traffic	4,526,428	11,275,413	4,526,428	6,776,089
	Length of season (mon.)	2[1]	5	2	3
	% distribution	16.7[2]	41.6	16.7	25.0
	Overlay modulus (ksi)	900	450	938	1,324
2	Traffic	1,151,132	1,533,307	768,956	1,151,132
	Length of season (mon.)	3	4	2	3
	% distribution	25.0	33.3	16.7	25.0
	Overlay modulus (ksi)	865	542	900	1,098

Note: Poisson's ratio was assumed to be 0.35 for AC material for all seasons.

TABLE 7 Overlay Design Results, MECHOD

Project	Overlay Thickness (in)	Total Pavement Damage (%)	
		AC Fatigue	Subgrade Rutting
1	4	96.5	2.2
2	2	98.3	11.3

design life of the pavement. For the projects evaluated, the results show that fatigue damage in the asphalt concrete layer will be a major concern, over 95 percent, whereas the rutting in the subgrade is not significant, less than 12 percent, after overlay is placed. This analysis used a reliability level of 50 percent because ODOT's present overlay design procedure does not take reliability into consideration during overlay design.

Overlay Design Using ODOT Procedure

The present procedure used to determine overlay requirements in Oregon is based on deflection measurements of the existing pavement (*9*). The design procedure is essentially that of the California Department of Transportation, with modifications for Oregon's Traffic and Crushed Base Equivalencies. The procedure suggests that tolerable deflection is a function of traffic and pavement thickness and that additional overlay thickness will reduce measured deflection. The deflections can be measured using either an FWD or the Dynaflect test equipment. Deflections are typically measured every 250 ft within a section. The measured deflections are normalized to an equivalent deflection for a 9,000-lb load at 70°F. For deflections measured using the FWD, the equivalent deflections are determined by interpolating between the deflections measured at loads above and below 9,000 lb. The equivalent deflections are adjusted to account for the in-place pavement temperature. This adjustment is a function of both the pavement temperature at the time the deflections were measured and the thickness of the existing AC layer. For an AC layer greater than 6 in., this procedure does not recommend temperature correction. For an AC layer less than 6 in., the equivalent deflections are multiplied by the temperature correction factor to establish the final normalized deflection.

The normalized deflection is determined for each location where deflections were measured. Statistical analysis is performed to determine average and standard deviation. The 80th-percentile deflection was then calculated and used as a design value to determine the overlay thickness. The 80th-percentile deflection is computed using the equation

$$D_{80} = X + 0.84 * S$$

where

D_{80} = design deflection value (80th-percentile deflection),
X = mean deflection, and
S = standard deviation of deflections.

The 80th-percentile deflection was then compared with a tolerable deflection, which is a function of future equivalent axle load repetitions and the thickness of the in-place pavement. If the 80th-percentile deflection is less than the tolerable deflection, then an overlay is not needed. If the 80th-percentile deflection is greater than the tolerable deflection, then the percentage reduction in deflection is calculated as

$$\% \text{ reduction} = 100 * (D_{80} - D_t)/D_{80}$$

where D_t is tolerable deflection. The value of percent reduction is used to determine the crushed base equivalence factor, meaning the 1-in.-thick asphalt concrete is equivalent to a certain thickness of gravel. The equivalent factor ranges from 1.52 to 2.5. A factor of 2.0 is used by ODOT for overlay design. The determined overlay thicknesses using the ODOT method is summarized in Table 8.

Comparison of Overlay Design Results

The comparison of design results, presented in Tables 7 and 8, indicated that both procedures recommended similar overlay thicknesses. These results may indicate that for these two projects the backcalculated layer moduli are reasonable and can be used in mechanistic approach for overlay design purposes. The basis for this statement is that the two procedures

TABLE 8 Overlay Design Results, ODOT Procedure

Project	D_{80} (mils)	D_t (mils)	% Deflection Reduction	Overlay Thickness (in)
1	14.1	8.0	43.3	3
2	22.1	14.0	36.8	2

yield similar overlay results. The final recommendation for rehabilitation treatment would be determined on the basis of both the required overlay thickness and the existing pavement condition.

FUTURE ACTIVITIES

Implementation of a backcalculation technique to determine pavement layer properties and the use of the backcalculated layer moduli in overlay design provide the practicing engineers a useful tool in understanding and characterizing pavement materials properties. For the state agency, because of the need of future rehabilitation activities, a cost-effective method for determining the structural capacity of existing pavements will provide a tremendous benefit in developing rehabilitation strategies. ODOT has recently purchased a new FWD made by Dynatest, Inc. This equipment has the capacity to obtain a large amount of deflection data quickly; this demands a means to evaluate these data. To automate the backcalculation process and analyze as many test data as possible, the BOUSDEF program is being modified to meet the demand by providing two options: one option allows the engineer to analyze a single set of deflection basin data as it does now and the other to directly access the FWD machine output and consequently perform backcalculation analysis. It is envisioned that this modification should significantly reduce the amount of time needed for the data entry process and provide considerable amount of information for pavement evaluation. It is hoped that with the availability of more information, a better assessment of pavement layer materials can be achieved.

CONCLUSIONS AND RECOMMENDATIONS

This paper has described the implementation of the backcalculation technique and the use of backcalculated results in pavement overlay design in Oregon. The results of the two projects appeared very promising and encouraging. The overlay design results from both the mechanistic approach and the ODOT method were very close, implying that the backcalculated moduli provided a reasonable estimate of the existing pavement layer properties. This conclusion is preliminary and is based on the results from these two projects. Further study on more projects may be necessary to evaluate the reasonableness of the backcalculated pavement layer moduli. In addition, other overlay design procedures may be used to verify the reasonableness of the designed overlay thicknesses.

As a recommendation, backcalculation on deflection basin data should be performed on as many test data as possible. This would avoid biased backcalculation results from using a single test datum. To consider seasonal effects on pavement layer properties, it is recommended that deflection testing be performed for each season and that the deflection data be backcalculated for layer moduli. Finally, limited laboratory tests also should be performed. These tests would provide necessary information for the engineer to verify the backcalculated results and increase the confidence in determining modulus values to be used in pavement design.

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