Comparison of Moduli of Kansas Superpave Asphalt Mixes

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Currently, hot-mix asphalt (HMA) mixture design and pavement structural design are not fully integrated, although Superpave® asphalt mixture design is somewhat project specific. The objective of this study was to compare elastic moduli assumed during structural design of pavements with the backcalculated moduli of HMA layers obtained from the falling weight deflectometer (FWD) tests and the dynamic modulus values measured in the laboratory. Five newly built Superpave pavements, designed by using the 1993 AASHTO Design Guide, were selected as study sites in this research. Deflection data were collected with a Dynatest 8000 FWD on a 1,000-ft test section at each site. The HMA layer moduli were then backcalculated by using an elastic-layer analysis program. Full depth cores were taken from each section and tested in the laboratory for dynamic moduli. The results showed that backcalculated and laboratory moduli were somewhat comparable for all practical purposes. The laboratory dynamic moduli increased with the loading frequency, indicating the need for consideration of vehicle speeds in the HMA pavement structural design. HMA design moduli, assumed by the Kansas Department of Transportation during pavement structural design, are lower than both backcalculated and laboratory dynamic moduli. Thus, current HMA design moduli are achievable in the field through Superpave mixture design, despite the fact that the pavement structural design and mix design processes are not integrated.

Currently, the process of providing hot-mix asphalt (HMA) pavements in most of the United States consists of three steps:

1. Structural design of pavements and mixture specifications are provided by the design unit of a highway agency;
2. HMA mixture design is done by the contractor during the bidding process; and
3. HMA mixture design is submitted (to the agency) by the contractor winning the bid, and the agency verifies and approves the mixture design.

Researchers and consultants have long recommended that HMA mixture and structural design be integrated into one system (*1*). However, these two operations typically remain independent for a number of practical reasons, such as lowest-bid acceptance, giving the contractor freedom to choose aggregates for most-economical mixture design, agency practice regarding bid timing, and the like. For example, in Kansas, bids are opened in late fall to give contractors enough time to haul aggregates to certain locations in the state where good-quality aggregates are not available. Furthermore, apparent disparity between the mixture design and the structural design results from the fact that currently most agencies use the 1993 AASHTO Design Guide for pavement structural design and the Superpave® volumetric method for mixture design. These design procedures use different material properties and design criteria (*1*). In addition, Von Quintus and Hall (*1*) pointed out the following several impediments to implementing an integrated system:

- Institutional and communication barriers (turf protection);
- Reluctance or resistance to change from standard practice;
- Insufficient confidence in new methods;
- Increased complexity of design methods compared with traditional procedures;
- Additional costs and time for pavement and mixture designs;
- Use of proof tests for confirmation of mixture designs (completed by contractor or agency itself);
- Mixture properties unfamiliar or not understood by agency and contractor personnel (unknowns create uncertainty or reluctance to support integration);
- Certification of personnel and equipment;
- Controversy on which transfer function is the "best" for predicting pavement distress;
- Unreasonable predictions from experience create misconceptions and reduce confidence in design process;
- Future changes to the mechanistic–empirical-based (ME-based) mixture tests, replacing transfer functions, ME-based test procedures, or both;
- Climatic effect on test conditions for structural and mixture design; and
- Applicability to quality assurance programs and test plans and forensic investigations.

Until today, however, no precise information is available to see whether the Superpave volumetric mixture design method is able to produce mixtures that will have the properties used in the 1993 AASHTO Design Guide for pavement structural design. For example, according to the AASHTO Guide, a structural layer coefficient of 0.44 translates to an HMA mixture modulus of 435,000 psi. Is that modulus achievable in the field by using an HMA mixture designed by the Superpave volumetric method? Superpave volumetric mixture design is project specific and uses the 20-year design traffic [cumulative 18-kip equivalent single-axle loads (ESALs)] used for the structural design of pavements in the 1993 AASHTO Design Guide.

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PROBLEM STATEMENT

The Kansas Department of Transportation (KDOT) is currently considering adoption of the *Mechanistic–Empirical Pavement Design Guide* (MEPDG) to replace the 1993 AASHTO design method in use now. For new HMA pavement design by MEPDG, the basic input parameter is the dynamic modulus of the HMA mixture. This dynamic modulus is measured in the laboratory with specimens produced in the Superpave gyratory compactor during the design phase. However, verification is needed on whether this input parameter can be achieved in the as-constructed pavement. This study was undertaken for this verification through in situ deflection tests by means of an FWD and concurrent laboratory tests for dynamic modulus on the cores taken from the as-constructed pavements.

OBJECTIVE OF STUDY

The main objective of this study was to compare elastic moduli assumed during structural design of pavements following the 1993 AASHTO Design Guide with the backcalculated moduli of HMA layers obtained from the FWD tests and the dynamic moduli values measured in the laboratory.

TEST SECTIONS

Five newly built Superpave pavements, designed by using the 1993 AASHTO Design Guide, were selected as study sites in this research. On each project, a section 1,000 ft long was set up as the test section. Table 1 lists the study sites, layer and material types, and thicknesses. All sites had a 9.5-mm nominal maximum aggregate size Superpave mixture (known as SM-9.5A and SM-9.5T in Kansas) with performance grade (PG) 64-28 binder in the surface course. The second and third layers consisted of fine-graded, 19-mm nominal maximum aggregate size Superpave mixture (SM-19A) with PG 64-28 and PG 64-22 binders, respectively. The base layer thickness varied from 5 to 8.5 in. The K-7 site in Doniphan County had the thinnest asphalt base (5 in.) because it also had an 11-in. crushed-stone base, designated as AB-3 in Kansas. All sites had lime-treated subgrade except K-7 in Doniphan County, where subgrade was modified with a Class C fly ash (*2*).

Table 2 shows volumetric properties of the mixtures at the test sites. Most properties were similar for all the sites. Binder content for the surface, binder, and base courses varied from 6.0% to 6.8%, 5.5% to 5.7%, and 5.2% to 5.7%, respectively. Information in Table 2 has been used to estimate dynamic moduli, and the results have been reported elsewhere by Gedafa et al. (*2*).

DATA COLLECTION

Deflection Data

Deflection data were collected on all sites with a Dynatest 8000 FWD approximately 8 to 10 weeks after construction. The load pulse duration was between 25 and 30 ms. This frequency enabled a comparison of the backcalculated HMA moduli with the laboratory-measured dynamic moduli at 25 Hz. The target loads used in FWD testing were 9 to 15 kips. Deflection measurements were made in the outside wheelpath of the travel lane at 11 stations at 100-ft intervals. The geophone spacing was 0, 8, 12, 18, 24, 36, and 48 in. for United States routes: US-54, US-77, and US-283. The last sensor was located at 60 in. on Kansas routes: K-7 and K-99. The pavement surface temperature measured during FWD testing allowed subsequent pavement middepth temperature calculation and then temperature corrections in the computed modulus values for the HMA layers. Surface temperature during deflection data collection varied from 63°F to 119°F—the lowest on US-54 and the highest on US-283 (*2*).

Samples for Laboratory Dynamic Modulus Test

From each test site, full-depth cores of 4-in. diameter were taken at the same locations at which FWD deflections tests were done. Cores for some of the sites were taller than 12 in. and cut into two samples each 6 in. tall. In most cases, cores were cut to get one sample. Base layer was favored because it was the thickest, and poor bond between layers also made it difficult to include different layers in the sample.

DATA ANALYSIS

Backcalculation of HMA Modulus

For backcalculation, FWD deflection data were normalized to a 9-kip load. The backcalculation was done on the basis of a multilayered linear-elastic theory. The moduli of thin surface layers or

TABLE 1 Layer Type and Thicknesses

			Thickness (in.)				
Layer	Layer Type	Material Type	US-54, Butler County	US-77, Butler County	US-283, Graham County	K-7, Doniphan County	K-99, Elk County
1	Surface	SM-9.5A (PG 64-28)	1.5[a]	1.5	1.5	1.5	1.5
2	Binder	SM-19A (PG 64-28)	2.5	2.5	2.5	2.5	2.5
3	Base	SM-19A (PG 64-22)	8.5	8	7	5	7
Total HMA thickness			12.5	12	11	9	11
4	Agg. base	AB-3	N/A	N/A	N/A	11	N/A
5	Subgrade	Modified subgrade	6[b]	6[b]	6[b]	6[c]	6[b]

NOTE: N/A means not applicable.
[a]SM-9.5T PG 64-28.
[b]Lime-treated subgrade.
[c]Fly ash–modified subgrade.

TABLE 2 Summary of Volumetric Properties of Superpave Mixes at the Test Sites

	US-54			US-77			US-283			K-7			K-99		
	Surface	Binder	Base	Surface	Binder	Base	Surface	Binder	Base	Surface	Binder	Base	Surface	Binder	Base
P_{200}	4.7	4.3	3.5	4.0	5.3	2.6	4.0	4.9	4.7	3.3	4.6	2.9	2.2	2.8	2.9
P_4	27.0	37.0	33.0	23.0	36.0	37.0	26.0	32.0	28.0	22.0	44.0	37.0	28.0	41.0	34.0
$P_{3/8}$	2.0	18.0	17.0	3.0	17.0	17.0	6.0	18.0	19.0	2.0	29.0	20.0	5.0	24.0	18.0
$P_{3/4}$	0.0	3.0	3.0	0.0	3.0	2.0	0.0	2.0	2.0	0.0	0.0	0.0	0.0	4.0	1.0
Gse	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Gsb	2.5	2.5	2.6	2.5	2.5	2.5	2.6	2.6	2.6	2.5	2.5	2.5	2.5	2.5	2.5
Gmb	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.2	2.2	2.2	2.3	2.3	2.3
Gmm	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Gb	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
%AC	6.0	5.6	5.2	6.1	5.5	5.2	5.8	4.9	4.8	6.4	5.7	5.7	6.8	5.5	5.5
VMA	16.9	16.2	16.5	15.6	14.8	14.1	16.2	15.6	15.2	17.6	15.9	16.3	17.3	15.7	16.1
VFA	72.6	64.3	60.7	74.4	69.2	65.5	72.2	62.4	64.1	64.2	59.9	58.1	74.3	61.3	58.1
Va	4.6	5.8	6.5	4.0	4.6	4.9	4.5	5.9	5.5	6.3	6.4	6.8	4.5	6.1	6.8
Veff	12.7	10.9	10.2	12.0	10.5	9.6	12.1	9.7	10.0	11.7	9.9	9.8	13.4	10.0	9.8

NOTE: P_{200} = percent passing 0.075-mm sieve; P_4, $P_{3/8}$, $P_{3/4}$ = cumulative percent retained on 4.75-, 9.5-, and 19-mm sieves, respectively; Gse, Gsb = effective and bulk specific gravities of aggregate, respectively; Gmb and Gmm = bulk and theoretical maximum specific gravities of the mixture, respectively; %AC and Gb = percent asphalt content and asphalt specific gravity, respectively; VMA and VFA = voids in the mineral aggregates (%) and percent of VMA filled with binder (%), respectively; Va and Veff = air voids (%) and effective asphalt content (%), respectively.

layers "sandwiched" between layers are usually difficult to obtain because surface deflections are often insensitive to changes in the moduli of these layers. Changes in the moduli of subgrade or other thick layers may mask similar changes in thin layers (*3*). In this study, all pavement sections were modeled as three-layer systems by combining all HMA layers into one layer. The backcalculation computer program EVERCALC was used.

EVERCALC is a linear elastic analysis backcalculation program developed by the Washington State Department of Transportation. It uses WESLEA as the response analysis program, a complex integration algorithm based on Wendle's rule and a nonlinear least-squares optimization technique (*4*). It is capable of evaluating HMA pavement structure containing up to five layers. The program uses an iterative approach to find a set of moduli that would provide a calculated deflection basin closest to the measured deflection basin as characterized by the root-mean-square (RMS) error (*5*).

The program requires a set of seed modulus values to start and adopts Newton's method to search for a set of deflections that best match the measured deflections. It uses regression equations to determine seed moduli for HMA pavements with up to three layers. The seed moduli must be user defined when the number of layers exceeds three.

Temperature Correction of Backcalculated Modulus

The most important environmental factor affecting surface deflections and backcalculated HMA moduli is the temperature of the HMA layer. To determine corrected HMA modulus, a two-step correction procedure was followed in this study, as described in the subsections on HMA layer temperature and temperature correction for HMA modulus.

HMA Layer Temperature

The BELLS equation (for S. Baltzer, H. Ertman-Larsen, E. Lukanen, and R. Stubstad, who developed the method) was developed by using the measured temperatures at different pavement depths from the Long-Term Pavement Performance (LTPP) database for predicting temperature at the one-third depth point of the HMA pavement (*6*). After the BELLS2 model was designed, a third model, BELLS3, was subsequently developed for use during routine FWD testing when a pavement surface is typically shaded for less than a minute. The BELLS3 model was used in this study to calculate middepth pavement temperature (*7*):

$$\begin{aligned} T_d &= 0.95 + 0.892T_s + (\log d - 1.25) \\ &\quad * \left[1.83\ \sin\left(2\pi\frac{A}{18}\right) - 0.448T_s + 0.621T_{\text{avg}}\right] \\ &\quad + 0.042T_s \sin\left(2\pi\frac{B}{18}\right) \end{aligned} \qquad (1)$$

where

T_d = pavement temperature at layer middepth (°C),
T_s = infrared surface temperature (°C),
T_{avg} = average of high and low air temperatures on the day before testing (°C), and
d = layer middepth (mm).

A and B are computed as follows:

$$A = \begin{cases} t_d + 9.5 & \text{if } 0 \le t_d < 5 \\ -4.5 & \text{if } 5 \le t_d < 11 \\ t_d - 15.5 & \text{if } 11 \le t_d < 24 \end{cases}$$

$$B = \begin{cases} t_d + 9.5 & \text{if } 0 \le t_d < 3 \\ -4.5 & \text{if } 3 \le t_d < 9 \\ t_d - 13.5 & \text{if } 9 \le t_d < 24 \end{cases}$$

where t_d = time of day (in decimal hours).

The last two variables are used as arguments to a pair of sine functions with 18-h periods and 15.5- and 13.5-h phase lags, respectively. One cycle per day is allowed. During the other 6 h of the day, A and B are set equal to –4.5, so that the sine functions return a value of −1.

Temperature Correction for HMA Modulus

Chen et al. (*8*) developed Equation 2 on the basis of deflections from intact locations (pavement in good condition). This equation was chosen for this study because it can be used to adjust HMA modulus to any temperature. The HMA modulus was corrected to 40°F, 70°F, and 95°F in this study to allow comparison with the design and laboratory moduli.

$$E_{T_w} = \frac{E_{T_c}}{\left[\left(1.8T_w + 32\right)^{2.4462} * \left(1.8T_c + 32\right)^{-2.4462}\right]} \tag{2}$$

where

E_{T_w} = adjusted modulus of elasticity at T_w (MPa),
E_{T_c} = measured modulus of elasticity at T_c (MPa),
T_w = temperature to which the modulus of elasticity is adjusted (°C), and
T_c = middepth temperature at the time of FWD data collection (°C).

Laboratory Tests for Dynamic Modulus

The core samples were trimmed to the required height of 6 in. for tests in a universal testing machine (UTM-25) in the laboratory. UTM-25 is a servo-control testing machine that produces a controlled sinusoidal (haversine) compressive loading. It can apply loads over a range of frequencies from 0.01 to 30 Hz and stress levels up to 400 psi. The environmental chamber holds the temperature of the specimen constant at any temperature ranging from 14°F to 140°F. The measurement system is fully automated. It measures and records the time history of the applied load and axial deformation.

The applied load is measured with an electronic load cell that is in contact with one of the specimen caps. Hardened steel disks transfer the load from the testing machine to the specimen. Top and bottom surface friction is a practical problem for compression-type testing. To eliminate the possibility of having shear stresses on the specimen ends during testing, a pair of rubber membranes with vacuum grease are placed on the top and bottom of each specimen during testing.

Axial deformations are measured with linear variable differential transformers (LVDTs) placed vertically on the diametrically opposite sides of the specimen. Parallel brass studs are used to secure the LVDTs in place. Two pairs of studs are glued on the two opposite cylindrical surfaces of a specimen. The studs in a pair are 4 in. apart and located at approximately the same distance from the top and bottom of the specimen. Base mixes were between the studs in general. Cores of some of the sites were cut into two samples, though there was no significant difference in dynamic moduli between top and bottom samples. This step enabled comparison of backcalculated and laboratory dynamic moduli.

The Standard Method of Test for Determining Dynamic Modulus of HMA Concrete Mixtures (AASHTO TP 62-03) was followed except for some minor modifications in test temperature and frequencies. Minor modifications were made because tests at low temperature took time and caused freezing of the UTM, whereas at high temperature, samples started softening and LVDTs could not be glued to the samples. In this study, three temperatures (40°F, 70°F, and 95°F) and six frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) were used.

KDOT Design HMA Modulus

As noted earlier, KDOT currently follows the 1993 AASHTO Design Guide for HMA pavement design. Equation 3*a* can be used to compute the design modulus of HMA pavements. If all HMA layers (surface, binder, and base) are considered as one layer (as assumed during backcalculation of HMA modulus in this study), the composite layer coefficient can be calculated by KDOT by treating the top 4 in. of the HMA thickness as the asphalt surface (layer coefficient $a_1 = 0.42$) and the remaining thickness as the asphalt base (layer coefficient $a_2 = 0.34$), as shown in Equation 3*b*. In this study, Equation 3*a* was used to compute moduli that represent elastic HMA moduli at about 70°F and 10 Hz.

$$E = 435 \log^{-1}\left(\frac{\text{composite}\, a_1 - 0.44}{0.4}\right) \tag{3a}$$

$$\text{composite}\, a_1 = \frac{\left(d_1 * a_1\right) + \left(d_2 * a_2\right)}{\left(d_1 + d_2\right)} \tag{3b}$$

where

E = HMA design modulus (ksi),
d_1 and d_2 = asphalt surface and base thickness, respectively, and
a_1 and a_2 = structural layer coefficients for the asphalt surface (0.42) and base (0.34), respectively.

Statistical Analysis

F-tests and paired t-tests were used to determine statistical differences in this study. Paired data arise when two dependent samples are observed by using two measurement methods on a subject, which is the case in this study because deflection data were used to backcalculate modulus and cores at the same locations were tested in the laboratory for dynamic modulus. The hypothesis test is performed on the difference of the means of the two samples. The default value is zero, which results in a test in which the two population means are equal. Statistical Analysis Software (SAS) was used to do F-tests and paired t-tests at the 5% level of significance.

RESULTS AND DISCUSSIONS

Backcalculated Moduli

The backcalculated moduli were corrected to 40°F, 70°F, and 95°F by means of Equation 2, on the basis of the calculated middepth pavement temperature from Equation 1. Calculated middepth pavement temperature varied from 63°F to 116°F, the lowest for US-54 and the highest for US-283. Figure 1 shows the average backcalculated HMA moduli of the sites. The U.S. routes had comparable backcalculated moduli except US-283, which was tested at the highest temperature. Although it was thinner, K-7 had a higher backcalculated moduli than K-99, presumably because of higher temperature. The highest difference between minimum and maximum backcalculated moduli was observed for US-77.

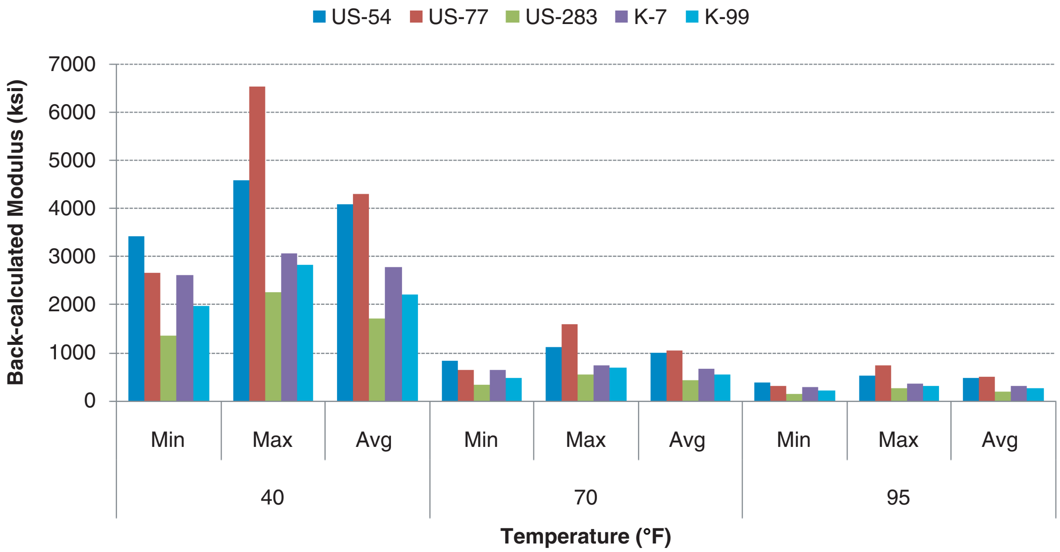

FIGURE 1 Average backcalculated moduli at various temperatures.

Table 3 lists the minimum, maximum, and average backcalculated HMA moduli; standard deviation (SD); and coefficient of variation (COV) for all sites. Eleven data points were used for computing the point statistics for all sites except K-7, where deflection data at Station 3 were anomalous and therefore discarded. The SD varied with temperature, whereas the COV remained the same at all temperature levels. The backcalculated modulus at US-77 had the highest average modulus, SD, and COV, whereas that on K-7 had the lowest SD and COV.

Laboratory Moduli

Effect of Frequency

Figure 2 shows the laboratory moduli for all sites at all six frequencies and 70°F temperature, which was selected because all samples were tested at this temperature and because of its closeness to the standard temperature. Comparison between backcalculated and laboratory-measured moduli was also done at this temperature. US-77 had the highest average dynamic modulus and highest difference between minimum and maximum moduli, such as backcalculated modulus at all frequencies, followed by US-54. K-7 had the lowest average dynamic modulus followed by K-99. Laboratory dynamic modulus increased with an increase in frequency. These results show that the speed of the vehicle in the design process cannot be ignored because it has a pronounced effect on the mechanistic response of the HMA layer material. Thus, in this study, HMA modulus corresponding to 10-Hz frequency (0.1-s load duration) was chosen for the comparison with the design modulus.

Table 4 lists the summary statistics of the laboratory dynamic modulus for all sites. The SD increased with an increase in frequency. The average modulus for the US-77 site was the highest, whereas that for

TABLE 3 Summary Statistics of Backcalculated Moduli

Temperature (°F)	Statistical Value	US-54	US-77	US-283	K-7	K-99
40	Min. (ksi)	3,428.7	2,652.3	1,357.5	2,622.1	1,976.0
	Max. (ksi)	4,591.6	6,541.1	2,248.3	3,072.8	2,822.2
	Avg. (ksi)	4,079.8	4,308.2	1,724.0	2,791.0	2,216.0
	SD (ksi)	306.2	1,205.1	313.1	141.0	266.6
	COV (%)	7.5	28.0	18.2	5.1	12.0
	N	11	11	11	10	11
70	Min. (ksi)	836.0	646.7	331.0	639.3	481.8
	Max. (ksi)	1,119.5	1,594.8	548.2	749.2	688.1
	Avg. (ksi)	995.1	1,050.4	420.3	680.5	540.3
	SD (ksi)	79.1	293.8	76.3	34.4	65.0
	COV (%)	8.0	28.0	18.2	5.1	12.0
	N	11	11	11	10	11
95	Min. (ksi)	393.3	304.2	155.7	300.8	226.7
	Max. (ksi)	526.7	750.3	257.9	352.5	323.7
	Avg. (ksi)	468.0	494.2	197.8	320.1	254.2
	SD (ksi)	35.1	138.2	35.9	16.2	30.6
	COV (%)	7.5	28.0	18.2	5.1	12.0
	N	11	11	11	10	11

NOTE: *N* = number of sites.

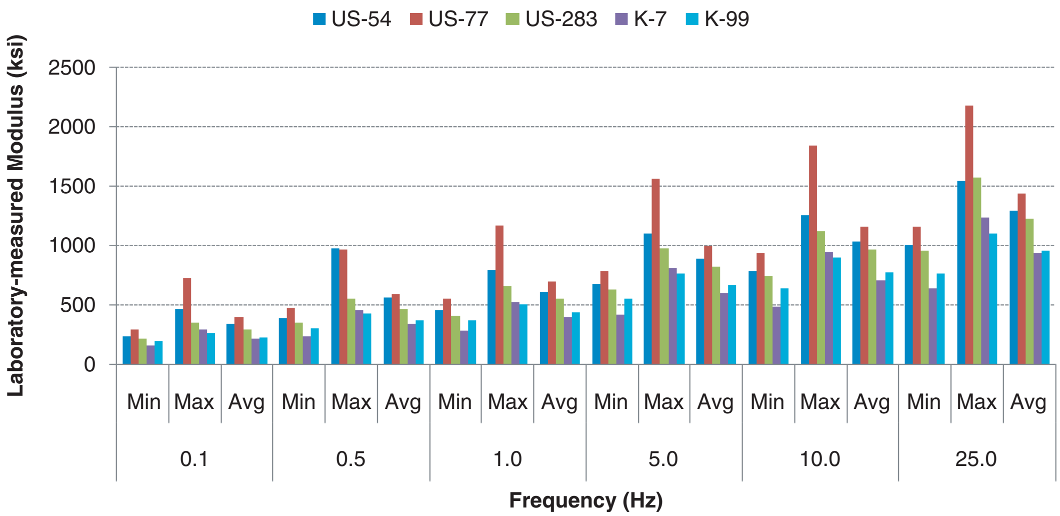

FIGURE 2 Laboratory dynamic moduli for all sites at 70°F.

TABLE 4 Effect of Frequency on Laboratory Moduli at 70°F

Site	Statistical Value	Frequency (Hz) 0.1	0.5	1	5	10	25
US-54	Min. (ksi)	240.9	389.1	456.4	676.2	788.6	1,007.3
	Max. (ksi)	464.0	980.8	792.9	1,103.8	1,251.7	1,540.6
	Avg. (ksi)	341.1	560.7	614.6	890.8	1,032.3	1,294.9
	SD (ksi)	62.6	168.8	97.7	129.7	142.9	170.0
	COV (%)	18.3	30.1	15.9	14.6	13.8	13.1
	N	9	9	9	9	9	9
US-77	Min. (ksi)	291.2	473.4	549.6	787.4	933.5	1,158.0
	Max. (ksi)	724.8	967.0	1,169.0	1,566.1	1,840.0	2,175.5
	Avg. (ksi)	398.4	596.6	696.6	994.2	1,160.3	1,434.8
	SD (ksi)	116.2	132.7	165.3	201.1	234.6	260.3
	COV (%)	29.2	22.2	23.7	20.2	20.2	18.1
	N	12	12	12	12	12	12
US-283	Min. (ksi)	217.9	353.0	413.5	631.4	745.8	952.6
	Max. (ksi)	357.2	555.2	662.7	978.6	1,122.9	1,568.8
	Avg. (ksi)	297.8	469.0	555.3	823.0	966.1	1,226.0
	SD (ksi)	39.7	56.0	66.4	87.8	102.2	155.1
	COV (%)	13.3	11.9	12.0	10.7	10.6	12.7
	N	11	11	11	11	11	11
K-7	Min. (ksi)	161.0	238.2	281.5	415.5	487.3	644.8
	Max. (ksi)	292.1	453.7	524.3	809.5	948.9	1,234.0
	Avg. (ksi)	222.3	340.9	401.9	599.4	708.0	934.6
	SD (ksi)	37.1	61.2	72.2	116.9	136.4	178.1
	COV (%)	16.7	17.9	18.0	19.5	19.3	19.1
	N	11	11	11	11	11	11
K-99	Min. (ksi)	194.9	307.0	370.1	557.7	641.1	768.9
	Max. (ksi)	267.9	431.3	506.9	766.7	895.8	1,099.0
	Avg. (ksi)	231.4	374.0	443.5	666.9	779.0	960.5
	SD (ksi)	19.5	35.1	39.3	67.2	81.6	101.4
	COV (%)	8.4	9.4	8.9	10.1	10.5	10.6
	N	11	11	11	11	11	11

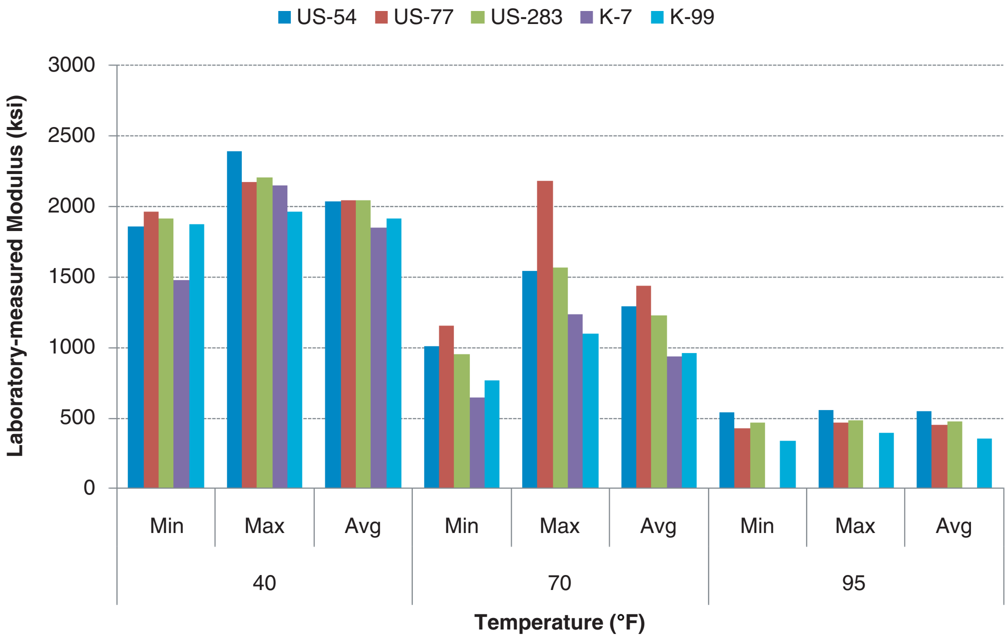

FIGURE 3 Laboratory dynamic moduli at 25 Hz for test sites.

K-7 was the lowest at all frequencies. The COV for the dynamic moduli at K-7 and K-99 increased slightly with an increase in frequency, whereas there was no specific trend for the U.S. routes. The number of samples tested varied from nine to 12. Some of the samples from US-54 were not tested because there were some cracks and poor bonding at the interlayers. One of the cores for US-77 was thick enough to get two samples, and the difference in dynamic modulus between the top and the bottom was not significant.

Effect of Temperature

Comparison of laboratory dynamic moduli for all sites was done at 40°F, 70°F, and 95°F temperature and at a frequency of 25 Hz, as shown in Figure 3. Frequency of 25 Hz was chosen because comparison of backcalculated and laboratory moduli were done at this frequency. The cores from the K-7 site were not tested at 95°F because the sample started to soften at this temperature and consequently LVDTs could not be glued to the specimens. The U.S. routes had comparable average laboratory dynamic modulus at 40°F as did the Kansas routes. US-77 had the highest moduli at 40°F and 70°F, whereas US-54 had the highest moduli at 95°F. These results show that even for the same mixture type, HMA moduli would vary from site to site. Furthermore, service temperature of the pavement should be accounted for in the design process.

The summary statistics for the laboratory dynamic modulus are shown in Table 5. At 70°F, US-77 had the highest average modulus. Only three samples were tested at 40°F and 95°F temperatures to

TABLE 5 Summary Statistics of Laboratory Dynamic Moduli at 25 Hz

Temperature (°F)	Statistical Value	US-54	US-77	US-283	K-7	K-99
40	Min. (ksi)	1,853.0	1,959.6	1,913.8	1,480.0	1,869.9
	Max. (ksi)	2,388.5	2,167.9	2,201.7	2,147.5	1,959.6
	Avg. (ksi)	2,037.3	2,039.0	2,045.6	1,845.3	1,914.7
	SD (ksi)	304.3	112.7	145.5	338.2	44.9
	COV (%)	14.9	5.5	7.1	18.3	2.3
	N	3	3	3	3	3
70	Min. (ksi)	1,007.3	1,158.0	952.6	644.8	768.9
	Max. (ksi)	1,540.6	2,175.5	1,568.8	1,234.0	1,099.0
	Avg. (ksi)	1,294.9	1,434.8	1,226.0	934.6	960.5
	SD (ksi)	170.0	260.3	155.1	178.1	101.4
	COV (%)	13.1	18.1	12.7	19.1	10.6
	N	9	12	11	11	11
95	Min. (ksi)	540.7	429.0	468.2	—	336.6
	Max. (ksi)	554.6	467.0	483.4	—	393.5
	Avg. (ksi)	546.9	451.2	478.1	—	358.7
	SD (ksi)	7.1	19.8	8.6	—	30.5
	COV (%)	1.3	4.4	1.8	—	8.5
	N	3	3	3	—	3

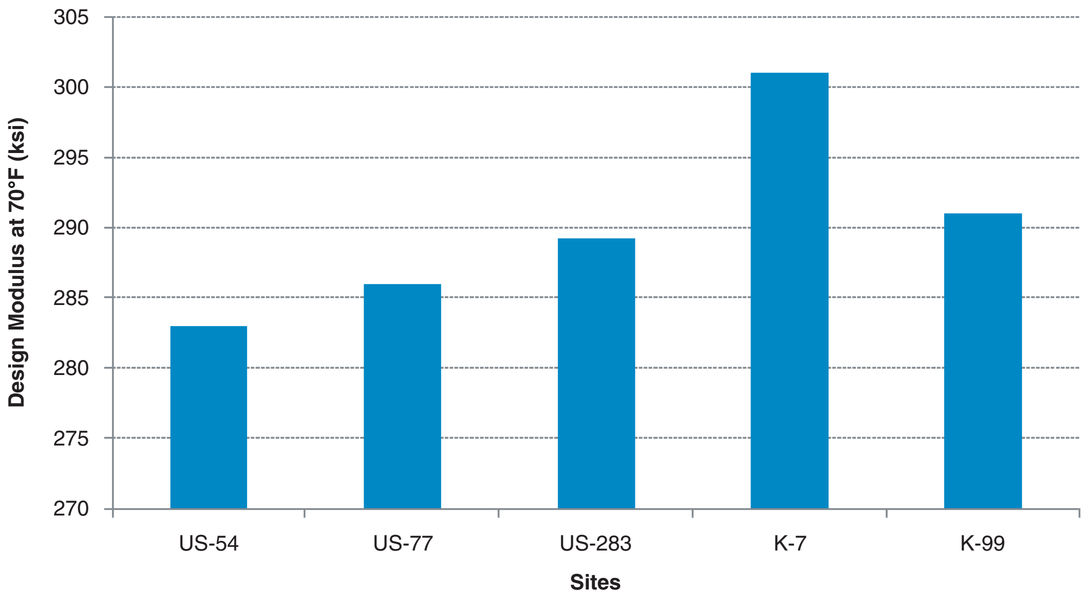

FIGURE 4 KDOT design HMA mixture modulus.

save testing time. Samples from the top, middle, and bottom of the cores were used.

Design HMA Moduli

As noted earlier, KDOT design moduli were computed with Equation 3*a*. These moduli, illustrated in Figure 4, represent elastic HMA moduli computed at about 70°F. K-7 had the highest HMA design modulus, and US-54 had the lowest modulus.

Comparison of Design Moduli with Backcalculated Moduli

The average backcalculated moduli at 70°F were compared with the design moduli, as shown in Figure 5. The back-calculated modulus was about two to four times as high as the design moduli, except for US-283. This section was tested at the highest temperature, and as a result, its backcalculated modulus was significantly affected. The difference was higher for the U.S. routes than the Kansas routes, again except for US-283. The results show that the design HMA moduli assumed during the 1993 AASHTO Design Guide design process can be easily achieved with the mixtures resulting from the current mix design process. Although the HMA pavement structural design and the HMA mix design processes are not integrated, the structural design assumptions are being met by the designed HMA mixture.

Comparison of Design Moduli with Laboratory Moduli

The design moduli were also compared with the average dynamic moduli obtained from the laboratory tests at 70°F temperature and 10-Hz frequency, as shown in Figure 6. The laboratory moduli were two to four times as high as the design HMA moduli. The highest and lowest differences were observed for US-77 and K-7, respectively.

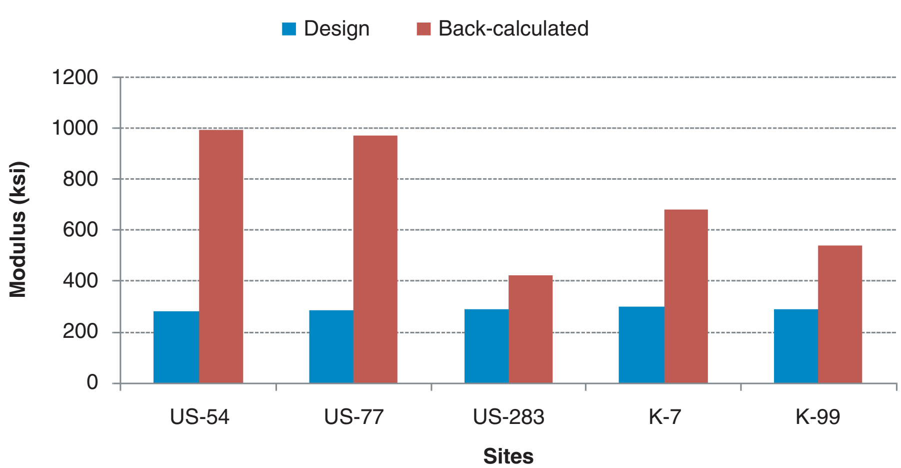

FIGURE 5 Comparison of design and backcalculated moduli at 70°F.

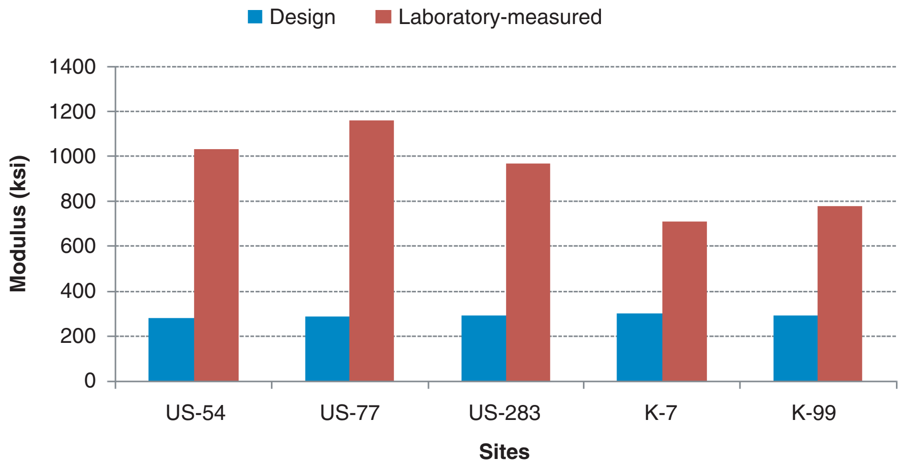

FIGURE 6 Comparison of design and laboratory moduli at 70°F and 10 Hz.

These results also show that the design HMA moduli assumed during the 1993 AASHTO Design Guide design process can be easily achieved with the Superpave mixtures currently used by KDOT.

Comparison of Backcalculated Moduli with Laboratory Moduli

Average backcalculated and laboratory HMA moduli at 70°F and 25 Hz were compared, as shown in Figure 7. Average laboratory moduli were higher than the average backcalculated moduli for all sites. The ratio of backcalculated-to-laboratory modulus varied from 0.34 to 0.77. The lowest and highest ratios were for US-54 and US-283, respectively. The lowest and highest surface temperatures during the deflection test were encountered on these sites.

Statistical Analysis

F-tests and paired *t*-tests were done for backcalculated and laboratory-measured moduli at 70°F and 25 Hz. The temperature was chosen because all the samples were tested in the laboratory at this temperature, whereas the frequency was chosen because the FWD deflection testing frequency (25 to 30 ms) was reasonably close to this frequency. Both the *F*-tests and the paired *t*-tests showed significant differences between backcalculated and laboratory-measured mean moduli at the 5% significance level for all sites except US-77.

CONCLUSIONS

Based on this study, the following conclusions can be drawn:

- The U.S. routes, except US-283, had comparable backcalculated HMA moduli.
- The FWD test temperature had a profound effect on backcalculated HMA moduli.
- Laboratory dynamic moduli on the U.S. routes were higher than on the Kansas routes. The laboratory dynamic moduli increased with load frequency.
- U.S. routes had comparable average laboratory moduli at 40°F.

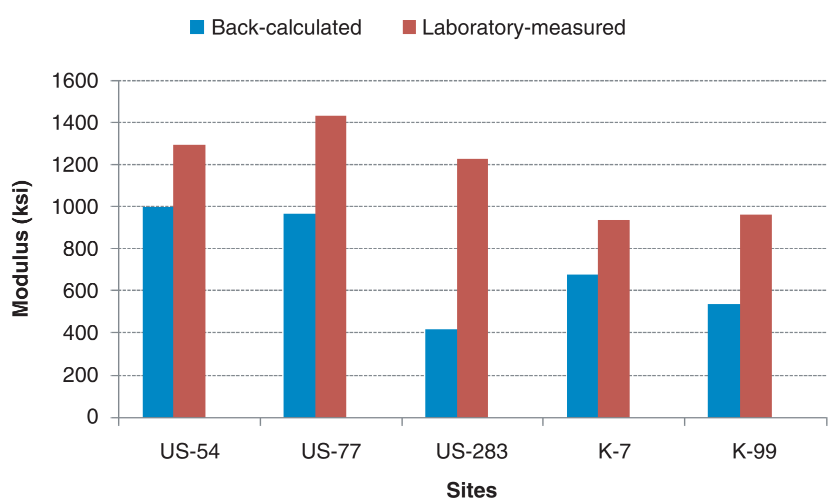

FIGURE 7 Comparison of backcalculated and laboratory moduli at 70°F and 25 Hz.

- KDOT design moduli were lower than both the backcalculated and the laboratory moduli. These data show that current design moduli are achievable in the field despite the fact that the pavement structural design and mix design processes are not integrated.
- Backcalculated and laboratory moduli were comparable from a practical point of view.

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