The Use of GIS, Deflection Data, Unsaturated Soil Mechanics and Distress Surveys to Determine Soil Properties and Calibrate a Mechanistic-Empirical Flexible Pavement Design Program for Low-Volume Roads

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ABSTRACT: The objectives of this project were to develop a model for predicting soil modulus values and to recalibrate Minnesota's mechanistic-empirical flexible pavement design program (MnPAVE) for low-volume roads. Pavement deflections at over 90,000 locations in Minnesota were used to estimate subgrade soil moduli. The structural information available for these locations was insufficient for backcalculation, so the Hogg forward calculation procedure that was used to analyze Long Term Pavement Performance (LTPP) deflection data was selected. Database functions were developed to automate the calculations. Backcalculated moduli from soils at the Minnesota Road Research Facility (MnROAD) were used to validate the Hogg results. The Hogg values compared well to EVERCALC backcalculation results for clay loam, but were approximately 30% lower than the EVERCALC results for sand. A geographic information system (GIS) soil map was used to determine the relationship between soil textural class and modulus. A model was developed to predict soil modulus based on clay and silt content. Unsaturated soil mechanics and laboratory test data were used to develop seasonal modulus adjustment factors. The new modulus values compare favorably to the default modulus values from MnPAVE Version 5.2. These values were also compared to typical resilient modulus ranges for equivalent soil types from the Mechanistic-Empirical Pavement Design Guide (MEPDG) Final Report. Distress surveys and pavement histories from county state aid highways (CSAH) were used to recalibrate the rutting transfer function in MnPAVE Version 5.3. There were not enough fatigue failures reported to recalibrate the fatigue transfer function.

KEY WORDS: MnPAVE, mechanistic empirical pavement design, unsaturated, FWD, modulus, soil.

1 INTRODUCTION

One objective was to select aggregate base and soil modulus models to develop default material properties for the MnPAVE mechanistic-empirical flexible pavement design program (Minnesota Department of Transportation 2008). Falling weight deflectometer (FWD) data from the Minnesota Road Research Facility (MnROAD) was used to backcalculate modulus values for soil and aggregate materials. Default seasonal values for Minnesota Department of Transportation (Mn/DOT) Class 3, 5, and 6 materials were obtained in this way. Since the soil at MnROAD is primarily loam to clay loam, a more comprehensive model was needed to determine default modulus values for soils in MnPAVE. An empirical equation that calculates a subgrade modulus using FWD deflections was validated using MnROAD data and then applied to the statewide FWD data.

Geographic Information System (GIS) data was used to determine the relationship between soil textural class and modulus. A model was developed to predict soil modulus based on clay and silt content. This model allows moduli to be predicted for any soil textural class. Adjustment factors were used to correct these optimal values for seasonal changes in moisture and temperature.

Finally, performance, traffic, and structural data collected on Minnesota highways in 2006 allowed the re-calibration of the MnPAVE rutting model and the validation of both the fatigue and rutting models.

2 MODEL SELECTION

2.1 Aggregate Base and Subbase Gradation

Most of the available laboratory testing data on Minnesota aggregates is from MnROAD. The Class 3, 4, 5, and 6 aggregates used at MnROAD followed stricter grading criteria than those listed in Mn/DOT's Standard Specifications for Construction and are designated as "Special". Table 1 lists the standard and special gradation specifications. The data used in this report refers to materials that comply with the special specifications. Models developed from this data are intended for use with materials in the standard and special specifications.

Table 1: Standard and Special Aggregate Specifications - Total Percent Passing

Material	**Class 3**		**Class 4**		**Class 5**		**Class 6**	
Sieve Size	**Std**	**Special**	**Std**	**Special**	**Std**	**Special**	**Std**	**Special**
50 mm (2“)	100	--	100	--	--	--	--	--
25 mm (1”)	--	100	--	100	100	100	100	100
19 mm (3/4”)	--	--	--	90 - 100	90 - 100	90 - 100	90 - 100	85 - 100
9.5 mm (3/8”)	--	95 - 100	--	80 - 95	50 - 90	70 - 85	50 - 85	50 - 70
4.75 mm (#4)	35 - 100	85 - 100	35 - 100	70 - 85	35 - 80	55 - 70	35 - 70	30 - 50
2 mm (#10)	20 - 100	65 - 90	20 - 100	55 - 70	20 - 65	35 - 55	20 - 55	15 - 30
425 μm (#40)	5 - 50	30 - 50	5 - 35	15 - 30	10 - 35	15 - 30	10 - 30	5 - 15
75 μm (#200)	5 - 10	8 - 15	4 - 10	5 - 10	3 - 10	3 - 8	3 - 7	0 - 5

2.2 Aggregate Base and Subbase Moduli and Seasonal Multipliers

Deflections on pavement test sections at MnROAD were used to backcalculate aggregate base moduli. The backcalculation program used was EVERCALC (Washington State Department of Transportation 2005). The analysis was limited to 3-layer asphalt sections (asphalt over base over subgrade) to avoid ambiguous results caused by multiple base layers. Results with root mean square error (RMSE) values greater than 5.0% were filtered out.

MnPAVE calculates the length of each season based on historical temperature data from nearby weather stations. The criteria for determining the beginning of each MnPAVE season are listed in Table 2 (Ovik et al. 2000).

Table 2: Criteria for Determining the Beginning of MnPAVE Seasons

Season	**Criteria**
Fall	3-day Average Temperature < 17 °C
Winter	Freezing Index > 90 °C-days
Spring Thaw	Thawing Index > 15 °C-days
Spring Recovery	2 Weeks After Beginning of Spring Thaw
Summer	3-day Average Temperature > 17 °C

Backcalculated modulus data from Spring Thaw through Fall were collected for Classes 3, 5, and 6 base materials at MnROAD. The season lengths for this location were used to group the modulus data for calculating seasonal averages. A lognormal distribution provided the best fit for the data so the natural log of the modulus data was used to calculate mean and variance. Equations 1 and 2 show a method of calculating the untransformed mean and variance (Devore 1991)

$$E(X) = e^{\mu+\sigma^2/2} \tag{1}$$

$$V(X) = e^{2\mu+\sigma^2} \cdot \left(e^{\sigma^2} - 1\right) \tag{2}$$

Where:
E(X) = Expected value (mean) of untransformed data
V(X) = Variance of untransformed data
μ = Mean of log-transformed data
σ^2 = Variance of log-transformed data

The difference between the Summer and Fall modulus values were insignificant so these two seasons were combined for the analysis. Table 3 lists the average modulus, coefficient of variation (COV), and seasonal multipliers for Class 3, 5, and 6 materials.

Table 3: Moduli and Seasonal Multipliers for Aggregate Base and Subbase Materials

	Spring Thaw			**Spring Recovery**			**Summer & Fall**		
Mat'l	**E,MPa (ksi)**	**COV %**	**Mult.**	**E,MPa (ksi)**	**COV %**	**Mult.**	**E,MPa (ksi)**	**COV %**	**Mult.**
Class 3	66.0 (9.57)	42	0.35	146 (21.2)	15	0.77	184 (26.7)	10	1.00
Class 5	53.8 (7.80)	11	0.29	156 (22.6)	23	0.84	186 (27.0)	16	1.00
Class 6	47.9 (6.95)	15	0.29	128 (18.6)	39	0.77	165 (23.9)	15	1.00

The high coefficients of variation in Spring Thaw and Recovery data can be attributed to spatial and temporal variability in moisture content during the testing period. By comparison, Table 4 lists the Mechanistic-Empirical Pavement Design Guide (MEPDG) ranges for

American Association of State Highway and Transportation Officials (AASHTO) granular soil classes (National Cooperative Highway Research Program 2004). Mn/DOT Classes 3 and 5 correlate roughly with A-1-b, and Class 6 with A-1-a.

Table 4: MEPDG Modulus Ranges for Base and Subbase Materials.

AASHTO Soil Class	Modulus Range (MPa)	Modulus Range (ksi)
A-1	245 - 290	35.5 - 42.0
A-2	148 - 259	21.5 - 37.5
A-3	169 - 245	24.5 - 35.5

2.3 Aggregate Base and Subbase Moisture Conditions

Moisture conditions within the pavement system vary over time and space. There is a need to estimate moisture retention properties of aggregate base and subgrade materials to predict resilient and shear response in the base and subgrade. At MnROAD, little correlation between precipitation and equilibrium moisture content was observed. Material properties and distance to water table are the best predictors of equilibrium moisture content. In this analysis, only three distinct moisture periods were evident: Spring, Summer and Winter.

Seasonal pore suction resistance factors were determined for granular materials at MnROAD (Roberson et al. 2005). These factors were determined using the Van Genuchten method for predicting matric suction from field moisture content shown in Equation 3 (Van Genuchten 1980).

$$\varphi = \frac{1}{\alpha}\left(\Theta^{-1/m} - 1\right)^{1/n} \tag{3}$$

Where

φ = matric suction (kPa)

Θ = degree of saturation

α, m, n = fitting parameters

The parameters calculated for MnPAVE materials are shown in Table 5. Moisture characteristics have been measured on many virgin and recycled base materials in Minnesota. Additional in situ moisture data will enable the development of pore suction resistance factors for these materials and improve the reliability of pavement designs (Gupta et al. 2005).

Table 5: Van Genuchten α and n values for MnROAD Materials (Roberson et al. 2005)

	Class 3	**Class 4**	**Class 5**	**Class 6**	**Subgrade**
α	49	34	4.77	97	1.00
n	1.35	1.28	1.44	1.28	1.23
θ_{res}	0.06	0.08	0.06	0.00	0.09
θ_{sat}	0.24	0.24	0.28	0.27	0.43

2.4 Subgrade Soil Moduli

There are 11 textural soil classes commonly found in Minnesota. Statewide FWD deflections are available, but without reliable information about the pavement structures, traditional backcalculation analysis cannot be performed for most of these soils. The Hogg model, a forward-calculating model, simulates a thin plate on an elastic foundation. It was originally developed in 1944, and modified in 1983. The best results were obtained using Case II coefficients and sensor offsets where the deflection is approximately half of the center deflection (Stubstad et al. 2006).

The full FWD dataset included 421,000 deflections. This data was filtered to include only 40 kN (9,000 lb) loads (± 10%), which corresponds to an equivalent single axle load (ESAL) (AASHTO 1993). Only data collected during late Summer and early Fall were used in order to eliminate frozen and Spring thaw conditions. The final data set consisted of 121,000 deflections .

In order to determine default modulus values for different soil textural classifications, GIS technology was used. Deflection data was superimposed on soil textural class data from the *Minnesota Soil Atlas* (University of Minnesota 2007) in order to associate the subgrade modulus values with different soil classes.

In order to create a model relating modulus and soil class, representative clay and silt contents were associated with each soil class. Deflection data corresponding with the sand classification was only available from three routes, with a total of 142 deflections. This was determined to be insufficient for model development, so deflections from Cell 24 at MnROAD, which has a sand subgrade, were used. Data used was collected between 1994 and 2006 and consists of approximately 3,600 deflections. As with the statewide data, only data from July, August, and September was used.

A spatial query was performed using ArcMap software to obtain subgrade modulus statistics by soil type. This modulus data fits a lognormal distribution. The mean and variance were calculated on the natural log of the modulus values

A 3D model was developed using online data modeling software (Phillips 2007) to relate clay and silt content to average subgrade modulus. The criteria used to select a model were smoothness (minimize number of coefficients), sum of absolute errors (minimize), and avoiding models with extreme values at edges. The model selected is shown in Equation 4. The value of σ from Equation 1 ranged from 0.11 to 0.47 with 0.355 providing the best fit for the model.

$$\mu = -1.93\left(CLAY^{-0.0558} SILT^{-0.0514}\right) \tag{4}$$

Where:

μ = Expected value of $\ln E$ (see Equation 1)
$CLAY$ = Clay content (on a scale of 0-1)
$SILT$ = Silt content (on a scale of 0-1)

Figure 1 illustrates the model's predictions compared to the data, as well as the limits defined by the 15th and 85th percentile values. Also shown on the chart are the default modulus values from MnPAVE Version 5.2 and typical resilient modulus ranges for equivalent soil types from the MEPDG Final Report (National Cooperative Highway Research Program,, 2004).

2.5 Subgrade Soil Moisture Conditions

Seasonal multipliers and pore suction resistance factors are applied to modulus values during the MnPAVE design process. Table 6 lists the current seasonal multipliers for soil moduli in MnPAVE.

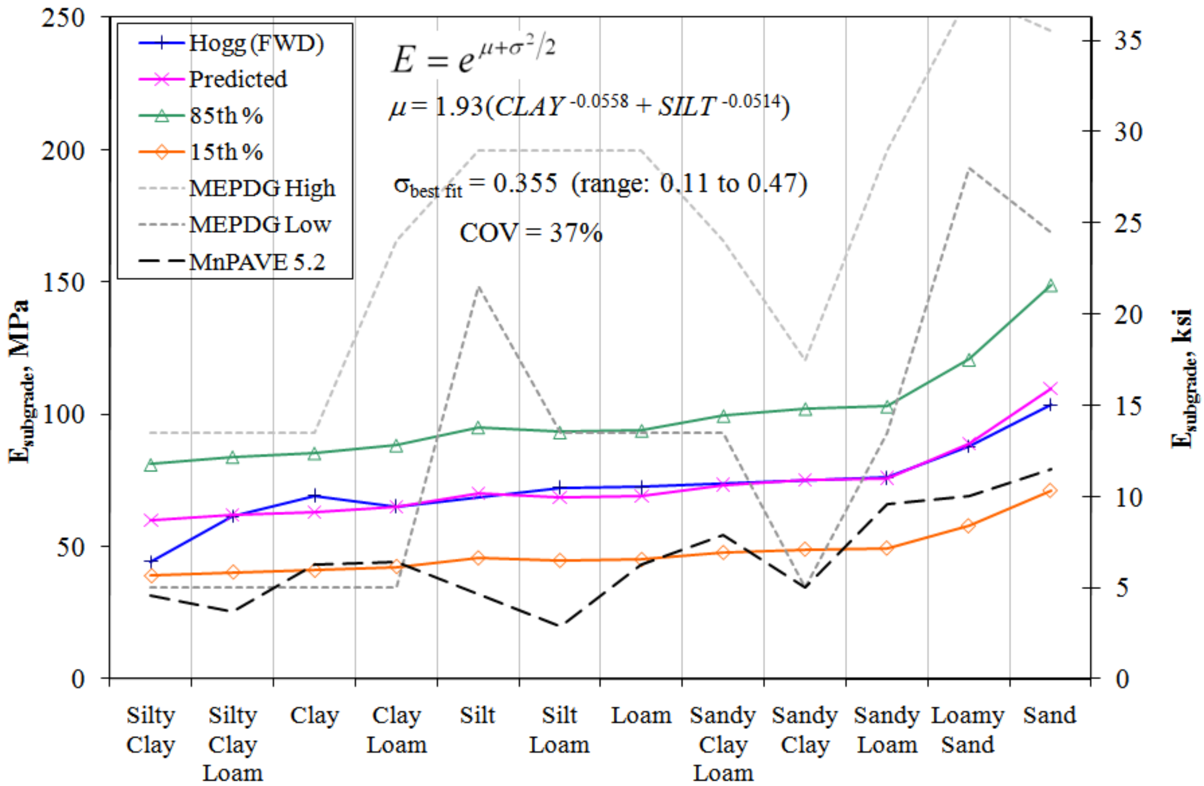

Figure 1: Modulus Model Predictions

Table 6: MnPAVE Seasonal Modulus Multiplier for Subgrade Soils

Season	Multiplier
Fall	1.00 (Optimum)
Winter	10.0 (Frozen)
Spring Thaw	10.0 (Frozen soil, Thawed Base)
Spring Recovery	0.70 (Thawed)
Summer	0.85 (Recovering)

In order to develop a more reliable method of determining seasonal variations in soil modulus, four Minnesota soils were tested to evaluate the relationship between moisture content, suction and modulus. Equation 5 shows a method of calculating modulus from matric suction values (Gupta, et al. 2007).

$$E = \alpha_1 \varphi^{\beta_1} \tag{5}$$

Where:

E = Design modulus
φ = matric suction
α_1, β_1 = empirical constants

Further testing will allow the determination of more accurate soil modulus values based on in situ moisture measurements.

3 MNPAVE CALIBRATION

The two performance measures used in MnPAVE are fatigue cracking and rutting. There is a transfer function for each measure to predict the number of repetitions of a given axle load the structure can withstand before it fails. Equations 6 through 8 make up a fatigue model (Finn et al. 1986) modified for MnPAVE.

$$N_F = CK_{F1}\varepsilon_h^{K_{F2}}E^{K_{F3}} \tag{6}$$

Where:

N_F = number of repetitions to fatigue failure ("Allowed Repetitions")
C = correction factor (See Equation 7)
S = shift factor (278 for 2002 MnPAVE calibration)
$K_{F1} = SK_{L1}$ (Design K_1)
$K_{L1} = 4.32 \times 10^{-3}$ (Laboratory K_1)
$K_{F2} = -3.291$
$K_{F3} = -0.854$
ε_h = horizontal tensile strain at the bottom of the HMA
E = HMA dynamic modulus (psi)

$$C = 10^M \tag{7}$$

$$M = C_{F1}\left(\frac{V_b}{V_a + V_b} + C_{F2}\right) \tag{8}$$

Where:

V_a = volume of air voids (%), 8.0% for MnPAVE calibration
V_b = volume of asphalt (%)
$C_{F1} = 4.84$
$C_{F2} = -0.69$

Equation 9 (Thompson 1987) describes the MnPAVE rutting model**.**

$$N_R = K_{R1}\varepsilon_v^{K_{R2}} \tag{9}$$

Where:

N_R = number of repetitions to rutting failure ("Allowed Repetitions")
$K_{R1} = 0.0261$ (2008 MnPAVE calibration)
$K_{R2} = -2.35$
ε_v = vertical strain at the top of the subgrade

The "Allowed Repetitions" from Equations 6 and 9 are used to predict the total rutting and fatigue damage over the life of the pavement using a summation known as "Miner's Hypothesis" (Miner 1959) as shown in Equation 10. Traffic is defined by applications of an 80kN (18,000 lb) equivalent single axle load (ESAL).

$$Damage = \sum_j \sum_i \frac{n_{season_i, load_j}}{N_{season_i, load_j}} \tag{10}$$

Where:

Damage = a factor indicating relative damage to the pavement where values ≥ 1 indicate failure.

N = Allowed repetitions of $load_j$ during $season_i$ (from equations 6 and 9)

n = Applied repetitions of $load_j$ during $season_i$

The MnPAVE rutting model was re-calibrated using traffic, structural, and performance data collected on CSAH routes in 2006. A spatial query was conducted to select routes that had significant distress as well as deflection, structural, and traffic data. A new fatigue calibration was not feasible because the data set was too small. Data from 22 pavements evaluated for Minnesota Investigation 183 (Lukanen 1980) was used to validate the fatigue and rutting models. These pavements were evaluated for ride smoothness rather than fatigue or rutting, but the smoothness values at the end of the evaluation period indicate they likely had no fatigue or rutting failures.

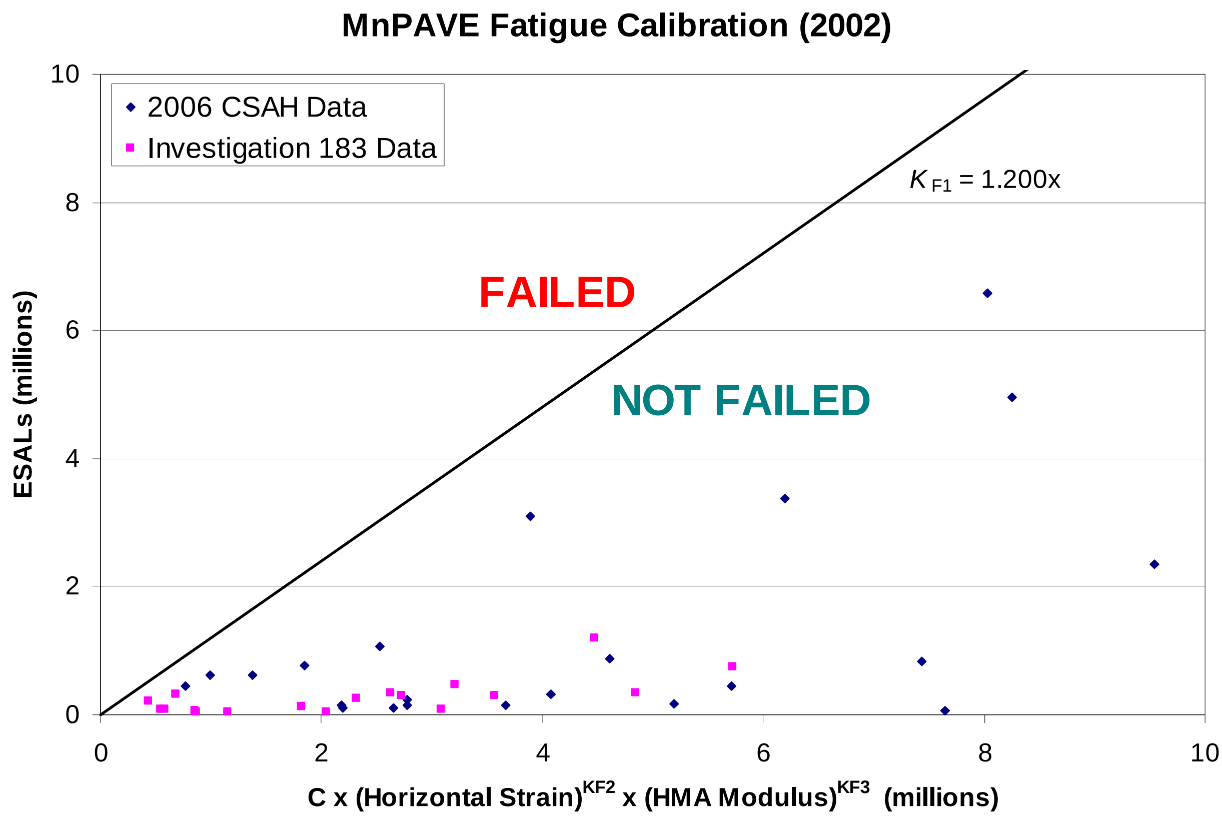

Figure 2: Validation of MnPAVE 2002 Fatigue Model (for up to 7 million ESALs).

Figure 2 illustrates the validation of the 2002 MnPAVE fatigue model. All data points represent pavements that had no fatigue failures at the time they were evaluated. The 2002 MnPAVE fatigue model was considered appropriate for low-volume roads. Figure 3 shows the new MnPAVE rutting calibration. The diamond data points represent pavements with rutting failures in 2006. The square data points represent Investigation 183 pavements used for validation and are assumed to have no rutting failures. A 50% reliability level was used in MnPAVE for the simulations, and a linear regression was performed on the 2006 CSAH data to determine the new rutting coefficient.

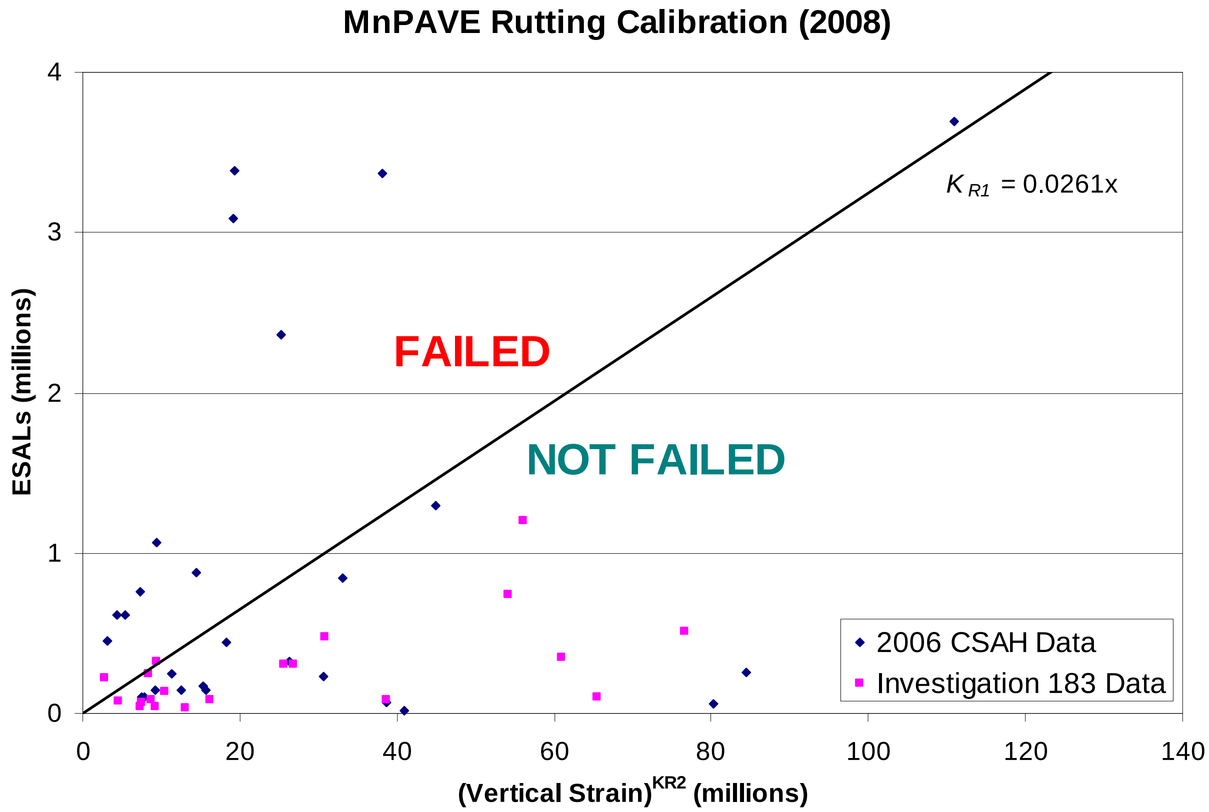

Figure 3: MnPAVE Rutting Calibration (2008)

4 CONCLUSIONS

Deflection data collected on Minnesota highways has enabled the development of a new statewide soil modulus model. In addition, new base and subbase properties were developed and unsaturated soil technology provides the potential for more reliable pavement designs based on seasonal differences in moisture content.

Structural, traffic, and performance data collected statewide enabled the calibration of a new rutting function for low-volume roads and the validation of fatigue and rutting models.

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