Determining Pavement Structural Number from FWD Testing

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A structural number is used as an indicator of pavement strength in a number of pavement design and deterioration models. In determining the structural number of an existing pavement structure, traditional methods of laboratory testing have become expensive and are not always appropriate. The parameter preferably is obtained from nondestructive deflection testing. Currently two techniques to determine structural numbers from surface deflections have been suggested and documented by AASHTO. A powerful alternative procedure for determining a pavement's structural number from falling-weight deflectometer surface deflections is presented. The approach has been verified and compared with other available techniques on 62 in-service pavement sections. The method is rapid, does not need mechanistic analysis tools, and is highly suitable for characterizing pavement strength in pavement management systems.

Notwithstanding acceptance and widespread use of mechanistic principles in pavement analysis and design, several agencies worldwide are using empirically based design and performance models. The concept of structural number, first defined by the AASHO road test (*1*), is a convenient and an often used index of pavement strength. Although the adequacy of the index has been debated by a number of researchers (*2–4*), the index is currently embedded in design and deterioration modeling procedures of organizations such as AASHTO, the Transport and Road Research Laboratory (*5*), and the World Bank (*6*).

Traditionally the structural number of a pavement has been determined from its layer thicknesses and laboratory-determined material properties. The 1986 AASHTO guide design for pavement provides additional techniques to determine a pavement's structural number using nondestructive deflection testing. Both techniques proposed in the AASHTO guide cause problems in characterizing the structural strength for pavement management at the network level. In this paper an alternative approach is provided, developed, and discussed whereby a pavement's structural number can be determined from its total thickness and the shape of the measured surface deflection bowl. This approach, verified on 62 pavement structures, provides a powerful technique that does not require the process of backcalculation of layer moduli.

BACKGROUND

The concept of structural number was first defined in the AASHO road test (*1*):

$$SN = \sum_{i=1}^{n} a_i h_i \qquad (1)$$

where

SN = structural number,
a_i = material and layer coefficient, and
h_i = layer thickness (in.).

In 1975 the Transport and Road Research Laboratory adopted the structural number as the index of pavement strength in the Kenya Road Transport Cost Study (*7*). However, in this study they included an additional variable, SN_{sg}, to account for variation in subgrade strength. The modified structural number, *SNC*, was defined as

$$SNC = \sum_{i=1}^{n} a_i h_i + SN_{sg} \qquad (2)$$

where

SNC = modified structural number,
$SN_{sg} = 3.51\ (\log \text{CBR}) - 0.85\ (\log \text{CBR})^2 - 1.43$, and
CBR = in situ California bearing ratio (percent).

The need for and rationale of modifying the structural number for subgrade effects was described by Hodges et al. (*7*):

> The most satisfactory way of taking into account the strength of the subgrade is to modify the measured structural number of the pavement so that it is equal to the structural number of a pavement of the same type which would behave in the same way but is built on a standard subgrade. To allow direct comparisons with the AASHO Road Test, the most convenient subgrade to use for this purpose is the subgrade of the AASHO road test itself.

The design charts of Road Note 31 were analyzed (*5*) to examine how the required structural number decreases as subgrade strength increases. The analysis resulted in the SN_{sg} term shown in Equation 2. In the Brazil/United Nations Development Program study (*8*), which followed the Kenya study, the structural number again was used as an index of pavement strength. During the study, an attempt was made to relate measured Benkelman beam deflections to the modified structural number as defined in Equation 2. It was found that the two parameters are not directly interchangeable, with a rather poor coefficient of determination (r^2 = 56 percent). Furthermore, it was established that the structural number was a better performance indicator than peak deflection. The structural number concept subsequently was adopted in the HDM-III pavement performance models (*9*). Because these models are promoted by the World Bank, they have been captured and used in several pavement management sytems in developing countries. The performance models use structural number as a

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variable, so this parameter is required for an entire network consisting of various pavement types, layer thicknesses, and strengths, which is built on a wide variety of subgrades. The nature and speed of nondestructive deflection devices, such as the falling-weight deflectometer (FWD), ideally should be used to provide this parameter.

The 1986 AASHTO design guide documents two procedures for determining structural numbers from FWD deflections; the first technique involves the backcalculation of layer moduli, a field actively researched in recent years (*10*). Once the layer moduli are determined, they are related to layer coefficients using a procedure documented in Volume 2 of the AASHTO guide. Although the AASHTO procedure is the preferred approach, it requires exact knowledge of layer thicknesses, is time consuming, and relies heavily on backcalculation expertise. A second approach uses outer deflection sensors to determine subgrade stiffness and then applies the peak deflection, D_o, to determine the pavement's structural number. The formulation documented in the AASHTO guide was modified by Ioannides (*4*) in 1990. He suggested the following relationship:

$$D_o = \frac{1.5P}{\pi a} \left\{ \frac{(0.0045h)^3}{SN^3} \left[1 - \frac{1}{(1 + (h/a)^2)^{1/2}} \right] + \frac{1}{E_s\left(1 + \frac{40000SN^2}{a^2E_s^{2/3}}\right)^{1/2}} \right\} \quad (3)$$

where

D_o = peak FWD deflection,
P = FWD load (lb),
h = pavement layer thickness (in.),
a = load radius,
E_s = subgrade modulus (psi), and
SN = structural number from Equation 1.

The problem with this approach in practice is that it is founded on Burmister's two-layer model in which the subgrade is assumed to be an infinitely thick linear-elastic material. Real pavements are founded on stress-sensitive subgrades that are often underlain by stiff layers or even bedrock. If Burmister's formulation is used, the subgrade stiffness is overpredicted, resulting in incorrect structural numbers.

DETERMINING *SN* FROM FWD DEFLECTIONS

The peak deflection measured below an FWD is a combination of deflection in the subgrade and the elastic compression of the pavement structure. In 1983 Irwin (*11*) suggested a general rule of thumb, the "two-thirds rule," which explains the stress distribution and origin of deflections found below an FWD. The rule is based on the fact that approximately 95 percent of the deflections measured on the surface of a pavement originate below a line deviating 34 degrees from horizontal (see Figure 1). With this simplification, it can be assumed that the surface deflection measured at an offset of 1.5 times the pavement thickness originates entirely in the subgrade. By comparing this deflection with the peak deflection, an index associated with the magnitude of deformation that occurs within the pavement structure can be defined:

$$SIP = D_o - D_{1.5Hp} \quad (4)$$

where

SIP = structural index of pavement (Figure 1),
D_o = peak deflection measured under a standard 40-kN (9,000-lb) FWD load,
$D_{1.5Hp}$ = surface deflection measured at offset of 1.5 times Hp under standard 40-kN (9,000-lb) FWD impulse load, and
Hp = total pavement thickness.

It is hypothesized that the index *SIP* should be strongly correlated with the stiffness of the pavement structure and subsequently with its structural number. To investigate this hypothesis and to develop a relationship between FWD-measured surface deflections and a pavement's structural number, a large number of pavements were analyzed using layered-elastic theory. A total of 7,776 pavement structures with a wide range of stiffness-thickness combinations was used. Properties of the analyzed pavements are presented in Table 1. For each of the pavement structures, the structural number was calculated using AASHTO guidelines:

$$SN = \sum_{i=1}^{n} h_i a_g \left(\frac{E_i}{E_g}\right)^{1/3} \quad (5)$$

where

a_g = layer coefficients of standard materials (AASHO road test),
E_g = resilient modulus of standard materials (AASHO road test),
h_i = layer thickness (in.), and
SN = structural number (units of h_i).

The best relationship was found after including the total pavement thickness in the analysis. A relationship of the following format was selected:

$$SN = k_1 SIP^{k2} Hp^{k3} \quad (6)$$

where

SN = structural number (in.), as used in HDM-III;
SIP = structural index of pavement (μm);
Hp = total pavement thickness (mm); and
$k1, k2, k3$ = coefficients as listed in Table 2.

Figure 2 illustrates the good correlation between the structural numbers determined by using Equation 6 on the data base of 7,776 pavement structures. However, it should be kept in mind that this relationship is purely theoretical and is founded on layer elastic theory. As described by Ullidtz (*12*):

> It is important to realize that layer elastic theory is only a rather poor approximation to the extremely complex conditions of real pavement structures. Most pavement materials will show viscous, visco-elastic and/or plastic deformations under stress, in addition to elastic deformations. Pavement materials are often inhomogeneous, anisotropic and have non-linear stress-strain (or stress-strain rate) relations. Many materials are even particulate, i.e., consisting of discrete particles.

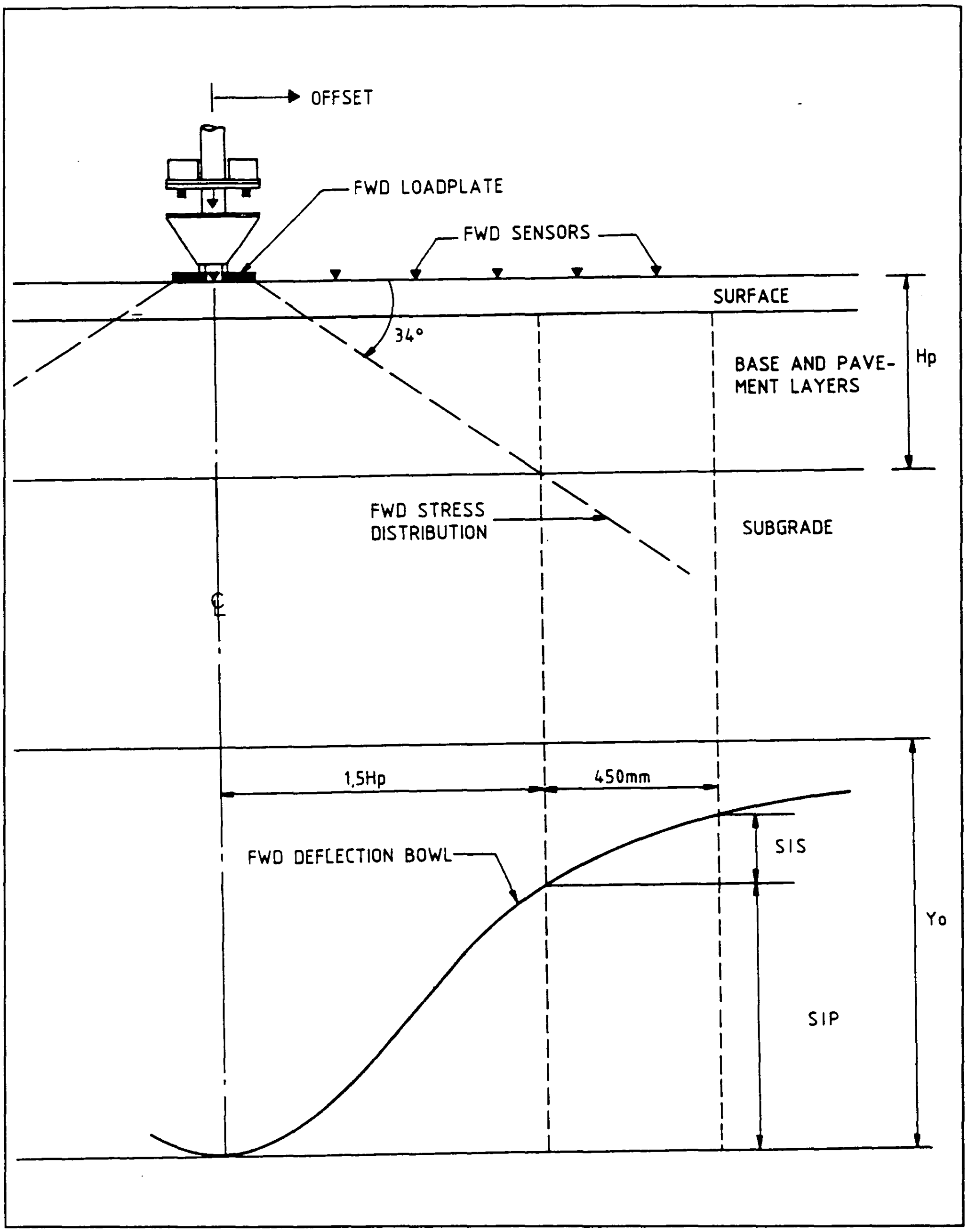

FIGURE 1 Stress distribution and measured deflection bowl beneath FWD load.

TABLE 1 Layer Moduli and Thicknesses Used To Develop *SN* Versus *SIP* Relationship

Layer	Moduli (MPa)	Thicknesses (mm)
Surface	1500, 3000, 5000	20, 50, 100, 200
Base	400, 700, 1000	150, 300
Subbase	150, 300, 500	0, 150, 300
Subgrade	50, 75, 100, 200	1500, 3000, 5000

Total Number of Combinations : 3x3x3x4x4x2x3x3 = 7776

TABLE 2 Coefficients for *SN* Versus *SIP* Relationships (Equation 6)

Surface Type	*k1*	*k2*	*k3*	r^2*	n**
Surface Seals	0,1165	-0,3248	0,8241	0,984	1944
Asphalt Concrete	0,4728	-0,4810	0,7581	0,957	5832

* Coefficient of Determination
** Sample Size

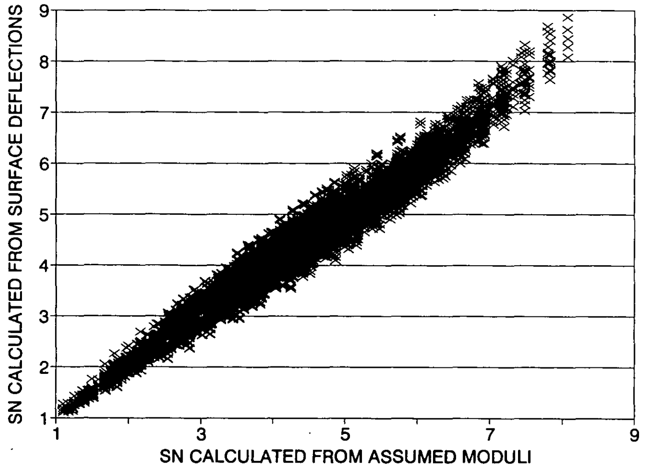

FIGURE 2 Correlation of structural numbers using Equation 6.

Discontinuities, like edges, joints or cracks, are often present, and the conditions at the interfaces (rough or smooth) are not well known.

To evaluate the effectiveness of the above theoretically based relationships on actual pavements, a detailed investigation was carried out on some 62 in-service pavements. The findings are described later in this paper.

The same rationale used to determine *SN* from surface deflections can be used to obtain the subgrade stiffness. It is argued that the weakest part of the subgrade, say the top 300 mm (1 ft), should be used for performance prediction purposes. Irwin's "two-thirds rule" (*11*) again can be used to define an index representing the subgrade strength. For this purpose a structural index for the subgrade (*SIS*) has been defined:

$$SIS = D_{1.5Hp} - D_s \tag{7}$$

where *SIS* equals the structural index of the subgrade (Figure 1) and D_s equals the surface deflection measured at an offset of (1.5*Hp* + 450 mm).

SIS and total pavement thickness were subsequently related to the subgrade stiffness using the following relationship:

$$E_{sg} = 10^{k4} SIS^{k5} Hp^{k6} \tag{8}$$

where E_{sg} equals the subgrade stiffness in megapascals, and *k*4, *k*5, and *k*6 are coefficients as listed in Table 3.

The approach to determine the structural number of a pavement from surface deflections can be summarized in the following steps:

1. Normalize measured FWD deflections to standard 40-kN (9,000-lb) load deflections.

2. Determine the deflection at an offset of 1.5*Hp*. This will require interpolation among deflections measured at the fixed sensor positions. For this purpose, the following relationship can easily be programmed:

$$D_X = \frac{(R_X - R_B)(R_X - R_C)}{(R_A - R_B)(R_A - R_C)} D_A + \frac{(R_X - R_A)(R_X - R_C)}{(R_B - R_A)(R_B - R_C)} D_B + \frac{(R_X - R_A)(R_X - R_B)}{(R_C - R_A)(R_C - R_B)} D_C \tag{9}$$

where

D_X = deflection at offset of R_X;
D_i = deflection at Sensor *i*;
R_i = offset of Sensor *i*;
i = A, B, C being three closest sensors to Point *X*; and
X = point for which deflection is determined.

3. Use Equations 4 and 6 to determine the pavement structural number. It should be noted that the calculated structural number is relevant for the prevailing temperature and moisture conditions at the time of deflection testing. To determine the structural number at a standard temperature, the peak deflection, Y_o, should be corrected to an equivalent peak deflection at the reference temperature. For this purpose, the correction factors proposed by AASHTO (Figure 3) should be used before Equation 4. For pavements with thin asphalt surfaces, no temperature correction is required.

TABLE 3 Coefficients for *E* Versus *SIS* Relationship (Equation 8)

Total Pavement Thickness	*k4*	*k5*	*k6*	r^2	n
$Hp \le$ 380mm	9,138	-1,236	-1,903	0,862	2592
380 mm < $Hp \le$ 525mm	8,756	-1,213	-1,780	0,810	2592
525 mm < Hp	10,655	-1,254	-2,453	0,809	2592

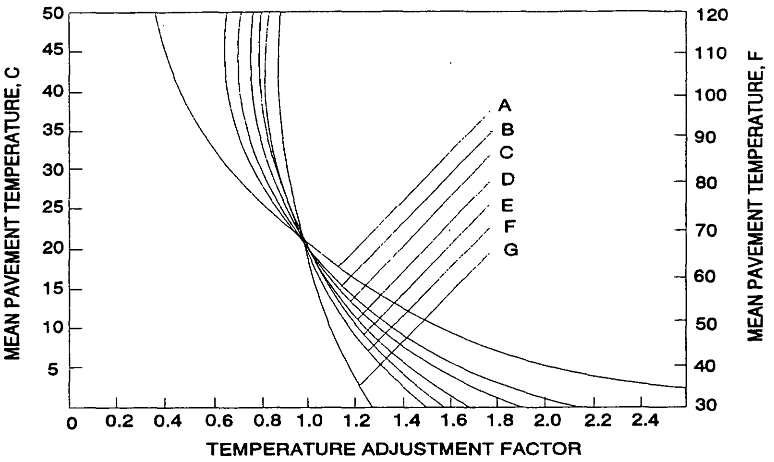

FIGURE 3 Temperature correction factors for peak measured deflections (AASHTO).

To determine the SN_{sg} for use in HDM-III model the following additional steps are required:

1. Determine D_s through interpolation (Equation 9),
2. Calculate SIS using Equation 7 and E_{sg} using Equation 8, and
3. Relate the subgrade modulus to equivalent CBR using a relationship such as that suggested by Emery (*13*):

$$E_{sg} = 30.79CBR^{0.44} \qquad (10)$$

where E_{sg} equals the subgrade modulus in megapascals.

4. Calculate SN_{sg} and SNC using Equation 2.

VERIFICATIONS

To evaluate the developed relationships, a detailed study was carried out on 52 in-service pavement structures. The test sections were selected specifically to cover a wide range of pavements with various ages, present conditions, pavement compositions, and subgrade conditions. A detailed visual condition assessment and FWD deflection testing were done on each test section. The information was analyzed statistically to select one representative test position within each section. Dynamic cone penetration (DCP) testing was done at this position, after which a test hole was dug to measure the actual layer thicknesses. Four methods were used to calculate the structural number from the information for each of the test positions.

Model A (Backcalculated Moduli, AASHTO NDT Method 1)

Method A involves the mechanistic analysis of measured deflections using two backcalculation programs: MODULUS (*14*) and ELMOD (*12*). The layer moduli are translated to layer coefficients using Equation 5. The determined layer coefficients and recorded layer thicknesses are then used to determine the structural number.

Method B (DCP Analysis)

Method B involves the analysis of the DCP results. First, the penetration rate through each granular pavement layer is used to determine the layer's in situ CBR by using the following relationship (*15*):

$$CBR = 410 \log DN^{-1,27} \qquad (DN>2 \text{ mm/blow})$$

$$CBR = 66.66DN^2 - 330DN + 563 \qquad (DN \leq 2 \text{ mm/blow}) \qquad (11)$$

where CBR is the in situ California bearing ratio (percent) and DN is the penetration rate of DCP (mm/blow).

CBRs were translated into layer coefficients using a relationship suggested by Patterson (*8*) and originally proposed by Chastain and Schwartz (*16*):

$$a_i = 29.14CBR - 0.1977CBR^2 + 0.00645CBR^3 \qquad (12)$$

where a_i is the layer coefficient for use in Equation 1 or 2. For the surface layers, a coefficient was assumed based on the visual condition.

Method C (AASHTO NDT Method II)

Method C is the second approach suggested in the AASHTO pavement design guide and involves purely the surface deflections. Outer sensors are used to determine the subgrade stiffness, after which Equation 3 is used to determine the pavement's structural number.

Method D (from the Shape of the Deflection Bowl)

Method D involves the use of the surface deflections only and the total layer thickness described earlier. For each pavement section the parameter SIP is determined using Equation 4. Parameter SIP and the total layer thickness H_p are then used to determine the structural number (Equation 6).

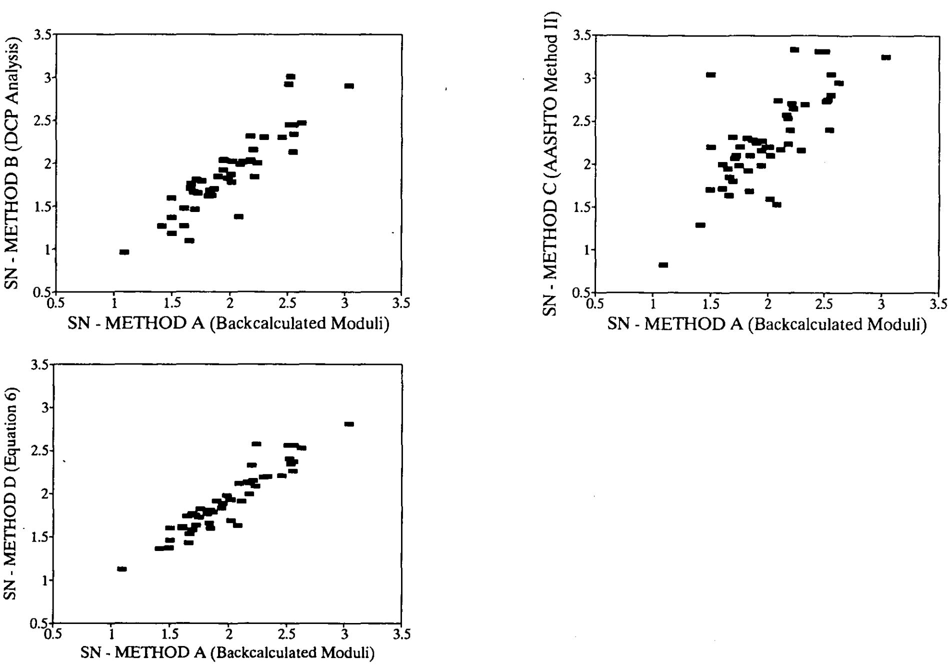

FIGURE 4 Comparison of results from four methods of analysis.

Results obtained from the four approaches are compared in Figure 4. The correlation coefficients calculated between the various methods on the 52 sections are given in Table 4. It is evident that the approach developed in this paper (Method D) leads to predicted structural numbers similar to those obtained when incorporating backcalculation techniques (Method A). As given in Table 4, a correlation of 0.928 was obtained between these two techniques.

The structural numbers obtained from the DCP analysis compare less favorably with the other techniques. The poor correlation is not surprising because the penetration test is a function of each layer's shear strength, whereas the measured deflection is a function of the elastic response of the entire layered system. The results from Method C, the second AASHTO method, correlate poorly with all the other techniques. This is probably because it takes no account of nonlinear elastic behavior of the subgrade or the presence of rigid layers below the subgrade. Both MODULUS (*14*) and ELMOD (*12*) do account for these factors. Through the inclusion of a rigid layer in the data base used to develop Equation 6, the presence of rigid layers below the subgrade has been accounted for also. Recent investigations (*17*) indicate that these factors should be accounted for in order to lead to realistic pavement modelling.

Although the procedure offers a rapid and effective method of determining structural numbers, issues such as seasonal variations should not be overlooked. Seasonal variations in the structural number can be obtained by measuring the deflections in various seasons and applying the above techniques. Pavement sections used in the verification process all consisted of relatively thin pavements with structural numbers of less than 3.5. The procedure was subsequently tested on a large data base of deflections collected on 10 in-service test pavement sections in Texas (Table 5).

On each pavement section, FWD deflections were measured monthly, in both the morning and the afternoon. For this study, deflections collected at two positions per test site were analyzed. Figure 5 compares structural numbers determined through backcalculation (Method A described above) and those obtained using Equation 6. The overall coefficient of determination for 436 tests

TABLE 4 Linear Correlations Between Parameters Calculated on 52 Pavement Sections

	Method A	Method B	Method C	Method D	*Do*	*SIP*	*Hp*
SN Method A	1.000	0.668	0.742	0.928	-0.320	-0.057	0.829
SN Method B	0.668	1.000	0.560	0.684	-0.355	-0.083	0.615
SN Method C	0.742	0.560	1.000	0.841	-0.374	-0.127	0.730
SN Method D	0.928	0.684	0.841	1.000	-0.383	-0.083	0.882
D_o	-0.320	-0.355	-0,374	-0,383	1.000	0.908	0.345
SIP	-0.057	-0.083	-0.127	-0.083	0.908	1.000	0.364
Hp	0.829	0.615	0.730	0.882	0.345	0.364	1.000

Method A	-	Through Backcalculation of Layer Moduli (AASHTO NDT Method 1)
Method B	-	From DCP Results
Method C	-	AASHTO NDT Method II
Method D	-	Procedure developed in this paper

TABLE 5 Texas Test Sections Used in Evaluation of Method To Determine Structural Numbers of FWD Testing

Site	Position (Road, Milepost)		Surface (mm)	Thickness Base (mm)	Subgrade	Comparison between Methods A and D	
						r^2*	n**
1	US 77	MP 4.1	165	150	Sand	0.94	50
2	SH 186	MP 33.2	25	223	Sand	0.91	50
4	FM 1425	MP 5	100	125	Clay	0.91	32
5	FM 1425	MP 3	150	150	Sand	0.93	46
6	FM 491	MP 6.1	30	200	Clay	0.58	30
7	IH 20	MP 293	250	280	Clay	0.96	32
8	IH 20	MP 273.6	200	330	Clay	0.96	44
9	FM 1235	MP 21	25	200	Clay	0.87	44
11	IH 20	MP 216	125	450	Sand	0.76	50
12	FM 1983	MP 1.0	25	200	Sand	0.81	580
All						0.98	4.36

* Coefficient of Determination
** Sample Size

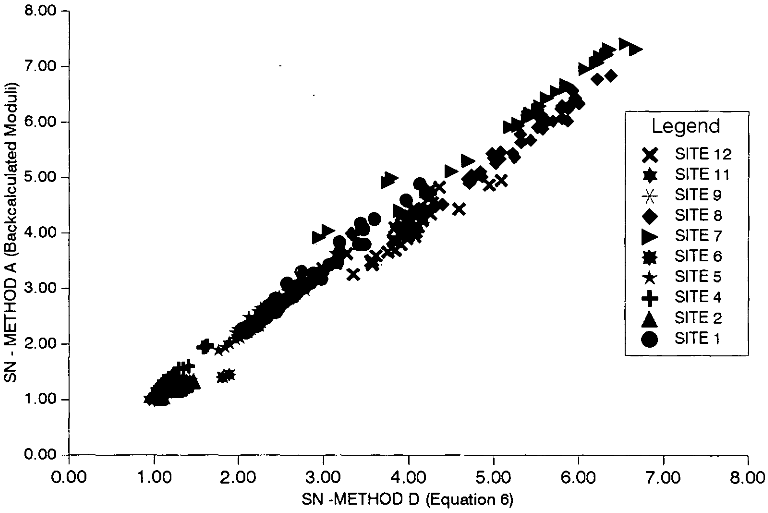

FIGURE 5 Comparison of structural numbers obtained by Method A and those obtained using Equation 6.

on the 10 sections is 98.6 percent. Results per test section are given in Table 5.

CONCLUSION

This paper describes the development of an effective method for calculating a pavement's structural number from FWD deflections. Through a detailed analysis of data collected on 52 in-service pavement structures in Africa and 10 sections in Texas, the authors determined that the developed procedure gives results similar to those obtained using backcalculation techniques, such as AASHTO NDT Method I. It also was shown that AASHTO NDT Method II provided disappointing results because it does not account for shallow rigid layers or stress-sensitive subgrades, a phenomenon commonly found in Sub-Saharan Africa.

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