VERIFICATION OF k-VALUE GUIDELINES

Summary of NCHRP 1-30 k-Value Findings

The elastic k-value on top of the subgrade or prepared embankment is the recommended design input. Only the elastic component of deformation is considered representative of the response of the subgrade to traffic loads on the pavement. Three categories of methods were compiled in NCHRP 1-30 for estimating the elastic k-value of the subgrade for a pavement design project: correlation methods, backcalculation methods, and plate testing methods.

Correlation Methods. Guidelines were developed for selecting an appropriate k-value based on soil classification, moisture level, density, California Bearing Ratio (CBR) data, Hveem stabilometer (R-value) data, or Dynamic Cone Penetrometer (DCP) data. It is anticipated that these correlation methods will be used routinely for design. The k-values obtained from correlation methods may need adjustment for embankment above the subgrade or a shallow rigid layer beneath the subgrade.

Backcalculation Methods. These methods are suitable for determining k-value for design of overlays of existing pavements, or for design of reconstructed pavements on existing alignments, or for design of similar pavements in the same general location on the same type of subgrade. An agency may also use backcalculation methods to develop correlations between nondestructive deflection testing results and subgrade types and properties.

Cut and fill sections are likely to yield different k-values. No embankment or rigid layer adjustment is required for backcalculated k-values if these characteristics are similar for the pavement being tested and the pavement being designed; however, backcalculated dynamic k-values need to be reduced by a factor of approximately two to estimate a static elastic k-value for use in design.

Plate Bearing Test Methods. The most direct method of determining k is by repetitive or nonrepetitive plate loading tests (AASHTO T221 or T222, ASTM D1195 or D1196) on a prepared section of the subgrade or embankment. Because these tests are costly and time-consuming, it is not anticipated that they will be conducted routinely. AASHTO T221 and T222 specify that if the pavement is to be built on an embankment, the plate bearing tests should be conducted on a test embankment.

In the repetitive test, the elastic k-value is determined from the ratio of load to elastic deformation (the recoverable portion of the total deformation measured). In the nonrepetitive test, the load-deformation ratio at a deformation of 0.05 in [1.25 mm] is considered to represent the elastic k-value, according to research by the U.S. Army Corps of Engineers. Note also that a 30-in- [762-mm-] diameter plate should be used to determine the elastic static k-value for use in design. Smaller diameter plates will yield much higher k-values that are inconsistent with slab behavior under load.

Assignment of k-Values to Seasons. A season is defined as a period of time within a year that can be characterized by some set of climatic parameters. Among the factors that should be considered in selecting seasonal k-values are the seasonal movement of the water table, seasonal precipitation levels, winter frost depths, number of freeze-thaw cycles, and the extent to which the subgrade will be protected from frost by embankment material.

The seasonal variation in degree of saturation is difficult to predict, but in locations where a water table is constantly present at a depth of less than about 10 ft [3 m], it is reasonable to expect that fine-grained subgrades will remain at least 70 to 90 percent saturated, and may be completely saturated for substantial periods in the spring. The highest position of the water table, but not its annual variation, can be determined from county soil reports.

A seasonally adjusted "effective" k-value may be obtained by combining the seasonal k-values. The effective k-value is essentially a weighted average based on some performance measure such as fatigue damage. The effective k-value results in the same performance over the entire year that is caused by the seasonally varying k-value. Determination of a seasonally adjusted effective k-value within the context of any specific design procedure must be done using the performance model intrinsic to that procedure. In NCHRP 1-30, an improved seasonal adjustment procedure was developed for the AASHTO Guide, using a proposed revised performance model calibrated to the seasonally adjusted k-value of the AASHO Road Test site.

Adjustment to k for Fill Thickness and Rigid Layer. A nomograph was developed for adjustment of the seasonally adjusted, effective subgrade k-value if: (1) fill material will be placed above the natural subgrade, and/or (2) a rigid layer (e.g., bedrock or hard clay) is present at a depth of 10 ft [3 m] or less beneath the existing subgrade surface. Note that the rigid layer adjustment should only be applied if the subgrade k was determined on the basis of soil type or similar correlations. If the k-value was determined from nondestructive deflection testing or from plate bearing tests, the effect of a rigid layer is already represented in the k-value obtained.

Availability of Subgrade Data in LTPP

Plate Load Data. Plate load test results were located in the LTPP database for 31 sections, of which 22 are GPS-3, -4, or -5 (concrete pavement) sections. Test type data were located for 16 of the 31 sections. The test type was indicated by a "1" if the k-value was obtained from a nonrepetitive test (AASHTO T222), or a "2" if the k-value was obtained from a repetitive test (AASHTO T221). If the tests were conducted in accordance with the AASHTO or equivalent ASTM (American Society for Testing and Materials) standard test method, the two test types—nonrepetitive and repetitive—should yield equivalent results. For the remaining 15 sections for which no test type was indicated, the assumption is made that the k-value reported was obtained from a real plate load test, rather than an estimation.

Other Soils Data. AASHTO soil classification data were available for 548 of the 723 GPS sections retrieved, or 76 percent. California Bearing Ratio (CBR) data were available for only 72 sections, or 10 percent, and R-value data were available for 120 sections, or 17 percent. Other soils data that were retrieved for purposes of checking the validity of the soil classification data were percent fines, and laboratory and in situ maximum densities and optimum moisture contents.

Depth of Soil Samples. Thin-walled tube and/or split spoon sampling was done to 5 ft [1.5 m] below the top of the subgrade, at one location each, before and after the test sections labeled A1 and A2. Augering of the untreated subgrade to 12 in [30 cm] below the top of the subgrade was done to obtain bulk samples at three other locations before the test sections labeled BA1, BA2, and BA3. A 4-ft by 6-ft [1.2-m by 1.8-m] test pit was dug to 12 in [30 cm] below the top of the subgrade after the test section labeled TP. Where a test pit could not be dug, an effort was made to retrieve bulk samples, labeled BA4, BA5, and BA6, from this area.

Deflection Data. Dynamic k-values, as well as concrete slab and base elastic moduli, were obtained from deflections measured on the GPS-3, -4, and -5 sections using a variety of methods, as described in the following section.

Evaluation of Backcalculation Methods

Backcalculation Algorithms. One of the backcalculation algorithms used was the AREA method currently included in the AASHTO Guide, by which the radius of relative stiffness is estimated as a function of the AREA of the deflection basin. This estimation, along with the subsequent calculation of subgrade k and slab E, is done without iteration. The other algorithm used was a best-fit method, which solves for the combination of the radius of relative stiffness (ℓ) and k that produces the best possible agreement between the predicted and measured deflections at each sensor.

- Sensor configurations: Experience has shown that different backcalculation results may be obtained for the same deflection basin using different numbers and positions of sensors. That this occurs routinely is evidence of the departure of the behavior of real pavements from the idealizations of plate theory and elastic theory. To investigate the significance of sensor configuration to backcalculation results, the following configurations were used:

Configuration Name	Algorithm	Sensor Position (inches)
B7	Best fit	0, 8, 12, 18, 24, 36, 60
B5	Best fit	12, 18, 24, 36, 60
B4	Best fit	0, 12, 24, 36
B3	Best fit	12, 24, 36
A7	AREA	0, 8, 12, 18, 24, 36, 60
A5	AREA	12, 18, 24, 36, 60
A4	AREA	0, 12, 24, 36
A3	AREA	12, 24, 36

[1 in = 2.54 cm]

- **Slab dimensions:** Each of the configurations listed above was used to analyze the deflection basins, assuming that the subgrade and pavement layers were horizontally infinite. In addition, corrections for finite slab size were applied in each case to the backcalculation results, as described later. Thus, a total of 18 solutions were obtained for each deflection basin.

- **Load level:** The deflection data were analyzed to determine whether, in the case of concrete pavements, load level has a significant effect on the backcalculation results.

AREA Algorithm. Hoffman and Thompson (6) first proposed the use of a deflection basin parameter called AREA for interpreting flexible pavement deflection basins. The AREA algorithm has been used extensively to analyze concrete pavement deflection basins since 1980. The AREA parameter is not truly an area, but rather has dimensions of length, since it is normalized with respect to one of the deflections in order to remove the effect of load level. For any given number and configuration of deflection sensors, the AREA may be computed from the trapezoidal rule. AREA is computed from the following equations for the four AREA-based methods examined in this study:

$$A7 = 4 + 6\left(\frac{d_8}{d_0}\right) + 5\left(\frac{d_{12}}{d_0}\right) + 6\left(\frac{d_{18}}{d_0}\right) + 9\left(\frac{d_{24}}{d_0}\right) + 18\left(\frac{d_{36}}{d_0}\right) + 12\left(\frac{d_{60}}{d_0}\right) \qquad [1]$$

$$A5 = 3 + 6\left(\frac{d_{18}}{d_{12}}\right) + 9\left(\frac{d_{24}}{d_{12}}\right) + 18\left(\frac{d_{36}}{d_{12}}\right) + 12\left(\frac{d_{60}}{d_{12}}\right) \qquad [2]$$

$$A4 = 6 + 12\left(\frac{d_{12}}{d_0}\right) + 12\left(\frac{d_{24}}{d_0}\right) + 6\left(\frac{d_{36}}{d_0}\right) \qquad [3]$$

$$A3 = 6 + 12\left(\frac{d_{24}}{d_{12}}\right) + 6\left(\frac{d_{36}}{d_{12}}\right) \qquad [4]$$

For each of these sensor configurations, the radius of relative stiffness (ℓ) may be estimated from the following equation, with the coefficients for use with each configuration given in Table 1:(5)

$$\ell = \left[\frac{ln\left(\frac{x_1 - AREA}{x_2}\right)}{x_3} \right]^{x_4} \qquad [5]$$

Table 1. Coefficients for AREA vs. ℓ equation.

AREA	x_1	x_2	x_3	x_4
A7	60	289.708	-0.698	2.566
A5	48	158.40	-0.476	2.220
A4	36	1812.279	-2.559	4.387
A3	24	662.272	-2.122	4.001

Once the radius of relative stiffness is known, the subgrade dynamic k-value may be estimated from the deflection measured at any distance d_r using the following equation:

$$k = \frac{P\, d_r^*}{d_r\, \ell^2} \qquad [6]$$

where P = load magnitude
d_r = measured deflection at radial distance r
d_r^* = nondimensional deflection coefficient for radial distance r:

$$d_r^* = a\, e^{\left[-b\, e^{(-c\,\ell)}\right]} \qquad [7]$$

The values for the a, b, and c constants in equation 7 are given in Table 2.(5)

Table 2. Coefficients for nondimensional deflection equation.

Radial distance (in)	a	b	c
0	0.12450	0.14707	0.07565
8	0.12323	0.46911	0.07209
12	0.12188	0.79432	0.07074
18	0.11933	1.38363	0.06909
24	0.11634	2.06115	0.06775
36	0.10960	3.62187	0.06568
60	0.09521	7.41241	0.06255

$R^2 \geq 99.7$ percent (predicted versus actual values) for all models.
$\sigma_Y \leq 0.01$ for all models.
1 in = 25.4 mm

Note that the equations presented here were developed for the falling-weight deflectometer (FWD) load plate radius of 5.9 in [150 mm]. Note also that to obtain an estimate of k that is independent of the estimated ℓ, one must use the coefficients for the deflection that was used to normalize the AREA equation, that is, d_0 for A7 and A4, and d_{12} for A5 and A3.

Among the advantages of the AREA algorithm are ease of use (i.e., being directly solvable with a spreadsheet or calculator, without any particular backcalculation software), use of several deflections to characterize the overall response of the subgrade and pavement, and applicability to concrete pavements with asphalt overlays or other pavements (such as very thick slabs) for which slab compression may be a significant factor in deflection under the load plate. The latter is accomplished using an AREA definition such as A5 or A3 that excludes d_0.

Among the disadvantages of the AREA algorithm are the sensitivity of the normalizing deflection (d_0 or d_{12}), the assumption that the slab and subgrade are horizontally infinite, and the characterization of the entire pavement structure above the subgrade as a single plate. To address the latter two limitations, an available method for correcting the backcalculation results for finite slab size was evaluated and improved in this study, as described later. Methods are also available for dividing the composite elastic modulus of the pavement into two moduli for a slab and base, but these were not evaluated in this study.

Best Fit Algorithm. The objective of the best fit backcalculation algorithm is to find a combination of concrete elastic modulus and subgrade k-value for which the calculated deflection profile closely matches the measured profile. The problem can be formulated as the minimization of the error function, F, defined as follows:

$$F(E,k) = \sum_{i=0}^{n} \alpha_i \left(w(r_i) - W_i\right)^2 \qquad [8]$$

where α_i is the weighting factor, $w(r_i)$ is the calculated deflection, and W_i is the measured deflection. The weighting factor might be set equal to 1, or $(1/W_i)^2$, or any other numbers.

For a given load radius and sensor configuration, the deflections at the sensor locations can be rewritten in the following form:

$$w(r_i) = \frac{p}{k} f_i(\ell) \qquad [9]$$

where p is the applied load pressure and f_i is the function of the radius of relative stiffness, distance from the center of applied load to the location of the ith sensor, and the parameters of applied load. The expressions for the function f_i can be found in Reference 7. The error function F can be presented in the following form:

$$F(E,k) \equiv F(\ell,k) = \sum_{i=0}^{n} \alpha_i \left(\frac{p}{k} f_i(\ell) - W_i \right)^2 \qquad [10]$$

To obtain the minimum of the error function F, the following conditions should be satisfied:

$$\frac{\partial F}{\partial k} = 0 \qquad [11]$$

$$\frac{\partial F}{\partial \ell} = 0 \qquad [12]$$

Substitution of the error function equation into the equation for the first condition yields the following equation for the k-value:

$$k = p \, \frac{\sum_{i=0}^{n} \alpha_i (f_i(\ell))^2}{\sum_{i=0}^{n} \alpha_i \, W_i \, f_i(\ell)} \qquad [13]$$

Substitution of the error function equation into the equation for the second condition yields the following equation for the radius of relative stiffness:

$$\frac{\sum_{i=0}^{n} \alpha f_i(\ell) f_i'(\ell)}{\sum_{i=0}^{n} \alpha_i (f_i(\ell))^2} = \frac{\sum_{i=0}^{n} \alpha_i \, W_i \, f_i'(\ell)}{\sum_{i=0}^{n} \alpha_i \, W_i \, f_i(\ell)} \qquad [14]$$

These equations could be solved using a spreadsheet or a computer program (ERESBACK 2.0) that ERES Consultants developed for this purpose under another study, with a trivially short execution time per basin.

In this study, the following procedures were used to apply this best fit algorithm to backcalculation of subgrade k-values:

1. Assign weighting factors. In this study, they were set equal to 1.
2. Determine the radius of relative stiffness that satisfies the ℓ equation.
3. Use the k equation to determine the modulus of subgrade reaction.

The ability to control the weights given to the various deflection measurements adds some flexibility to the best fit solution process. Among the disadvantages are the complexity of the solution process and two of the same disadvantages described earlier for the AREA algorithm—the need for a correction for finite slab size and the need to divide the composite elastic modulus of the pavement structure into individual moduli for the slab and base.

Comparisons of Sensor Configurations and Backcalculation Algorithms. The results of the application of all of the backcalculation methods to the LTPP GPS-3, -4, and -5 data permit several comparisons.

1. Best fit versus AREA for equal sensor configurations:

B7 versus A7: 0, 8, 12, 18, 24, 36, 60 in (see Figure 1)
B5 versus A5: 12, 18, 24, 36, 60 in (see Figure 2)
B4 versus A4: 0, 12, 24, 36 in (see Figure 3)
B3 versus A3: 12, 24, 36 in (see Figure 4)
[1 in = 2.54 cm]

In every case, the AREA method produces slightly higher k-values than the best fit method. This is believed to be due to the greater sensitivity of the AREA method to the maximum deflection used (D_0 or D_{12}). Better agreement is achieved with the two configurations that exclude D_0, the deflection at the center of the load plate.

2. Effect of deflection basin radius for same algorithm:

B7 versus B4: 0, 8, 12, 18, 24, 36, 60 in versus 0, 12, 24, 36 in (see Figure 5)
B5 versus B3: 12, 18, 24, 36, 60 in versus 12, 24, 36 in (see Figure 6)
A7 versus A4: 0, 8, 12, 18, 24, 36, 60 in versus 0, 12, 24, 36 in (see Figure 7)
A5 versus A3: 12, 18, 24, 36, 60 in versus 12, 24, 36 in (see Figure 8)
[1 in = 2.54 cm]

With each method, the use of D_{60} gives a slightly lower k-value. This is more noticeably true for the AREA methods.

3. Effect of deflections under load for same algorithm:

B7 versus B5: 0, 8, 12, 18, 24, 36, 60 in versus 12, 18, 24, 36, 60 in (see Figure 9)
B4 versus B3: 0, 12, 24, 36 in versus 12, 24, 36 in (see Figure 10)
A7 versus A5: (Same as B7 versus B5) (see Figure 11)
A4 versus A3: (Same as B4 versus B3) (see Figure 12)
[1 in = 2.54 cm]

In each case, the use of D_0 produces a somewhat lower k-value than the exclusion of D_0. This is most noticeably true for the AREA methods.

Correction for Slab Size. The backcalculation procedures presented above are based on Westergaard's solution for interior loading of an infinite plate. A concrete slab, however, has finite dimensions. If the slab is sufficiently small that its behavior does not approximate that of an ideal infinite slab, the backcalculation results may be distorted. In general, analyzing a small slab as if it were an infinite slab will lead to underestimation of the k-value and overestimation of the concrete modulus. In 1993, Crovetti developed the following slab size correction procedure for a square slab, based on the results of finite element analysis using the computer program ILLI-SLAB:

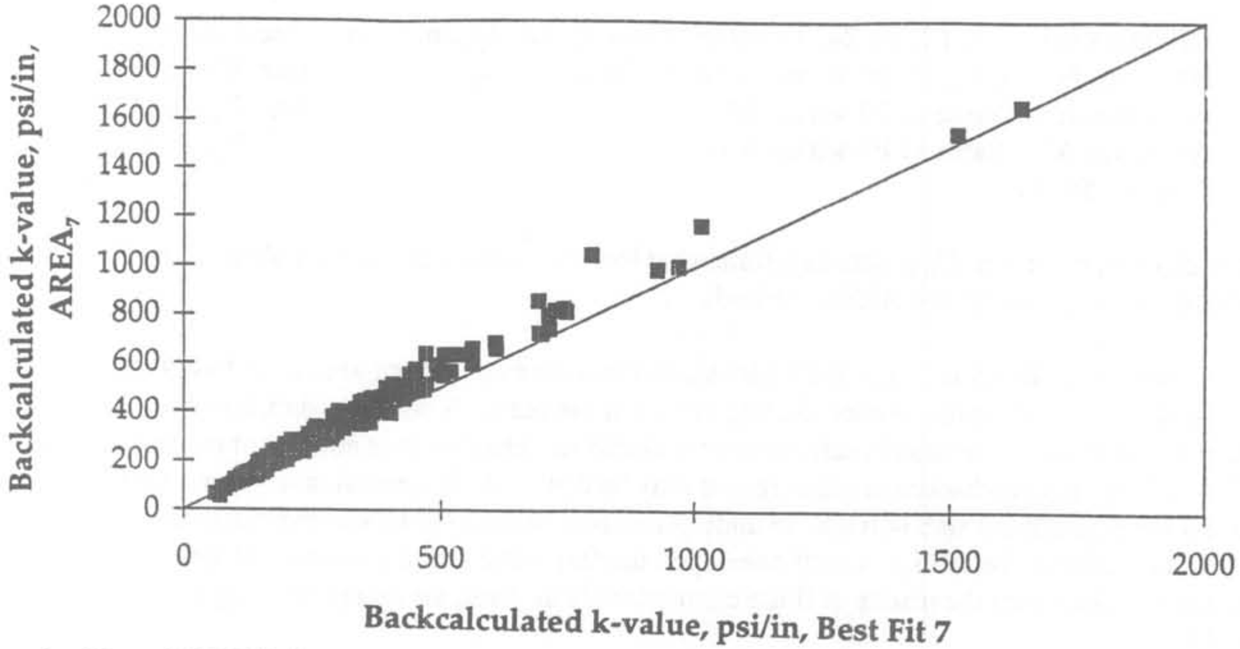
1. Estimate ℓ from the infinite slab size backcalculation procedure.
2. Calculate L/ℓ_{est}, where L is the square slab size (both L and ℓ are expressed in the same units).
3. Calculate adjustment factors for maximum deflection (d_0) and ℓ from the following equations:

$$AF_{d_0} = 1 - 1.15085\ e^{-0.71878 \left(\frac{L}{\ell_{est}} \right)^{0.80151}} \qquad [15]$$

$$AF_{\ell} = 1 - 0.89434\ e^{-0.61662 \left(\frac{L}{\ell_{est}} \right)^{1.04831}} \qquad [16]$$

4. Calculate adjusted d_0 = measured $d_0 * AF_{d0}$.
5. Calculate adjusted ℓ = measured $d_0 * AF_{\ell}$.
6. Backcalculate the subgrade k-value and concrete E using the adjusted d_0 and ℓ.

This procedure has some limitations. First, it considers only a single slab, assuming no load transfer to adjacent slabs. Second, the above equations were developed for square slabs, although they are considered to be sufficiently accurate for use with rectangular slabs, where L is taken as the smaller slab dimension, length or width. Third, the deflection adjustment factor was developed for d_0, whereas some of the backcalculation methods evaluated for this study did not use the maximum deflection.



1 psi/in = 0.271 kPa/mm

Figure 1. Backcalculated dynamic k-value, best fit 7 versus AREA$_7$.

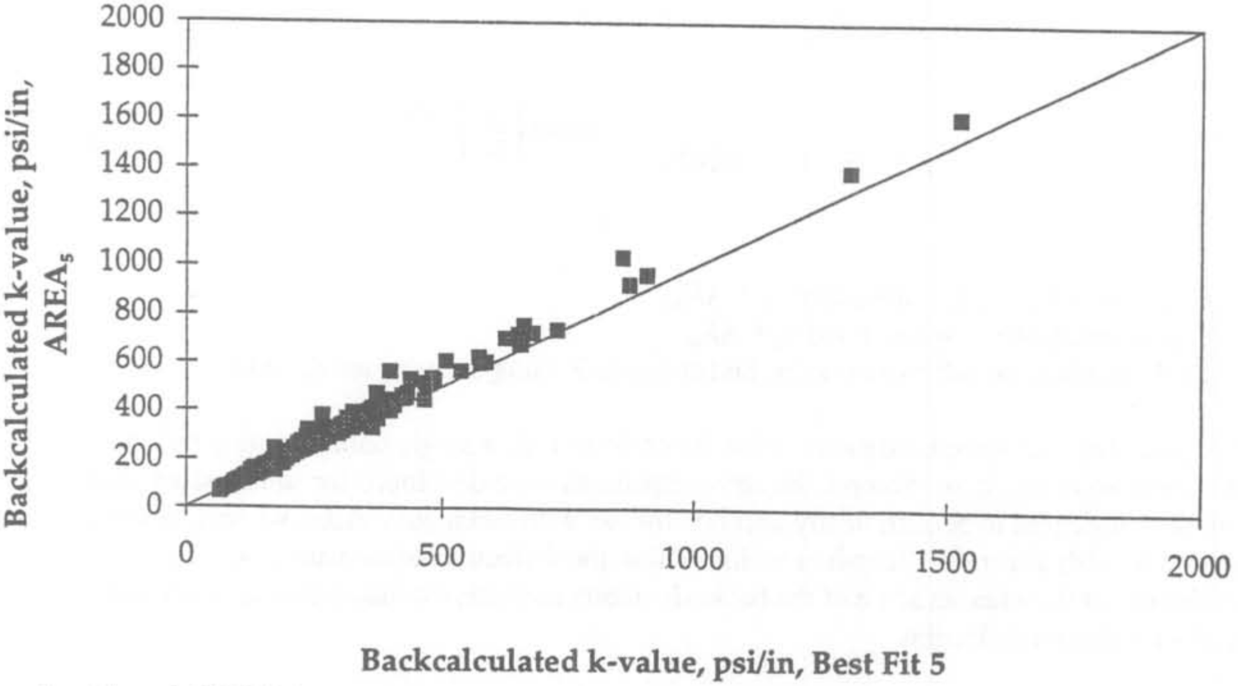


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Figure 2. Backcalculated dynamic k-value, best fit 5 versus AREA$_5$.

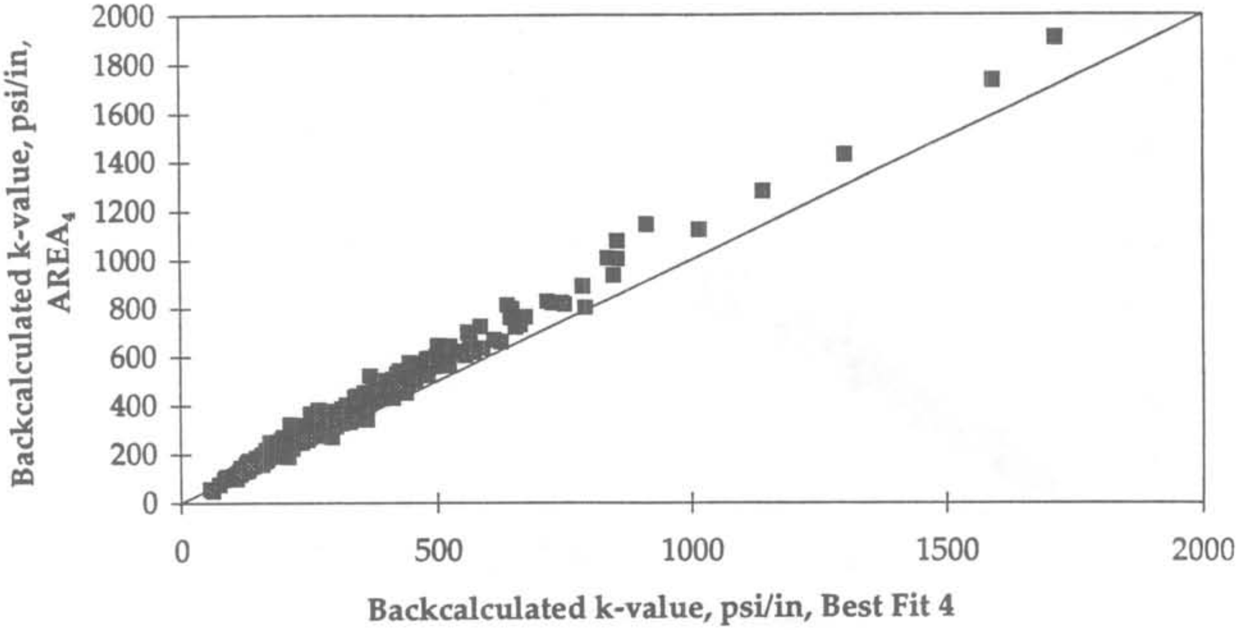

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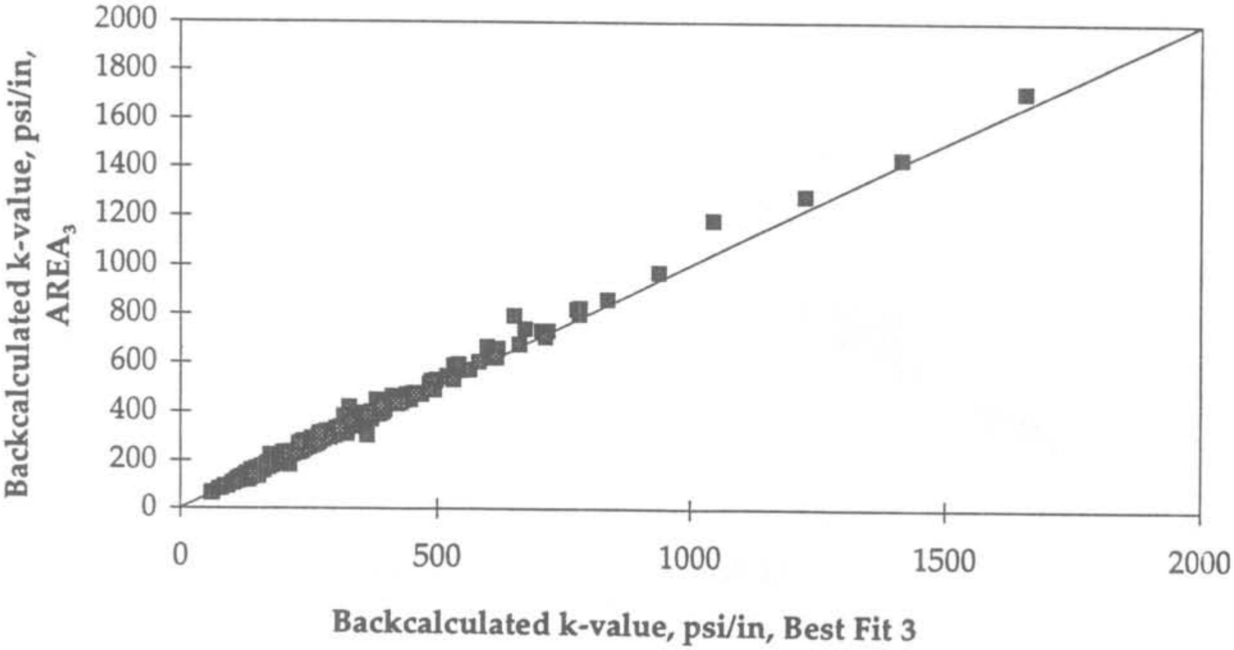
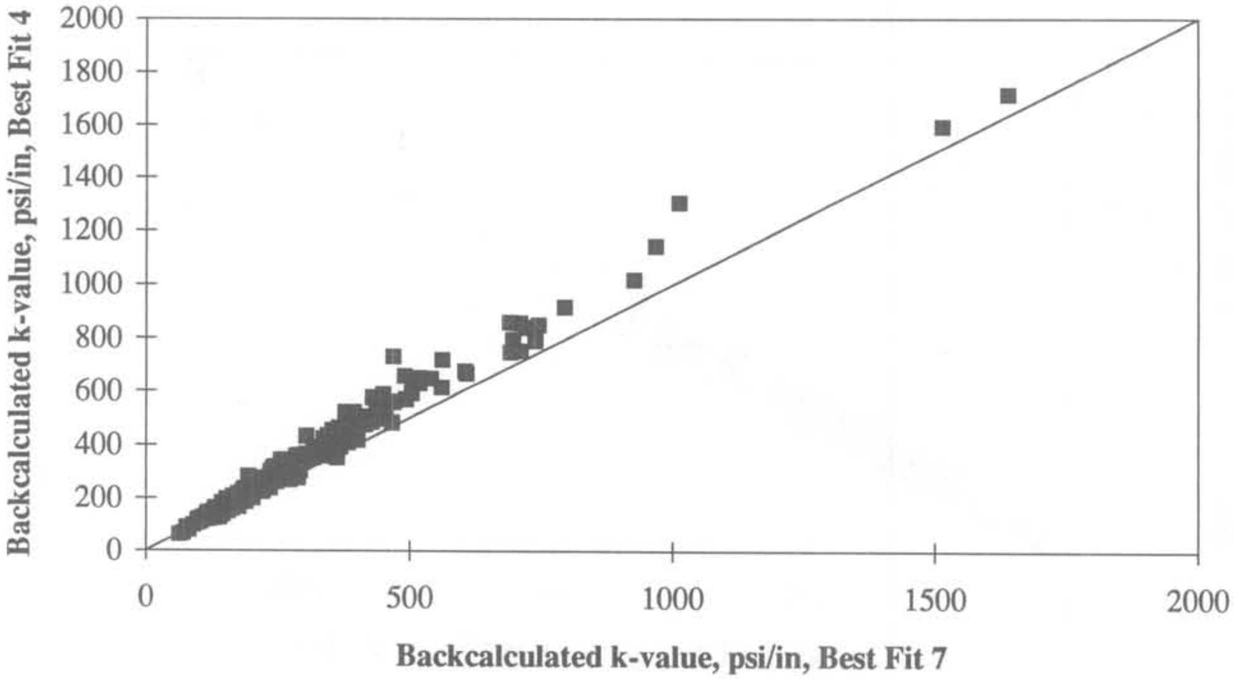
Figure 3. Backcalculated dynamic k-value, best fit 4 versus AREA$_4$.



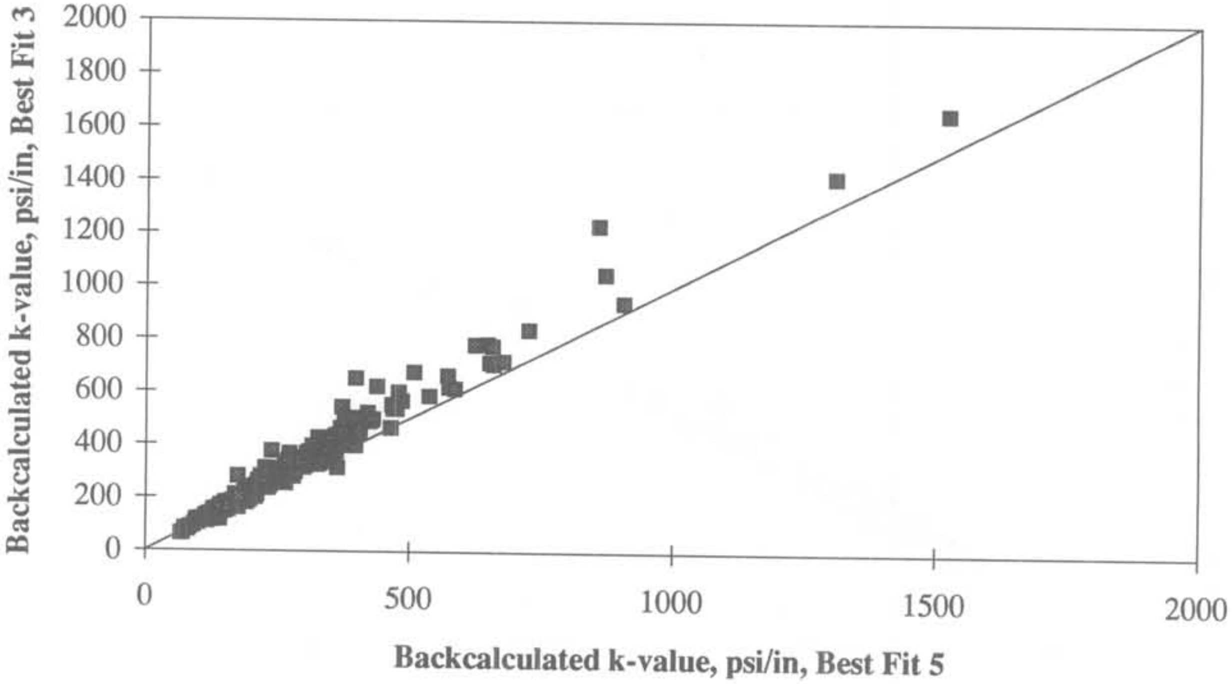
1 psi/in = 0.271 kPa/mm

Figure 4. Backcalculated dynamic k-value, best fit 3 versus AREA$_3$.



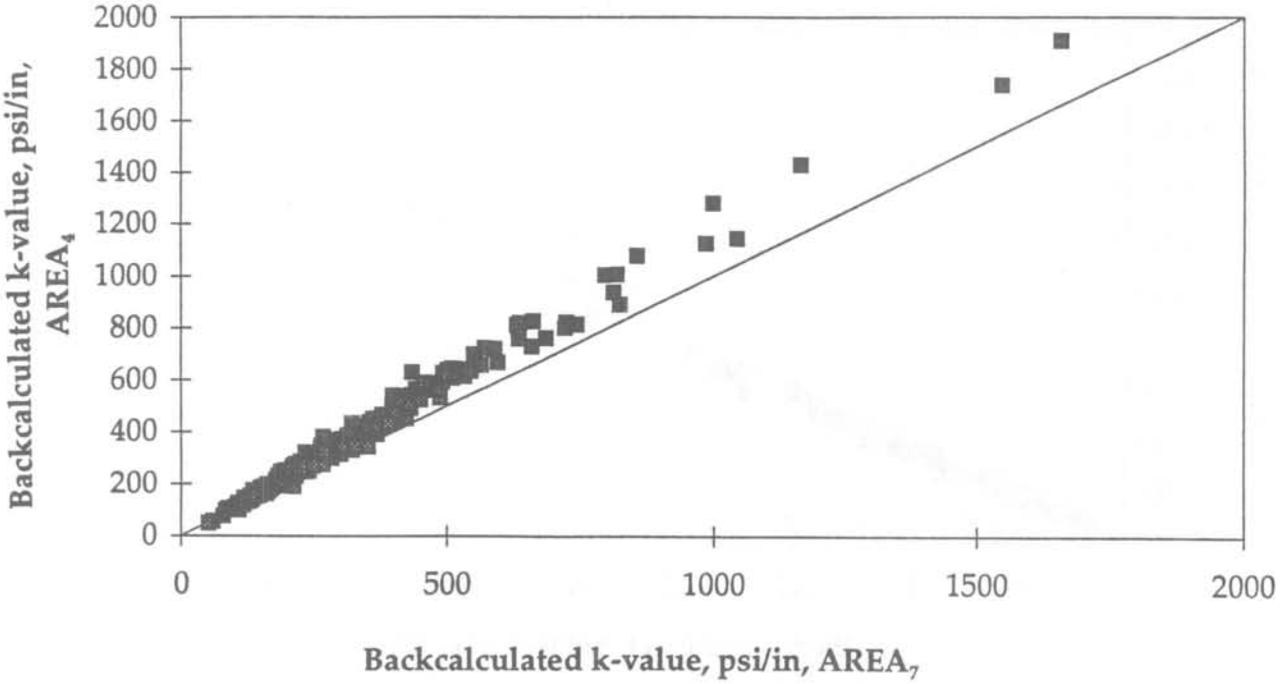
1 psi/in = 0.271 kPa/mm

Figure 5. Backcalculated dynamic k, best fit 7 versus best fit 4.



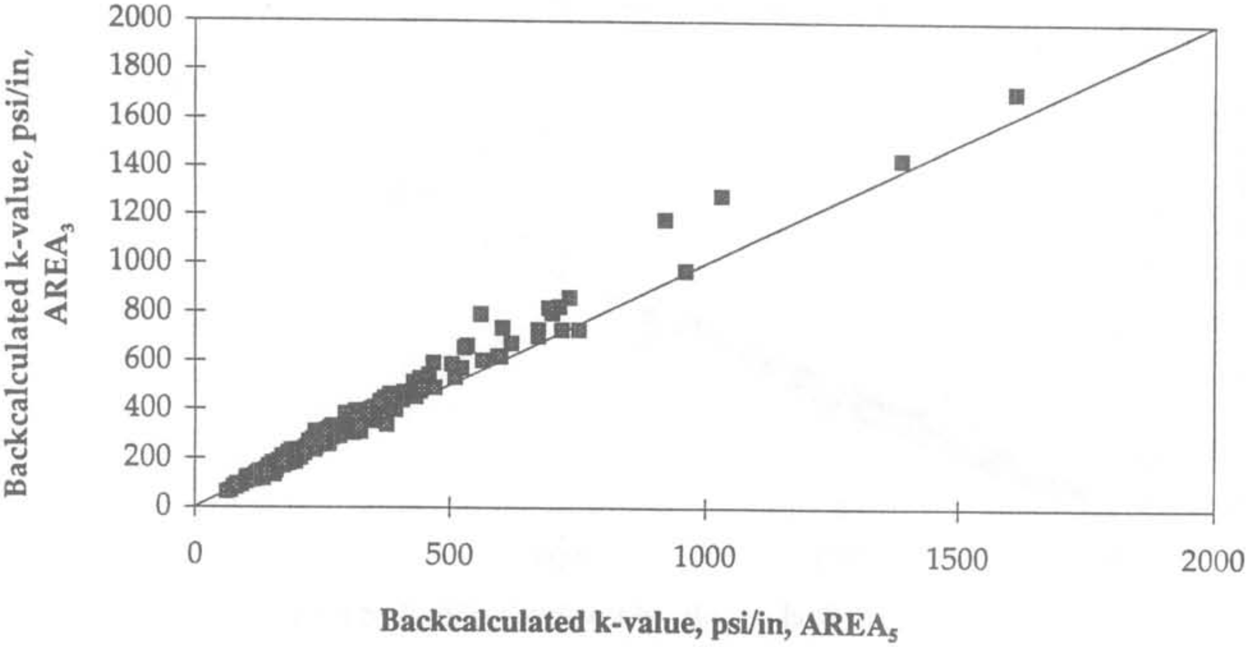
1 psi/in = 0.271 kPa/mm

Figure 6. Backcalculated dynamic k, best fit 5 versus best fit 3.



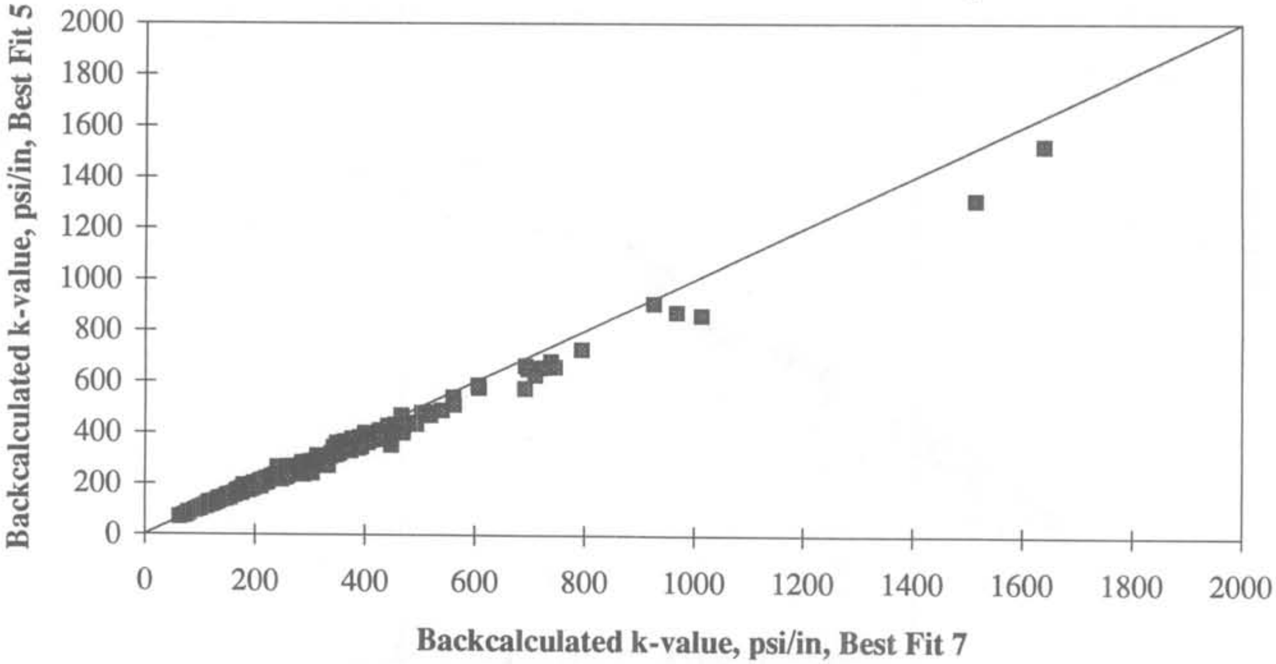
1 psi/in = 0.271 kPa/mm

Figure 7. Backcalculated dynamic k, AREA$_7$ versus AREA$_4$.



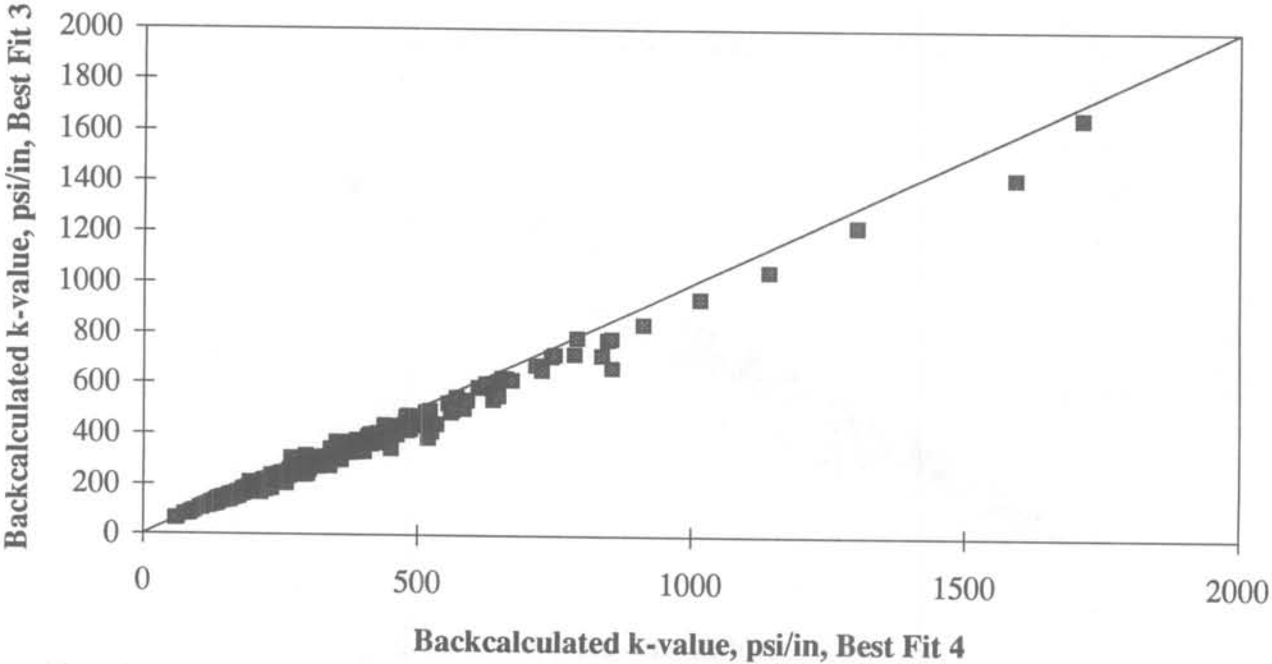
1 psi/in = 0.271 kPa/mm

Figure 8. Backcalculated dynamic k, AREA$_5$ versus AREA$_3$.



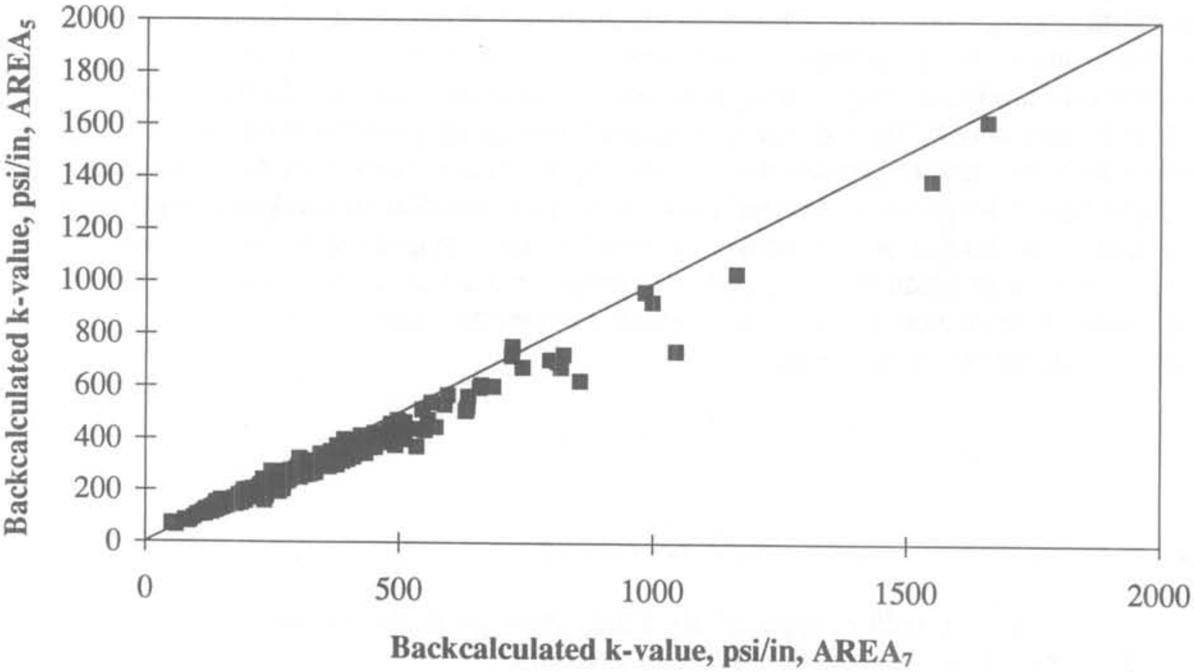
1 psi/in = 0.271 kPa/mm

Figure 9. Backcalculated dynamic k, best fit 7 versus best fit 5.



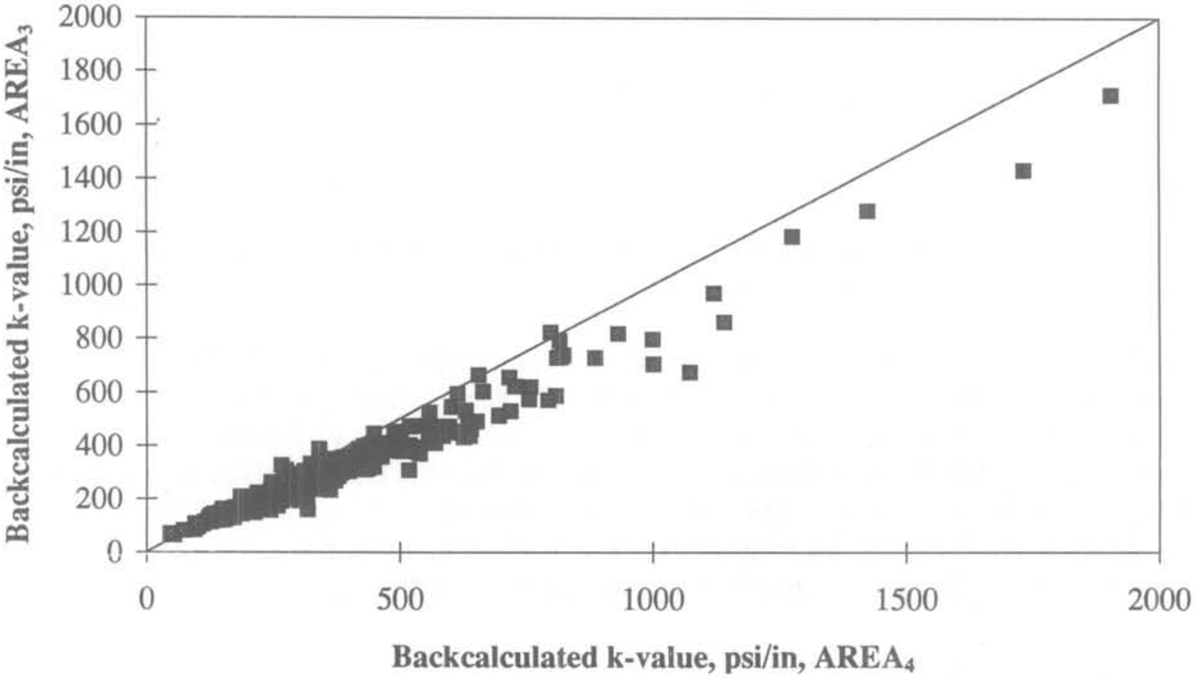
psi/in = 0.271 kPa/mm

Figure 10. Backcalculated dynamic k, best fit 4 versus best fit 3.



1 psi/in = 0.271 kPa/mm

Figure 11. Backcalculated dynamic k, $AREA_7$ versus $AREA_5$.



1 psi/in = 0.271 kPa/mm

Figure 12. Backcalculated dynamic k, $AREA_4$ versus $AREA_3$.

In this study, Crovetti's procedure for slab size correction was verified using an analytical closed-form solution and generalized to address the second and third limitations. Crovetti developed his procedure using the results of finite element analysis. To verify this procedure, an alternative procedure was developed using an analytical solution for interior loading of a finite size slab obtained by Korenev.(8) The solution generalizes Westergaard's solution for deflection of an infinite slab to the case of a circular slab. To find the deflection distribution in a rectangular and not very long slab for points located not too close to the edges, Korenev recommended using the solution for a circular slab with a surface area equal to the rectangular slab's area. In this study, Korenev's recommendation was modified. It is proposed that Crovetti's correction factors be applied using an equivalent square slab, L, which provides the same surface area of the rectangular and square slabs, that is,

$$L = \sqrt{L_1 \; L_2} \qquad [17]$$

where L_1 and L_2 are slab width and length, respectively.

This recommendation should be applied only if the slab length is no more than twice the slab width. For longer slabs, an equivalent slab size is equal to:

$$L = \sqrt{2} \; L_1 \qquad [18]$$

To address the third limitation, an alternate correction was developed, in which steps 4 and 6 above are replaced by the following equation for the k-value:

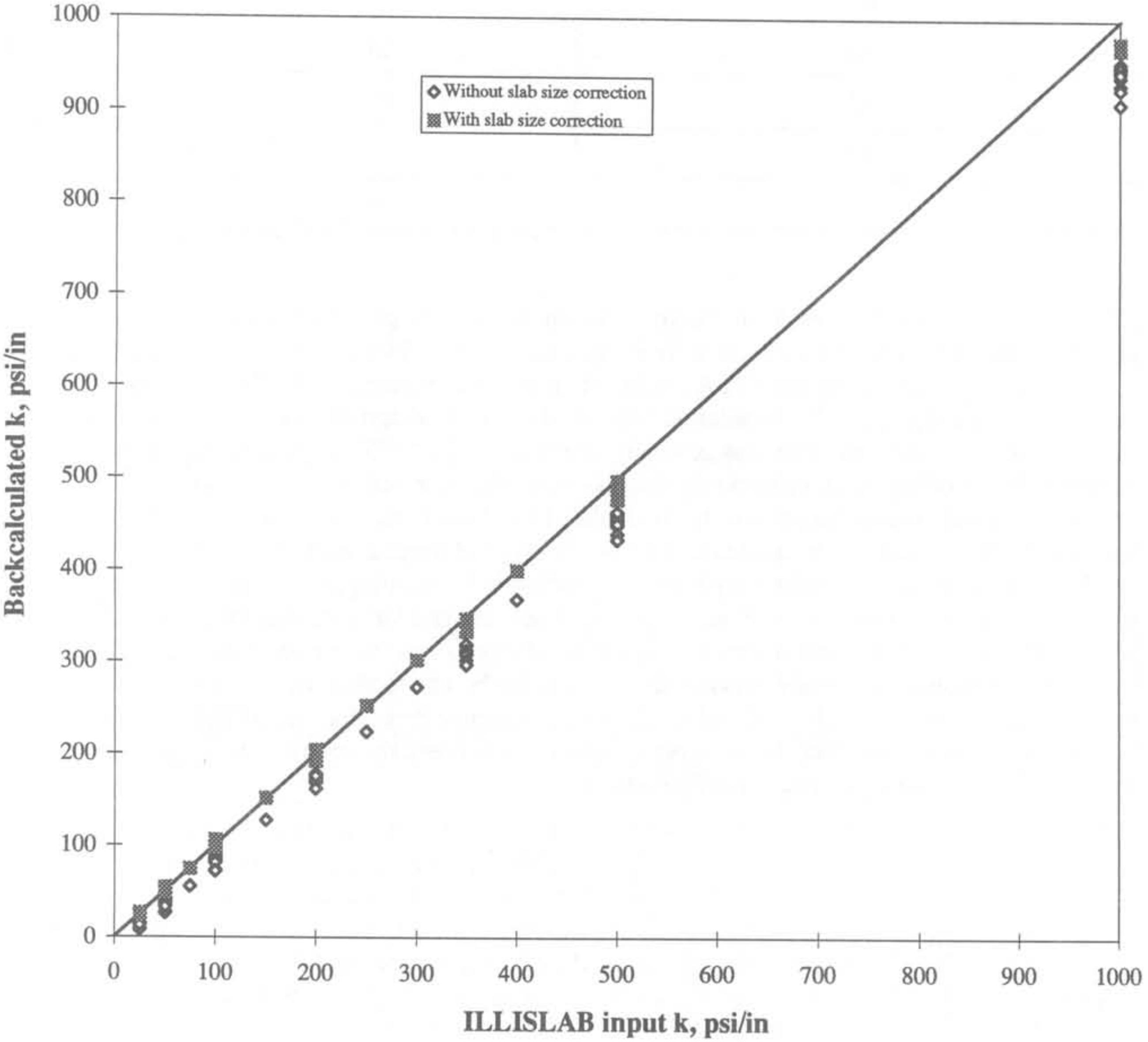
$$k = \frac{k_{est}}{(AF_{\ell_{est}})^2 \;\; AF_{d_0}} \qquad [19]$$

This correction factor can be applied with any backcalculation procedures, including the AREA-based procedures and the best fit procedures.

To verify the proposed modifications, a series of deflection profiles modeling FWD tests were generated using the finite element program ILLI-SLAB. The length of the slab was varied from 12 ft to 60 ft [3.7 m to 18.3 m], and the radius of relative stiffness was varied from 25 in to 55 in [63.5 cm to 139.7 cm]. The coefficients of subgrade reaction were backcalculated using the Best Fit 4 algorithm, and deflection profiles were generated and compared with ILLI-SLAB inputs. Figure 13 shows the results of this comparison. The modified slab size correction procedure provides a good correlation between the input and backcalculated k-values.

Effect of Slab Size Correction on Backcalculated k

For every backcalculation method investigated, the correction for finite slab size produces an increase in the k-value. The percentage increases in the backcalculated dynamic k-value for 287 GPS-3 and GPS-4 sections are shown in Table 3. The mean increase ranges from 17 to 27 percent for the various methods. However, within each method, the increase in k with slab size correction varies a great deal; thus, it is not reasonable to pick a single percentage to be applied to infinite slab backcalculation results in all cases.



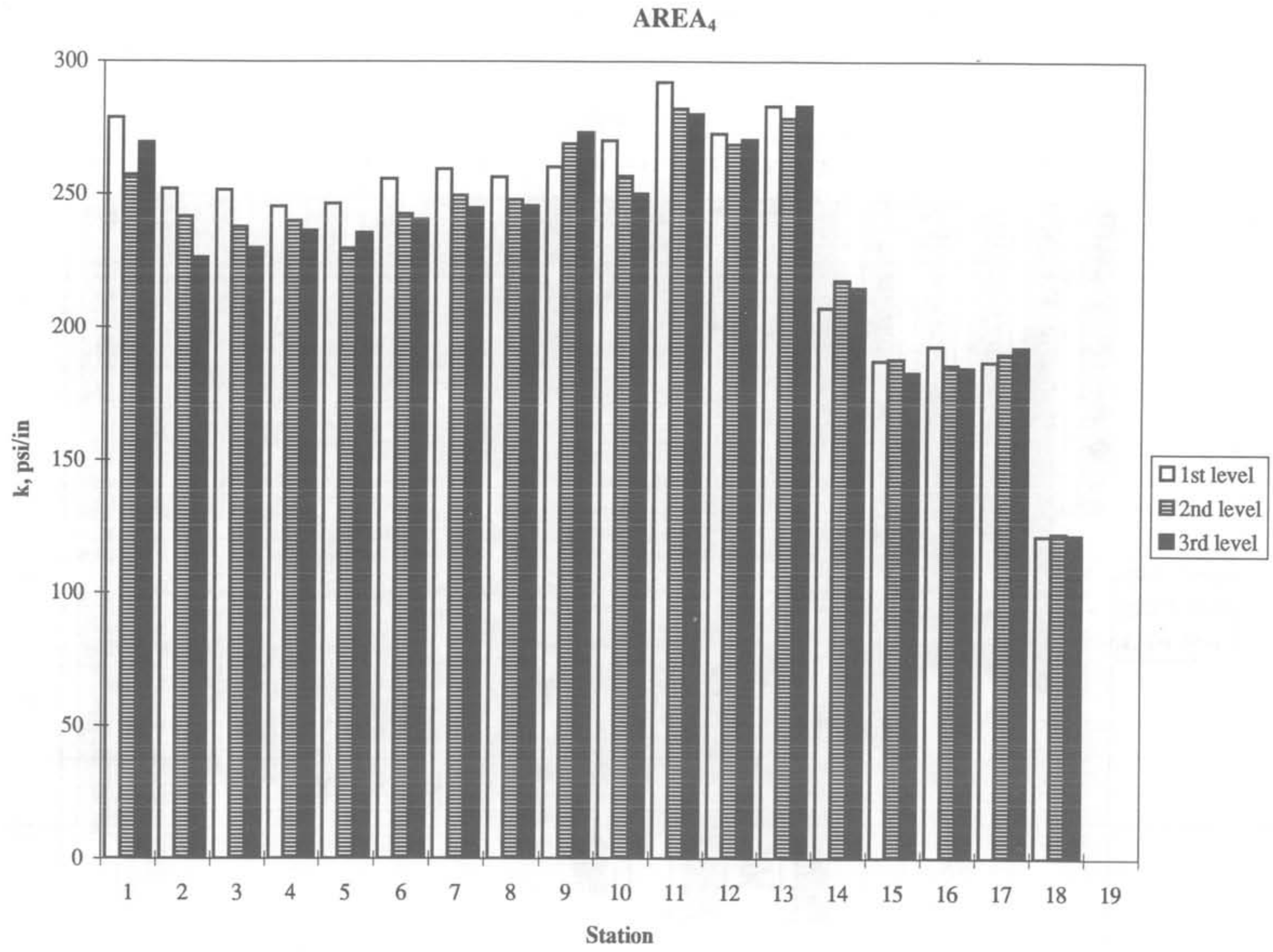
1 psi/in = 0.271 kPa/mm

Figure 13. Improvement in backcalculated k-value with modified slab size correction.

Table 3. Effect of slab size correction on backcalculated dynamic k-value.

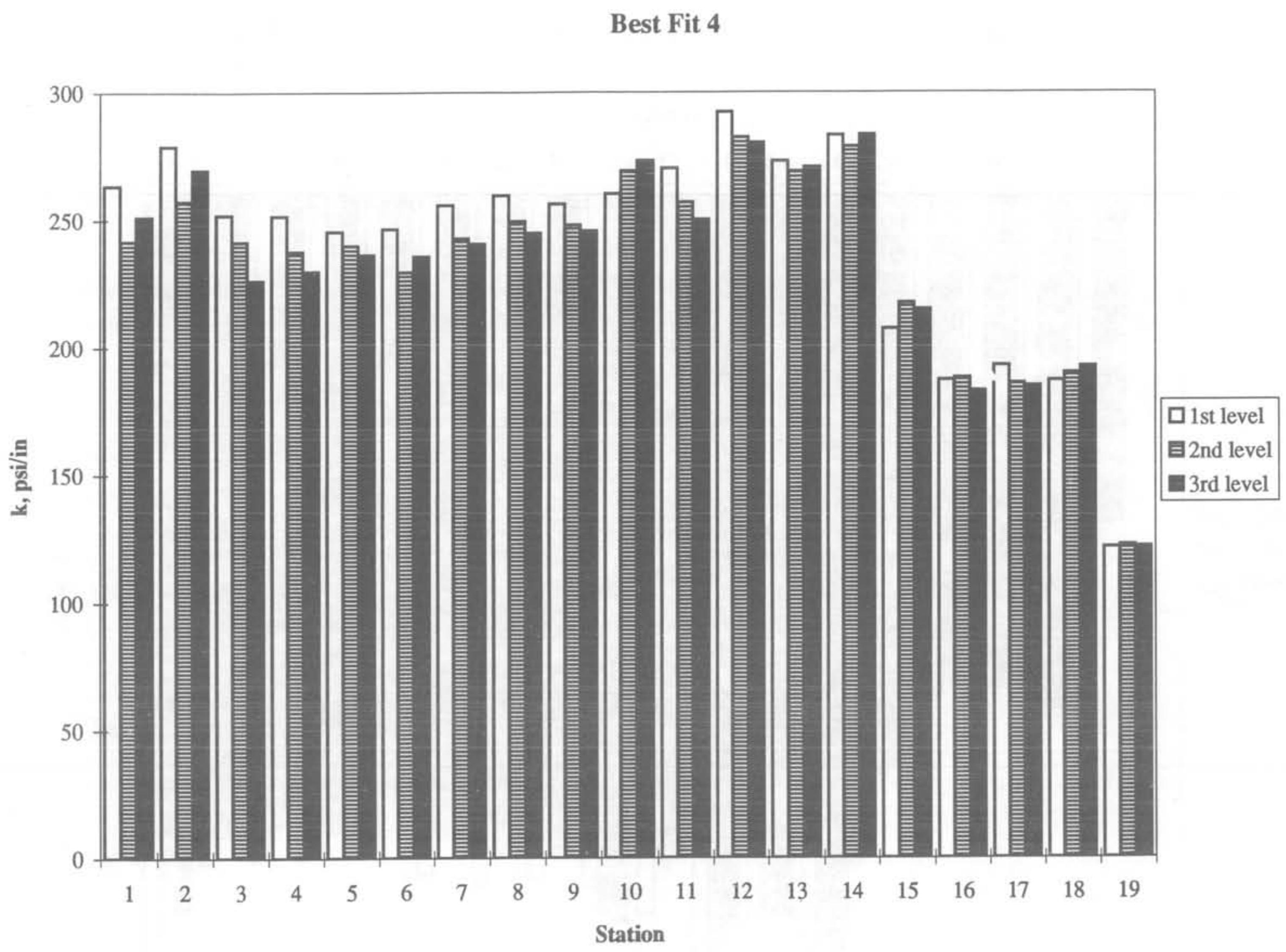
Method	Percent increase in k-value with correction mean	range
B7	24	1 - 92
B5	27	1 - 106
B4	21	1 - 72
B3	24	1 - 103
A7	20	0 - 80
A5	25	1 - 107
A4	17	0 - 90
A3	23	1 - 111

Effect of Load Level. The results of backcalculation for concrete pavements usually do not depend on load level if the load level is sufficiently large. Figures 14 and 15 show comparisons of backcalculated k-values using the $AREA_4$ and Best Fit 4 methods, respectively, for different stations of the same project. No correlation between the load level and backcalculated k-values is observed for either method. This was generally true of all of the LTPP sections analyzed; no significant effect of load level on backcalculated k-value was observed. Figure 16 shows a histogram of coefficient of variation of backcalculated k-values for the GPS-3 sections for particular locations based on backcalculation from 12 drops (4 drops at each of 3 load levels). For all of the methods, the median coefficient of variation in k for multiple drops and multiple load levels at a given station is less than or equal to 5 percent, and for more than 80 percent of the GPS-3 sections, the coefficient of variation at a given station is less than or equal to 10 percent. Figure 16 also shows that for any sensor configuration, the best fit method yields a lower coefficient of variation in backcalculated k-values from multiple drops than the AREA method. For both methods, exclusion of D_0 yields better agreement between the coefficients of variation obtained for otherwise equal sensor configurations.



1 psi/in = 0.271 kPa/mm

Figure 14. Effect of load level on AREA$_4$ backcalculated k-values for an example project.



1 psi/in = 0.271 kPa/mm

Figure 15. Effect of load level on best fit 4 backcalculated k-values for an example project.

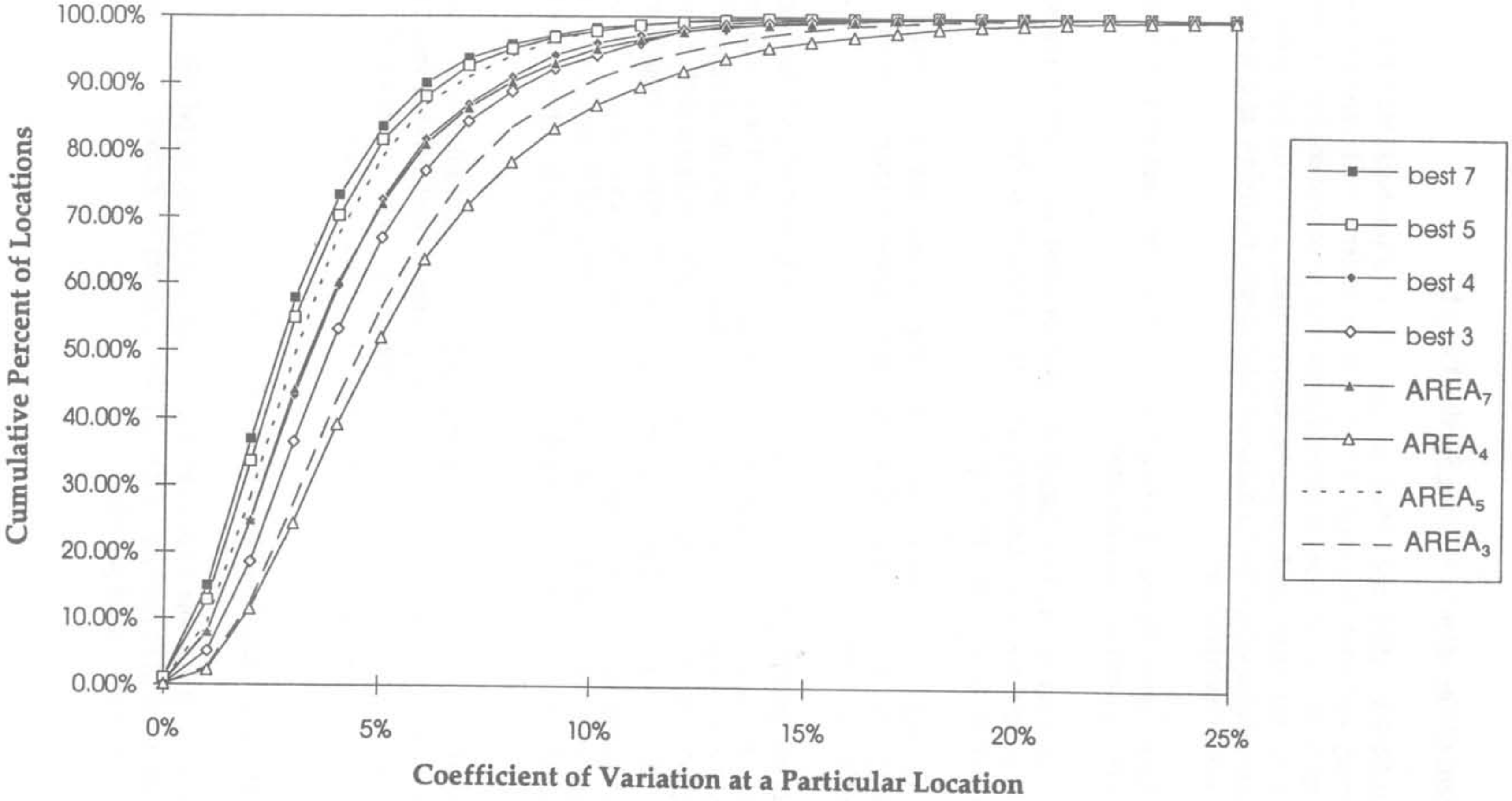


Figure 16. Coefficient of variation in backcalculated k-value for multiple load drops and load levels.

Coefficient of Variation in k Along Section Length

Using the GPS-3, GPS-4, and GPS-5 data sets, a k-value was backcalculated for every station and for every load level. For some sections, a large scatter of backcalculated k-values resulted, which may be due to variations in material properties, pavement condition (proximity of cracks to deflection basins), pavement layer thicknesses, interface conditions, and so on. To determine the most representative values for the backcalculated values, the following data screening procedure was applied for each section:

Step 1. Using the backcalculation results for all stations and load levels, the mean and standard deviation of the k-value were calculated.

Step 2. The backcalculated k-values from each individual station were compared with the mean values. If at least one value differed by more than two standard deviations from the mean value, the results from that station were dropped.

Step 3. If at least one station was dropped in Step 2, a new mean and standard deviation was calculated for the section and Step 2 was repeated; otherwise, the mean value was accepted as the final results for the section.

Figure 17 compares the mean values of backcalculated k for the GPS-3 data set obtained before and after screening. For most cases, these values are very close. The difference is significant for only a few cases. Figures 18 and 19 show cumulative frequency distributions of the coefficient of variation of backcalculated k-values for the GPS-3 sections before and after screening, respectively. Before screening, the median coefficient of variation is about 20 percent for all backcalculation methods. After screening, the median coefficient of variation is about 10 percent for all methods. Of course, it must be remembered that the LTPP sections are relatively short; a larger coefficient of variation in backcalculated k-values might be expected for a project of greater length.

As a rule of thumb, a coefficient of variation in backcalculated k that is less than 20 percent after screening of outliers is reasonable. Significantly higher k coefficients of variation suggest significant changes in the subgrade soil type, the embankment thickness, or the depth to bedrock. Division of the project into subsections of more consistent k-values may be appropriate in some cases.

Comparisons of Plate Load Data With Other Data

Perhaps the most valuable set of LTPP data for use in verifying the NCHRP 1-30 k-value guidelines is the set of plate load test results available for 31 sections. For these sections, the following comparisons are possible.

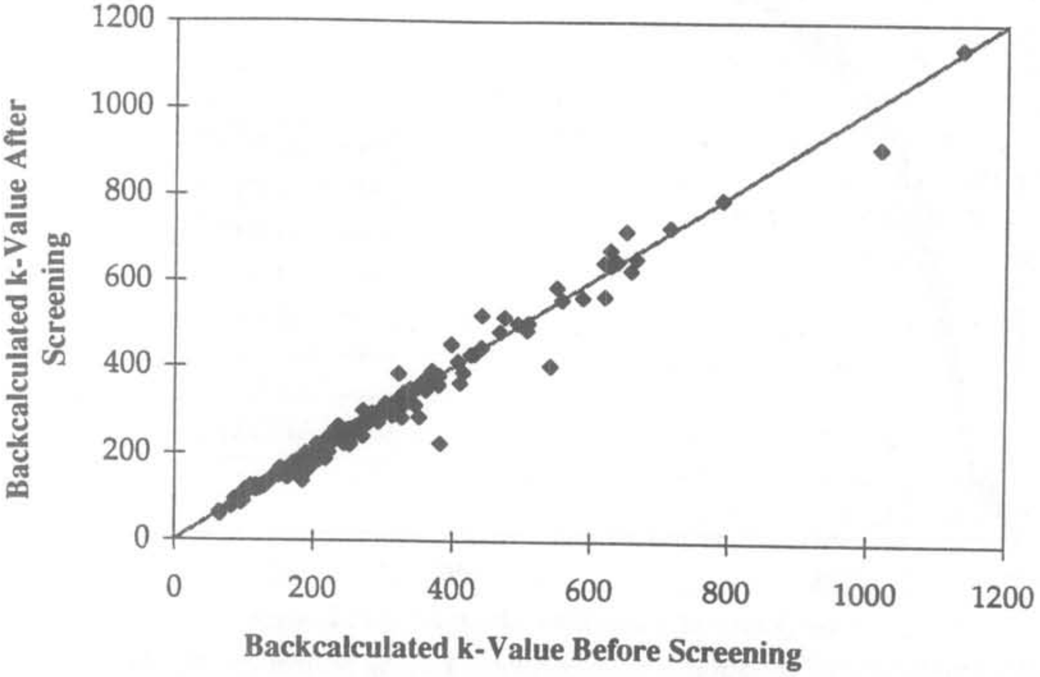


Figure 17. Mean backcalculated k-value before and after screening.

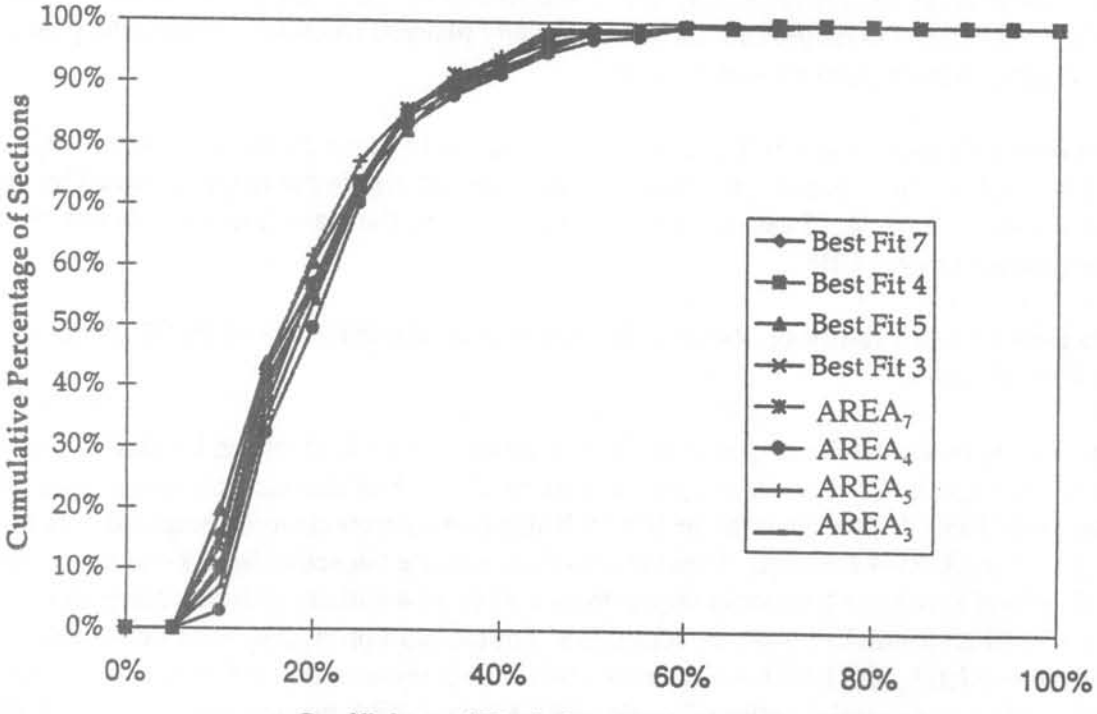


Figure 18. Coefficient of variation in backcalculated k along project length, before screening.

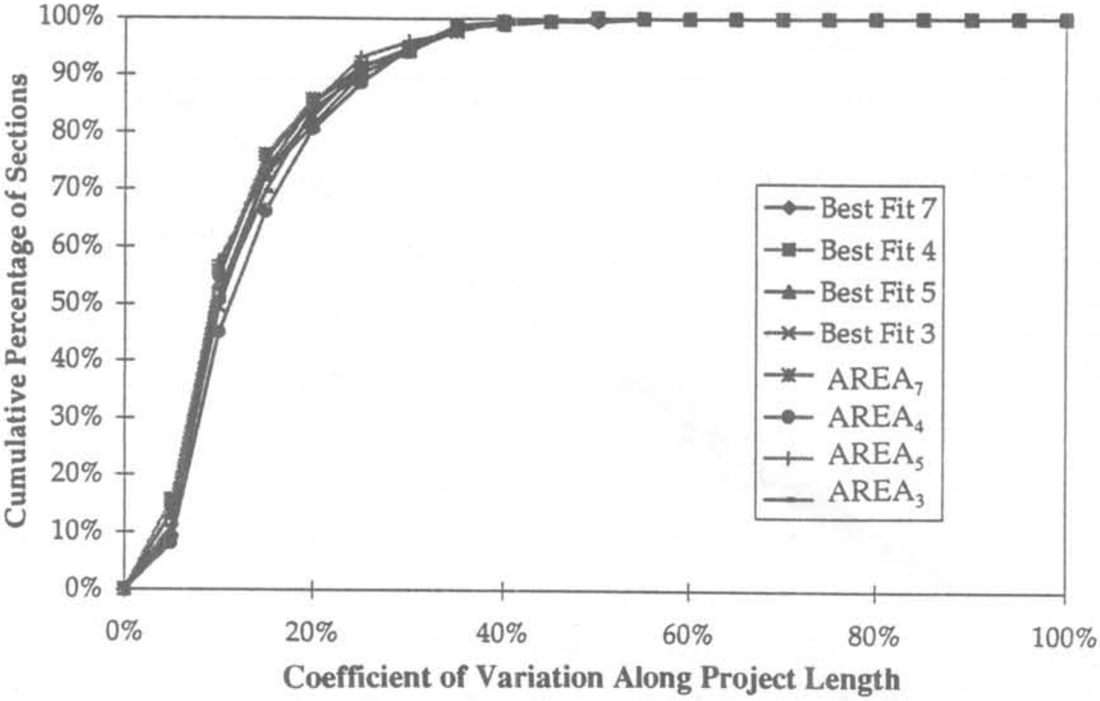


Figure 19. Coefficient of variation in backcalculated k along project length, after screening.

1. **Plate load k versus soil class:** As shown in Table 4, the plate load k-value fell within the ranges recommended for the AASHTO soil class in 27 of 31 cases. In the other four cases, three were gravelly materials (A-1-a, A-1-b, and A-2-4) for which the plate load k was lower than the recommended range, and one was a gravelly material (A-2-4) for which the plate load k was higher than the recommended range.

2. **Plate load k versus CBR:** CBR data were available for 15 of the 31 sections with plate load k-values. As shown in Table 5, the plate load k-values fell within the range indicated by the CBR values in 12 of the 15 cases. In the other three cases, the plate load k was below the range indicated by the CBR.

3. **Plate load k versus R-value:** R-value data were not available for any of the 31 sections with plate load k-values.

4. **Plate load k versus backcalculated k:** The mean ratio of backcalculated k-value to plate load k-value for the 22 concrete pavement sections, for each of the backcalculation methods, is shown in Table 6. Note that the results with slab size correction were computed only for the GPS-3 and GPS-4 sections. These results show that the backcalculated k-values exceeded the plate load k-values by factors ranging from 1.37 to 1.84 without slab size correction, and from 1.78 to 2.16 with the slab size correction. For the most promising solution for each algorithm—$AREA_7$ and BEST 4—the ratios with slab size correction are very close to the traditionally recommended factor of 2. For $AREA_7$ (the AREA method applied to the SHRP sensor configuration), the mean ratio with slab size correction is 1.97, and for BEST 4 (the best-fit method applied to the traditional four-sensor configuration), the mean ratio is 1.99.

Table 4. Plate load k versus AASHTO soil class.

Section	Plate load k	AASHTO class	Rec range (psi/in)	Plate Load Test k in range?
3053 46	140	A-1-a	300-450	N
3010 46	110	A-2-4	300-500	N
3012 55	138	A-4	5-220	Y
3006 19	125	A-6	5-255	Y
3009 19	125	A-6	5-255	Y
3028 19	125	A-6	5-255	Y
3033 19	115	A-6	5-255	Y
3055 19	125	A-6	5-255	Y
3009 46	162	A-6	5-255	Y
3013 46	169	A-6	5-255	Y
6600 46	161	A-6	5-255	Y
3012 46	157	A-7-6	40-220	Y
3052 46	160	A-7-6	40-220	Y
3010 49	120	A-7-6	40-220	Y
6702 31	600	A-2-4	300-500	N
9126 19	100	A-4	5-220	Y
5046 19	150	A-1-b	200-400	N
5042 19	120	A-4	5-220	Y
9116 19	110	A-6	5-255	Y
5020 46	165	A-6	5-255	Y
5040 46	160	A-6	5-255	Y
5025 46	175	A-7-6	40-220	Y
6049 19	120	A-6	5-255	Y
1016 27	150	A-3	150-300	Y
1030 31	200	A-4	5-220	Y
7049 46	135	A-6	5-255	Y
9187 46	80	A-7-6	40-220	Y
9197 46	145	A-6	5-255	Y
1028 47	165	A-7-5	5-215	Y
3110 47	160	A-7-5	5-215	Y
9020 08	110	A-7-6	40-220	Y

1 psi/in = 0.271 kPa/mm

Table 5. Plate load k versus California Bearing Ratio (CBR).

Section	Plate load k	CBR	Rec range (psi/in)	Plate Load Test k in range?
3053 46	140	5	8-220	Y
3010 46	110	9	150-310	N
3012 55	138	-		
3006 19	125	-		
3009 19	125	-		
3028 19	125	-		
3033 19	115	-		
3055 19	125	-		
3009 46	162	6	100-240	Y
3013 46	169	7	110-250	Y
6600 46	161	46	380-580	N
3012 46	157	10	150-320	Y
3052 46	160	6	100-240	Y
3010 49	120	4	50-200	Y
6702 31	600	-		
9126 19	100	-		
5046 19	150	-		
5042 19	120	-		
9116 19	110	-		
5020 46	165	7	110-250	Y
5040 46	160	6	100-240	Y
5025 46	175	7	110-250	Y
6049 19	120	-		
1016 27	150	-		
1030 31	200	-		
7049 46	135	5	8-220	Y
9187 46	80	27	290-460	N
9197 46	145	7	110-250	Y
1028 47	165	7	110-250	Y
3110 47	160	-		
9020 08	110	-		

1 psi/in = 0.271 kPa/mm

Table 6. Backcalculated k versus plate load k.

Method without correction	Backcalculated k / plate load k	Method with correction	Backcalculated k / plate load k
B7I	1.47	B7F	1.85
B5I	1.37	B5F	1.78
B4I	1.63	B4F	1.99
B3I	1.47	B3F	1.85
A7I	1.62	A7F	1.97
A5I	1.43	A5F	1.82
A4I	1.84	A4F	2.16
A3I	1.53	A3F	1.91
Average:	1.54	Average:	1.91

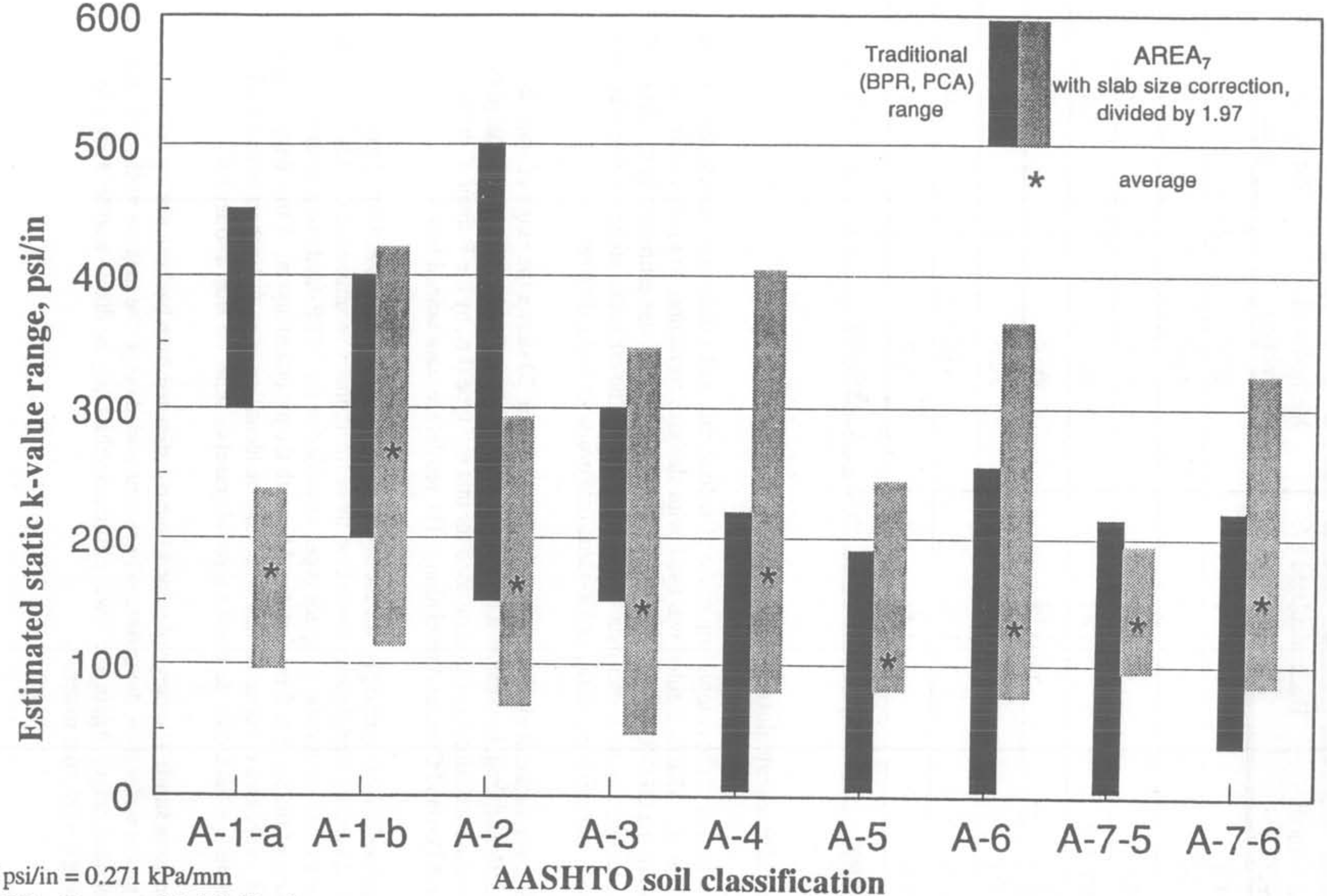
Comparison of Backcalculated k and Other Soils Data

Based on the results of the comparison of the plate load data with other soils data available in the LTPP database, the AREA$_7$ method was used, with slab size correction, to estimate static k-values for all of the GPS-3, -4, and -5 sections. The static k-value was estimated by dividing the mean backcalculated k-value after data screening by 1.97. The estimated static k-value was then compared with any soil type, CBR, and R-value data available in the database.

1. **Static k from backcalculation versus soil class.** Figure 20 shows the range of static k-values estimated from backcalculation results, for each soil type, compared to the range of static k-values traditionally recommended for that soil type (i.e., by the Bureau of Public Roads and Portland Cement Association). The results are summarized below:

- **A-1-a, gravel:** Not surprisingly, the mean and range of static k-values estimated from backcalculation are significantly lower than those traditionally recommended. This is thought to be due to the fact that the subgrade types identified in the LTPP database may only be descriptive of the top 1 to 2 m of material beneath the pavement layers. A true deep subgrade of A-1 is a very rare occurrence, and what may be identified as an A-1 subgrade in the LTPP database may, in fact, only describe a layer of gravel or stone fill atop a softer soil.

- **A-1-b, coarse sand:** The range of static k-values estimated from backcalculation results is similar to, but wider than, the traditionally recommended range; the mean is well within the recommended range. Again, the lower estimated values may be due to a softer subgrade underlying the granular material.



1psi/in = 0.271 kPa/mm
BPR = Bureau of Public Roads
PCA = Portland Cement Association

Figure 20. Static k-value estimated from backcalculation compared to traditionally recommended ranges.

- **A-2, granular materials with high fines:** The range of static k-values estimated from backcalculation results overlaps the recommended range between about 150 and 300 psi/in [40.8 and 81.6 kPa/mm], but the range of values estimated for the LTPP sections extends below 100 psi/in [27.2 kPa/mm] and no values above 300 psi/in [81.6 kPa/mm] were estimated, whereas the traditionally recommended range for A-2 materials extends to 500 psi/in [136 kPa/mm]. The mean estimated k for the LTPP sections, at about 150 psi/in [40.8 kPa/mm], is close to the low end of the traditionally recommended range. The lower estimated values may be due to a softer subgrade underlying the granular material.

- **A-3, fine sand:** The range of static k-values estimated from backcalculation results is wider than the traditionally recommended range, and the mean is just below the lower limit of the traditionally recommended range, i.e., 150 psi/in [40.8 kPa/mm]. The lower estimated values may be due to a softer subgrade underlying the granular material.

- **A-4, silt and silt/sand/gravel mixtures:** A wide range of static k-values was estimated from the backcalculation results, but the mean is well within the recommended range. Only a few sections are responsible for the high upper limit on the estimated range, as evidenced by the fact that the mean is much closer to the lower limit. It is not surprising that the recommended range goes much lower than the estimated range, considering that the recommended range encompasses saturation levels up to 100 percent saturation; however, the LTPP sections, in general, were tested in the summer and fall months when the degree of subgrade saturation was likely to have been lower. This applies to all of the fine-grained soil types, as Figure 20 illustrates.

- **A-5, poorly graded silt:** The mean of the estimated static k range agrees very well with the midrange of the recommended range. Just a few sections with high values are responsible for the upper limit of the estimated range being higher than that of the recommended range, as evidenced by the fact that the mean is much closer to the lower end of the estimated range.

- **A-6, plastic clay:** Just as for the A-5 soils, the mean of the estimated static k range agrees very well with the midrange of the recommended range. Just a few sections with high values are responsible for the upper limit of the estimated range being higher than that of the recommended range, as evidenced by the fact that the mean is much closer to the lower end of the estimated range.

- **A-7-5, moderately plastic clay:** The range of estimated static k-values was fairly narrow and was contained within the recommended range.

- **A-7-6, highly plastic elastic clay:** Just as for the A-5 soils, the mean of the estimated static k range agrees very well with the midrange of the recommended range. Just a few sections with high values are responsible for the upper limit of the estimated range being higher than that of the recommended range, as evidenced by the fact that the mean is much closer to the lower end of the estimated range.

For coarse-grained soils, these comparisons indicate that, in general, the static k-values estimated from backcalculation results tend to be somewhat lower than the traditionally recommended values, and that values near the upper limit of the traditionally recommended range should not be used unless the subgrade is known to indeed consist of a substantial thickness, i.e., several meters, of coarse-grained materials.

For fine-grained soils, the static k-values estimated from backcalculation results are typically consistent with the traditionally recommended range, as indicated by the mean values estimated for each fine-grained soil class. Values higher than those traditionally recommended were obtained for a few LTPP sections, but are not typical. The LTPP sections did not yield estimated static k-values approaching the lower ends of the traditionally recommended ranges, which is not surprising considering that the LTPP sections were not tested during times of maximum subgrade saturation.

2. **Static k from backcalculation versus CBR:** Figure 21 illustrates the comparison of CBR values and static k-values estimated from backcalculation results for those GPS-3, -4, and -5 sections for which both types of data were available. In general, the estimated k-values agree reasonably well with the recommended range of values, although a downward shift in the lower bound would be necessary to encompass several of the values. Also, a few sections with high CBR values had estimated static k-values that were considerably below the recommended range. This may be an indication that the subgrades for these sections are not actually granular layers of substantial thickness.

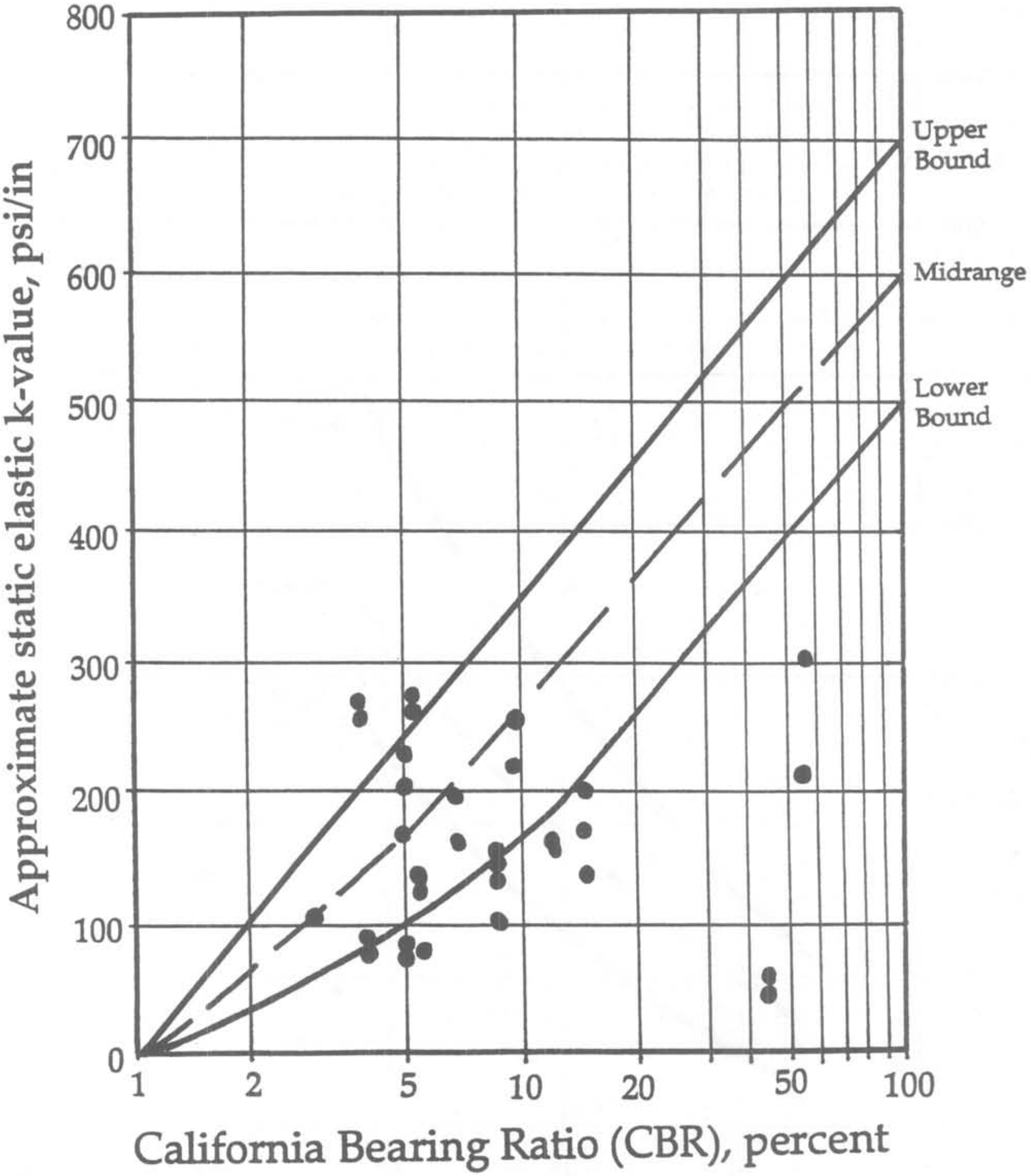
3. **Static k from backcalculation versus R-value:** Figure 22 illustrates the comparison of R-values and static k-values estimated from backcalculation results for those GPS-3, -4, and -5 sections for which both types of data were available. The range shown by the lines on the chart are based on correlations between R and CBR given in the AASHTO Guide (Part II, Figures 2.6 and 2.7). The results in Figure 22 do not indicate any relationship between the R-values and the static k-values estimated from backcalculation results for the LTPP sections.

Improvements to NCHRP 1-30 k-Value Guidelines

Based on the results of these analyses using the data from the LTPP GPS-3, -4, and -5 pavement sections, the following improvements to the NCHRP 1-30 k-value guidelines are recommended and have been made in the proposed revision to the AASHTO Guide (see the appendix).

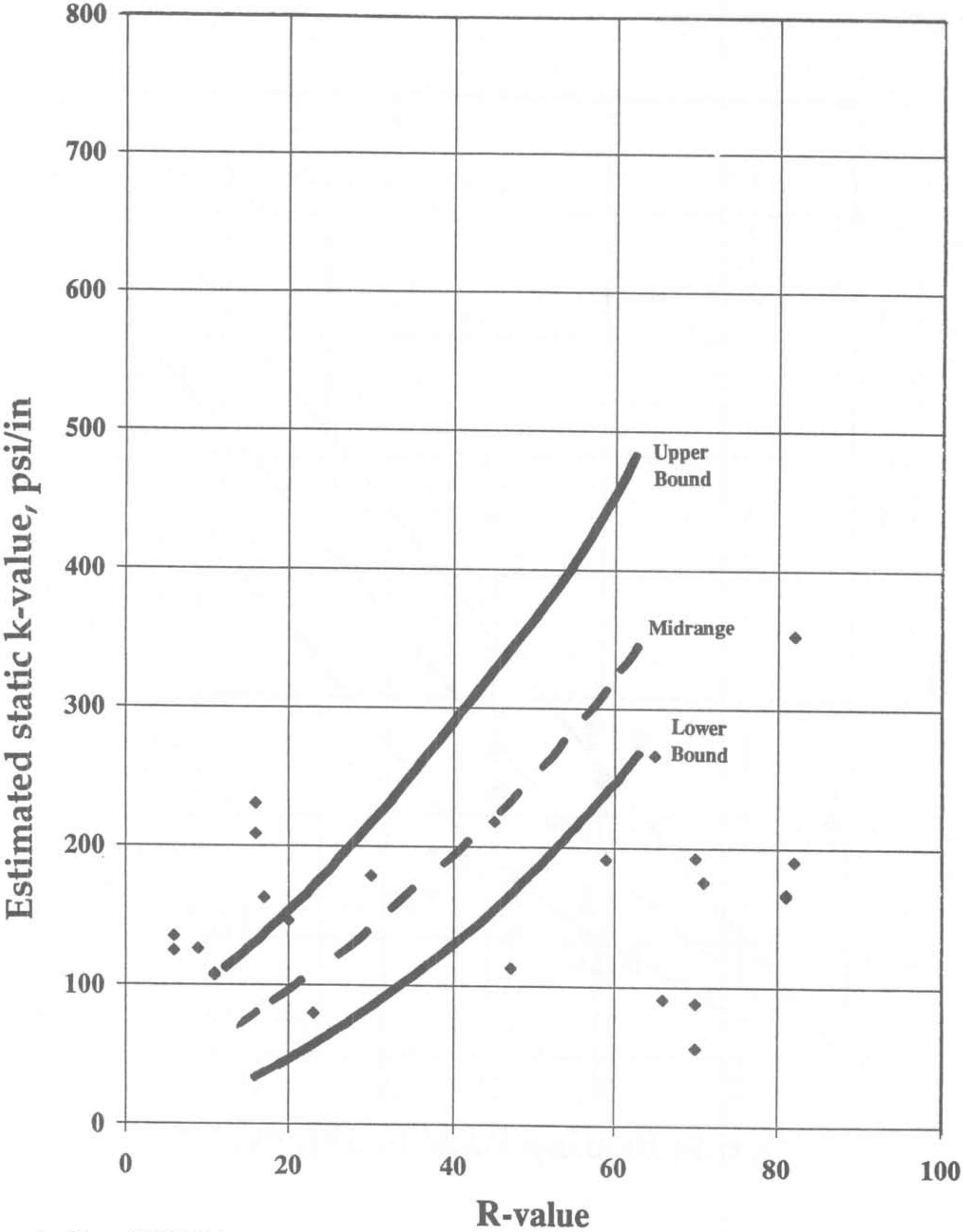
1. **R-value vs. k-value correlation eliminated.** The LTPP data analyses indicated not only that the R-k correlation showed no agreement with the available data, but also that the available data did not demonstrate any significant trend in k-value with R-value.

2. **Plate load testing on a test embankment** is only recommended if the embankment is at least 10 ft [3.0 m] thick. Otherwise, the k of the underlying subgrade should be determined based on testing or correlations and adjusted as a function of the thickness and density of the embankment. Testing on top of a granular embankment only a few feet thick may result in k-values too high for use in design.



1 psi/in = 0.271 kPa/mm

Figure 21. Comparison of static k-values estimated from backcalculation results and CBR.



1 psi/in = 0.271 kPa/mm

Figure 22. Comparison of static k-values estimated from backcalculation results and R-value.

3. **A minimum static k-value of 25 psi/in [6.8 kPa/mm] is recommended** for fine-grained soils at 100 percent saturation. Deflection testing and backcalculation of all of the LTPP sections and many other pavements around the United States have never yielded k-values lower than this.

4. **A summary table** was developed that lists soils by AASHTO soil class, Unified soil class, and descriptive name, and identifies corresponding reasonable ranges for dry density, CBR, and static elastic k-value.

5. **The correlation of CBR to k-value** was plotted with CBR on a log scale to better illustrate the relationship of CBR to k in the CBR range of 1 to 10.

6. **The best fit backcalculation algorithm** yielded more consistent results than the AREA algorithm with respect to differences in sensor configuration, basin radius, inclusion of deflections under and very near the load plate, coefficient of variation with multiple load levels and load drops, and coefficient of variation along the project length. In general, use of the best fit methods is preferable to use of the AREA methods, but depends on software availability. For highway pavements, the Best Fit 4 solution is recommended.

7. **The AREA$_7$ method is proposed for use in the AASHTO Guide** because it involves a few equations that can be easily presented on paper and solved by calculator or spreadsheet, and because among the AREA methods, AREA$_7$ yielded the closest results to the best fit methods. The AREA$_7$ method can therefore be considered a quick and reasonable approximation of the results that best fit analysis would yield.

8. **A slab size correction is strongly recommended** to correctly backcalculate the k-value, because all of the solution methods reviewed in this study are based on the assumption of infinite slab behavior, which is not realistic for highway slabs. It should be noted, however, that the slab size correction procedure originally developed by Crovetti and modified in this study still does not consider the effect that transverse and longitudinal joint load transfer and edge support, such as a tied PCC shoulder, may have in increasing the effective slab size. Crovetti has researched this topic, but further investigation is needed to develop a reliable and easy-to-use procedure to correct backcalculated k-values for rectangular slab sizes and partial load transfer.

9. **The k-values backcalculated from FWD deflections exceeded plate load k-values**, for those LTPP sections for which plate load data were available, by factors averaging very close to 2 for all of the backcalculation algorithms. Thus, the simple rule for dividing the backcalculated k by 2 to estimate the plate load k is considered to be valid.