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Research, Development and Technology Division

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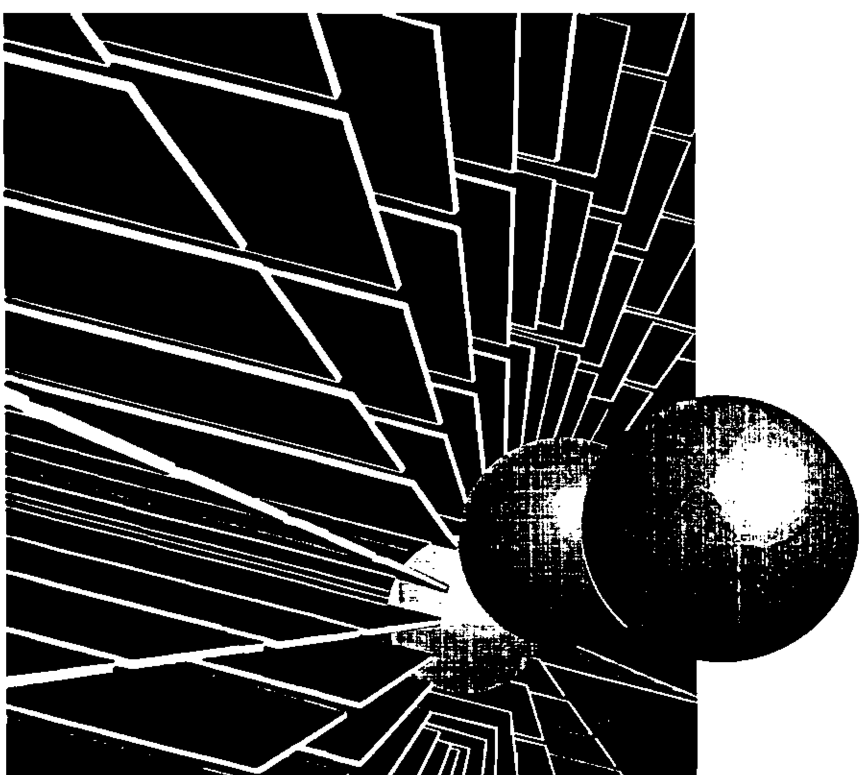
Final Report

Layer by Layer Evaluation of a PCC Pavement as It Was Constructed

Comparison of Backcalculated Values to Lab Material Values

RI 93-01



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16. Abstract

This study was conducted to observe the backcalculated layer strengths of a pavement structure as each layer was constructed and compare these layer strengths to laboratory tested sample strengths. The objective was carried out by gathering Falling Weight Deflectometer deflection data on each sequential layer. The laboratory samples included bulk samples of the base, shelby tube samples of the subgrade, and concrete core samples from the pavement's structure. Laboratory tests were performed on these extracted samples to estimate the resilient modulus of the subgrade, and determine the modulus of elasticity of the concrete. The resilient modulus testing on the base samples was not performed because the backcalculated base results were inconclusive and no comparison could be made.

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RESEARCH INVESTIGATION 93-01

LAYER BY LAYER EVALUATION OF A PCC PAVEMENT AS IT WAS CONSTRUCTED. COMPARISON OF BACKCALCULATED VALUES TO LAB MATERIAL VALUES

FINAL REPORT

PREPARED BY

MISSOURI DEPARTMENT OF TRANSPORTATION
MATERIALS AND RESEARCH DIVISION

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JEFFERSON CITY, MISSOURI
DATE SUBMITTED: MAY 1, 1995

EXECUTIVE SUMMARY

The purpose of this study was to test each layer of a PCC pavement's structure with the Falling Weight Deflectometer and backcalculate the material strength of each layer before and after the following layer was added. The backcalculated material strengths, which were found by more than one method, were compared to each other as well as to available laboratory sample strength values.

Before summarizing the results of the non-destructive testing performed on the subgrade only layer, the following should be noted. This type of testing permanently deforms the top of the subgrade, therefore the accuracy of these results are suspect. Also the dynamic *k* values were not calculated by the AASHTO T221-90 and T221-81 method, instead a modified Plate Bearing Equation was adapted to employ the FWD deflections *(6)*. Therefore the accuracy of these results are also suspect.

From the non-destructive testing performed atop the subgrade, the Boussinesq Equation, MODULUS Program, and Plate Bearing Equation yielded somewhat similar results. In general the MODULUS backcalculated results were approximately 28% higher than the Boussinesq Equation results, but yet the strengths consistently paralleled each other throughout the project.

When comparing the resilient modulus (M_r) to the subgrade dynamic *k* value (k), both calculated from tests atop the subgrade, the same paralleling of strengths is depicted. According to AASHTO, the basic relationship of k to M_r is $M_r/k = 19.4$ *(6)*. The average values obtained in this study were $M_r / k = 11.28$ for the Boussinesq Equation values divided by the Plate Bearing Equation values and $M_r / k = 15.57$ for the MODULUS program values divided by the Plate Bearing Equation values.

The results for the base strength modulus were inconclusive because the MODULUS Program has difficulty backcalculating thin layers with Poisson's ratios similar to the underlying layer.

The MODULUS program's backcalculated concrete modulus of elasticity values (E_{pcc}) were higher than the lab sample strengths. The DARWin program's E_{pcc} fluctuated above and below the lab sample strengths. The MODULUS and DARWin program's backcalculated values were more variable than the lab values. This variation is due to the fact that the backcalculated values reflect some of the underlying material strength characteristics of the base and subgrade. The average E_{pcc} was backcalculated by the DARWin program and fell within the average static and dynamic lab values. Therefore, in the analysis of full depth portland cement concrete (PCC) pavement, the DARWin program best depicted the actual lab value strength of the concrete. The DARWin program also backcalculated the lowest dynamic *k* when analyzing subgrade bearing capacity.

The overall conclusion is that the backcalculation process, on a full depth PCC pavement structure, can differentiate between strong and weak pavement structure areas. However, the procedure's accuracy in assigning the exact material strength to each layer of the structure is only a competent estimation and not an exact calculation. The DARWin Program, which uses the AASHTO procedure, backcalculated E_{pcc}, M_r and subgrade bearing capacity *k* values that were closest to the actual lab values. The overall strength of the pavement structure is best depicted by the AASHTO procedure. The DARWin program is accurate enough to calculate overlay thicknesses for rehabilitation of pavement, because the *k* and E_{pcc} values can both vary substantially in the overlay design equations yet have little effect on the computed overlay thickness *(3)*.

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LIST OF ABBREVIATIONS

a = Falling Weight Deflectometer plate radius (in)

AASHTO = American Association of State Highway and Transportation Officials

ASTM = American Society of Testing Materials

d_0 = deflection under center of Falling Weight Deflectometer plate (mils)

d_z = deflection at distance z (mils)

E = Modulus of Elasticity (psi)

E_{pccp} = Modulus of Elasticity of Portland cement concrete pavement

f'_c = 28 day compressive strength of concrete (psi)

FWD = Falling Weight Deflectometer

k = subgrade reaction dynamic k (pci)

M_r = resilient modulus of subgrade (psi)

NDT = non-destructive testing

P = magnitude of the load applied to the FWD plate (lbs.)

PCCP = Portland cement concrete pavement

s_0 = plate pressure on surface of subgrade (psi)

u = Poisson's ratio

V = volume of the soil directly beneath the plate that is displaced by the load

z = depth below pavement surface (in)

ABSTRACT

This study was conducted to observe the backcalculated layer strengths of a pavement structure as each layer was constructed and compare these layer strengths to laboratory tested sample strengths. The objective was carried out by gathering Falling Weight Deflectometer deflection data on each sequential layer. The laboratory samples included bulk samples of the base, shelby tube samples of the subgrade, and concrete core samples from the pavement's structure. Laboratory tests were performed on these extracted samples to estimate the resilient modulus of the subgrade and determine the modulus of elasticity of the concrete. The resilient modulus testing on the base samples was not performed because the backcalculated base results were inconclusive and no comparison could be made.

OBJECTIVE

The objective of this study was to test each layer of a pavement's structure with the Falling Weight Deflectometer (FWD) and backcalculate the material strength of each layer before and after the following sequential layer was constructed.

This data was collected to observe if the backcalculated material strengths of each layer would change or remain constant after each following pavement layer was constructed and to compare backcalculated values to lab values. The intent was to further investigate *Chapter 5, Rehabilitation Methods with Overlays*, of the American Association of State Highway Transportation Officials (AASHTO) Guide for Design of Pavement Structures, 1993.

In order to meet this objective, the Falling Weight Deflectometer was employed to perform non-destructive testing (NDT) on each layer of the pavement structure. Samples of the subgrade, base, and concrete were also collected at the same locations at which the FWD tests were performed. These samples were tested in the lab, to compare the lab values to the backcalculated values.

INTRODUCTION

In order to fulfill the objective of this research investigation, each layer strength of a pavement system was tested with the Falling Weight Deflectometer (FWD) before and after the addition of the next layer.

Job # J5P0411C Route 54 in Callaway County west of Fulton was the project chosen for Research Investigation 93-01. This pavement was constructed of 12" non-reinforced portland cement concrete (PCC) pavement with 15' doweled joints. The mainline width was 28', with a 14' driving lane and a 14' passing lane. The shoulders were also constructed of non-reinforced PCC pavement and tied to the main line pavement. The base was 40' wide and consisted of 4" Type III base. The project was placed over numerous cut/fill sections of varied depths and testing was performed on both cut, fill, and transition sections.

After the pavement was constructed, concrete cores, bulk base, and shelby tube samples of the subgrade were extracted from the pavement structure. When possible, the laboratory strength values of these samples were measured and compared to the backcalculated values.

The FWD data was taken on the subgrade, on the base laid on top of the subgrade, and on the complete pavement structure. This data was analyzed by the MODULUS *(1)* and DARWin *(2)* software programs which assign layer strengths according to the measured deflections (See Appendix A for more information on the parameters used in running MODULUS and DARWin.). Layer strengths were found for each station where the FWD acquired deflection data. The FWD testing on the subgrade and subgrade/base layers required the use of a 17.7" diameter plate instead of the normal 11.8" diameter plate. Even the use of this larger plate caused permanent deformation of the subgrade and subgrade/base layers, so the accuracy of these backcalculated values are suspect.

INVESTIGATION PROCEDURE

As mentioned in the INTRODUCTION, the FWD testing was completed on a section of Route 54 in Callaway County twice during construction and once after construction. After each run, strength moduli layer values were calculated using the deflection data and the MODULUS and/or DARWin software programs.

Subgrade Soil Strength Values

The AASHTO Design Guide *(3)* employs the use of two subgrade strength values, depending on rigid or flexible pavement construction. For flexible pavement, the subgrade resilient modulus (M_r) is used, while for rigid pavement, the effective modulus of subgrade reaction or effective static ***k*** value is used. Since the Route 54 pavement is rigid, the subgrade strength would normally be defined in terms of the effective modulus of subgrade reaction ***k***. However, the software program MODULUS calculates the subgrade soil strength in terms of a resilient modulus and the laboratory values are also measured in this way. Therefore, the subgrade soil strength values will be discussed and compared in terms of the two values.

The MODULUS program used FWD deflection data to calculate resilient modulus values for the subgrade layer only, the base and subgrade layer, and the total pavement structure.

There were two estimates for the subgrade soil resilient moduli. One was through Boussinesq's layered elastic theory. The other was through classifying the soil samples by the ASTM and AASHTO classification systems and obtaining general backcalculated resilient modulus ranges for each classification.

In 1885, Boussinesq published his layered elastic theory for computing stresses and deflections in a homogeneous, isotropic, and linearly elastic material (soil). *(4)* He stated that the deflection (d_Z), at depth z, can be found by the following equation:

$$d_z = \frac{(1+u)s_0 a}{E}\left(\frac{1}{\sqrt{1+\left(\frac{z}{a}\right)^2}} + (1-2u)\left(\sqrt{1+\left(\frac{z}{a}\right)^2} - \frac{z}{a}\right)\right)$$

Where: s_0 = stress on surface (psi)
E = elastic modulus (ksi)
a = plate radius (in)
z = depth below pavement surface (in)
u = Poisson's ratio

By rearranging the equation and assuming that z = 0, in order to substitute the FWD surface deflection (d_0) in for d_Z, the resulting equation is as follows:

$$E = \frac{(1+u)s_0 a}{d_0}[1+(1-2u)]$$

When dealing with subgrade,
E = M_r, the resilient modulus (psi)
$u = 0.4$
a = 8.85 in. (the large FWD plate was used in this case)
s_0 = 9000 lb./ area of plate in $(\text{inches})^2$ = 36.58 psi.
d_0 = deflection under FWD load plate (in)

At various stations where Falling Weight Deflectometer data is available, d_0 is then substituted in the equation and a value for M_r is found at that station, (See Appendix B for sample calculations of Boussinesq's equation.).

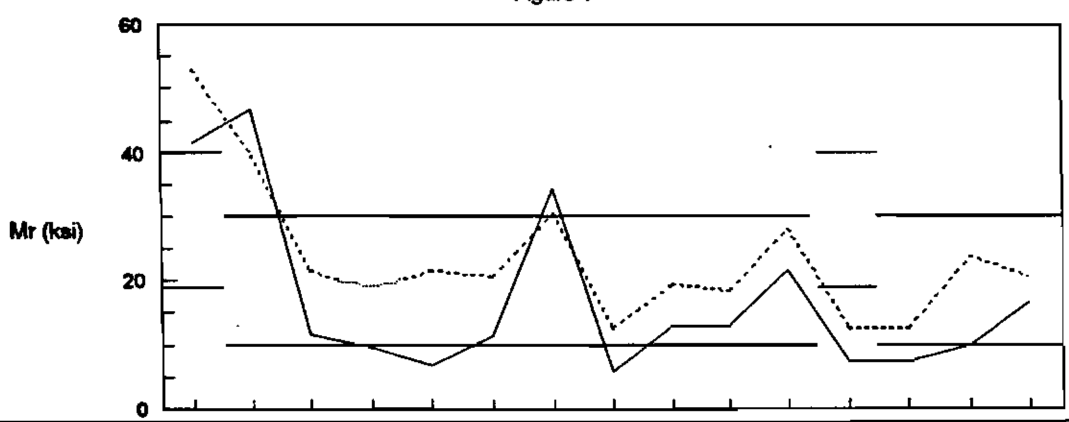
As mentioned above, the soil samples were classified by the MHTD laboratory using the AASHTO and ASTM soil classification system. With this categorization, general ranges of backcalculated M_r values related to soil classifications were estimated from information found in the 1993 Federal Highway Administration ASTM Backcalculation Training Course Manual *(4)*, (See Appendix C).

Figure 1 graphically shows the subgrade soil resilient modulus values calculated by the various methods.

Subgrade Resilient Modulus*

Calculated from FWD testing on the subgrade layer only.

Figure 1



Station	229	217	200	188	173	158	125	115	110	100	93	84	76	69	55	average
– Boussinesq	41.3	46.8	11.8	9.6	7.0	11.5	34.4	5.7	13.0	13.1	21.6	7.3	7.4	9.9	16.6	17.13
-- MODULUS	53	39.6	21.8	18.6	21.6	20.8	30.6	12.8	19.5	18.7	28.1	12.6	12.8	23.8	20.6	23.66
ASTM Classification	SC	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	SC	CL	CL	CL	CL
Mr Range (ksi)	18-40	9-30	9-30	9-30	9-30	9-30	9-30	9-30	9-30	9-30	9-30	18-40	9-30	9-30	9-30	9-30

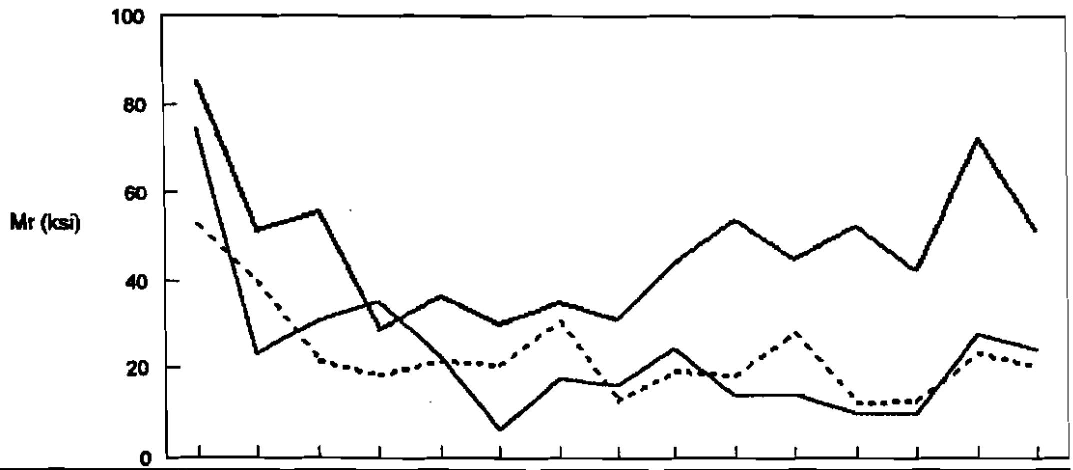
Route 54, Callaway County

* Calculated from FWD testing on Subgrade Layer Only

The MODULUS program's M_r values are shown in Figure 2. M_r was calculated for the subgrade only, subgrade/base, and full pavement structure.

Subgrade Resilient Modulus *

Figure 2



Station	229	217	200	188	173	158	125	115	110	100	93	84	76	69	55
· Subgrade Only	53	39.6	21.8	18.6	21.6	20.8	30.6	12.8	19.5	18.7	28.1	12.6	12.8	23.8	20.6
– With Base	74.6	23.2	30.7	35.3	22.8	5.9	17.7	16	24.5	13.9	14.1	9.9	9.8	27.8	23.9
– After Traffic	85.1	51.6	56.2	29.1	36.5	30.5	35.4	31.4	44.5	54.4	45.2	52.8	42.6	72.6	51.1

Route 54, Callaway County

* All values were calculated by the MODULUS program

It can be seen in Figure 2 that the MODULUS program backcalculated M_r value increases with the addition of each pavement layer. This is due to the method in which the MODULUS program assigns layer strengths. In the upcoming analysis on the backcalculation of the concrete modulus of elasticity (E_{pcc}), the MODULUS program calculated the highest values of E_{pcc} for the project. Therefore, in the analysis of rigid pavement with no asphalt overlay, the MODULUS program depicts high material strength values for both the subgrade and the concrete pavement.

The subgrade reaction dynamic *k* values were calculated by the DARWin software program for the integrated pavement structure. To calculate the subgrade reaction dynamic *k* values, the DARWin program follows the AASHTO Design Guide procedure. *Section L4.2 of Appendix L* in the 1993 AASHTO Guide for Design of Pavement Structures *(3)* documents the procedure for estimating the subgrade reaction dynamic *k* value and the E_{pccp}, from NDT deflections.

The subgrade reaction dynamic *k* values for the subgrade only and the base/subgrade layers, were calculated by inserting FWD data into the AASHTO re-definition of the Plate Bearing Test equation. The re-definition can be found in *Appendix HH* in Volume 2 of the AASHTO Guide for Design of Pavement Structures, 1986. *(6)* The equation is defined as follows:

$$k = \frac{P}{V}$$

where: k = subgrade reaction dynamic k (in pounds per square inch per inch)
P = magnitude of the load applied to FWD plate (in pounds)
V = the volume of soil directly beneath the plate that is displaced by the load

(See Appendix D for example calculation of dynamic *k*).

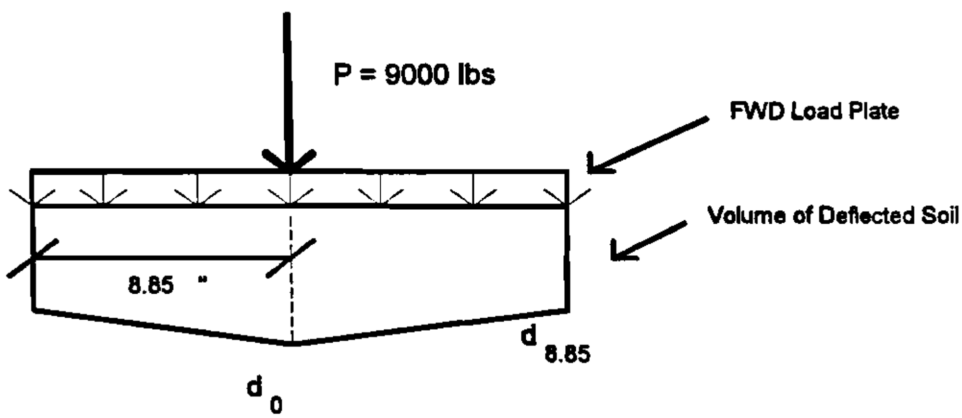
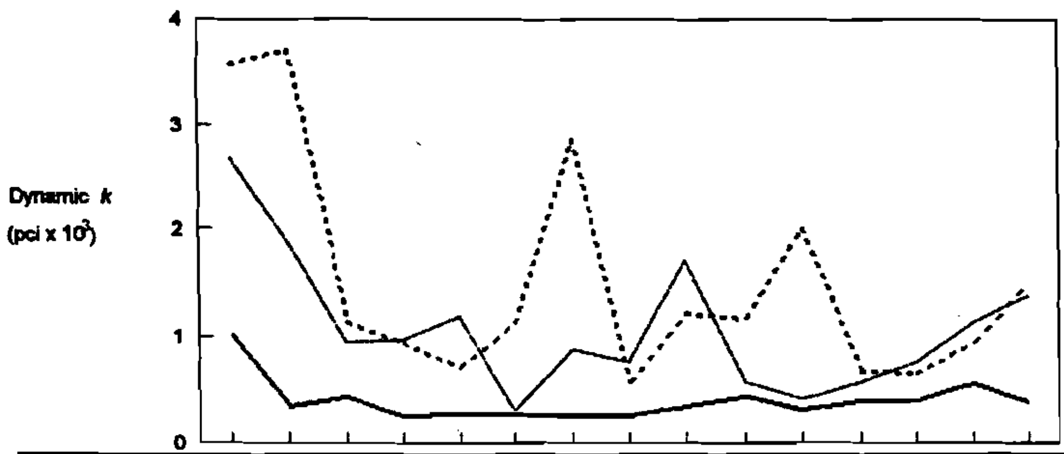


Figure 3 depicts the subgrade reaction dynamic *k* values calculated using the aforementioned procedures. Dynamic k values greater than 1500 pci are not practical and are suspect in accuracy.

Subgrade Dynamic K

Figure 3



	Station	229	217	200	188	173	158	125	115	110	100	93	84	76	69	55	average
*	- Subgrade only	3.60	3.72	1.13	0.94	0.70	1.13	2.84	0.57	1.21	1.16	2.01	0.67	0.66	0.95	1.49	1.519
*	– With base	2.67	1.68	0.95	0.96	1.18	0.30	0.87	0.74	1.71	0.56	0.41	0.56	0.74	1.13	1.36	1.068
**	– After Traffic	1.02	0.35	0.44	0.25	0.28	0.25	0.26	0.26	0.36	0.44	0.32	0.41	0.40	0.57	0.38	0.401

Route 54, Callaway County

* Calculated using Plate Bearing test equation

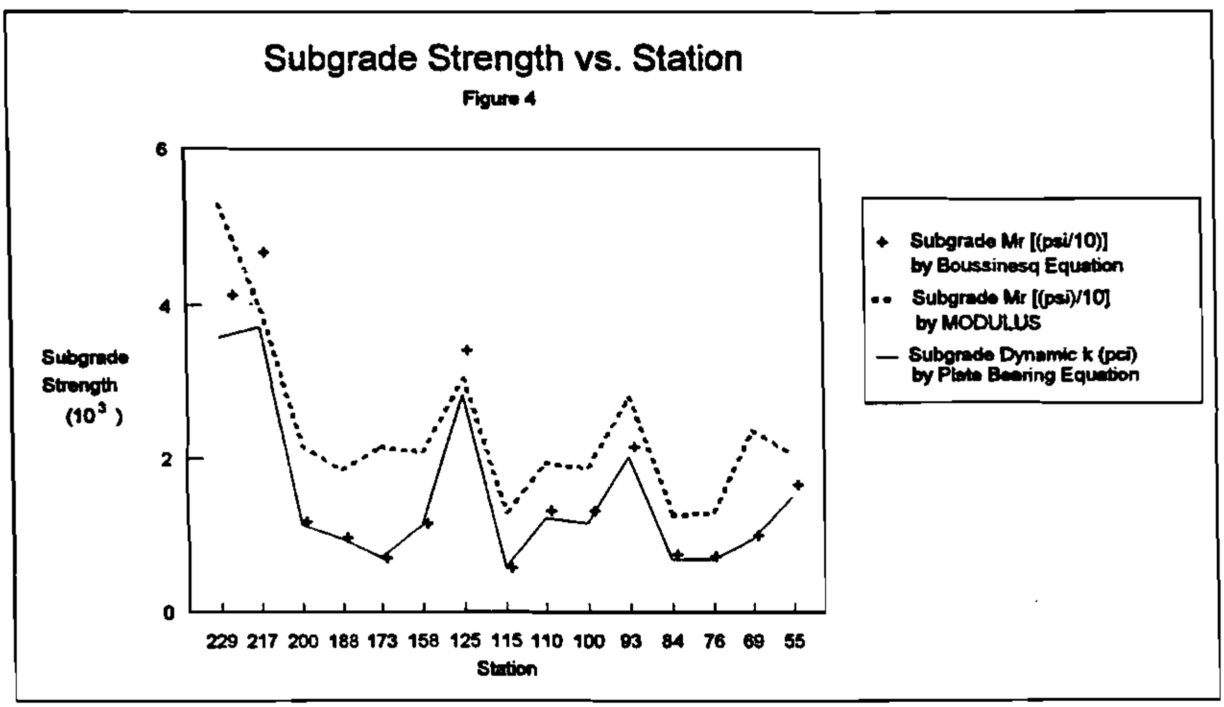
** Calculated by Darwin

Figure 3 shows that the backcalculated subgrade dynamic *k* values have decreased with the addition of each pavement layer. As stated at the beginning of this research investigation, the M_r and subgrade reaction dynamic *k* values calculated from testing atop the subgrade and base /subgrade layers are suspect in accuracy. They are suspect because this testing caused permanent deformation to these layers and the plate bearing test equation is usually employed for a static loading condition, not a dynamic. The deflection values used to calculate these subgrade bearing capacity values were obtained after a portion of the permanent deformation had taken place. Therefore this preconsolidation of material and dynamic versus static load makes the accuracy of these result questionable.

When comparing the subgrade only M_r values to dynamic *k* values, in Figure 4, it can be seen that the strength parameters do parallel each other. According to *Appendix HH*, Volume 2 of the AASHTO Guide for Design of Pavement Structures. (6) the basic relationship between M_r and the effective dynamic *k* value should be:

$$k = \frac{M_r}{19.4}$$

The actual average values obtained in this study are $M_r/k = 11.28$ for the Boussinesq Equation values divided by the Plate Bearing Equation values, and $M_r/k = 15.57$ for the MODULUS program values divided by the Plate Bearing Equation values.

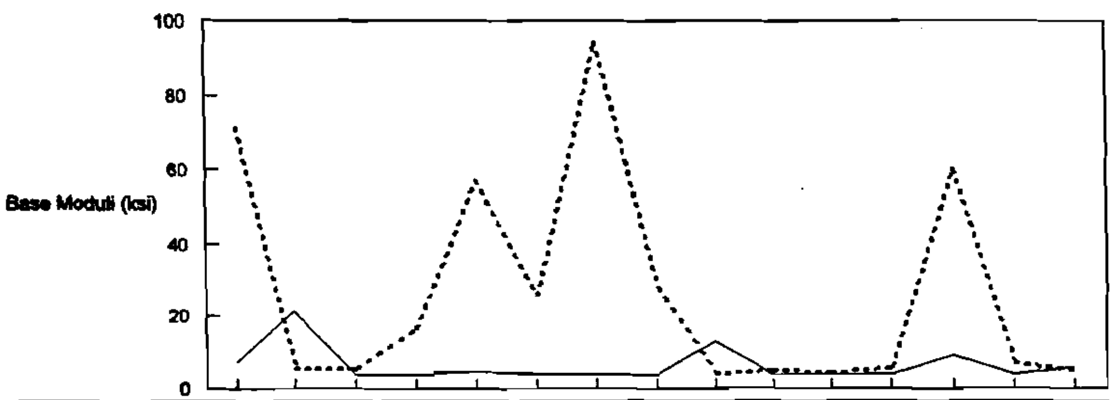


Base Moduli Strength Value

The MODULUS software program is the backcalculation method which was employed in this study to estimate the base layer moduli values from the FWD deflection data. Figure 5 depicts the base moduli values for before and after the addition of the concrete layer. The accuracy of the backcalculated base values are suspect because the MODULUS program has difficulty backcalculating thin layers whose Poisson's ratio is nearly the same as the underlying layer.

Base Modulus*

Figure 5



Station	229	217	200	188	173	158	125	115	110	100	93	84	76	69	55
— Base & Subgrade	7	21	4	4	5	4	4	4	13	4	4	4	9	4	6
·· After Traffic	71.3	5.6	5.6	16.3	57	25.3	94.1	28	4.5	5.4	4.8	5.7	59.9	7.3	5.5

Route 54, Callaway County

* As found by MODULUS software program

No real conclusions were formulated from the analysis of the backcalculated base moduli, except that the MODULUS program assigns greater strength values to the subgrade as additional pavement layers are added.

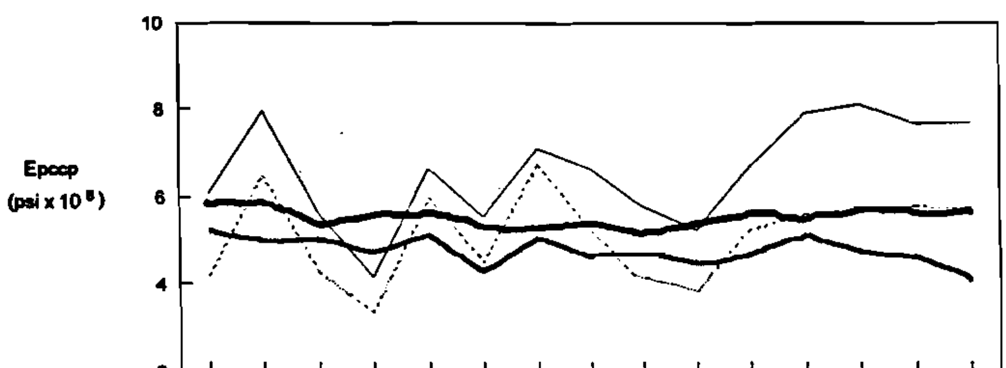
Elastic Modulus of Portland Cement Concrete Pavement

Both aforementioned software programs, MODULUS and DARWin, were used to compute E_{pccp} values for the complete pavement structure. Concrete cores were also extracted from the pavement and tested in the laboratory to determine the static and dynamic modulus of elasticity of the concrete. The static and dynamic modulus of elasticity were determined by performing ASTM C469 and ASTM C215 test methods respectively.

Figure 6 shows that the average backcalculated E_{pccp} value, found by the DARWin program, lies between the average static and dynamic lab values. It also shows that the backcalculated values are more variable than the lab values. This is due to the fact that the backcalculated E_{pccp} values reflect the strength of the underlying subgrade and base.

Modulus of Elasticity of PCCP

Figure 6



Station	229	217	200	188	173	158	125	115	110	100	93	84	76	69	55	average
·· Darwin	4.23	6.50	4.30	3.34	5.98	4.49	6.74	5.25	4.02	3.88	5.26	5.64	5.65	5.80	5.71	5.12
— MODULUS	6.07	7.98	5.64	4.18	6.64	5.52	7.09	6.64	5.79	5.23	6.69	7.95	8.12	7.69	7.74	6.60
— Static Lab	5.15	4.90	4.95	4.65	5.05	4.20	4.95	4.55	4.60	4.40	4.60	5.05	4.65	4.55	4.05	4.69
— Dynamic Lab	5.73	5.82	5.33	5.54	5.60	5.27	5.28	5.34	5.07	5.37	5.57	5.47	5.69	5.59	5.65	5.49

Route 54, Callaway County

RESULTS AND CONCLUSIONS

The objectives of the study were:

1) to examine the backcalculated material strengths of each pavement layer before and after the following sequential pavement layer was constructed
2) to compare these values and observe any changes in values and
3) to compare the backcalculated values to the lab values.

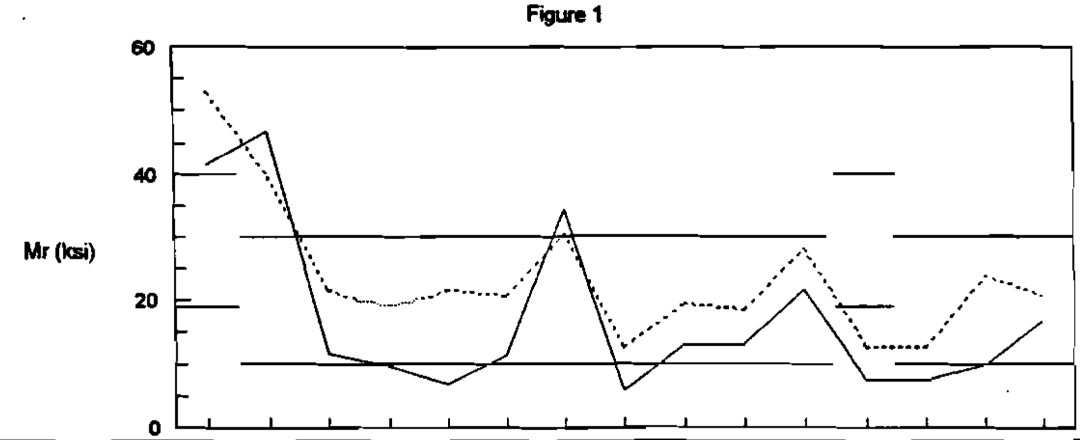
The objectives were met and the Results and Conclusions are as follows.

Using FWD deflections on the subgrade only layer, the M_r backcalculation results from the MODULUS program and the Boussinesq equation differ, yet parallel each other throughout the project. Figure 1 depicts the resilient modulus values from the two different backcalculation procedures. As can be seen, the MODULUS program values are approximately 28% higher than the Boussinesq Equation values throughout the length of the project. As stated before, these values are suspect, due to the permenant deformation of the subgrade and the preconsolidation of the subgrade material before the deflection data, used to calculate these values, were obtained.

Subgrade Resilient Modulus*

Calculated from FWD testing on the subgrade layer only.

Figure 1



Station	229	217	200	188	173	158	125	115	110	100	93	84	78	69	55	average
- Boussinesq	41.3	46.8	11.8	9.6	7.0	11.5	34.4	5.7	13.0	13.1	21.6	7.3	7.4	9.9	16.6	17.13
·· MODULUS	53	39.6	21.8	18.6	21.6	20.8	30.6	12.8	19.5	18.7	28.1	12.6	12.8	23.8	20.6	23.66
– Laboratory Data																
ASTM Classification	SC	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	SC	CL	CL	CL	CL
Mr Range (ksi)	18-40	9-30	9-30	9-30	9-30	9-30	9-30	9-30	9-30	9-30	9-30	18-40	9-30	9-30	9-30	9-30

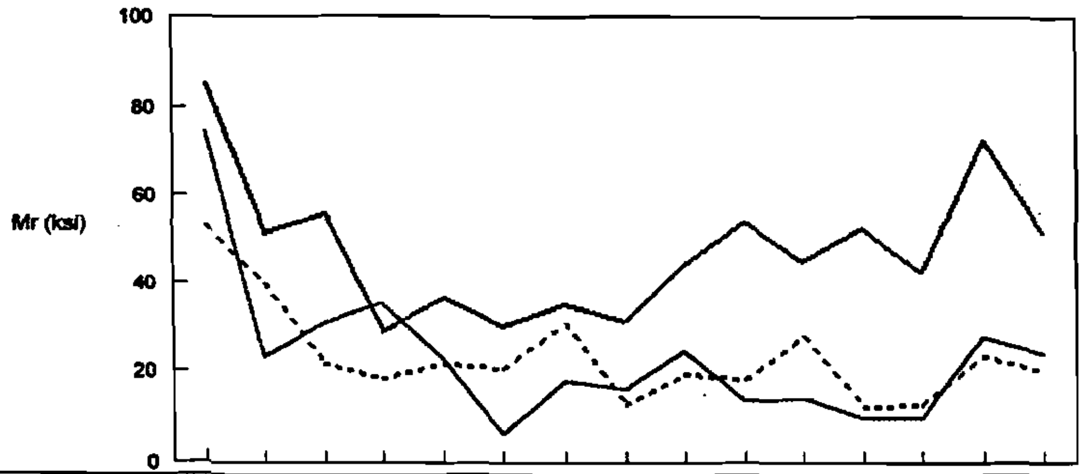
Route 54, Callaway County

* Calculated from FWD testing on Subgrade Layer Only

The MODULUS program was used exclusively to backcalculate the M_r values after each additional pavement layer was constructed. Figure 2 depicts these M_r values increasing after each additional pavement layer is constructed.

Subgrade Resilient Modulus *

Figure 2



Station	229	217	200	188	173	158	125	115	110	100	93	84	76	69	55
· Subgrade Only	53	39.6	21.8	18.6	21.6	20.8	30.6	12.8	19.5	18.7	28.1	12.6	12.8	23.8	20.6
~ With Base	74.6	23.2	30.7	35.3	22.8	5.9	17.7	16	24.5	13.9	14.1	9.9	9.8	27.8	23.9
– After Traffic	85.1	51.6	56.2	29.1	36.5	30.5	35.4	31.4	44.5	54.4	45.2	52.8	42.6	72.6	51.1

Route 54, Callaway County

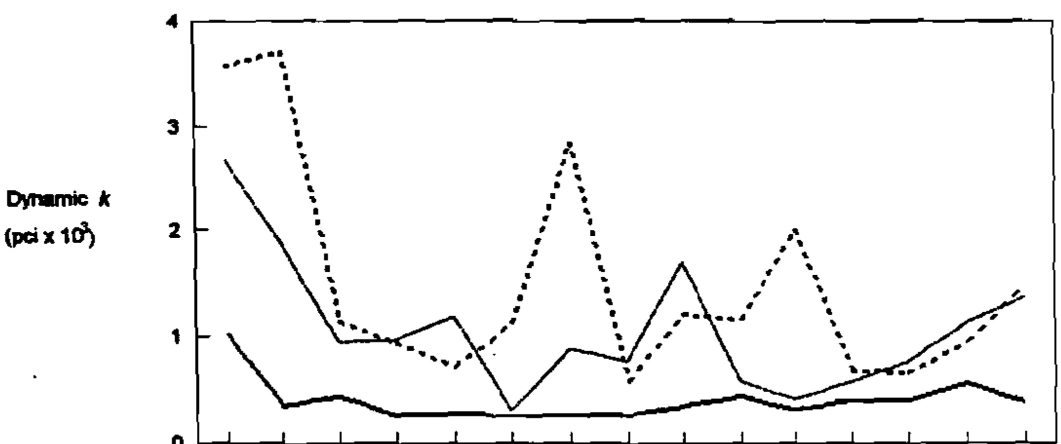
* All values were calculated by the MODULUS program

The only conclusion that can be drawn from this evaluation is the fact that the MODULUS program assigns greater layer strength values to the subgrade as each additional pavement layer is added.

When backcalculating subgrade effective dynamic *k* values, the subgrade only and base/subgrade *k* values were calculated by the Plate Bearing test equation. The full pavement structure values were calculated by DARWin. Figure 3 shows the *k* values decreasing as additional pavement layers are added. When comparing the subgrade only values to the base/subgrade value, calculated by the Plate Bearing Equation, the base/subgrade *k* value should be higher. This is expected due to the smaller volume of material displaced (i.e., $k = P/V$). One explanation for this inconsistency is that the amount of pre consolidation of material was greater on the subgrade only testing than the base/subgrade testing.

Subgrade Dynamic K

Figure 3

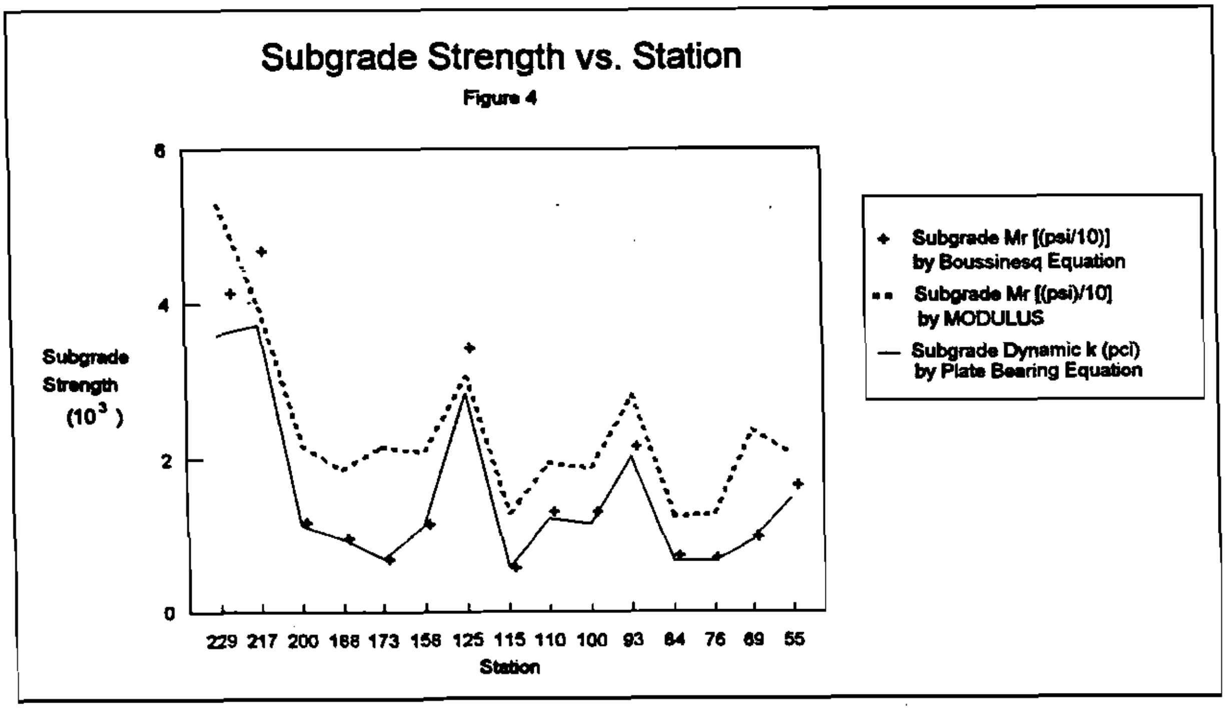


	Station	229	217	200	188	173	158	125	115	110	100	93	84	76	69	55	average
*	- Subgrade only	3.60	3.72	1.13	0.94	0.70	1.13	2.84	0.57	1.21	1.16	2.01	0.67	0.66	0.95	1.49	1.519
*	- With base	2.67	1.88	0.95	0.96	1.18	0.30	0.87	0.74	1.71	0.56	0.41	0.56	0.74	1.13	1.36	1.068
**	- After Traffic	1.02	0.35	0.44	0.25	0.28	0.25	0.26	0.26	0.36	0.44	0.32	0.41	0.40	0.57	0.38	0.401

Route 54, Callaway County

* Calculated using Plate Bearing test equation
** Calculated by Darwin

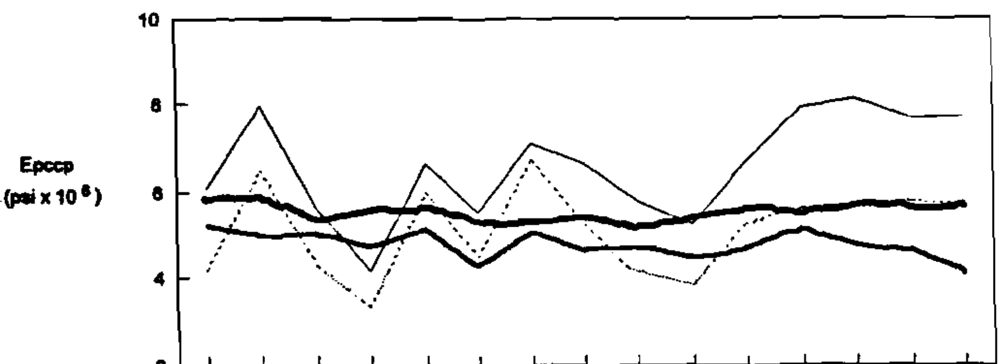
When comparing the two M_r values to the effective dynamic *k* value, the relationship of M_r / k = 19.4 was not confirmed. The average values obtained in this study are M_r / k = 11.28 for the Boussinesq Equation values divided by the Plate Bearing Equation values, and M_r / k = 15.57, for the MODULUS program values divided by the Plate Bearing Equation values. As stated before, the plate bearing *k* values accuracy is suspect, therefore the M_r/k values are also suspect. Figure 4 depicts a graphical representation of these values.



The backcalculated E_{pccp} and the dynamic and static lab values of E_{pccp} correlated well. The average MODULUS backcalculated E_{pccp} value is greater than the average lab E_{pccp} values, as shown in Figure 6. Whereas the average backcalculated DARWin value lies between the average static and dynamic lab values. The Darwin program calculated E_{pccp} values which were closest to the lab values, however, the backcalculated values are more variable than the lab values. The reason for this variation is due to the fact that the backcalculated values reflect part of the underlying subgrade and base strength characteristics. The backcalculation process can differentiate between strong and weak pavement structure areas, however, the procedure's accuracy in assigning the exact strength to each layer of the structure is an estimation rather than an exact calculation.

Modulus of Elasticity of PCCP

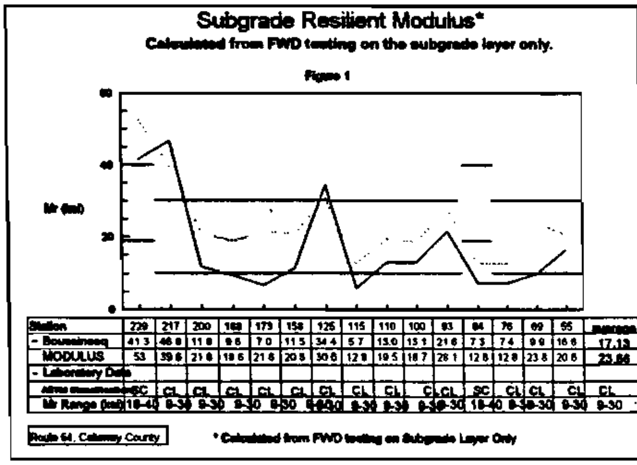
Figure 6

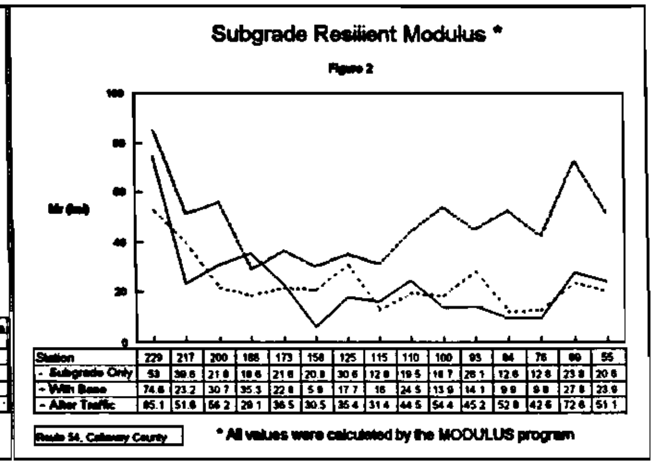


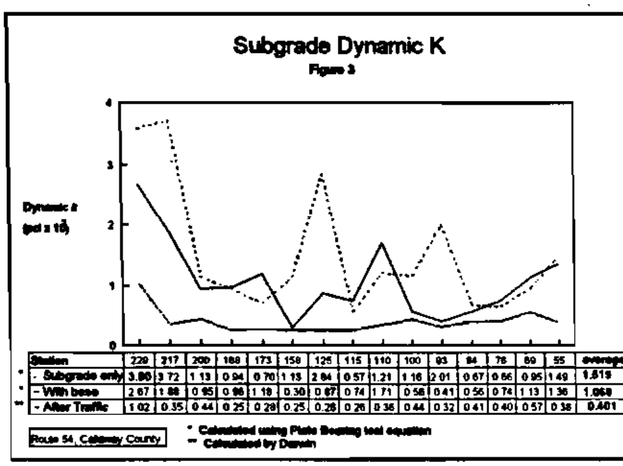
Station	229	217	200	188	173	158	125	115	110	100	93	84	76	69	55	average
Darwin	4.23	6.50	4.30	3.34	5.98	4.49	6.74	5.25	4.02	3.88	5.26	5.64	5.65	5.80	5.71	5.12
MODULUS	6.07	7.98	5.64	4.18	6.64	5.52	7.09	6.64	5.79	5.23	6.69	7.95	8.12	7.69	7.74	6.60
Static Lab	5.15	4.90	4.95	4.65	5.05	4.20	4.95	4.55	4.60	4.40	4.60	5.05	4.65	4.55	4.05	4.69
Dynamic Lab	5.73	5.82	5.33	5.54	5.60	5.27	5.28	5.34	5.07	5.37	5.57	5.47	5.69	5.59	5.65	5.49

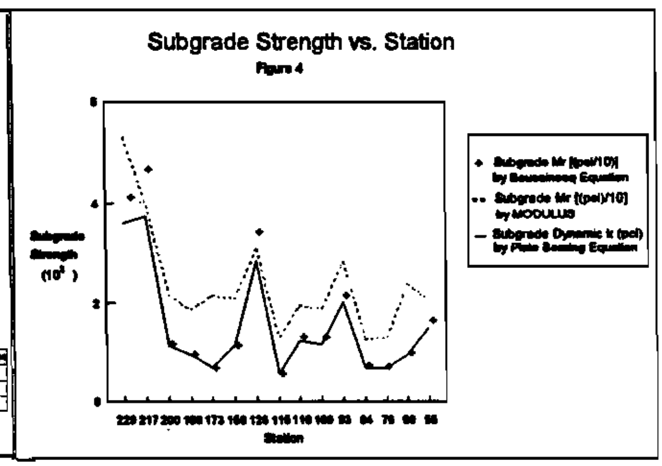
Route 54, Callaway County

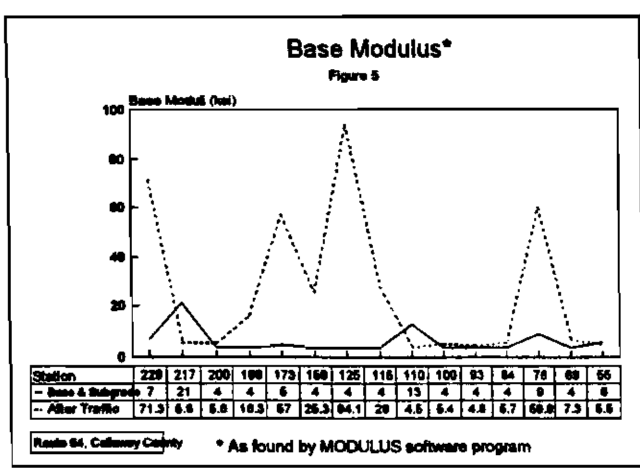
By viewing each graph of material strength versus project stationing it can be seen that the peaks and valleys of the strengths occur at approximately the same stationings.

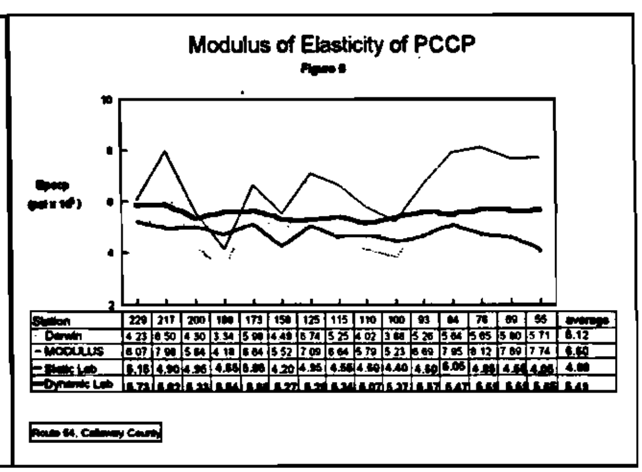












The overall conclusion is that for analysis of full depth rigid pavements the AASHTO backcalculation procedure, the DARWin program, gives a competent depiction of the PCC pavement's material characteristics. This procedure should be accurate enough to calculate overlay thicknesses for rehabilitation of full depth PCC pavements because the subgrade *k* and E_{pccp} values can both vary substantially and yet have little effect on the computed overlay thickness *(3)*.

REFERENCES

(1) *MODULUS 4.2* software program, developed by the Texas Department of Transportation and the Texas Transportation Institute, part of the Texas A&M University System.

(2) *DARWin 2.01 Pavement Design System*, developed by Eres Consultants, Savoy, Illinois, A Proprietary AASHTOWARE Computer Software Product.

(3) *AASHTO Guide for Design of Pavement Structures, Volume 1, 1993.* American Association of State Highway and Transportation Officials, Washington, D.C. (1993).

(4) *National Highway Institute FHWA Backcalculation Training Course Manual.* Athens, Ohio, October 1993

(5) *Civil Engineering Reference Manual, Fifth Edition*, Lindeburg, M.R., Professional Publications, Inc., Belmont, California, 1989.

(6) *AASHTO Guide for Design of Pavement Structures, Volume 2, 1986.* Prepared for: American Association of State Highway and Transportation Officials, Under Contract with: National Cooperative Highway Research Program, Transportation Research Board, National Research Council (NCHRP) Project 20-7 (Task 24 & 28), August 1988.

(7) "Use of Layered Theory in the Design and Evaluation of Pavement Systems", Hicks, R.G. and McHattie, R. L., Alaska Department of Transportation, Report #FHWA-AD-RD-83-8, 1982.

APPENDIX A
MODULUS And DARWin Parameters

The parameters used for the MODULUS runs are found in Table A1 below.

TABLE A1: MODULUS Parameters

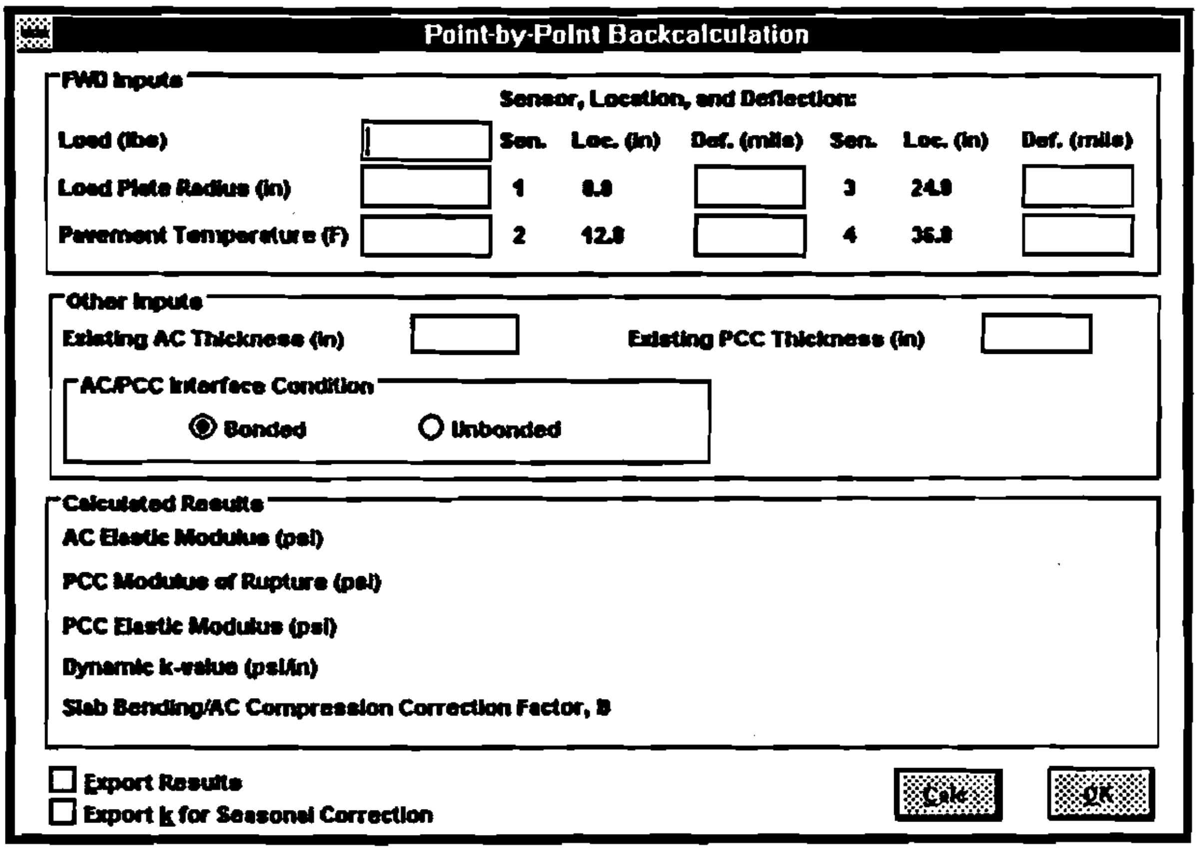
	Subgrade	Base	Concrete Pavement
Thickness	infinite	4"	12"
Poisson's Ratio	0.40	0.35	0.15
Moduli Range (ksi)	~20	4-150	1000-9000

The parameters used in the DARWin program are as follows. The average deflections for each station were input into the DARWin program as a point-by-point backcalculation analysis of a PCC pavement which was to be rehabilitated with an AC overlay.

Load (lbs) = 9000   Load Plate Radius (in) = 5.9   Existing PCC Thickness (in) = 12

In the Sensor, Location, and Deflection input request, the corresponding average deflections for each sensor location were input. From this information the DARWin program then backcalculated the PCC Elastic Modulus (psi) and the Dynamic k-value (psi/in). On the next page is an excerpt of the point-by-point backcalculation screen from the DARWin program.

Some of the FWD deflection data used in the above programs were edited before running in the backcalculation programs. This was necessary for the subgrade only and the base/subgrade deflection data. Testing on these unstable materials resulted in some suspect FWD data.


Point-by-Point Backcalculation
FWD Inputs
Sensor, Location, and Deflection:
Load (lbs)
Sen. Loc. (in) Def. (mils) Sen. Loc. (in) Def. (mils)
Load Plate Radius (in)
1 0.0
3 24.0
Pavement Temperature (F)
2 12.0
4 36.0
Other Inputs
Existing AC Thickness (in)
Existing PCC Thickness (in)
AC/PCC Interface Condition
Bonded
Unbonded
Calculated Results
AC Elastic Modulus (psi)
PCC Modulus of Rupture (psi)
PCC Elastic Modulus (psi)
Dynamic k-value (psi/in)
Slab Bending/AC Compression Correction Factor, β
Export Results
Export k for Seasonal Correction
Calc
OK

APPENDIX B
Sample Boussinesq Calculation

In 1885, Boussinesq published his layered elastic theory for computing stresses and deflections in a homogeneous, isotropic, and linearly elastic material (soil). *(4)* He stated that the deflection (d_z), at depth z, can be found by the following equation:

$$d_z = \frac{(1+u)s_0 a}{E}\left(\frac{1}{\sqrt{1+\left(\frac{z}{a}\right)^2}} + (1-2u)\left(\sqrt{1+\left(\frac{z}{a}\right)^2} - \frac{z}{a}\right)\right)$$

Where: s_0 = stress on surface (psi)
E = elastic modulus (ksi)
a = plate radius (in)
z = depth below pavement surface (in)
u = Poisson's ratio

By rearranging the equation and assuming that z = 0, in order to substitute the FWD surface deflection (d_0) in for d_z, the resulting equation is as follows:

$$E = \frac{(1+u)s_0 a}{d_0}[1+(1-2u)]$$

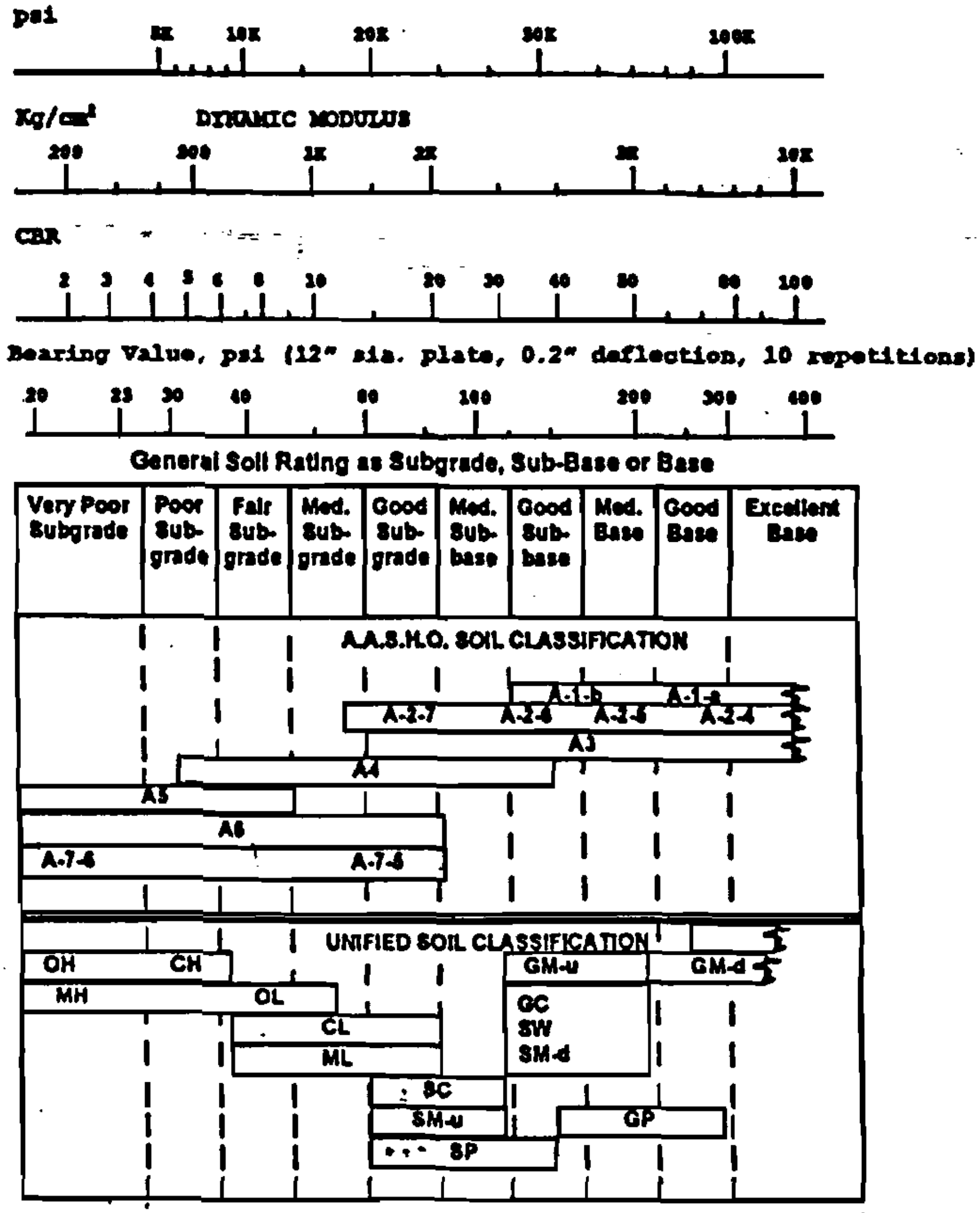
When dealing with subgrade,
E = M_r, the resilient modulus (psi)
u = 0.4
a = 8.85 in. (the large FWD plate was used in this case)
s_0 = 9000 lb./ area of plate in $(\text{inches})^2$ = 36.58 psi.
d_0 = deflection under FWD load plate (in)

From FWD data on this project, a sample d_0 = 13.01 mils.

$$M_r = \frac{(1+0.4)(36.58)(8.85)}{13.01 * 10^{-3}}[1+(1-2*0.4)] = 41{,}800 \text{ psi}$$

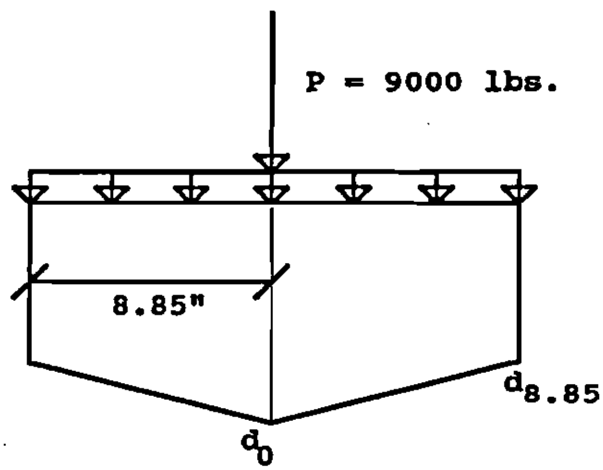
APPENDIX C
ASTM Soil Classifications and Table Depicting Range of Resilient Modulus Values

Crude Empirical Relationships Between Resilient Modulus and Other Test Data (7)&(4)



APPENDIX D
Sample Bearing Plate Test Equation

$$k = \frac{P}{V} = \frac{load\ (lbs.)}{volume\ displaced\ (in^3)}$$



Interpolate to find $d_{8.85}$:

$$\frac{d_{12} - d_{8.85}}{d_{12} - d_0} = \frac{12 - 8.85}{12 - 0}$$ where d_{12} and d_0 are known values.

d_0 = 13.01 mils
d_{12} = 4.79 mils
interpolated $d_{8.85}$ = 6.95 mils

$$\text{average depth of deflection} = \frac{d_0 + d_{8.85}}{2} = \frac{13.01 + 6.95}{2} = 9.98 \text{ mils}$$

volume of displacement =

$$V = pi * r^2 * \text{average depth of deflection} = pi * (8.85)^2 * 9.98x10^{-3}$$

$$V = 2.455 \text{ in}^3$$

$$k_{dynamic} = \frac{P}{V} = \frac{9000 \text{ lbs.}}{2.455 \text{ in}^3} = 3665 \text{ pci}$$

$$k_{static} = \frac{1}{2} k_{dynamic} = 1833 \text{ pci}$$