John A. Siekmeier[1], Duane Young[1], and David Beberg[1]

Comparison of the Dynamic Cone Penetrometer with Other Tests During Subgrade and Granular Base Characterization in Minnesota

---

Reference: Siekmeier, J. A., Young, D., and Beberg, D., 1999, "**Comparison of the Dynamic Cone Penetrometer with Other Tests During Subgrade and Granular Base Characterization in Minnesota,**" *Nondestructive Testing of Pavements and Backcalculation of Moduli: Third Volume, ASTM STP 1375,* S. D. Tayabji and E. O. Lukanen, Eds., American Society for Testing and Materials, West Conshohocken, PA.

Abstract: During the 1998 construction season, the dynamic cone penetrometer (DCP), Loadman portable falling weight deflectometer (PFWD), and Humboldt soil stiffness gauge (SSG) were used to characterize the subgrade and granular base for several projects in Minnesota. The DCP penetration index (DPI) was converted to modulus using previously established correlations between the DPI, California bearing ratio (CBR), and modulus. Standard FWD tests were also performed at some locations and the moduli backcalculated using EVERCALC. The moduli were then compared to determine the ability of each device to accurately measure in situ stiffness. Finally, thin-wall and bag samples were collected from some locations for laboratory resilient modulus testing and the results compared to the field-derived moduli.

The results show the stress dependent nature of the materials tested and that a strong correlation exists between the instruments that are designed to measure modulus. The results also show a weaker, yet still useful, correlation between the strength, as measured with the DCP, and the elastic deformation modulus, measured using the PFWD and SSG.

Keywords: DCP, granular base, Loadman, mechanistic, modulus, specifications, subgrade, stiffness

---

Research Engineer, Pavement Design Engineer, and Senior Grading and Base Specialist, respectively, Office of Materials and Road Research, Minnesota Department of Transportation, 1400 Gervais Avenue, Maplewood, MN 55109-2044.

Introduction

The Minnesota Department of Transportation (Mn/DOT) has traditionally utilized experienced engineers and technicians to evaluate the strength, stiffness, and uniformity of subgrade soils and granular bases during construction. Their evaluations utilize compaction testing, test rolling, and engineering judgement to accept suitable areas or identify areas that require additional improvement. To improve the evaluation, other tools are required that provide quantitative data. These tools must be both portable and capable of providing accurate results in the field.

Currently in Minnesota, quality assurance testing of the subgrade and granular base materials is based on a combined "recipe" and end-product specification, which consists mainly of soil classification, gradation, moisture control, lift thickness limits, and compaction testing. With the coming transition from empirical to mechanistic-empirical pavement design procedures, it will be advantageous to move towards more mechanistic-based specifications (Fleming et al. 1998, Pidwerbesky 1997, Pinard 1998, van Niekerk et al. 1998). Mechanistic-based specifications focus on the mechanical properties of the materials. This is desirable because it facilitates quantitative evaluation of alternative construction practices and materials, such as reclaimed materials (Fleming 1998), both of which have beneficial cost and environmental implications.

In the future, it is expected that quality assurance testing in Minnesota would include in situ shear strength and modulus measurement using the dynamic cone penetrometer (DCP), Loadman portable falling weight deflectometer (PFWD), and Humboldt soil stiffness gauge (SSG). These field measurements would be compared to the shear strength and modulus used for design in order to verify the design assumptions. However, because material properties change with time due to changes in moisture, temperature, and other factors it will be essential that seasonal adjustments be considered. The in situ measurements could also be used to quantify incentive-based contracts that reward contractors for producing higher quality products. Bonuses could be paid in proportion to an increase in stiffness and uniformity above a minimum specified.

Accurate measurement of in situ properties continues to be a challenge that requires both appropriate devices and methods (Newcomb and Birgisson 1999). In addition to the project summarized in this paper, others are conducting similar efforts that compare various devices (Chen and Bilyeu 1999). As a result, it is expected that the DCP, PFWD, and SSG will become more common at pavement construction sites throughout the nation as more public and private organizations learn of their utility and specific criteria are defined.

Beginning in 1991, Mn/DOT began investigating the use of the DCP for a variety of applications. The DCP was found to be a quick and inexpensive testing device that provided a quantitative measure of the in-situ shear strength of soils and other materials. Based on that field experience, Mn/DOT incorporated the DCP into its specification for pavement edge drain backfill and granular base compaction (Siekmeier et al. 1998). In addition, to facilitate greater use of the DCP, Mn/DOT began the "DCP Loan Program" in 1998. The program allows interested public and private organizations in Minnesota to borrow a DCP for a month to become familiar with the device. More than a dozen DOTs and Federal agencies are currently using the DCP and several, including Minnesota, Ohio, and Florida, have manufactured automated DCPs (Parker et al. 1998).

Many useful correlations between the DCP penetration index (DPI) and other material properties continue to be reported (Vandre et al. 1999). Interesting relationships between the shear strength, moisture susceptibility, resilient modulus, and electrical properties of base course aggregates are being developed (Saarenketo et al. 1998). Others have shown correlations between the DPI and various moduli (Chua 1988, Newcomb et al. 1996, Syed and Scullion 1998).

Test Locations

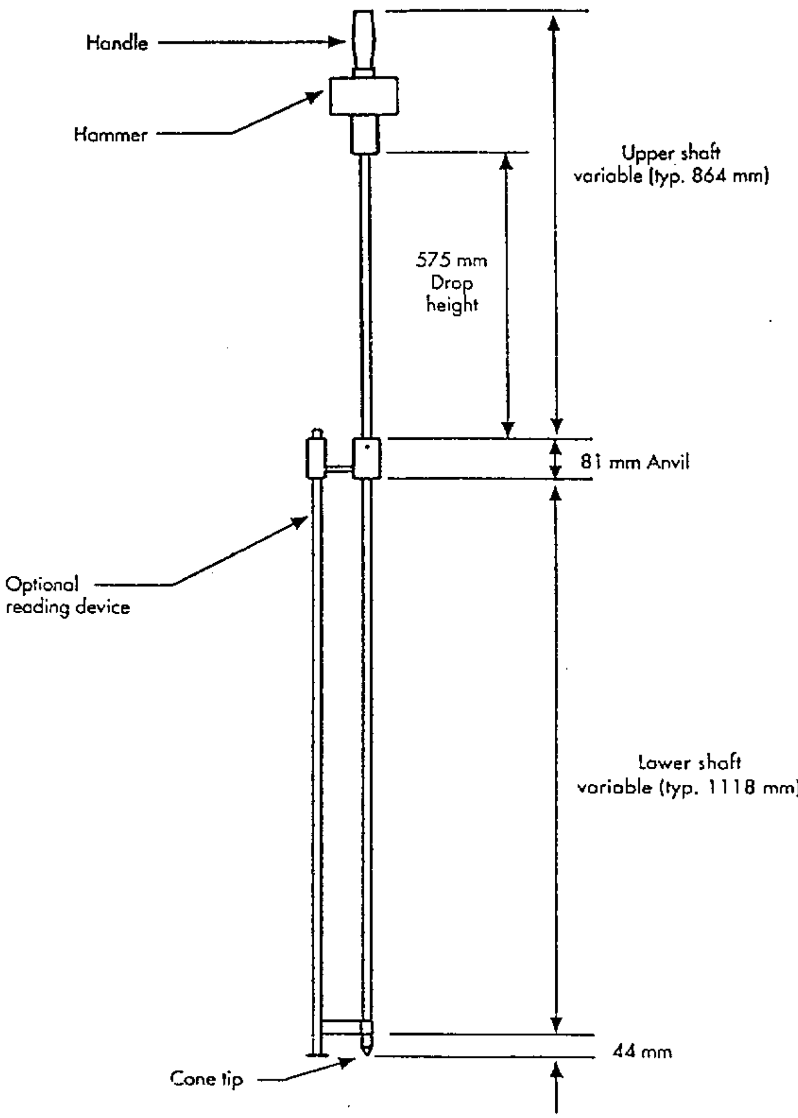
Testing was performed for 13 different pavement sections at five locations around Minnesota. Location 1 was located on Interstate 94 south of Monticello at the Mn/ROAD test facility. Testing was performed on seven of the test sections located on the interstate as part of a forensic evaluation of those test sections. Location 2 was located on the low volume test road, also located at the Mn/ROAD test facility adjacent to the interstate. Testing there was performed on three of the aggregate surfaced test sections. Location 3 was located on state TH 169 near Onamia, location 4 on state TH 12 west of Delano, and location 5 on state TH 610 in Coon Rapids.

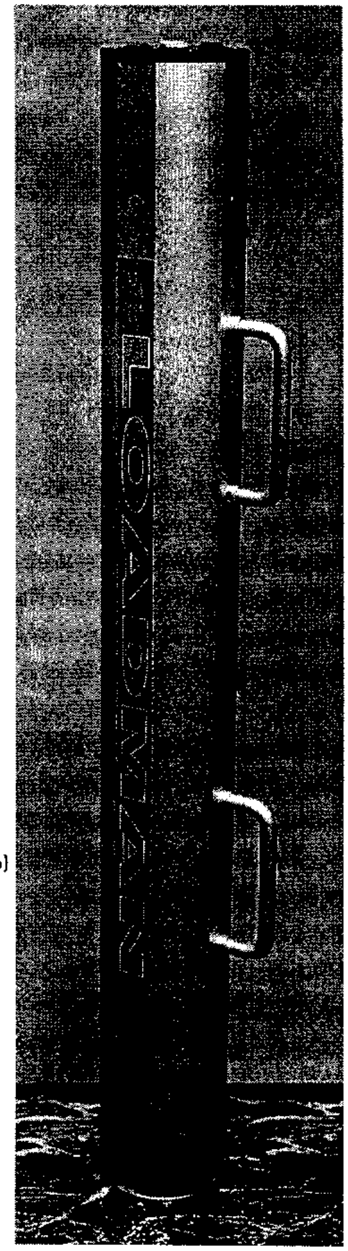
Testing Equipment

The dynamic cone penetrometer (DCP) was used to measure the shear strength from which a deformation modulus was estimated. The Loadman portable falling weight deflectometer (PFWD), Humboldt soil stiffness gage (SSG), and Dynatest falling weight deflectometer (FWD) were used to estimate an elastic deformation modulus. Laboratory resilient modulus tests were performed on thin-wall samples of the cohesive subgrade materials and recompacted samples of the granular base materials. Finally, conventional sandcone (SC) and nuclear gauge (NG) tests were used to measure the density and moisture.

The DCP used by Mn/DOT (Figure 1) consists of an 8-kg hammer that falls 575 mm and drives a 60-degree 20-mm-diameter cone into the soil or aggregate base. The DCP produces shear failure in the material and is most useful for verifying consistency and uniformity at specific construction sites. It also supports more accurate communication between the field observer and the office because it provides a consistent quantitative measure of the strength.

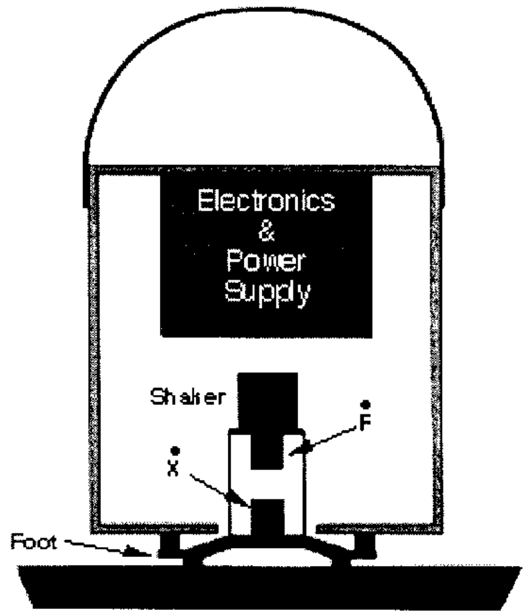
The PFWD (Figure 2) is a portable device used to estimate the in situ modulus by measuring the deflection beneath a falling weight. The device can be used on most unbound materials used in normal pavement engineering applications. The total weight is 16 kg, the height is 1170 mm, and the diameter is 130 mm. The deflection is caused by dropping a 10-kg weight 800 mm inside the hollow body of the device on to a loading plate, which rests on the material being tested. Two different loading plates, with diameters of 132 mm and 200 mm, can be used depending on the stiffness of the material being tested. The impulse load lasts approximately 10 ms and the device is powered by three 9 V batteries. Deflections from approximately 0.2 to 5 mm can be measured by the accelerometer mounted within the device and the acceleration is double integrated to calculate the deflection. The results are displayed after each test as the bearing capacity modulus (MPa), maximum deflection (mm), time of the loading impulse (ms), and the approximate percentage of the rebound deflection compared to the maximum deflection (Al-Engineering 1998).





Figures 1 and 2 - *DCP and Loadman PFWD*

The SSG (Figures 3 and 4) is an instrument for measuring the in situ stiffness of compacted soil. The SSG produces soil stress and strain levels common for pavement, bedding, and foundation applications (0.021 to 0.034 MPa). The SSG does not measure deflection resulting from the weight of the device, rather the SSG vibrates to produce small changes in the force applied that in turn produce small deflections. Geophones are used to measure both the change in force and the change in deflection for 25 different frequencies between 100 and 200 Hz. This allows the SSG to eliminate the interference of nearby equipment by discarding frequencies with low signal to noise ratios. The depth of material tested is 100 to 150 mm and the test requires 1.5 minutes. Six D-size batteries provide power for 1000 to 1500 tests (Humboldt 1998).



Figures 3 and 4 - *Humboldt Soil Stiffness Gauge*

The FWD used for this study was a Dynatest model 8000. The FWD is used by pavement management and research programs throughout the world to determine the elastic stiffness of asphalt concrete (AC) pavements and to detect voids and quantify load transfer at joints and cracks in portland cement concrete (PCC) pavements. The FWD automatically raises and drops weights from selected heights to impose specified stresses on the pavement surface. A line of geophones is used to measure the velocity of the surface as it deflects downward due to the impacting weights. The velocity-time histories are integrated to determine the deflection at each sensor location. When combined with elastic layer analysis, FWD testing can be used to analyze different pavement structures and can also be used to track changes in layer stiffness that occur due to temperature and moisture changes.

Test Procedures

The following test procedures were used during this study in order to standardize the data collection operation. The manufactures and other organizations may have alternative procedures.

DCP

For this study the penetration for each drop was recorded. In general this is not necessary unless the intent is to locate an interface between different materials or to measure subtle changes in the penetration with increasing depth. For most projects in which the average strength of a single layer is desired it is sufficient to simply record the total number of blows for a 75-mm or 150-mm depth and calculate the average penetration per blow. Before beginning the actual test, it is reasonable to perform one or two seating drops from full height. The penetration for each blow should still be watched closely in order to detect large changes in penetration with depth resulting from impacts with large gravel or hard/soft layers.

PFWD

Before leaving for the site, test the PFWD on a surface of unchanging stiffness in order to identify possible drift of the measurements with time. During transport, be sure that falling weight is down and stays down in order to prevent damage to the device. Before beginning the test, check that all screws are tight and switch the power on for at least one minute prior to testing. Press the green button to reset prior to each test and then the red button "shortly" to drop the falling weight. For each test location, perform five tests, record all, but average the last three for modulus calculation. While testing, the PFWD must be vertical and the plate must be in full contact. It may be necessary to fill small voids at the surface with native fines. The influence depth of the impact load is about one plate diameter and the lateral influence is about one plate diameter beyond plate edge (Peploe 1998). If deflection of the small plate exceeds 3 mm use the large plate. Five millimeters is the recommended maximum deflection that should be attempted because large deflections put great stress on the bottom screw joints. The absolute minimum deflection that can be measured is 0.2 mm. The recommended minimum deflection that should be attempted is 0.5 mm.

SSG

The ring should be in full contact if possible. It may be necessary to fill small voids at the surface with native fines. Alternatively, contact should be a minimum of 75 percent distributed uniformly around the circumference. Twisting the SSG back and forth through a 90-degree arc will help to seat the ring. Very little, if any, downward force should be applied. Perform two tests per point, record both, but use the second. If the two tests differ by more than 3 percent, repeat the test at a new location.

FWD and Resilient Modulus

The FWD testing procedures are documented elsewhere (Siekmeier et al. 1999). The laboratory resilient modulus tests were performed in general accordance with Strategic Highway Research Program (SHRP) Protocol P 46.

SC, NG, and Compaction

The sandcone (SC) density tests were performed in general accordance with ASTM D1556-90 (1996) e1 Standard Test Method for Density and Unit Weight of Soil in Place by the Sand-Cone Method. Nuclear gage (NG) density tests were performed in general accordance with ASTM D2922-96 e1 Standard Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth). The NG tests were performed around each probe hole at four different orientations, 90 degrees apart. In order to lessen the effect of air voids directly beneath the gage, the maximum probe depth (305 mm) was used unless a different material would have been penetrated. The percent compaction was calculated for both the SC and NG tests using the Standard Proctor test, ASTM D698-91 (1998) Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3), as the reference density.

Data Analyses and Calculations

DCP

The DPI for each drop was used to calculate an average DPI for both the upper 75-mm (3-inch avg.) and 150-mm (6-inch avg.). The first seating drop was not used. These average DPIs were then used to calculate the California bearing ratio (CBR) using equations 1 and 2 developed by the Corps of Engineers (Webster et al. 1992, 1994).

$$\text{CBR (percent)} = 292 / \text{DPI}^{1.12} \tag{1}$$

Equation 1 is used for CBR greater than 10 percent and DPI units are in mm/blow.

$$\text{CBR (percent)} = 1 / (0.017019 * \text{DPI})^{2} \tag{2}$$

Equation 2 is used for CBR less than 10 percent and DPI units are in mm/blow.

The CBR was then used to calculate an elastic deformation modulus (E) using equation 3 published by Powell et at (1984).

$$\text{E (MPa)} = 17.6 * \text{CBR}^{0.64} \tag{3}$$

PFWD

An average deflection was calculated using the third, fourth, and fifth drops and a modulus (E) calculated using equation 4 (Harr 1966).

$$E\ (\text{MPa}) = 2 * P * (1 - v^2) * r * a / A / d \tag{4}$$

where

P = dynamic load (kN)
v = Poisson's ratio (0.4 for typical materials, 0.5 for incompressible)
r = plate radius (m)
a = plate shape and rigidity factor (0.79 for rigid, 1.0 for flexible)
A = plate area (m^2)
d = deflection (mm)

The dynamic load recommended in the manual (Al-Engineering 1997) is 21.5 kN, however since the actual dynamic load varies with the stiffness of the material tested it is important to take this into consideration. A tentative approximation was used and is shown as equation 5. It is based on engineering judgement and a very limited number of tests performed by the manufacturer. Additional testing is required and it is certain that equation 5 will be modified. Future versions of the PFWD may include a load cell to directly measure the applied dynamic load.

$$P = 25 / d^{0.6} \tag{5}$$

SSG

The second measurement of the stiffness at the test location was used to calculate a modulus (E) using equation 6 (Egorov 1965).

$$E\ (\text{MPa}) = P * (1 - v^2) * b / r / d \tag{6}$$

where

P / d = S_{hg} = SSG reading (MN/m)
b = 2 * a / PI (a = 0.89 for rigid ring with radius ratio = 1.3)
PI = 3.14

Results

The following figures show a sample of the type of results generated from the study. Figure 5 shows the results from test section 17 located on the interstate section of the Mn/ROAD test facility. The moduli and compaction of the granular base are shown versus test point location. The granular base was a sand and gravel mixture with less than ten-percent fines. Locations 1 and 2 were located beneath the inside wheel path, 3 and 4 between the wheel paths, and 5 and 6 beneath the outside wheel path. It can be seen that there is an increase in both stiffness and compaction in the wheel paths. All three of the portable instruments (DCP, PFWD, and SSG) were able to detect the variation in stiffness and show a similar trend, however the magnitude of the measurement varies with the instrument used. This shift in magnitude can be partially explained by the stress condition imposed by the instrument used. The SSG imposed the lowest vertical stress of about 0.02 to 0.03 MPa and therefore reported the lowest modulus. The PFWD imposed a vertical stress of about 0.7 to 0.9 MPa beneath the large plate and 1.5 to 2.0 MPa beneath the small plate.

The moduli that were backcalculated from the FWD deflection data ranged from about 190 to 230 MPa depending on location and the dynamic load delivered by the FWD. The backcalculated moduli did not indicate greater stiffness in the wheel paths as was measured by the other instruments. However, the FWD deflection data was collected while the AC pavement was in place and therefore the higher moduli and lack of

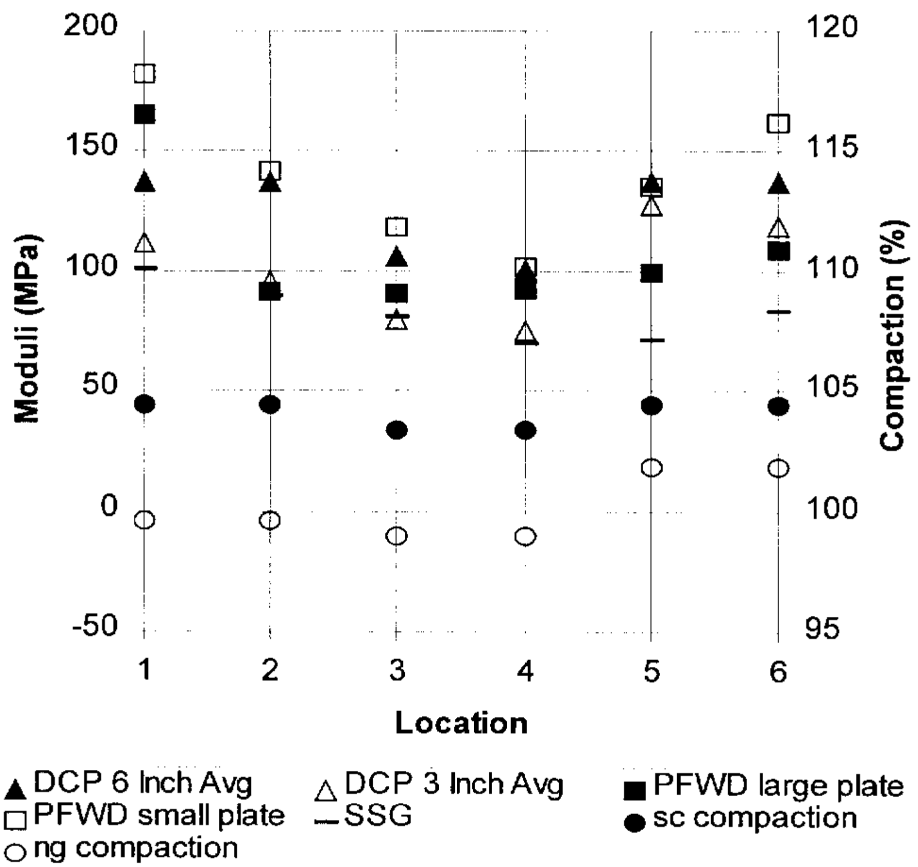


Figure 5 - *Moduli versus Location for Granular Base*

agreement with the other instruments may be due to the confinement provided by the pavement and other factors affecting the accuracy of the backcalculated moduli, such as pavement edge effects not considered in the axisymetric linear elastic layer method used by EVERCALC (WSDOT 1997). The vertical stress at the top of the granular base was calculated using EVERCALC and found to be 0.06 to 0.16 MPa.

Two resilient modulus tests were performed on the granular base sampled at this location. Prior to laboratory testing, the samples were returned to within 1 percent of the average in situ moisture (7.4 percent by weight) and compacted to within 1 percent of the average in situ density (2020 kg/m^3). The resilient moduli were found to range from about 180 to 320 MPa for principal stresses of 0.06 to 0.16 MPa corresponding to bulk stresses of 0.1 to 0.3 MPa. These results compared favorably to the backcalculated moduli at lower stresses, but diverged at higher stresses. This can be partially explained by recalling that resilient modulus test is performed with a uniform principal stress whereas the in situ tests have stress decreasing with depth. Therefore the resilient moduli determined when the principal stress was 0.16 MPa is expected to be greater than the backcalculated moduli determined for a vertical stress that decreased with depth from 0.16 MPa at the top of the granular base.

Figure 6 shows the results from TH 610 at TH 169 for the mixture of clayey and silty sand fill used to construct an embankment for a bridge approach. At this location the test points 1, 2, 3, and 4 were separated by several tens of meters. It can be seen again that each of the portable instruments shows a similar trend. For all instruments location 1 is the stiffest whereas location 2 is the softest. Locations 3 and 4 are intermediate except for the deeper DCP test. However, it can also be seen that the results from the DCP, PFWD, and SSG are in conflict with the reported compaction. Unlike Figure 5, which shows good agreement with compaction, Figure 6 shows no agreement.

This discrepancy was not completely unexpected because it has been observed at several of the locations tested during this study. The lack of agreement between the percent compaction and moduli can be partially explained as follows. In the real world of compaction testing it is not practical to know the Proctor maximum density for every possible mixture of soil at a given construction site. At the time of testing at the TH 610 site, about twelve Proctor tests had already been performed. These Proctor tests covered the typical range of soil mixtures at the site, however they did not perfectly match every conceivable mixture that could occur at the specific location of an in situ density test.

Since it is obviously not practical to perform a new Proctor test for every in situ density test, the best available Proctor test was used. Therefore it is important that the inspector exercise judgement when selecting the appropriate Proctor test to compare to the in situ density. This results in calculated compaction percentages that vary from the true compaction percentage. These subtle variations are usually not a concern since specifications typically require a minimum percent compaction. It is usually not important to define whether the actual compaction is 97 percent or 99 percent when the minimum required is 95 percent.

However, this can be an important consideration when comparing compaction test results to other in situ tests. Figure 6 clearly shows that common compaction testing can not be used to define subtle changes in the stiffness when the material being tested is an ever-changing soil mixture. Comparisons between stiffness and compaction are possible when the material is very uniform, as was the case shown in Figure 5.

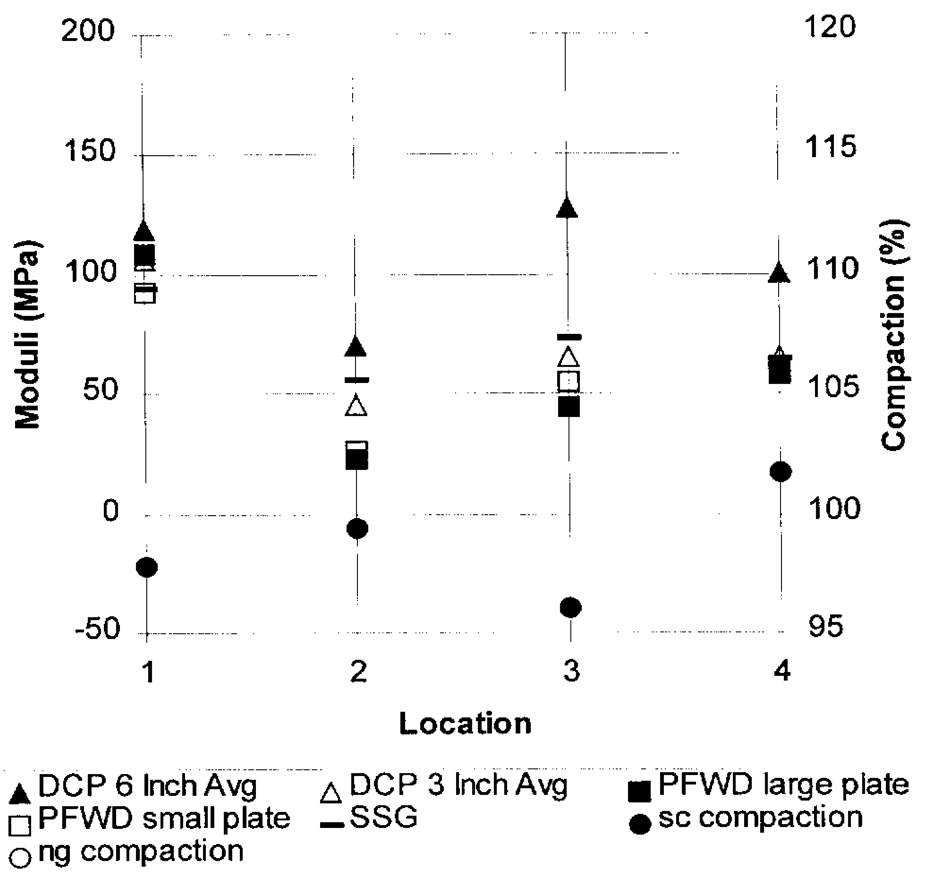


Figure 6 - *Moduli versus Location for Common Soil Fill*

Conclusions

The results show a strong correlation between the instruments designed to measure modulus and that it is important to consider the stress imposed by the instrument when stress dependent materials are tested. The results also show a weaker, yet still useful, correlation between the strength, as measured with the DCP, and the elastic deformation modulus, measured using the PFWD and SSG. In addition it was shown that compaction tests could be compared to in situ modulus tests only when the material is uniform with respect to a single maximum Proctor density. Finally, this study demonstrates the importance of clearly defining which "modulus" is desired. At a minimum the following must be defined: static or dynamic loading, stress level, boundary conditions, relative density, and moisture.

New Specification

The following minimum shear strength requirement is now part of Minnesota's "Standard Specifications for Construction." "The full thickness of each layer of classes 5 or 6 shall be compacted to achieve a penetration index value less than or equal to 10 mm per blow." "...must be tested and approved within 24 hours of placement and final compaction. Beyond the 24 hour limit, the same aggregate can only be accepted by the Specified Density Method" (sandcone and standard Proctor). "Water shall be applied to the base material during the mixing, spreading and compacting operations when and in the quantities the Engineer considers necessary for proper compaction."

Recommendations

The transition to mechanistic design should continue and be supported by quality control and quality assurance testing that measures the mechanical properties of the constructed pavement system. Other properties, such as moisture sensitivity and drainage, also require quantitative testing techniques that assure quality. Laboratory testing should be standardized to provide the designer with the best-case and worst-case material properties expected during life of the pavement structure. In addition, construction contracts should be written to provide incentives to the contractor for producing pavement structures that are stronger, stiffer, and more uniform than the minimum specified. Stiffer and more uniform subgrades and granular bases will result in lower strains, less fatigue, and longer lasting pavements.

Acknowledgements

The research reported in this publication was made possible with the help of many others from the Office of Materials and Road Research and Mn/DOT's construction inspectors. In particular the authors would like to thank Ryan McKane for his tireless spreadsheet construction and manipulation.

References

Al-Engineering, 1997, "Instructions for Use, Loadman, Portable Falling Weight Deflectometer," 11 pp.

Al-Engineering, 1998, http://www.al-engineering.fi.

Chen, D.H. and Bilyeu, J., 1999, "Comparison of Resilient Modulus Between Field and Laboratory Testing: A Case Study," *Transportation Research Board Annual Meeting*, 25 pp.

Chua, K.M., 1988, "Determination of CBR and Elastic Modulus of Soils Using a Portable Pavement Dynamic Cone Penetrometer," *Penetration Testing*, pp. 407-414.

Egorov, K.E., 1965, "Calculation of Bed for Foundation with Ring Footing," *Proceedings 6th International Conference of Soil Mechanics and Foundation Engineering*, Vol. 2, pp. 41-45.

Fleming, P.R., 1998, "Recycled Bituminous Planings as Unbound Granular Materials for Road Foundations in the UK," *Fifth International Conference on the Bearing Capacity of Roads and Airfields*, Vol. 3, pp. 1581-1590.

Fleming, P.R., Rogers, C.D.F., and Frost, M.W., 1998, "Performance Parameters and Target Values for Construction of UK Road Foundations," *Fifth International Conference on the Bearing Capacity of Roads and Airfields*, Vol. 3, pp. 1491-1501.

Harr, M.E., 1966, *Foundations of Theoretical Soil Mechanics*, McGraw-Hill, p. 81.

Humboldt Mfg. Co., 1998, *User Guide: Soil Stiffness Gauge*, Version 2.1, 16 pp.

Newcomb, D.E. and Birgisson, B., 1999, "Measuring In-Situ Mechanical Properties of Pavement Subgrade Soils," *NCHRP Project 20-5, Synthesis Topic 29-08*, Transportation Research Board.

Newcomb, D.E., Chadbourn, B.A., VanDeusen, D.A., and Burnham, T.R., 1996, "Initial Characterization of Subgrade Soils and Granular Base Materials at the Minnesota Road Research Project," *MN/RC 96-19*, 149 pp.

Parker, F., Hammons, M., and Hall, J., 1998, "Development of an Automated Dynamic Cone Penetrometer for Evaluating Soils and Pavement Materials," *Final Report WPI# 0510751*, Florida Department of Transportation, 59 pp.

Peploe, R., 1998, personal communication.

Pidwerbesky, B., 1997, "Predicting Rutting in Unbound Granular Basecourses from Loadman and Other In Situ Non-Destructive Tests," *Road and Transport Research*, Vol. 6, No. 3, September, pp. 16-25.

Pinard, M.I, 1998, "Innovative Compaction Techniques for Improving the Bearing Capacity of Roads and Airfields," *Fifth International Conference on the Bearing Capacity of Roads and Airfields*, Vol. 3, pp. 1471-1480.

Powell, W.D., Potter, J.F., Mayhew, H.C., and Nunn, M.E., 1984, "The Structural Design of Bituminous Roads," *TRRL Report LR 1132*, 62 pp.

Saarenketo, T., Scullion, T., and Kolisoja, P., 1998, "Moisture Susceptibility and Electrical Properties of Base Course Aggregates," *Fifth International Conference on the Bearing Capacity of Roads and Airfields*, Vol. 3, pp. 1401-1410

Siekmeier, J.A., Burnham, T., and Beberg, D., 1998, "Mn/DOT's New Base Compaction Specification Based on the Dynamic Cone Penetrometer," *46th Geotechnical Engineering Conference*, University of Minnesota, 23 pp.

Siekmeier, J.A., VanDeusen, D., Rosen, N., and McKane, R., 1999, "Field Testing Manual and Guidelines for Mn/ROAD FWD Operations," unpublished report, 50 pp.

Syed, I. and Scullion, T., 1998, "In-Place Engineering Properties of Recycled and Stabilized Pavement Layers," *Fifth International Conference on the Bearing Capacity of Roads and Airfields*, Vol. 3, pp. 1619-1630.

Vandre, B., Budge, A., and Nussbaum, S., 1999, "DCP-A Useful Tool for Characterizing Soil Properties at Shallow Depths," *34th Symposium on Engineering Geology and Geotechnical Engineering*, Utah State University, pp. 287-301.

Van Niekerk, A.A., Houben, L.J.M, and Molenaar, A.A.A., 1998, "Estimation of Mechanical Behavior of Unbound Road Building Materials from Physical Material Properties," *Fifth International Conference on the Bearing Capacity of Roads and Airfields*, Vol. 3, pp. 1221-1233.

Webster, S.L., Brown, R.W. and Porter, J.R., 1994, "Force Projection Site Evaluation Using the Electric Cone Penetrometer and the Dynamic Cone Penetrometer," *Technical Report GL-94-17*, U.S. Waterways Experimental Station, 172 pp.

Webster, S.L., Grau, R.H., and Williams, T.P., 1992, "Description and Application of Dual Mass Dynamic Cone Penetrometer," Instruction Report GL-92-3, U.S. Waterways Experimental Station, 50 pp.

WSDOT, 1995, *WSDOT Pavement Guide*, Washington State Department of Transportation.