Title

Relationship between DCP, Stiffness, Shear Strength, and R-value

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EXECUTIVE SUMMARY

A brief review of some studies undertaken reveal that direct relationships between DCP penetration and R-value are not reliable for general use in California. Limited studies appear to have been carried out and any relationships developed are based on very small samples that have significant variation. Good correlations between DCP penetration and shear strength and DCP penetration and stiffness have been developed, although these are material property dependent and need to be used with caution. Very little work on the development of relationships between these properties and R-value appears to have been carried out. Thus attempting to predict R-value from DCP penetration indirectly through the shear strength or stiffness will be very unreliable. A statistically valid relationship between DCP penetration and R-value is probably feasible in that some soil properties influencing the result are common to both. However, a very large experiment will need to be carried out in order to develop a reliable relationship. The need for such an experiment is questioned given that wider use of mechanistic empirical analysis and design methods will render the R-value obsolete in favor of modulus tests. It is therefore recommended that:

- Any relationships already developed between DCP penetration and R-value should be used with extreme caution, especially if those relationships were developed outside of the area and/or on different soils in which the DCP penetrations have been carried out
- Indirect prediction of R-value from DCP penetration using the elastic or resilient modulus is not recommended
- If the development of a relationship between DCP penetration and R-value is pursued, a comprehensive factorial experimental design should be followed, which considers a wide variety of soil properties, soil moistures, densities and confining pressures. The reproducibility and repeatability of the R-value test should also be quantified.

TABLE OF CONTENTS

1.0 INTRODUCTION

Since its development in the 1950's, the Dynamic Cone Penetrometer (DCP) has been widely used as a simple, but effective means of determining the in-situ shear strength of subgrade materials and pavement layers. The California Bearing Ratio (CBR) is the most commonly used measure of strength. Many studies have been conducted around the world to correlate measurements in the field with laboratory determined CBR. More recently, these studies have been extended to develop relationships with other measures of strength and stiffness such as unconfined compressive strength (UCS), elastic modulus (E), and resilient modulus (M_r).

In California, the resistance value (R-value) is typically used as a measure of the subgrade strength (structural quality) of pavement materials. However, it is not commonly used elsewhere and no published data could be located on the development of a relationship between R-value and DCP penetration. A number of states provide comparative tables between DCP and R-value in their pavement design guides, however, no information could be located on the research carried out to develop these tables and hence their predictive accuracy and applicability to California could not be established.

This Technical Memorandum provides a brief summary of work undertaken to relate DCP penetration to strength and stiffness parameters, discusses considerations for the development of an equation to predict R-values from DCP penetration, and makes recommendations on the use of other DCP-stiffness relationships to predict R-value.

2.0 BACKGROUND

Considerable research has been carried out around the world on relating DCP penetration to strength and stiffness, both laboratory and field determined. Initially, studies were focused on the CBR, but more recently they have been extended to unconfined compressive strength and elastic and resilient modulus. Although good correlations have been obtained, all studies have found that the results are material and moisture dependent, and that equations should be used with care and only with a full understanding of the material properties of the soils on which the equation was developed and the soil being tested (*1, 1, 2*).

Although DCP interpretation is a very good indicator of in-situ strength and stiffness, inherent inaccuracies in most laboratory strength and stiffness test results, coupled with the material dependency of the DCP results, imply that they should never be used as an absolute indicator, but rather as a relative indicator, of the in situ strength or stiffness of a material in a pavement or subgrade. Care must also be taken in the choice of equation used to determine the required strength or stiffness parameter, as the equations are sensitive to material properties and are typically only reliable over the range of data from which they were derived.

It should also be remembered that strengths and stiffnesses predicted from DCP penetration are determined at the in-situ moisture content and density of the pavement layers at the time of testing, which must be taken into consideration when relating these values back to those determined in a laboratory.

No published research appears to have been conducted in California to relate DCP penetration to R-value, or any other strength parameter, apart from a study conducted in 1966 to develop a correlation between R-value and K-value as a basis for concrete pavement design (*3*).

3.0 RELATING DCP TO R-VALUE

The R-value is a measure of the resistance to deformation of a saturated soil under compression at a given density. It is measured with the stabilometer and an expansion pressure measurement apparatus to provide an indication of the ability of a soil to carry the dead load of the structural pavement section and the superimposed traffic live load in pavement design.

The test is based on the assumption that almost all compacted soils have a tendency to expand when exposed to moisture, which decreases the ability of that soil to support a load. The amount of expansion created by an increase in moisture content and the consequent loss of density is, however, limited by the overlying dead load of the structural section materials placed over the soil. When the loading pressure of the overlying material and the expansive forces within the soil become equal, the expansion is halted and theoretically, no further deformation (i.e., loss of R-value) occurs. The soil is now considered to be in the most unstable state it will reach with the given dead load pressure of the overlying structural section layers. The required structural section design thickness and strength, sufficient to protect the soil in question from differential deformation or displacement from the traffic live loads, can be determined from this value.

The test is relatively complex, requires subjective judgement and produces a result that is empirical and does not represent a fundamental soil property. It is therefore difficult to relate R-value back to a field measured property. Although no published documentation on reproducibility and repeatability of the test could be located, indications from the literature point to the potential for the test results to be highly variable, even over a relatively small area.

3.1 Considerations in Developing a Relationship

There is no published information on the correlation of R-value and DCP penetration in California. Due to the significant variation in the properties and moisture contents of subgrade soils in California, care would need to be taken when attempting to develop any such relationship. Research has shown that relationships between DCP penetration and the CBR, which is a relatively simple test, are highly moisture and material dependent and a range of models to accommodate this dependency have been reported (*4*). The relative complexity of the R-value test, coupled with the potentially doubtful reproducibility and repeatability implies that added caution would be required in the development of a relationship of this test and DCP penetration.

Factors that would need to be considered in the development of a relationship include, but are necessarily limited to:

- Material properties, including particle size distribution, particle shape, hardness and durability, plasticity, and moisture sensitivity
- Moisture contents and saturation levels
- Compaction densities
- Confining pressures (laboratory) and overlying layers (field)

A comprehensive factorial experiment comparing laboratory test results with field measurements would thus be required to develop this relationship and a wide range of sites would need to be investigated to ensure that a statistically representative sample for California conditions was obtained.

The reproducibility, repeatability and variability in results of the R-value test would also have to be determined.

3.2 Related Work in California

A number of studies have been conducted by the Pavement Research Center in which both R-value and DCP penetrations have been determined (*5–8*). Comparisons of the two parameters are made in these references. However, no attempts to correlate them were made given the limited data sets. Although a separate project to investigate a potential correlation between DCP and R-value was proposed (*9*), this work has not been completed given the complexity and volume of testing required to develop a reliable equation.

In the first study, conducted in 1996, a wide range of R-values (4–30, average 17, standard deviation 12) were determined for the subgrade over a relatively small area for Heavy Vehicle Simulator (HVS) test sections at the Pavement Research Center HVS test site, which is located Richmond Field Station of the University of California, Berkeley. The range was reduced somewhat for the subbase (55–82, average 70, standard deviation 10) and considerably reduced for the base (78–83, average 81, standard deviation 3), although fewer samples were tested. The resilient moduli determined from NCHRP charts (*10*) and Huang's equation (*11*) showed similar trends, with the equation derived moduli significantly higher than the chart derived moduli. DCP tests conducted at four points on the pavement immediately after construction and again 10 days after construction, all at in-situ moisture contents, also showed wide variation, as did the DCP-derived effective modulus values determined using a South African relationship (*12*). The results are shown in Table 1. It is unlikely that the R-value tests were determined in exactly the same positions as the DCP penetrations.

Table 1 Comparison of Elastic Modulus for HVS Test Sections (*5*)

Layer	**Sample**	**R-value**	**Chart Modulus (MPa)**	**Equation Modulus (MPa)**	**Pre-construction DCP Modulus (MPa)**	**Post-construction DCP Modulus (MPa)**
Subgrade	SG-1	28	41	115	171	51
	SG-2	4	17	23	43	69
	SG-3	7	19	35	56	43
	SG-4	30	42	122	49	55
	SG-5	16	26	69	-	-
Subbase	SB-1	75	124	295	391	305
	SB-2	72	117	283	116	230
	SB-3	82	193	322	211	296
	SB-4	55	93	218	197	389
	SB-5	67	110	264	-	-
Base	B-1	82	193	322	160	727
	B-2	78	183	306	149	482
	B-3	83	200	325	202	429
	B-4	-	-	-	284	493

In another study (*8*), DCP tests were carried out on the subgrade prior to construction of a concrete test section, close to the section described above. R-value tests were not conducted, but were instead predicted using a relationship developed by the Portland Cement Association (*13*). The results are summarized in Table 2.

Table 2 Results of DCP Investigation on HVS Test Section

Sample	Predicted R-Value	DCP Modulus (MPa)
1	39	43
2	34	38
3	34	37
4	46	51
5	34	39
6	24	30

The results indicate a significant difference between R-values determined from laboratory tests and those predicted using the PCA equation when compared with DCP predicted modulus. In the 1996 study, the modulus predicted from DCP penetration was significantly larger than the laboratory determined R-value, whereas in the 1999 study, the moduli and R-values predicted from DCP penetration were very similar, which is unlikely. This is illustrated in Figure 1.

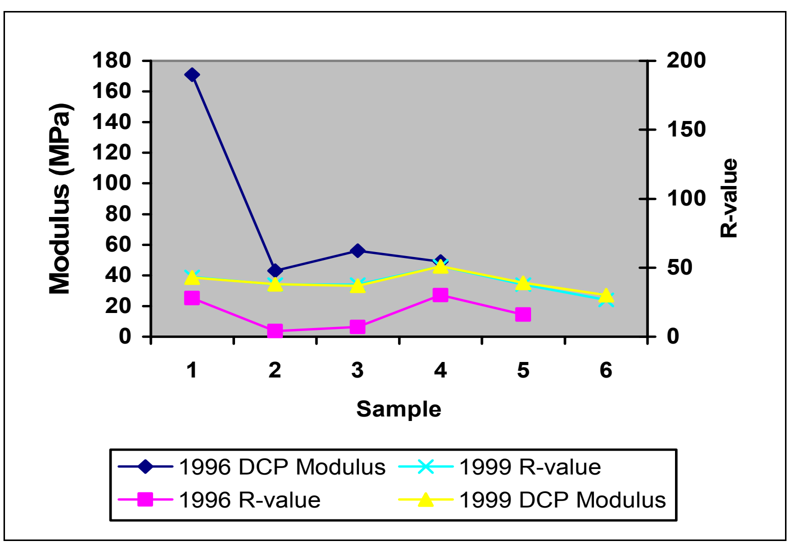

Figure 1. Plot of subgrade DCP moduli and R-values.

These results show the need to exercise care when attempting to predict certain material properties from other material properties.

3.3 Related Work in Other States

Studies to correlate DCP penetration with R-value are not widely reported. Some work has been conducted in Minnesota and comparative tables showing estimated DCP penetration (in mm/blow) against laboratory determined R-values for a range of AASHTO classified soil types are presented in the Low-volume Road Pavement Design Guide (*14*). No documentation on the actual studies to develop the relationship could be located and hence reliability and applicability to California could not be established. A copy of relevant parts of the table is provided in Table 3. In the table, the significant range in measured R-values versus predicted parameters indicates that the predicted values are not particularly accurate.

Table 3 Minnesota DOT Moduli Correlations

Soil classification		Strength				Moduli			
Textural Class[1]	AASHTO	R-value Estimated	R-value[2] Measured	CBR Estimated	DCP Estimated	Winter	Spring	Summer	Fall
G	A-1	70	-	21	12	350	62	78	78
Sa	A-1 A-3	70	-	21	12	350	62	78	78
LSa	A-2	30	46-74	6	22	350	33	41	41
SaL	A-2 A-4	30	17-49	4	27	340	27	34	34
L	A-4	15	14-26	4	27	330	27	33	33
SiL	A-4	12	10-40	4	28	320	26	32	32
SaCL	A-6	17	14-27	5	26	350	28	35	35
CL	A-6	13	13-21	4	28	350	26	33	33
SiCL	A-6	10	11-21	-	-	-	-	-	-
SaC	A-7	14	-	-	-	-	-	-	-
SiC	A-7	8	-	4	30	300	24	30	30
C	A-7	12	10-17	4	28	320	26	32	32

[1] G - Gravel
Sa - Sand
L - Loam
Si - Silt
C - Clay

[2] 240 psi exudation pressure

The New Mexico Department of Transport undertook a study to assess the sensitivity of an equation relating R-value and elastic modulus on eight typical New Mexico soils (*15*). R-values were determined on the soils, but elastic modulus was unfortunately not determined to assess the accuracy of the equation. Statistical analyses were also not published in the paper. The study found that the R-value, exudation pressure, overconsolidation ratio, Poisson's ratio and the angle of internal friction of the material were all significant in the prediction of the elastic modulus. The compaction pressure was found to have an influence if the material is time-dependent or viscoelastic and the R-value and elastic modulus were both shown to be sensitive to the moisture content.

3.4 Indirect Prediction of R-value from DCP

The literature indicates that R-value could potentially be indirectly calculated from elastic or resilient modulus, determined from FWD measurements, laboratory testing, or predicted from DCP penetration, using the New Mexico or other similar equations. However, experience has shown that these predictions would be highly sensitive to material properties, moisture condition, and density and probably only accurate within the range of values of the dataset from which they were originally developed. It is therefore recommended that indirect relationships are not used to predict R-value from DCP penetration.

4.0 CONCLUSIONS AND RECOMMENDATIONS

A brief review of studies undertaken at the Richmond Field Station and elsewhere in the USA reveal that direct relationships between DCP penetration and R-value are not reliable for general use in California. Limited studies appear to have been carried out, either in California or in other states, and any relationships developed appear to be based on very small samples that have significant variation within the dataset over relatively small areas, especially in terms of R-value.

Good correlations between DCP penetration and shear strength and DCP penetration and stiffness have been developed, although these are material property dependent and need to be used with caution. Very little work on the development of relationships between stiffness and R-value and shear strength and R-value appears to have been carried out. Thus, attempting to predict R-value from DCP penetration indirectly through the stiffness will be very unreliable.

A statistically valid relationship between DCP penetration and R-value is probably feasible in that some soil properties influencing the result are common to both. However, a very large experiment will need to be carried out in order to develop a reliable relationship. Key issues that will need to be considered in the experimental design will include soil properties, soil moisture, densities, confining pressures and the reproducibility and repeatability of the R-value test. The need for such an experiment is questioned given that wider use of mechanistic empirical analysis and design methods will probably render the R-value obsolete in favor of modulus tests.

It is therefore recommended that:

- Any relationships already developed between DCP penetration and R-value should be used with extreme caution, especially if those relationships were developed outside of the area and/or on different soils in which the DCP penetrations have been carried out.
- Indirect prediction of R-value from DCP penetration using the elastic or resilient modulus is not recommended.
- If a relationship between DCP penetration and R-value is pursued, a comprehensive factorial experimental design should be followed, which considers a wide variety of soil properties, soil moistures, densities (in situ and compacted) and confining pressures. The reproducibility and repeatability of the R-value test should also be quantified.

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