Resilient Behavior Characterization of Geomaterials for Pavement Design

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ABSTRACT: Resilient modulus (M_R) test and the California Bearing Ratio (CBR) test have been the two most common tests for laboratory characterization of geomaterials, i.e., fine-grained subgrade soils and unbound aggregate materials for road and airfield pavements analysis. However, there is a major difference between the two tests in terms of materials properties. Whereas CBR test evaluates the potential strength of geomaterials, resilient modulus is a stiffness property obtained under repeated/cyclic load test. The determination of resilient modulus requires sophisticated equipment and skilled personnel for laboratory and field testing. Therefore, some agencies continue to use CBR to estimate resilient modulus for flexible pavement design. In this paper, two well-known M_R-CBR empirical models were investigated for predicting resilient modulus of fourteen subgrade soils for the analysis and design of a new runway at a commercial airport in the United States. Repeated load and CBR tests were conducted in the laboratory on the subgrade samples to obtain M_R and CBR data to develop the empirical models. The results suggest that constitutive models obtained directly from laboratory test data would be more appropriate to characterize the resilient behavior of subgrade soils a high reliability design of runways than empirical correlation models.

KEY WORDS: Resilient modulus, CBR, repeated load test, subgrade soils, runway.

1 INTRODUCTION

A comprehensive laboratory testing was conducted at the Federal Aviation Administration (FAA)'s Center of Excellence (COE) for Airport Technology located at the University of Illinois at Urbana-Champaign to characterize the resilient behavior of fourteen in-place subgrade soils as the pavement foundation for a new runway. The runway construction was part of an airfield expansion project of the Piedmont Triad international airport in Greensboro, North Carolina. The project involved the construction of a hub facility for Federal Express operations and a new runway capable of accommodating large capacity aircrafts. Figure 1 shows the site for various project activities, including the proposed airfield pavements.

Proper evaluation of subgrade soil is an integral part of any good airport pavement construction and design practice (Tutumluer and Thompson, 1997). Repeated load tests are commonly employed to evaluate the resilient properties of pavement foundation geomaterials, i.e., fine-grained subgrade soils and unbound aggregate materials. Resilient modulus used for the elastic stiffness of pavement materials is defined as the ratio of the repeatedly applied wheel load stress to the recoverable strain determined after shakedown of the material.

Current pavement design methods including the new American Association of Highway and Transportation Officials (AASHTO) design guide (NCHRP 1-37A 2004) and the FAA design guide for airports carrying new large aircraft (LEDFAA) recommend the use of resilient modulus values as a primary input. Although the resilient modulus test is a better representative of the traffic loading, it is very expensive and time consuming experiment compared to cheaper and easier CBR test. Resilient modulus values obtained through empirical correlations with materials strength properties including California Bearing Ratio (CBR) and Hveem Resistance (R) value are therefore routinely accepted by transportation agencies for flexible pavement analysis.

This paper focuses on characterizing the resilient behavior of 14 subgrade soil materials using data obtained from repeated load and CBR tests. Tests were conducted based on the FAA criteria for evaluating subgrade materials for airport flexible pavement design. The experimental program was carried to determine the resilient modulus and CBR properties of the 14 subgrade soils at optimum moisture content and 95% of modified Proctor compaction density. Two commonly used resilient modulus-CBR empirical correlation models were investigated for predicting resilient modulus of the 14 subgrade soils. The measured resilient modulus values obtained from laboratory tests are compared with values predicted from the empirical correlation models.

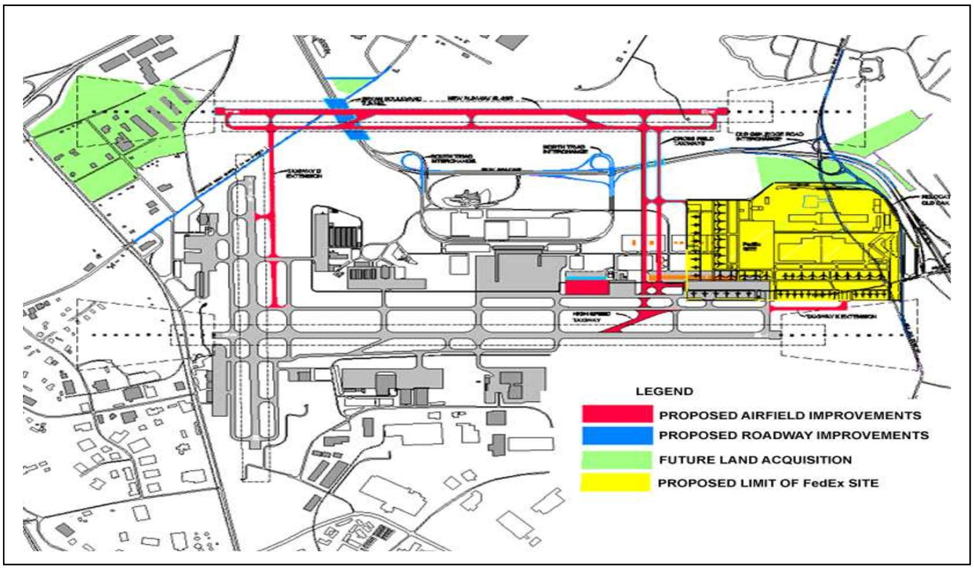


Figure 1: Outline of project site at the Piedmont triad international airport.

2 SUBGRADE MATERIALS AND PROPERTIES

Fourteen subgrade soil samples were obtained from the project site, i.e., Piedmont Triad International Airport (PTIA) in Greensboro, North Caronia, where the runway and the associated taxiways and aprons were to be constructed. Samples were collected from selected boreholes along the runway, taxiways, aprons, and borrow pits at the project site. Accordingly, the 14 samples are represented herein as R-1 to R-4 (runway samples), T-1, T-2 (taxiways samples), F-1 to F-6 (apron samples), and B-1, B-2 (borrow pits samples). All the 14 subgrade samples were shipped to the University of Illinois's Advanced Transportation Research Laboratory (ATREL) for the laboratory tests.

Index properties tests were first conducted on the subgrade samples in accordance with ASTM D 4318 specification to obtain the Atterberg's limits, including the liquid limit (LL), plasticity limit (PL) and plasticity index (PI). The index tests were followed by particle size analysis test on the samples using ASTM D 422 test procedure. Based on the Atterberg limits and particle size test results, the subgrade samples were generally classified as MH, ML, SM, CL, or SC according to Unified Soil Classification System (USCS). The average LL and PI for the 14 subgrade soils was 50% and 17%, respectively. As expected, the sandy soils had smaller LL and PI values. The FAA considers MH soils as poor subgrades with high compressibility and high susceptibility to expansion.

In addition, moisture-density tests were performed on the subgrade soils in accordance with ASTM D 1557 method to establish the maximum dry density and the optimum moisture content of the samples. Compaction curves obtained from the modified Proctor tests were used to define a target density and moisture contents at which the subgrade specimens were prepared for testing. Figure 2 shows the maximum dry density and optimum water content for all the 14 subgrade soils tested. Each soil group had its own characteristic moisture-density relationship under the same compaction requirements. There were no unique trends in the subgrade samples compaction results even in the same group of soil classification. The maximum dry density ranged from 16.8kN/m^3 to 20.3kN/m^3, with corresponding optimum water contents varying from 20.9% to 8.6%, respectively. As expected, the sandy soils samples had higher maximum dry densities and lower optimum moisture contents.

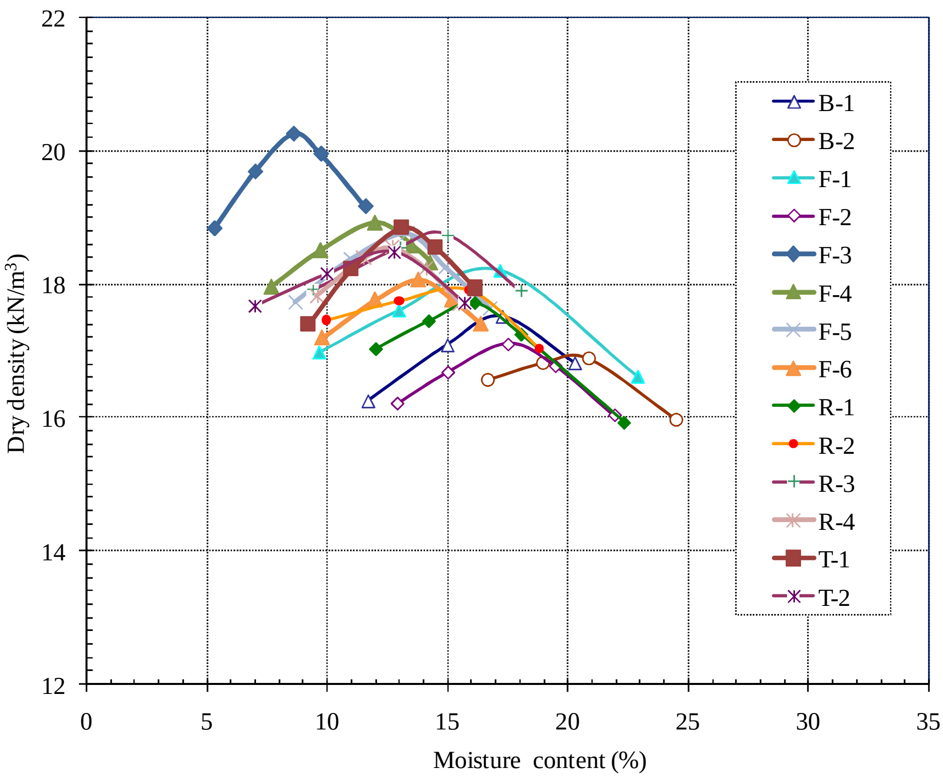


Figure 2: Modified Proctor compaction properties of the 14 subgrade soil samples.

3 CALIFORNIA BEARING RATIO TESTING AND TEST RESULTS

California Bearing Ratio (CBR) value is a strength parameter mostly used by the FAA for airport pavements design. The CBR test was conducted on the subgrade samples using the standard America Society of Testing Materials (ASTM) procedure D 1883. The tests were performed on the 14 subgrade soil specimens compacted at the 95% of the maximum dry densities at optimum moisture contents in approximately 150 mm diameter by 114 mm high metal molds.

Each specimen was compacted in five lifts into the testing molds. After compaction, the mold assembly with the specimen was immersed in a soaking tank to saturate for 96 hours (4 days) before conducting the CBR tests. Following the soaking period, the mold was drained of free water and the mold assembly was then placed under a loading device for testing. During testing the subgrade samples were subjected to the applied load by a standard cylindrical penetration piston of 50 mm at a rate of 1.3 mm per minute. The total load at 11 different penetrations including 0.64, 1.27, 1.91, 2.54, 3.18, 3.81, 4.45, 5.08, 7.62, 10.16, and 12.7 mm for each sample were recorded. The test results were compared to a standard curve of 100% CBR.

3.1 Calculation of CBR Values

The penetration stresses were calculated from the penetration readings and the stress–penetration curve was plotted for the subgrade samples. Using the corrected stress values of the stress-penetration curve for either 2.54mm or 5.08mm penetrations, the bearing ratios were calculated for each sample by dividing the corrected stresses by the standard stresses of 6.9MPa and 10.3MPa, respectively, and multiplying the result by 100 as shown in Equation 1. Note that the standard stress is the resisting force of a well graded crushed stone.

$$\text{CBR} = \frac{\text{Load per unit area of penetration at 2.54 mm}}{\text{Standard stress of 6.9 MPa of crushed stone}} \text{x}\,100 \qquad (1)$$

Table 1 shows the CBR test results for all the 14 subgrade soils tested. Based on the CBR values, the samples obtained from the boreholes along runway section (R samples) appear to be stronger although one of the taxiway sample (F-4) showed extremely high CBR value, i.e., 18.7. The average CBR value obtained for the subgrade soils was 7.1. Due to high variability in the strength properties of subgrade soils, it has been customarily for FAA to use the 85th percentile CBR value of subgrade soils for airport flexible pavement design (Advisory Circular 150/5320-6D). From Table 1, it can be seen that the 85th percentile value of the subgrade soils at PTIA was 3.5, i.e., 85% of the CBR data were greater than or equal to 3.5.

Table 1: CBR results for the 14 subgrade soils tested.

Sample ID	B-1	B-2	F-1	F-2	F-3	F-4	F-5	F-6	R-1	R-2	R-3	R-4	T-1	T-2
CBR	2.5	4.7	3.5	7.1	6	18.7	4.7	3.6	11	9.5	14.3	3.1	6.2	4.2

4 RESILIENT MODULUS TESTING AND TEST RESULTS

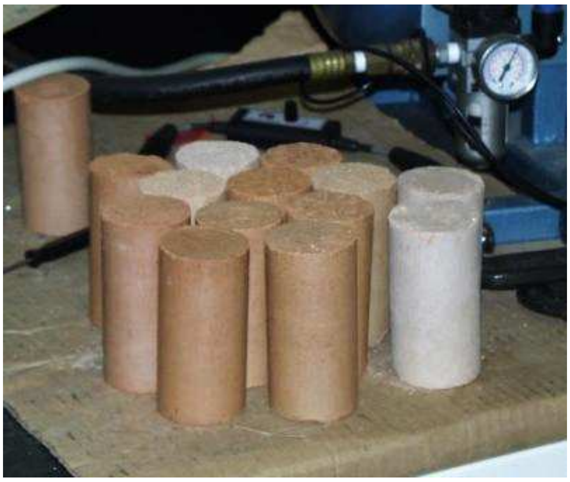
Repeated load tests were conducted in accordance to the University of Illinois in-house testing procedure to determine resilient modulus properties of the subgrade soil at optimum water content corresponding to the target 95% maximum dry density of the modified Proctor compaction. The subgrade samples were compacted to prepare cylindrical test specimens 51 mm diameter by 102 mm high. An Industrial Process Controls (IPC), Universal Testing Machine (UTM-5P) pneumatic type equipment available at the University of Illinois ATREL was used for applying repeated stresses on the specimen (see Figure 3b).

During testing, specimens were first conditioned by applying 200 load pulses at 41.4kPa deviator stress. A haversine load pulse was used with load duration of 0.1s and rest period of 0.9s similar to the AASHTO T307. No confining pressure was applied on the specimens by this test procedure. It is well known that confining pressures acting on top of pavement subgrade are generally very low. Accordingly, the unconfined conditions on the test specimens would possibly simulate the worst loading conditions in the field. After conditioning, the samples were subjected to 8 different pulsed deviator stress levels of 13.8, 27.6, 41.4, 55.2, 68.9, 82.7, 96.5, and 110.3kPa. Each stress level was applied 100 times and the resilient modulus (M_R) was calculated based on the average values of the last 5 cycles using Equation 2.

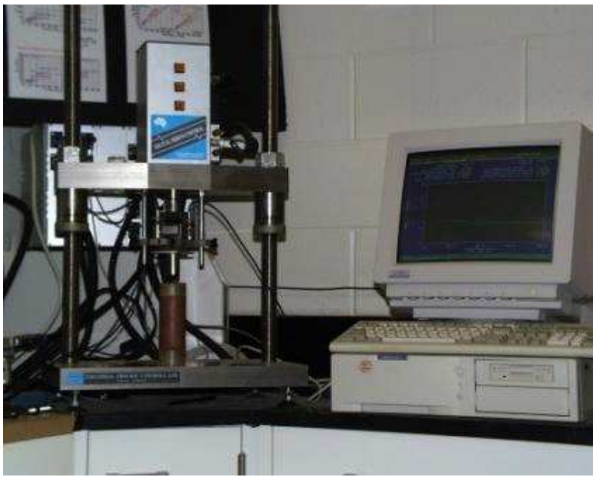
$$M_R = \frac{\sigma_d}{\varepsilon_r} \tag{2}$$

where, σ_d is the dynamic deviator stress and ε_r is the resilient (recoverable) axial strain.

Figure 3a shows the compacted subgrade specimens ready for testing, while Figure 2b shows the IPC UTM-5P test setup used for the resilient modulus testing.



(a): Compacted subgrade specimens.



(b): IPC UTM-5P M_R test setup.

Figure 3: Resilient modulus testing of subgrade soils at ATREL.

4.1 Resilient Modulus Characterization

The resilient modulus of fine-grained subgrade soils is stress dependent. Typically, subgrade soil modulus decreases in proportion with increasing stress levels to exhibit stress-softening type behavior. The stress-strain curve has very steep slope during the early portion of the testing and flatter slope near the end of the test. Thus the stress-strain plots of subgrades exhibit a bilinear curve. A bilinear or arithmetic relationship presented in Equations 3 and 4 is therefore commonly used to analyze the resilient modulus test data of subgrade soils. The bilinear relationship has been found to predict the stress softening of fine-grained soils as a function of the applied repeated deviator stress (σ_d) quite well (Thompson and Robnett, 1979).

The bilinear relationship was used to analyze the test data of the 14 subgrade soils for their resilient moduli. Table 2 shows the resilient modulus characterization results for all the subgrade samples tested.

$$M_R = k_1 + k_3 (k_2 - \sigma_d) \text{ when } \sigma_d < k_2 \quad (3)$$

$$M_R = k_1 - k_4 (\sigma_d - k_2) \text{ when } \sigma_d > k_2 \quad (4)$$

where k_1, k_2, k_3, and k_4 are material constants obtained from laboratory repeated load test data.

It can be seen that the resilient modulus of all the subgrade soils is highly dependent of the k_1 parameter. The effects of k_2, k_3, and k_4 on resilient modulus values were negligible for all 14 subgrade soils tested.

Table 2: Resilient modulus results for the subgrade materials tested.

Sample	k_1(MPa)	k_2(MPa)	k_3	k_4	M_R (MPa)
B1	86.814	0.038	-0.373	0.444	86.8
B2	56.498	0.053	-0.006	0.111	56.5
F1	99.216	0.050	-1.182	-0.517	99.2
F2	65.579	0.059	-0.181	-0.159	65.6
F3	86.435	0.065	-0.487	0.155	86.4
F4	94.049	0.050	-2.213	-0.063	94.0
F5	67.639	0.063	0.222	0.116	67.6
F6	69.589	0.041	-0.334	-0.143	69.6
R 1	94.675	0.043	-0.490	0.697	94.7
R 2	70.278	0.046	-0.301	0.183	70.3
R 3	80.117	0.048	-0.079	0.389	80.1
R 4	71.656	0.059	-0.812	0.083	71.7
T1	90.604	0.039	-0.625	0.138	90.6
T2	80.613	0.055	-0.699	0.269	80.6

5 RESILIENT MODULUS/CBR CORRELATIONS

Resilient modulus is the main input variable for AASHTO, FAA's LEDFAA, and the next generation of mechanistic based flexible pavement design procedures. It has been a challenge for pavement engineers to estimate in most cases the resilient modulus values in the absence of laboratory test results. Therefore, correlating CBR values to resilient modulus inputs has been very common in practice. In this study, two commonly used M_R-CBR empirical models were used to correlate the modulus of each subgrade soil sample with the CBR equivalent in order to check the validity of these relationships and to evaluate if such correlations can be used with confidence in airport pavement design.

The two models are the conventional Heukelom and Klomp (1962) model and the newly adopted AASHTO 2002 design guide model (NCHRP 1-37A 2004). Equations 5 and 6 represent the Heukelom and Klomp and the AASHTO 2002 design guide models, respectively.

$$M_R\ (\text{MPa}) = 10.3 \times \text{CBR} \tag{5}$$

$$M_R\ (\text{MPa}) = 17.6 \times \text{CBR}^{0.64} \tag{6}$$

Table 3 lists the measured resilient modulus and CBR test results together with the predicted moduli from the two models. It can be seen that resilient modulus of the subgrade materials could be extremely over-predicted or under-predicted by the two selected models. Thus, none of the models could provide a good correlation between CBR and M_R for the subgrade soils tested. Figure 4 shows the correlation results represented by a plot of predicted M_R against the measured M_R from the repeated load tests.

Various mathematical forms such as exponential, linear and logarithmic functions were used to fit the data with the purpose of verifying the extent of correlations between the measured and predicted M_R values. Table 4 shows the correlation coefficient values (R^2) for the three selected functions. There were essentially weak or no correlations between measured and predicted resilient modulus values of the subgrade materials tested using the two well established correlation models. It would appear that the Heukelom & Klomp model could be better based on the relatively high R^2 with linear and logarithmic functions when compared with the NCHRP 1-37A adopted model. However, the extremely low R^2 values simply indicate that none of the two models can be reliable for correlating the modulus and CBR properties of subgrade soils with similar characteristics as the 14 samples tested.

Table 3: Measured and predicted resilient modulus values.

Subgrade Sample	Measured M_R (MPa)	CBR %	Predicted M_R, (MPa)		% Prediction	
			M_R = 10.3*CBR	M_R = 17.6*CBR$^{0.64}$	M_R = 10.3*CBR	M_R = 17.6*CBR$^{0.64}$
B1	86.8	2.5	25.9	31.8	-235	-173
B2	56.5	4.7	48.6	47.7	-12	-14
F1	99.2	3.5	36.2	39.5	-143	-123
F2	65.6	7.1	73.4	62.1	+11	-6
F3	86.4	6.0	62.1	55.7	-39	-55
F4	94.0	18.7	193.4	115.3	+51	+18
F5	67.6	4.7	48.6	47.7	-39	-42
F6	69.6	3.6	37.2	40.2	-87	-73
R1	94.7	11.0	113.8	82.1	+17	-15
R2	70.3	9.5	98.2	74.8	+28	+6
R3	80.1	14.3	147.9	97.1	+46	+18
R4	71.7	3.1	32.1	36.5	-123	-96
T1	90.6	6.2	64.1	56.9	-41	-59
T2	80.6	4.2	43.4	44.3	-86	-82

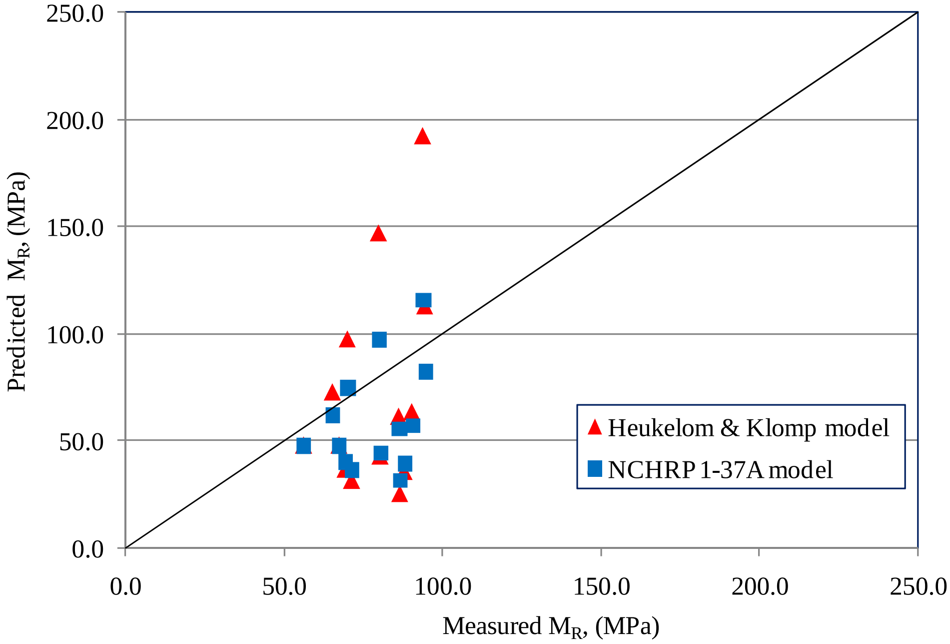


Figure 4: Comparison between measured and predicted M_R values.

Table 4: R^2 values obtained for different functions.

Mathematical function	Heukelom & Klomp Model	NCHRP 1-37A Model
Exponential	0.009	0.009
Linear	0.046	0.032
Logarithmic	0.054	0.039

Figure 5 presents the measured resilient moduli plotted with the corresponding CBR values for all the 14 subgrade soils. It appears there is no apparent trend for correlating the two engineering properties of the subgrade materials tested. Thompson and Robnett (1979) could not find a suitable correlation between CBR and resilient modulus of subgrade soils. Also it is well known that the CBR is primarily a measure of bearing capacity (strength) property under static load whereas resilient modulus is basically a measure of stiffness of the material under repeated load. It is therefore a major challenge to pavement engineers to develop correlation models that better characterize the resilient behavior of subgrade soils for incorporating pavement foundation data into pavement analysis and design.

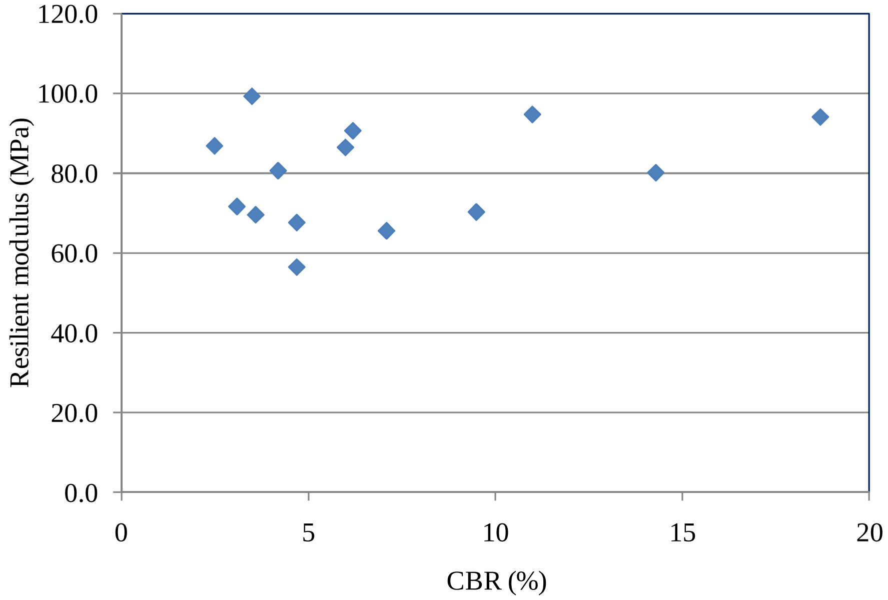


Figure 5: Resilient modulus test results plotted against CBR test results.

6 SUMMARY AND CONCLUSIONS

Pavement geomaterials including subgrade soils and unbound aggregate materials are characterized by the resilient modulus, which can be obtained from the repeated load tests. Due its complexity, time and the need for highly trained technicians to conduct resilient modulus tests, empirical correlations between resilient modulus (M_R) and California Bearing Ratio (CBR) is used to prediction resilient modulus for pavement design. This paper investigated two M_R-CBR empirical models for 14 subgrade soil samples for the construction of a new runway at a commercial airport in North Carolina, United States.

Repeated load tests, which simulate the effects of aircraft wheel loading, were used to determine the resilient moduli of the subgrade soils, whereas, the CBR tests were conducted to determine their strength. All the tests were conducted to meet FAA specifications and testing requirements of materials used as subgrade for an airport pavement construction.

The empirical correlation results indicate that resilient modulus values could not be well predicted for the 14 subgrade materials tested using the two popular empirical models. The models overall, either over predict the resilient modulus by more than 40% or under predict the resilient modulus by approximately 100% or more for the subgrade materials tested. The results obtained from this study indicate that constitutive models obtained directly from laboratory test data would be more appropriate to characterize the resilient behavior of the subgrade soils for both roads and airport pavements analysis and design.

ACKNOWLEDGMENTS/DISCLAIMER

This paper is prepared from a study conducted in the Center of Excellence for Airport Technology at the University of Illinois at Urbana-Champaign. The study was funded by the FAA under Piedmont Triad International Airport, and Trigon Engineering Consultants Inc. in Greensboro, North Carolina. The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the FAA.

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