Correlating Resilient Moduli from Pressuremeter Tests to Laboratory California Bearing Ratio Tests

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In order to increase the usefulness of the pressuremeter (PMT) in the area of pavement design and evaluation, resilient moduli, determined from a special PMT test, were correlated to California Bearing Ratio (CBR) test results. The PMT resilient moduli–CBR correlations developed compared well with existing resilient moduli–CBR correlations. The special PMT test, called the resilient modulus PMT test, was developed to enable six resilient moduli to be determined from six unload-reload cycles conducted for various load durations along the linear portion of the in situ stress-strain response. The various cycle lengths enabled resilient moduli to be determined as a function of the load durations typically encountered during the traffic loading of a pavement. The cycle length used were 10, 20, 30, 60, 120, and 240 sec. The PMT used was the monocell TEXAM pressuremeter built by Roctest, Inc. It was concluded that the current TEXAM PMT cannot be used to accurately conduct 10-sec unload-reload loops to determine resilient moduli, but can be used to acurately determine resilient moduli for the remaining cycle lengths and that the resilient moduli from these cycles are reasonable for use in design.

In an attempt to increase the usefulness of the pressuremeter (PMT) (Figure 1) in the field of pavement design, simple correlations were developed between PMT resilient moduli and PMT limit pressures and laboratory California Bearing Ratio (CBR) values. The PMT resilient moduli were correlated to the CBR values using the empirical relationship $M_r = B \times \text{CBR}$, where the constant B has a published range of 200 to 3,000, depending on the soil type, with a recommended value of 1,500 for design (*1*). Pavement designers have been attempting to determine reasonable values of resilient moduli for design since the 1986 AASHTO *Guide for the Design of Pavement Structures* (*2*) presented pavement design procedures based on resilient moduli. Cosentino (*3*) showed the usefulness of the pavement pressuremeter in predicting resilient moduli for airport pavements. The pavement pressuremeter is a scaled-down version of the PMT shown in Figure 1, with a probe length of 10 in. (25.4 cm), and a probe diameter of 1.30 in. (3.30 cm) (*3*). One major conclusion of the pavement PMT (1987) study was that all PMT models could be used to determine the stress-strain of soils subjected to various loading rates or durations. Because the pavement PMT was not available at Texas Tech University, where the study was conducted, the TEXAM PMT owned by the civil engineering department was used.

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Resilient moduli arc typically found from either cyclic triaxial tests or nondestructive pavement evaluation tests, such as falling weight deflectometer or dynaflect tests. The resilient modulus is defined as the modulus associated with the elastic rebound, or resiliency, of the paving materials. It can be more simply described as the unload stress-strain slope developed during the impulse loading that occurs as vehicles pass over the pavement. The resilient modulus for one vehicle load is depicted in Figure 2 as

$$M_r = \sigma_d/\varepsilon_r$$

where

M_r = resilient modulus,
σ_d = deviator stress or applied stress, and
ε_r = is the resilient or elastic rebound strain.

The current PMT models are only capable of yielding stress-strain data at points A, B, and C in Figure 2. Determining resilient moduli from cyclic triaxial tests appears to be the most logical approach from an engineering standpoint. During cyclic triaxial testing, samples of the base, subbase, or subgrade are placed in a triaxial chamber, subjected to appropriate confining pressures, and loaded by impulse loads, by pulsing the axial load at rates and magnitudes similar to those encountered on the pavement. Stress-strain plots are used to determine the design resilient modulus. The major drawbacks of cyclic triaxial tests are the time requirements of a single test (2 to 8 hr, depending on the material), the initial equipment costs ($20,000 to $100,000, depending on system chosen), and the expertise required to conduct cyclic triaxial tests on representative samples. These drawbacks have prevented the industry from easily adopting the cyclic triaxial test as a standard.

Nondestructive testing (NDT) is used to backcalculate resilient moduli of the individual pavement layers, and have proven useful for determining the existing structural capacity of large sections of pavement. The major drawback of backcalculating moduli from NDT is the requirement that the layer thickness be precisely known. Thus, even though NDT of pavements is an efficient approach for determining layer moduli, the moduli found can be highly questionable simply because of the uncertainty of the layer thicknesses. Pavement practitioners who use NDT have difficulty determining design resilient moduli values for input into overlay design procedures.

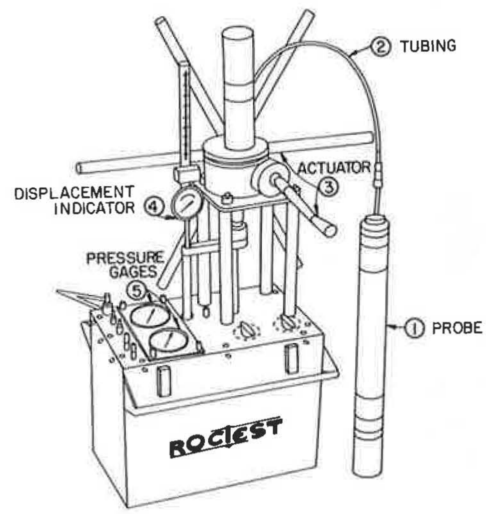

FIGURE 1 TEXAM PMT.

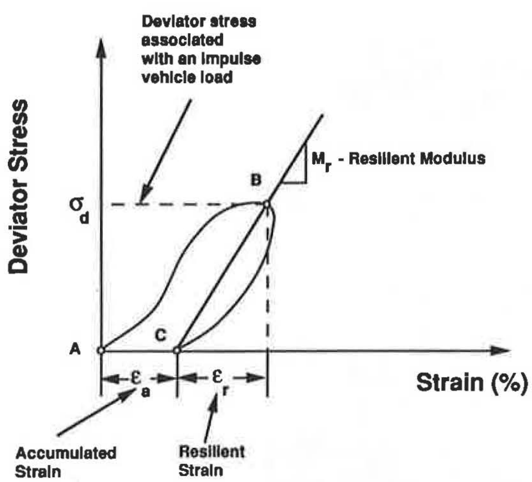

FIGURE 2 Representation of resilient modulus.

TESTING EQUIPMENT DESCRIPTION

The equipment used for this research is the TEXAM PMT (Figure 1) and the standard CBR equipment typically used in pavement design (Figure 3).

Pressuremeter

The PMT, originally developed in 1956 by Ménard (*4*) is an in situ testing device that has a rubber membrane that expands cylindrically in a test hole when pressurized with a fluid (Figure 1). Because PMT tests can be conducted in any type of soil or rock and can be used to run either stress-controlled or strain-controlled tests, they have become a useful geotechnical engineering tool. The TEXAM monocell PMT, manufactured by Roctest, Inc., Plattsburg, New York (Figure 1), consists of a control unit, a 50-ft (15 m) section of nylon tubing, and an expandable probe. The PMT shown costs about $10,500. Tests are conducted once the PMT is placed at the required depth in a 3-in. (7.62 cm) diameter borehole. During testing, the 18-in.-long (46 cm), 2.94-in. (7.5 cm) diameter cylindrical probe, covered with a flexible membrane, is inflated with water by moving a piston with the manual actuator. The inflation creates pressure against the wall of the borehole, which is the radial stress (σ_{rr}). Throughout the test, the pressure is recorded from a pressure gauge, and the increase in volume of the probe ΔV is recorded from the displacement indicator. A calibration that determines the initial volume (V_o) allows for the volumetric increase ($\Delta V/V_o$) to be obtained. This volumetric increase is converted to the hoop strain $\varepsilon_{\theta\theta}$ (*5*) and an in situ stress-strain curve is obtained. Figure 4 shows a typical in situ stress-strain curve from a pressuremeter test. Assuming the length to diameter ratio of the PMT is of sufficient length to simulate an expansion of an infinitely long cylindrical cavity, soil moduli can be determined from the theory of elasticity. Baguelin et al. (*4*) developed the following equation for determining elastic moduli between any two points on the stress-strain curve (Figure 4):

$$E = 2(1 + \nu)\left(\frac{\Delta p}{\Delta V}\right)V_m \tag{1}$$

where

E = soil modulus,
ν = Poisson's ratio,
Δp = change in pressure on the cavity wall ($\Delta\sigma_{rr}$)
ΔV = change in volume of the PMT, and
V_m = the volume midway through the pressure increment.

Equation 1 was revised as follows to enable calculation of elastic moduli based on the hoop strain (*5*).

$$E = (1 + \nu)\left[\left(1 + \frac{\Delta R_1}{R_o}\right)^2 + \left(1 + \frac{\Delta R_2}{R_o}\right)^2\right] \left[\frac{\sigma_{rr2} - \sigma_{rr1}}{\left(1 + \frac{\Delta R_2}{R_o}\right)^2 - \left(1 + \frac{\Delta R_1}{R_o}\right)^2}\right] \tag{2}$$

where

ΔR_1 = increase in probe radii at the beginning of the pressure increment,
ΔR_2 = increase in probe radii at the end of the pressure increment,
σ_{rr1} = radial stress at the cavity wall at the beginning of the pressure increment,
σ_{rr2} = radial stress at the cavity wall at the end of the pressure increment, and
R_o = initial radius of the probe.

This revised calculation makes it possible to compare results from various size PMTs, because the reduced data is plotted as radial stress versus hoop strain instead of radial stress versus volumetric increase ($\Delta V/V_o$). A single PMT test like the one shown in Figure 4 involves increasing the initial volume of the probe from V_o to $1.5V_o$ during 10 min in order to simulate undrained soil behavior. The initial volume of the TEXAM PMT is 108 in.^{3} (1770 cc), and a test is completed when 73 in.^{3} (1200 cc) of water is added in 3.7 in.^{3} (60 cc) increments,

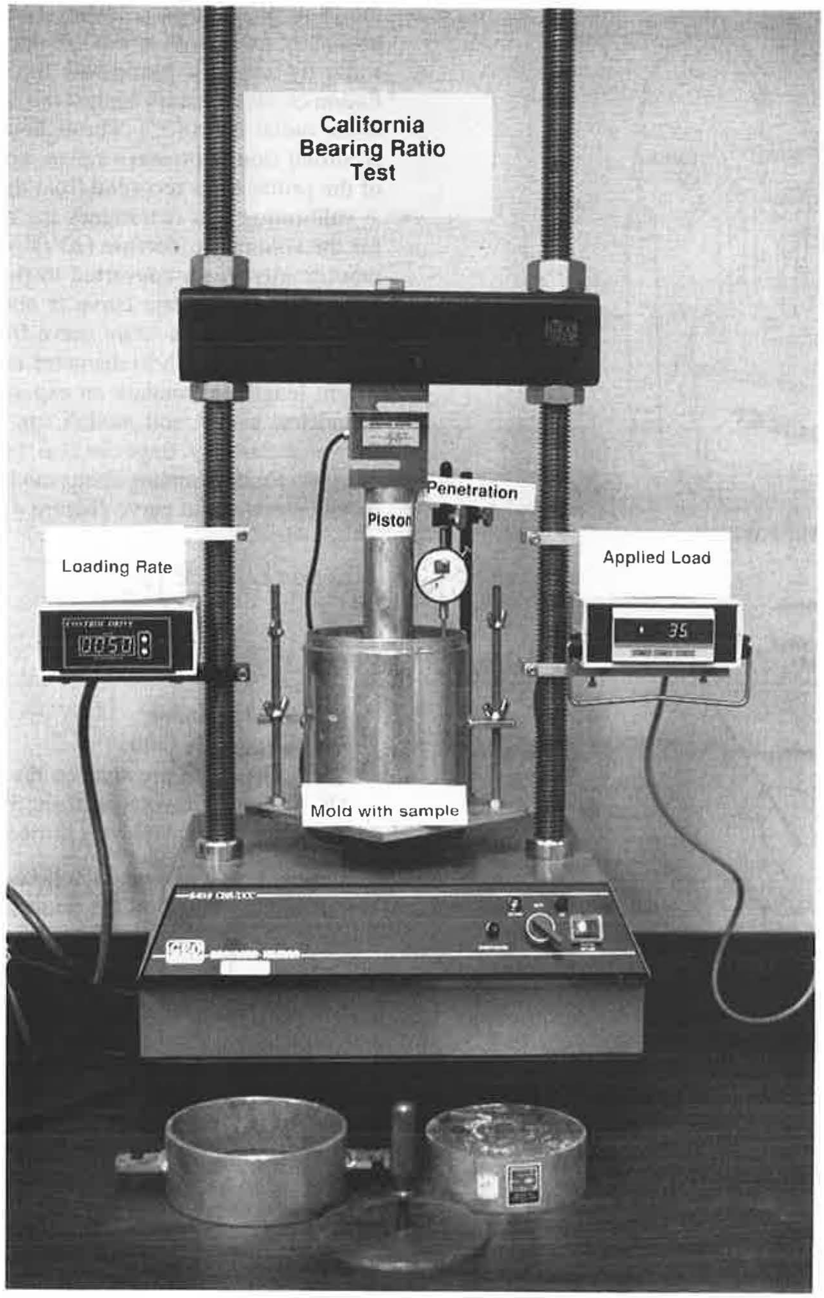

FIGURE 3 Standard CBR equipment.

which are each held constant for 30 sec. Each PMT test requires calibrations for membrane resistance, system expansion, and hydrostatic pressure. The membrane and system expansion calibrations are conducted with the PMT in the field, whereas the hydrostatic correction is simply applied to the recorded pressures. Details of the calibration techniques can be found elsewhere (*6*).

The California Bearing Ratio

The standard CBR equipment as required by ASTM D1883-73 (Figure 3) was used for this research (*7*). CBR tests were conducted in a triaxial load frame on unsoaked samples, which were compacted to in situ moisture-density conditions.

FIELD TESTING SITES

Five testing locations were used during the research. An initial PMT testing phase was conducted at three sites in Lubbock County Texas (Figure 5) such that a resilient modulus PMT test (Figure 6) could be developed for the PMT-CBR correlations. Site 1 was the Texas Tech University (TTU) National Science Foundation (NSF) Wind Research site. Site 2 was the grass-covered area near the east entrance of the TTU

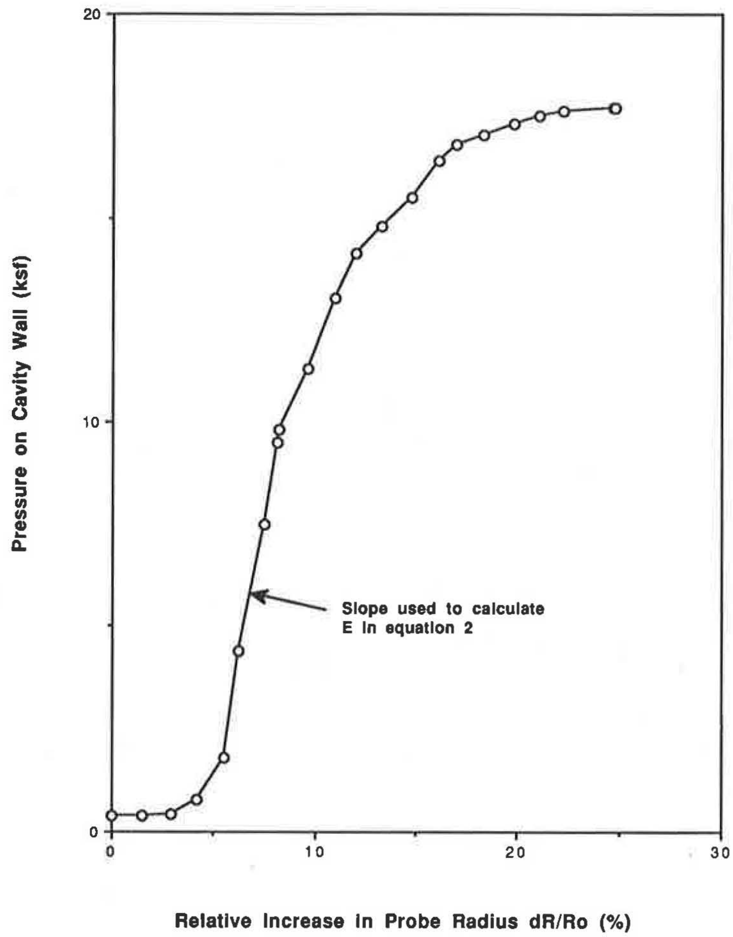

FIGURE 4 Stress-strain curve from a standard PMT test.

civil engineering building. Site 3 was located at Tech Tracer Park, on Boston and 29th streets in the city of Lubbock (Figure 5). Problems were encountered at sites 1, 2, and 3; therefore, once the resilient modulus PMT test was developed, 2 new test sites (4 and 5) (Figure 5) in Lubbock County were used to perform tests for the PMT-CBR correlations. Problems during the testing program are described in the Testing Program section. Site 4 during the final testing phase for the PMT-CBR correlations was the off-base recreational area near the tennis courts at Reese Air Force Base (AFB). Site 5 was the playa used by the TTU Water Resources Center in Shallowater, Texas (Figure 5).

SOIL CONDITIONS

In geologic terms the three sites used for development of the resilient modulus PMT test are part of the Acuff soils formed during the Pleistocene age. These soils are eolian materials that were deposited during dry periods of high winds. They originated in the southwestern regions of the United States and are commonly referred to as cover sands. They vary from clayey sands in the southern portions of Lubbock County to sandy clays in the northern portions of Lubbock County. Two different soil deposits were encountered during testing for the PMT-CBR correlations. The soil encountered at Reese AFB is an eolian clayey sand from the Acuff formation, whereas the soil in the playa at Shallowater is an organic Randall series clay. The Randall clays formed along with the Acuff soils during the Pleistocene age at the bottom of the playa lakes.

From an engineering standpoint, the soil at Site 1 was a medium dense reddish brown, cemented sandy clay (Table 1). These soils commonly exhibit angles of internal friction from 40 to 45 degrees when dry; however, if they become wet, a significant loss of shear strength occurs. The soils at sites 2 and 3 are a loose reddish brown, cemented sandy clay (Table 1), which exhibit the same loss of shear strength during wetting. The soils at Site 4 are a loose grayish brown cemented sandy clay. Their cementitious properties also affect shear strength upon wetting. The soil at Site 5 is a soft dark gray organic clay. The typical soil properties for the five sites are summarized in Table 1. In the Acuff soils, sites 1 through 4, the unit weight ranged from 105 to about 115 pcf (16.5 to about 18.0 kN/m^3), with water contents ranging from 6.4 to 14.2 percent. In the organic clay at Site 5, the unit weights ranged from 79.8 to 94 pcf (12.5 to 14.7 kN/m^3), with water contents ranging from 22.7 to 30.3 percent.

TESTING PROGRAM

The testing program consisted of 29 PMT tests, 32 CBR tests, 9 standard penetration tests (SPTs), 21 troxler nuclear

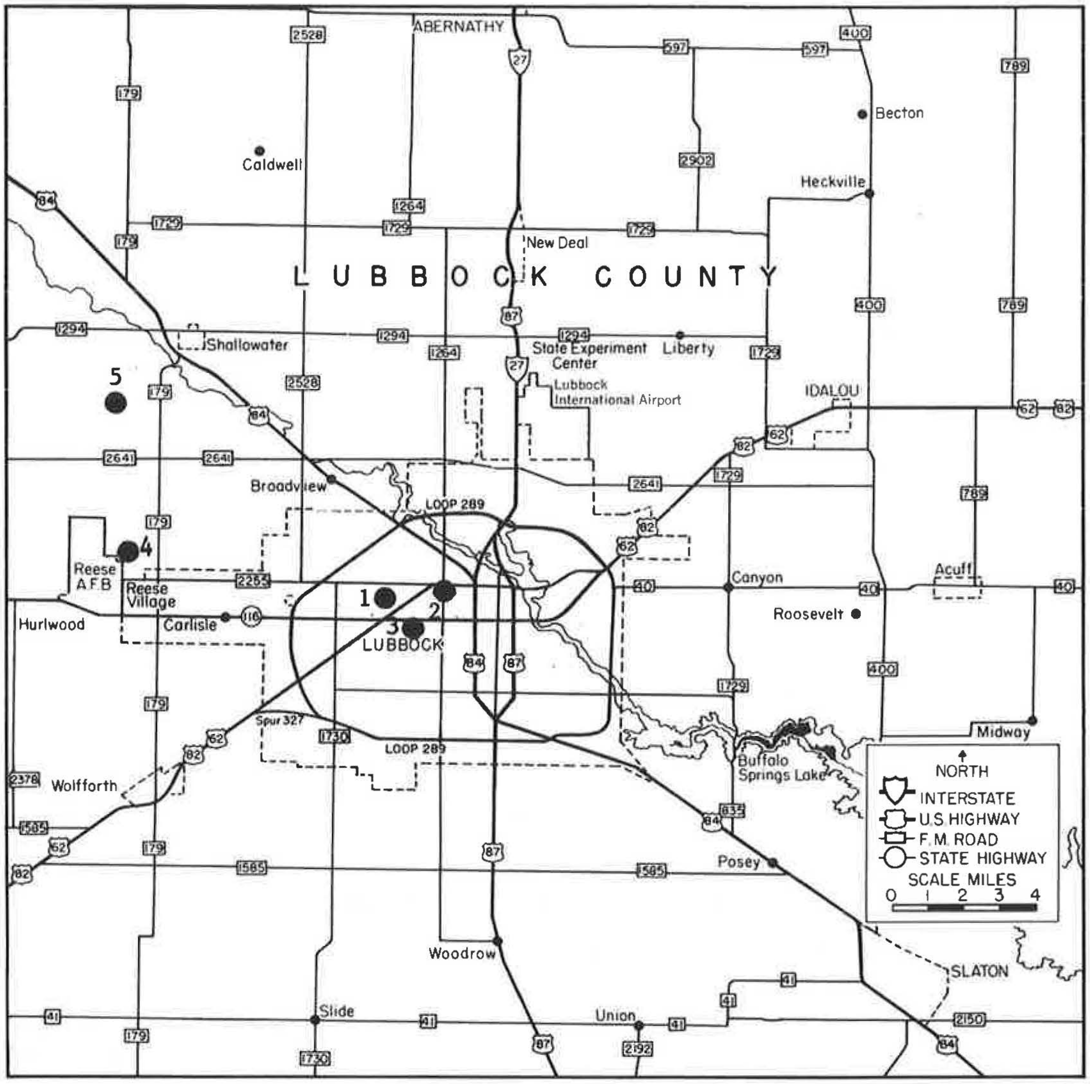

FIGURE 5 Test sites: 1, NSF Wind Research site; 2, TTU; 3, Tech Tracer Park; 4, Reese AFB; and 5, Shallowater.

moisture-density tests, 33 laboratory water content determinations, and 2 grain size analyses. During the initial phase at sites 1, 2, and 3, 11 PMT tests, 5 troxler tests, and 9 laboratory moisture content tests were conducted. During the PMT-CBR correlation phase at sites 4 and 5, 18 PMT tests, 32 CBR tests, 9 SPTs, 16 troxler tests, 24 laboratory moisture content tests, and 2 grain size analyses tests were conducted. PMT tests were typically conducted in hand-augered test holes about 4 ft deep.

Three different sites were considered during the initial testing phase to enable the various site specific testing problems encountered during this research to be alleviated. Only one PMT test was conducted at Site 1 because of difficulties encountered during hand-augering the borehole for PMT testing. The medium dense cemented sandy clay at site 1 required nearly 4 hr of hand-augering. At Site 2, 6 PMT tests were conducted. The soil types encountered during these tests were similar to those at Site 1. The main difference in the soils was that the top 18 in. (46 cm) at Site 2 was a recompacted sandy clay. This recompacted zone allowed hand-augering to be accomplished; however, due to the cemented nature of the sandy clay, the remaining portion of the hand-augering for the 4-ft (1.2 m) deep PMT hole was difficult. The total time required to hand-auger a single PMT hole at Site 2 was about 2 hr. Site 3, at Tech Tracer Park, was a cemented sandy clay that was also difficult to hand-auger. Only 1 PMT test was conducted at Site 3 because the hand-augering process again required 4 hr. The purpose of the initial testing phase was to establish the procedure for the resilient modulus PMT test. Because this was accomplished with the 8 PMT tests at sites 1, 2, and 3, Phase 1 of the PMT testing was halted.

The final testing phase for the PMT-CBR correlations took place at Reese AFB and at the playa test site in Shallowater, Texas (Figure 5). On the basis of SPT blow counts, the soil at Reese AFB was identified as a loose cemented clayey silty sand, and visual identification techniques indicated that the soil at Shallowater was a soft organic clay (Table 1).

During the testing at Reese AFB, PMT boreholes were advanced with a drill rig, which enabled fast augering of the four PMT boreholes and made it possible to conduct nine SPTs above and below the PMT tests. Six resilient modulus PMT tests were conducted at Reese; 15 samples were taken

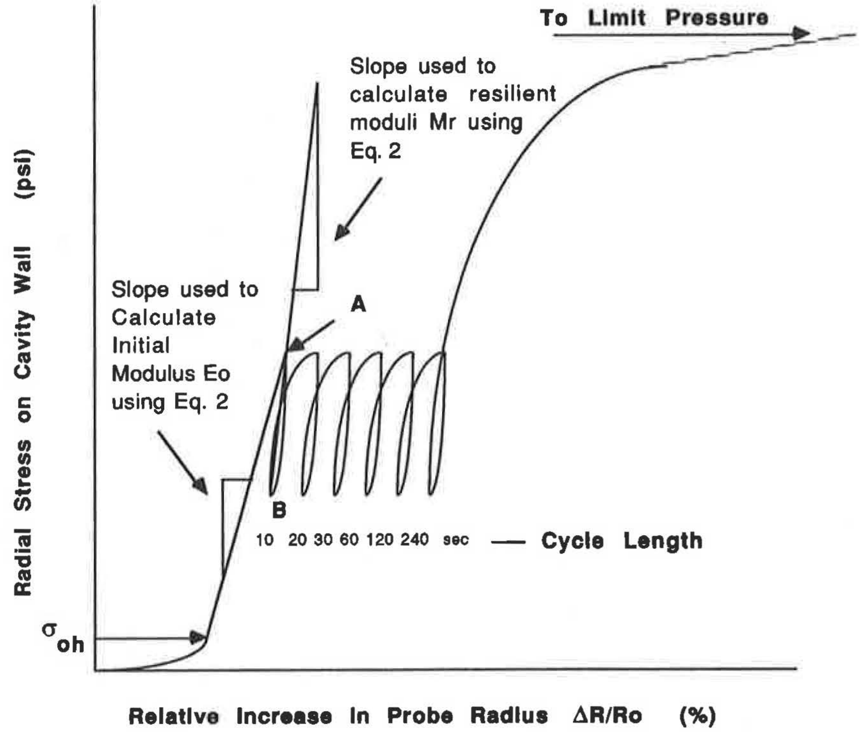

FIGURE 6 Stress-strain curve for a resilient modulus PMT test.

TABLE 1 SITE INFORMATION

Test Site	Soil Description	Average Density (pcf)	Range of Densities (pcf)	Average Water Content (%)	Range of Water Contents (%)
NSF[1]	Med. Dense Reddish brown sandy clay, trace of caliche	115[6]	115[6]	7.6	7.5 - 7.8
TTU CAE[2]	Loose Reddish brown sandy clay, some caliche, trace of gravel	108.6	108.5 - 108.7	8.1	6.4 - 10.3
TTPark[3]	Loose grayish brown silty clay, trace of sand	106.4	104.9 - 110.3	13.7	8.6 - 14.2
Reese AFB[4]	Loose Reddish brown sandy clay, trace of gravel and caliche (SC-CL)	110.8	107.4 - 113.1	11.6	9.1 - 12.9
Shallowater[5]	Very soft dark gray clay (OH)	89.7	79.8 - 94.0	28.6	22.7 - 30.3

1. National Science Foundation Wind Research Site, Texas Tech University, Lubbock, Texas
2. Civil/Agricultural Engineering Building, Texas Tech University
3. Tech Tracer Park, Lubbock, Texas
4. Reese Air Force Base, Lubbock, Texas
5. Texas Tech University Water Resources Center Site, Shallowater, Texas
6. Assumed unit weight for site 1

Note: 1 pcf = 0.1572 kN/m^3

for CBR testing; 8 troxler moisture-density tests were performed; and 10 samples were taken for water content determinations.

The testing conducted at Shallowater included 14 resilient modulus PMT tests, 20 CBR tests, and 8 troxler moisture-density tests. Hand-augering at this site was simple because the clay soil was soft. Typically 15 min or less was required to auger a 4 ft (1.2 m) deep borehole.

Development of the Resilient Modulus Pressuremeter Test

In order to correlate PMT moduli to CBR values in a manner similar to those published (*8*), it was determined that several resilient moduli should be found with a single PMT test such that the cycle lengths simulated during testing corresponded to various ranges of pavement vehicle loading rates. On the basis of work with the pavement pressuremeter, the principal author (*3*) determined that resilient moduli could be determined from four types of pavement pressuremeter loading sequences. The sequences are variation of stress level, strain level, loading rate, and number of cycles. This knowledge was used to develop a PMT test that would show how the PMT predicts resilient moduli, which vary with cycle length. The PMT test developed (Figure 6) included 6 unload-reload cycles conducted at a predetermined stress level during the linear portion of the soil's stress-strain response, with cycle lengths of 10, 20, 30, 60, 120, and 240 sec. These cycle lengths were chosen because it was assumed that they could be easily conducted with the TEXAM PMT (Figure 1). The inclusion of the cycles resulted in a 17.5-min PMT test. Details of the entire PMT test procedure can be found in work by Chen (*6*).

Development of the CBR Test

The purpose of the CBR test was to accurately simulate field CBR conditions in the laboratory. Field CBR tests could not be conducted because of funding constraints. In order to simulate field conditions, in situ moisture and density values were determined for each site using a Troxler 3401B moisture-density gauge. The moisture content of the soil augered during PMT testing was then determined and laboratory CBR samples were compacted at the PMT moisture content with a 5-lb (22.2 N) hammer using 25 blows per layer in 3 layers. This procedure enabled in situ densities to be accurately established in the CBR mold (Figure 3). The laboratory CBR tests were conducted in accorance with ASTM D1883-73 (*7*) on samples obtained from Reese AFB and Shallowater.

DATA ANALYSIS

The data analysis made it possible to compare moduli and limit pressures from PMT tests with CBR values found from laboratory CBR tests.

Analyzing PMT Data

From one resilient modulus PMT test, six resilient moduli values were determined using Equation 2, and a soil limit pressure was determined by extrapolating the resulting stress-strain curve (Figure 6) to a hoop strain $\Delta R/R_o$ of about 41 percent. It was concluded that the PMT moduli determined during the 10-sec cycle were not reliable because of the difficulty encountered while controlling the cycle pressures and volumes during the 5-sec loading and 5-sec unloading sequence. The 5 remaining resilient moduli values from each test were normalized using the resilient modulus associated with the 20-sec cycle length and plotted versus cycle length on a log-log plot (Figure 6). This procedure allowed Riggins' power law model (*9*), which was originally developed for time dependent behavior of soils subjected to creep loadings, to be modified to account for cyclic loading. Riggins' original model (*9*) related increase in undrained shear strength S_u to the time of failure as

$$\frac{S_{u1}}{S_{u2}} = \left(\frac{t_2}{t_1}\right)^{n_c} \quad (3)$$

where S_{u1} and S_{u2} are the undrained shear strengths measured at times to failure t_1 and t_2, respectively, and n_c is the viscous exponent, which can be determined from the slope of a log-log plot of S_{u1}/S_{u2} versus t_2/t_1. Based on 76 n_c values obtained from 152 laboraotry tests on undrained clays Briaud and Garland (*10*) determined that n_c has typical values from 0.02 to 0.10 and an average value of 0.061. Riggins' model (*9*) was used by Cosentino to account for the variation in secant moduli with time from pavement pressuremeter tests (*3*). Using secant moduli the viscous model can be written as follows:

$$\frac{E_{t2}}{E_{t1}} = \left(\frac{t_2}{t_1}\right)^{n_c} \quad (4)$$

where E_{t1} and E_{t2} are the secant moduli determined from PMT tests at times t_1 to t_2, respectively, and n_c is the viscous exponent, which is negative for a negative slope on the log-log plot of E_{t2}/E_{t1} versus time. In order to model the change in resilient moduli with cycle length, the secant moduli values in Equation 4 were replaced with resilient moduli values to yield the following:

$$\frac{M_{rt2}}{M_{rt1}} = \left(\frac{t_2}{t_1}\right)^{n_r} \quad (5)$$

where M_{rt1} and M_{rt2} are the resilient moduli determined from PMT tests over cycle lengths t_1 and t_2, respectively, and n_r is the associated exponent relating cycle length to resilient modulus (Figure 7).

Analyzing CBR Data

The procedure in ASTM D1883-73 (*7*) requires the determination of empirical CBR values at piston penetrations of 0.1 (0.25 cm) and 0.2 in. (0.51 cm); and if the CBR value determined at 0.2 in. (0.51 cm) is larger than the value at 0.1 in. (0.25 cm), the test must be rerun. The CBR value is determined by comparing the load developed by the soil tested to the load developed by a standard crushed stone using a 3 in.^{2} (19.4 cm^2) piston penetrating the sample at a loading rate of 0.05 in./min. The standard crushed stone develops 3,000 lb (13350 N) of resistance at 0.1 in. (0.25 cm) of penetration and 4,500 lb (20020 N) of resistance at 0.2 in. (0.51 cm) of penetration. Therefore, for example, if the soil tested was able to develop a load of 300 (1335 N) lb at 0.1 in. of penetration and less than 450 lb (2000 N) at 0.2 in. (0.51 cm) of penetration, the CBR value would be 10. ASTM requires corrections to the CBR values based on the shape of the load versus deflection curve.

DISCUSSION OF TEST RESULTS

From the use of the resilient moduli and the limit pressures from the 29 PMT tests and the CBR values from the 32 CBR tests at sites 4 and 5 (Table 1), the following results were

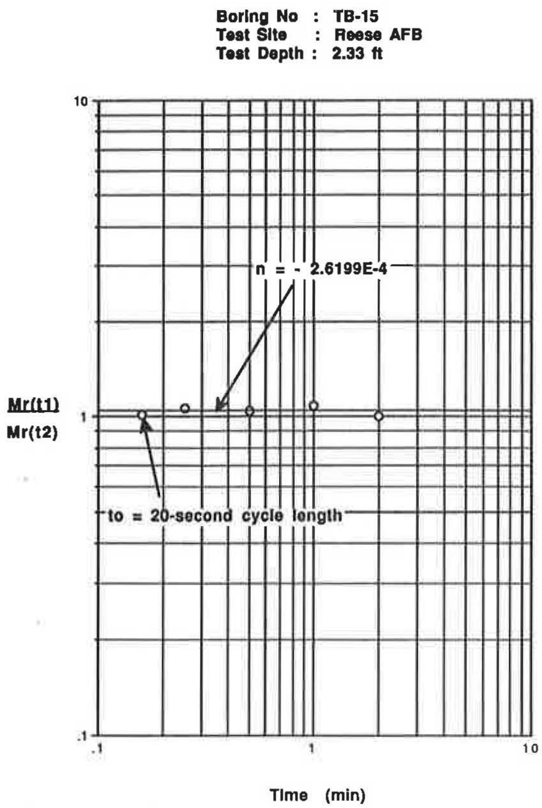

FIGURE 7 Typical normalized resilient modulus versus cycle length plot.

obtained. Values of the resilient moduli for all 29 PMT tests at the 5 sites are presented in Table 2. As can be seen from the table, the resilient modulus generally decreases with increasing cycle length. Additionally, the cemented Acuff soils tests at sites 1, 2, 3, and 4 would be considered good quality subgrade materials, whereas the Randall clay tested at Site 5 would be considered a poor quality subgrade material.

Effects of Loading Rate Variation

The variation of loading rate was studied using Equation 5. The slope of the log-log plot of resilient modulus versus time, n_r, was determined for each set of resilient modulus PMT test results. During this portion of the study, PMT tests from all five sites were used because the PMT testing procedure used for the resilient modulus PMT test was constant throughout the study. Careful examination of the log-log plots representing Equation 5 (Figure 7) indicated that more consistent values for n_r could be obtained if resilient moduli from the 20-sec cycle were excluded. Table 3 presents a summary of the power law exponents considering both the 30-, 60-, 120-, 240-sec and 20-, 30-, 60-, 120-, 240-sec approaches. The values of n_r for the 29 PMT tests ranged from -0.328 to 0.165 if four cycles were used and from -0.126 to 127 if five cycles were used. Because the soils tested ranged from a soft clay to medium dense cemented sands, finding both positive and negative values for n_r could result from a combination of reasons. Negative n_r values indicate that the resilient modulus is decreasing with increasing cycle length. This would be the result expected if sufficient rest time was allowed between successive cycles; however, because cycles were conducted without any rest period, a residual effect should have occurred after each cycle was conducted. The residual effect most likely would result in locked in residual strains, which may or may not affect the remaining cyclic responses. Positive n_r values indicate that the resilient modulus is increasing with increasing cycle length. Although this increase seems unusual, it is indeed possible for the loose to medium dense cemented soils found at sites 1 through 4, because they may simply be experiencing a compaction or strain-hardening process during each cycle due to the absence of the appropriate rest period. There is also a logical reason for the positive n_r values found in the soft clay at Shallowater. In soft clays the TEXAM PMT does not have the precision required to accurately determine elastic moduli values. The TEXAM PMT is only capable of determining moduli values with an accuracy of ± 100 psi (690 kPa). This accuracy range results from the errors accumulat-

TABLE 2 SUMMARY OF RESILIENT MODULUS PMT TEST DATA

Test Site	Resilient Modulus (psi) Range (Average)				
	10 sec	15 sec	30 sec	60 sec	120 sec
NSF	7380 (7380)	7824 (7824)	6819 (6819)	7622 (7622)	6838 (6838)
TTCamp	9237 - 27054 (16915)	9874 - 22660 (15851)	9238 - 19026 (15543)	8931 - 22674 (16856)	9253 - 21655 (16198)
TTPark	8985 (8985)	9874 (9874)	9416 (9416)	9888 (9888)	10073 (10073)
Reese	11926 - 22007 (17086)	12853 - 22755 (18274)	5953 - 22774 (16085)	13121 - 22795 (18696)	11341 - 28330 (19722)
SHWTR	658 - 2290 (1456)	735 - 3052 (1600)	656 -3439 (1472)	663 - 2503 (1598)	633 - 2057 (1479)

1. National Science Foundation Wind Research Site, Lubbock, Texas
2. Civil/Agricultural Engineering Building, Texas Tech University
3. Tech Tracer Park, Lubbock, Texas
4. Reese Air Force Base, Lubbock, Texas
5. Texas Tech University Water Resources Center Site, Shallowater, Texas

Note: 1 psi = 6.985 kPa

TABLE 3 SUMMARY OF POWER LAW EXPONENTS

PMT Test No.	Test Site	n_R 4 pts[1]	n_R 5 pts[2]
TB-01	NSF	-0.042	-0.039
TB-02	TTCamp	0.006	-0.111
TB-03	TTCamp	0.085	-0.081
TB-05	TTCamp	0.030	0.128
TB-08	TTPark	0.016	0.201
TB-09	TTCamp	0.057	0.137
TB-10	TTCamp	-0.077	0.050
TB-11	TTCamp	-0.024	0.137
TB-15 (2.42 ft.)	Reese	-0.049	0.075
TB-15 (7.25 ft.)	Reese	-0.039	0.012
TB-16	Reese	0.063	0.146
TB-17	Reese	0.095	0.125
TB-12	Shallowater	-0.044	0.016
TB-13	Shallowater	-0.071	0.037
TB-22	Shallowater	-0.009	0.071
TB-23	Shallowater	-0.063	-0.031
TB-24	Shallowater	0.025	0.082
TB-25	Shallowater	0.009	0.144
TB-26	Shallowater	0.165	0.153
TB-27	Shallowater	-0.024	0.073
TB-28	Shallowater	-0.328	0.168
TB-29	Shallowater	0.069	0.259

1. Determined using the 30-, 60-, 120-, and 240-second cycles
2. Determined using the 20-, 30-, 60-, 120-, and 240-second cycles

Note: 1 ft = .3048 m.

TABLE 4 RESILIENT MODULUS-CBR CORRELATION (M_r = B × CBR)

Test Site	Modulus used	B_{ave}	B_{min} - B_{max}
Reese AFB[1]	E^2_o	172	123 - 288
	$Mr^3_{0.1}$	1516	1386 - 1748
	Mr^4_{30}	1324	1013 - 1941
	Mr^5_{60}	1633	1504 - 2006
	Mr^6_{120}	1954	1300 - 2149
Shallowater[7]	E_o	24	12 - 41
	$Mr_{0.1}$	186	75 - 382
	Mr_{30}	144	71 - 438
	Mr_{60}	159	69 - 288
	Mr_{120}	149	69 - 246

1. Reese Air Force Base, Lubbock, Texas
2. Elastic Modulus associated with linear portion of PMT curve (Fig. 6)
3. M_r of 0.1-second cycle length
4. M_r of 30-second cycle length
5. M_r of 60-second cycle length
6. M_r of 120-second cycle length
7. Texas Tech University Water Resources Center Site, Shallowater, Texas

ing due to the precision limitations of the pressure gauge, the volume recording gage, and the membrane, volume and hydrostatic corrections required for each PMT test (*6*). The combination of residual effects and the lack of precision from the data make it difficult to give precise reasons for the variation of resilient modulus with various cycle lengths. The current TEXAM PMT is not equipped to aid in solving this problem.

Inspection of the Shallowater n_r values shown in Table 3 indicates the sensitivity of the exponent: three positive n_r values become negative when only four cycles were used. Based on the n_r values shown in Table 3, it would be possible to predict resilient moduli associated with a large range of loading rates. Typical loading rates on the order of 0.1 sec are encountered on pavements. The falling weight deflectometer (FWD) applies impulse loads during a 0.2-sec period, although AASHTO recommends that a 0.1-sec loading rate be achieved during cyclic triaxial testing (*8*).

Correlations Between Pressuremeter Resilient Moduli and CBR Values

Correlations between resilient moduli and CBR values were established by calculating PMT resilient modulus values for the 30-, 60-, and 120-sec cycles from the Reese and Shallowater sites and comparing them directly with CBR values (Table 4). To ensure that the correlations were valid, PMT resilient moduli and CBR values were compared for soils at the same density and moisture content (Table 4). Also shown in Table 4 is a correlation between M_r and CBR values for resilient moduli found for 0.1-sec cycle lengths using Equations 5. All of the *B* values found for Reese AFB (Table 4) compare well with the published correlations between resilient moduli and CBR values (*1,8,11,12*). Published ranges of *B* for pavement materials vary depending on the pavement layer analyzed. The values of *B* for subgrade soils range from 700 to 3,000; for granular base courses, *B* ranges from 300 to 9,000; and for granular subbase courses, *B* ranges from 200 to 1,100. The values for *B* for the soft clay at Shallowater are on the low end of the published values (Table 4). These low values may be attributed to the precision errors associated with using the TEXAM PMT in soft soils. The percent error possible for resilient moduli varying from 633 to 3469 psi (4360 to 23290 kPa), as is the case for the Shallowater data, ranges from approximately 3 to 16 percent. If an average error of 8 percent is assumed applicable and applied to the *B* values determined from resilient moduli (Table 4), then the average *B* values fall within the 200 to 1,100 range published for granular subbases, but not within the 300 to 9,000 range for subgrade soils. The only explanation possible for this discrepancy is that the soft clays may not have been included in the data base used for the subgrade correlations because they are not suitable roadbed soil; therefore, the Shallowater correlations may indeed be reasonable for soft clays.

CONCLUSIONS AND RECOMMENDATIONS

The major goal of this research—to increase the usefulness of the PMT—was achieved. The correlations developed between the PMT and the CBR tests are a clear indication of the use the PMT does have in the pavements field. The obvious next step is to develop a standard PMT test procedure that can reliably be used to determine resilient moduli. The main problem facing researchers who understand the PMT is which resilient modulus is correct for design purposes. The researchers in the pavement industry need to clearly define the proper loading rates for resilient moduli on various roadways.

Conclusions from this study are as follows:

- A resilient modulus PMT test was developed that allows resilient moduli as a function of unload-reload cycle length to be found. This PMT test requires about 17 min to conduct once the PMT hole is augered (Figure 6).
- Correlations between the resilient moduli values from PMT tests and CBR values are similar to the published values (Table 4).
- Because this research was not sponsored, the amount of data formulated was limited. This problem should be studied further, using field CBR tests and pavement PMT tests. The pavement PMT is capable of testing layers 10 in. (25.4 cm) in thickness or less and would be more versatile than the TEXAM PMT. Field CBR tests would be more accurate for direct correlations of CBR values to PMT resilient moduli.
- The effects on the stress-strain response, of conducting 6 cycles without soil healing allowed between cycles is not understood. A study of these effects would be helpful in determining the proper resilient modulus for use in pavement design.

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