Pavement Analysis and Design

TE-503 A/TE-503

Lecture-8
04-11-2019

Dr. Zia-ur-Rehman
DTEM

Material Characterization

Resilient Modulus

The resilient modulus is the elastic modulus to be used with the elastic theory.

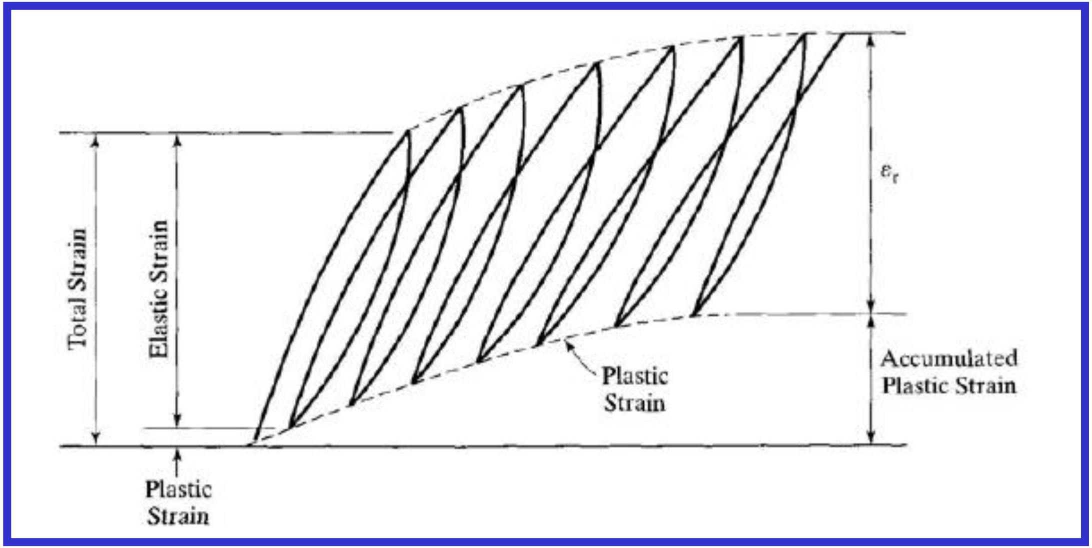
It is well known that most paving materials are not elastic, but experience some permanent deformation after each load application.

However, if the load is small compared to the strength of the material and is repeated for a large number of times, the deformation under each load repetition is nearly completely recoverable (and proportional to the load) and can be considered elastic.

Material Characterization

Resilient Modulus

Figure shows the straining of a specimen under a repeated load test. At the initial stage of load applications, there is considerable permanent deformation, as indicated by the plastic strain in the figure. As the number of repetitions increases, the plastic strain due to each load repetition decreases.



Material Characterization

Resilient Modulus

After 100 to 200 repetitions, the strain is practically all recoverable, as indicated by ε_r in the figure. The elastic modulus based on the recoverable strain under repeated loads is called the resilient modulus M_R, defined as:

$$M_R = \frac{\sigma_d}{\epsilon_r}$$

in which σ_d is the deviator stress, which is the axial stress in an unconfined compression test or the axial stress in excess of the confining pressure in a triaxial compression test.

Because the applied load is usually small, the resilient modulus test is a nondestructive test, and the same sample can be used for many tests under different loading and environmental conditions.

Loading Waveform

The type and duration of loading used in the repeated load test should simulate that actually occurring in the field.

When a wheel load is at a considerable distance from a given point in the pavement, the stress at that point is zero.

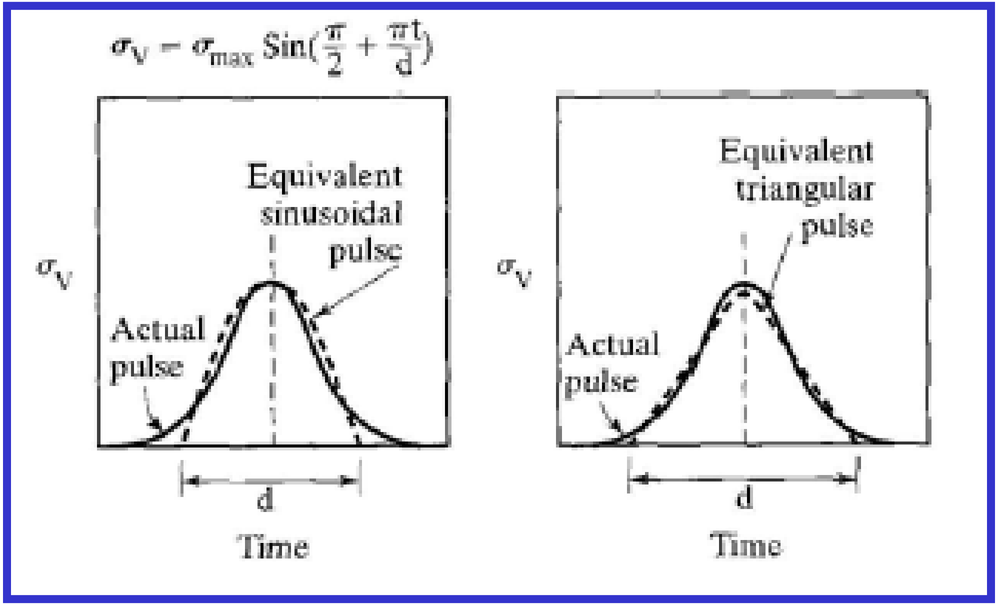
When the load is directly above the given point, the stress at the point is maximum.

It is therefore reasonable to assume the stress pulse to be a haversine or triangular loading, the duration of which depends on the vehicle speed and the depth of the point below the pavement surface.

Material Characterization

Loading Waveform

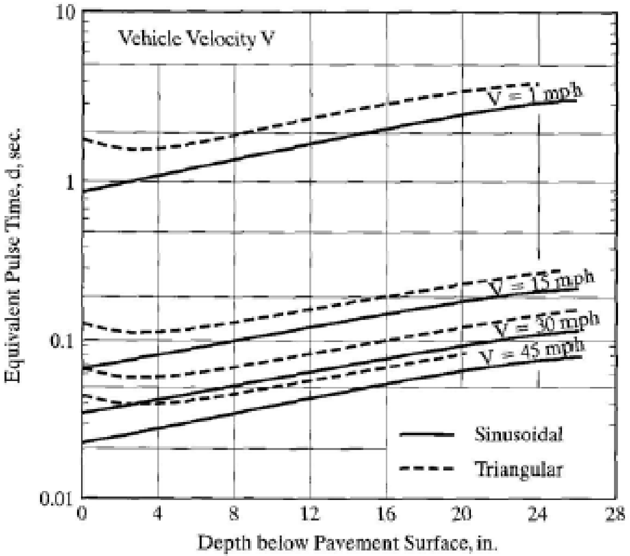
Barksdale (1971) investigated the vertical stress pulses at different points in flexible pavements. The stress pulse can be approximated by a haversine or a triangular function, as shown in Figure.



Material Characterization

Loading Waveform

After considering the inertial and viscous effects based on the vertical stress pulses measured in the AASHO Road Test, the stress pulse time can be related to the vehicle speed and depth, as shown in Figure.



Loading Waveform

Because of these effects, the loading time is not inversely proportional to the vehicle speed.

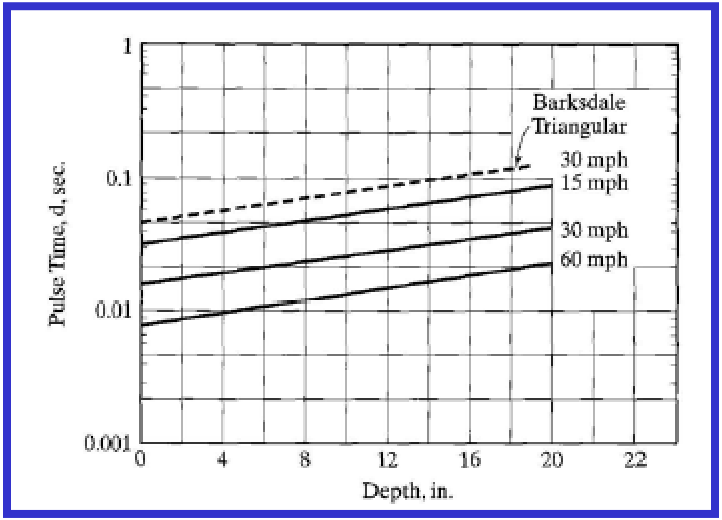
Brown (1973) derived the loading time for a bituminous layer as a function of vehicle speed and layer thickness.

The loading time is based on the average pulse time for stresses in the vertical and horizontal directions at various depths in the bituminous layer.

For thicker layers, his loading times are slightly smaller than those obtained by Barksdale.

Material Characterization

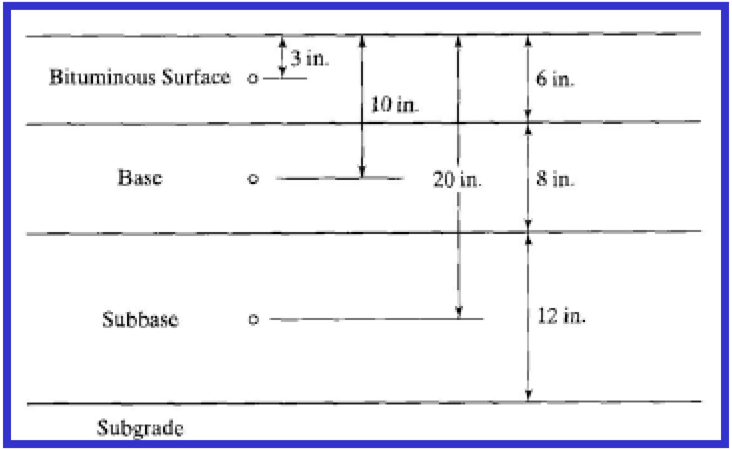
Loading Waveform



McLean (1974) determined the loading time for an equivalent square wave vertical pulse, as shown in Figure, on which the Barksdale's results for 30 mph triangular loading are superimposed for comparison.

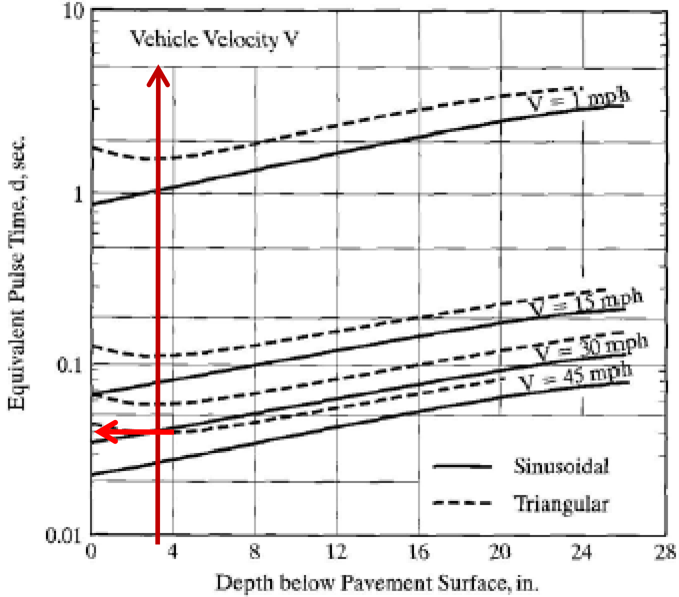
Loading Waveform-Numerical Problem

Repeated load compression tests are employed to determine the resilient moduli of the surface, base and subbase materials in a flexible pavement, as shown. The points at the midheight of each layer are used to determine the stress pulse times. If the vehicle speed is 40 mph, what should be the load durations of haversine and square wave loadings for each material?



Material Characterization

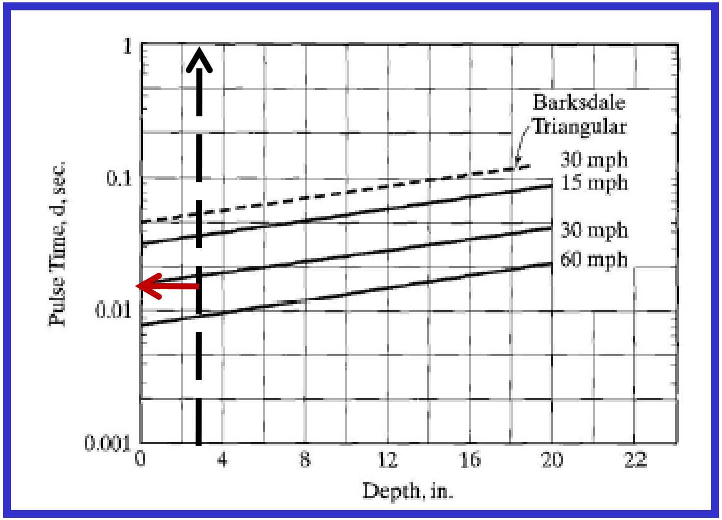
Loading Waveform-Numerical Problem



With a depth of 3 in. below the surface and a vehicle speed of 40 mph, the vertical stress pulse time is 0.028 s for a haversine load.

Material Characterization

Loading Waveform-Numerical Problem



With a depth of 3 in. below the surface and a vehicle speed of 40 mph, the vertical stress pulse time is 0.014 s for a square wave.

Loading Waveform-Numerical Problem

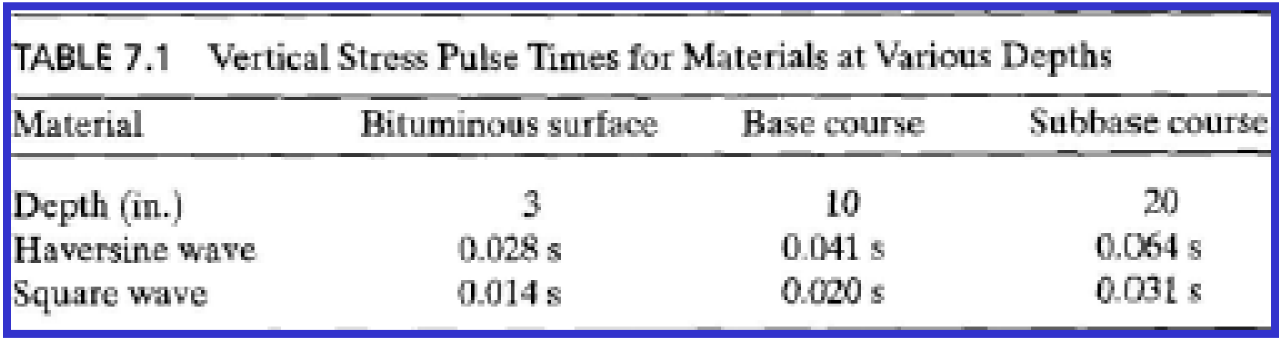


TABLE 7.1 Vertical Stress Pulse Times for Materials at Various Depths

Material	Bituminous surface	Base course	Subbase course
Depth (in.)	3	10	20
Haversine wave	0.028 s	0.041 s	0.064 s
Square wave	0.014 s	0.020 s	0.031 s

The results for all three materials are shown in Table 7.1

Material Characterization

Equipment

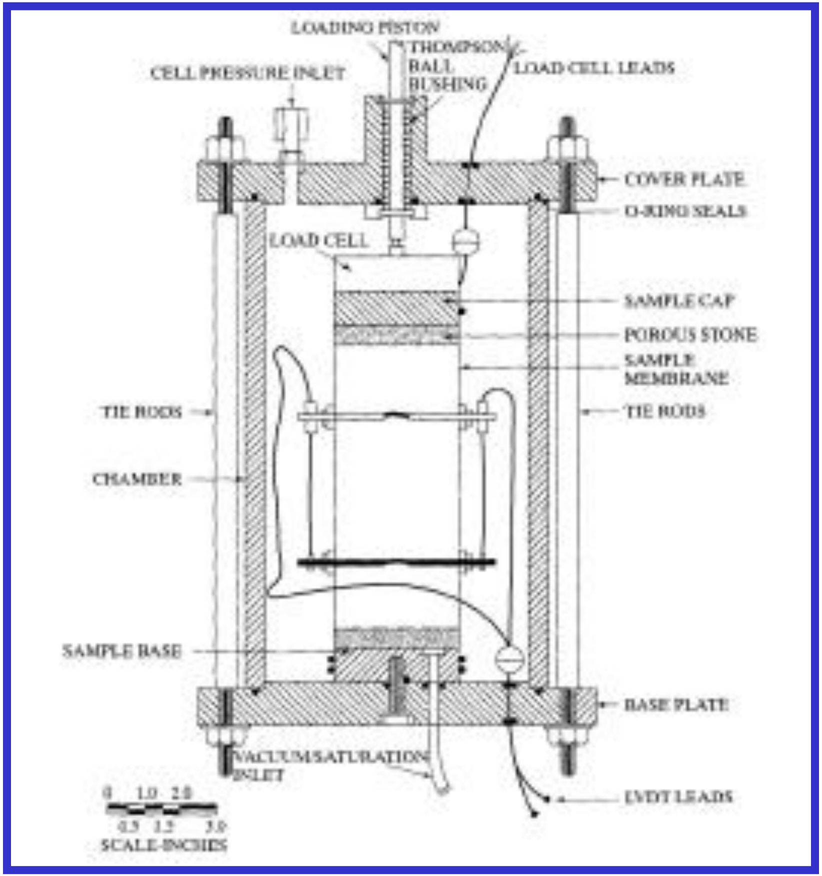
The resilient modulus of granular materials and fine-grained soils can be determined by the repeated load triaxial test. Figure shows the test setup recommended by FHWA (1978).

The sample is 4 in. (102 mm) in diameter and 8 in. (203 mm) in height.

The triaxial cell is similar to most standard cells, except that it is larger to accommodate the internally mounted load and deformation measuring equipment and has additional outlets for the electrical leads from the measuring devices. With the internally mounted measuring devices, air, instead of water, should be used as the confining fluid.

Material Characterization

Equipment



Material Characterization

Equipment

Other cells with suitable externally mounted load and deformation measuring equipment also may be used.

However, the use of internal measuring equipment has the advantage that the effects of equipment deformation, end restraint, and piston friction can be eliminated.

The repetitive loading device can be an air-actuated piston assembly with electronic solenoid control or a sophisticated electrohydraulic testing machine with precise control on the shape of load pulse.

The deformation measuring equipment consists of two linear variable differential transformers (LVDT) attached to the specimen by a pair of clamps at the upper and lower quarter points.

Material Characterization

Equipment

The setup shown in Figure can be used to determine the resilient modulus of asphalt mixtures.

Unless the temperature or the level of stress is high, the confining pressure has very little effect on the resilient modulus, so the repeated load unconfined compression test without confining pressure, rubber membrane, and porous stones can be used.

A temperature control system should be used to maintain a constant temperature in the specimen during the test.

Material Characterization

Equipment

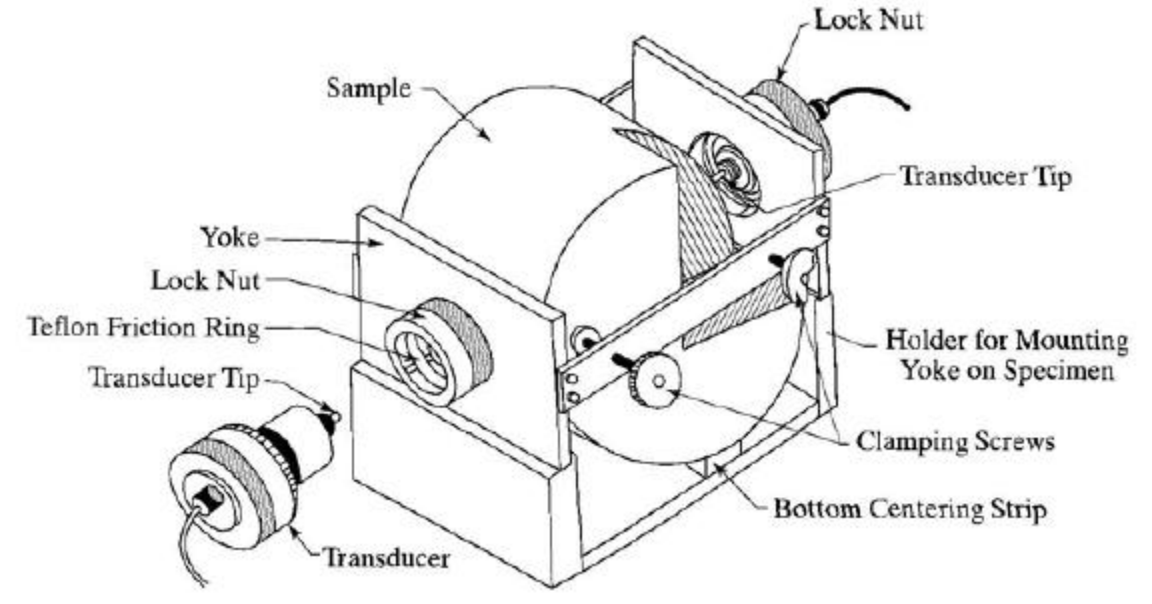
The resilient modulus of asphalt mixtures can also be determined by the repeated load indirect tension test.

A compressive load with a haversine or other suitable waveform is applied in the vertical diametric plane of a cylindrical specimen through a loading strip, and the resulting horizontal recoverable deformation is measured.

The repetitive loading device is the same as that used in the compression test. The transducer arrangement to measure the resilient modulus is shown in Figure.

Material Characterization

Equipment



Material Characterization

Equipment

The resilient modulus is computed from M_R

$$M_R = \frac{P(\nu + 0.2734)}{\delta t}$$

in which P is the magnitude of the dynamic load in pounds, v is Poisson ratio, δ is the total recoverable deformation in inches and t is the specimen thickness in inches. The Poisson ratio is generally taken to be 0.35.

Equipment-Resilient modulus for Granular Materials

The resilient modulus test for granular materials and fine-grained soils is specified by AASHTO (1989) in "T274-82 Resilient Modulus of Subgrade Soils." Sample conditioning can be accomplished by applying various combinations of confining pressures and deviator stresses, as follows:

1. **Set the confining pressure to 5 psi, and apply a deviator stress of 5 psi and then 10 psi, each for 200 repetitions.**
2. **Set the confining pressure to 10 psi, and apply a deviator stress of 10 psi and then 15 psi, each for 200 repetitions.**
3. **Set the confining pressure to 15 psi, and apply a deviator stress of 15 psi and then 20 psi, each for 200 repetitions.**

Equipment-Resilient modulus for Granular Materials

After sample conditioning, the following constant confining pressure–increasing deviator stress sequence is applied, and the results are recorded at the 200th repetition of each deviator stress :

1. Set the confining pressure to 20 psi, and apply deviator stresses of 1, 2, 5, 10, 15, and 20 psi

2. Reduce the confining pressure to 15 psi, and apply deviator stresses of 1, 2, 5, 10, 15, and 20 psi

3. Reduce the confining pressure to 10 psi, and apply deviator stresses of 1, 2, 5, 10, and 15 psi

4. Reduce the confining pressure to 5 psi, and apply deviator stresses of 1, 2, 5, 10, and 15 psi

5. Reduce the confining pressure to 1 psi, and apply deviator stresses of 1, 2, 5, 7.5, and 10 psi

Stop the test after 200 repetitions of the last deviator stress level or when the specimen fails.

Material Characterization

Equipment-Resilient modulus for Granular Materials-Numerical Problem

Table 7.2 shows the results of resilient modulus tests on a granular material. The distance between the LVDT clamps is 4 in. The average recoverable deformations measured by the two LVDTs after 200 repetitions of each deviator stress are shown in Table 7.2. Determine the nonlinear coefficient K_1 and exponent K_2 in Eq. 3.8

$$E = K_1 \theta^{K_2}$$

Material Characterization

Equipment-Resilient modulus for Granular Materials-Numerical Problem

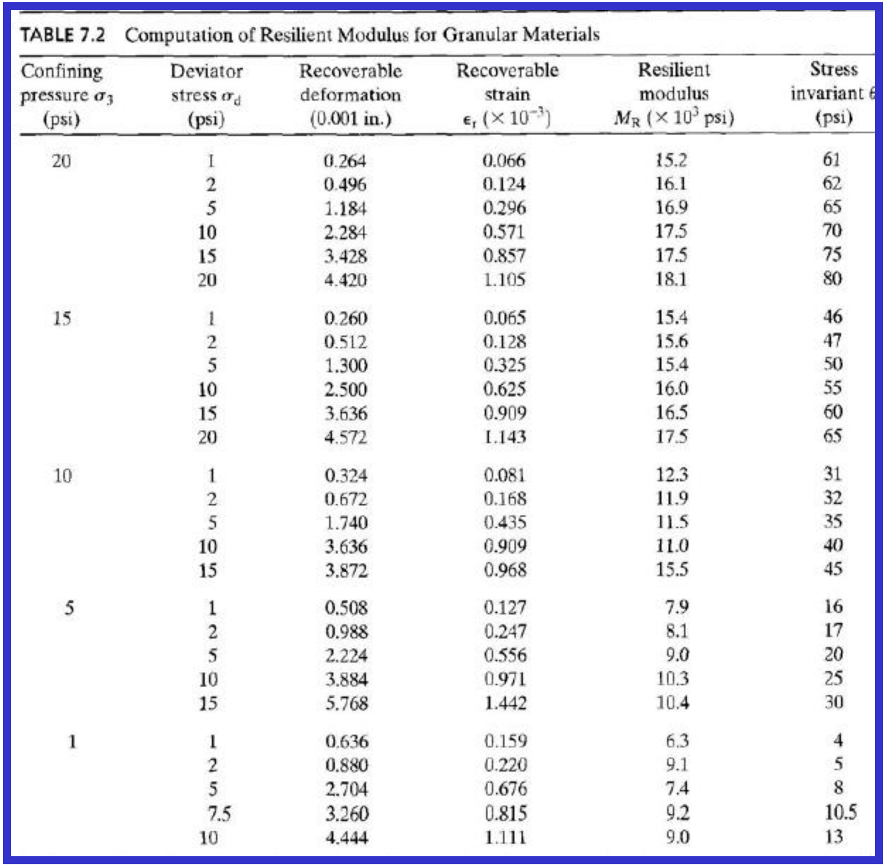


TABLE 7.2 Computation of Resilient Modulus for Granular Materials

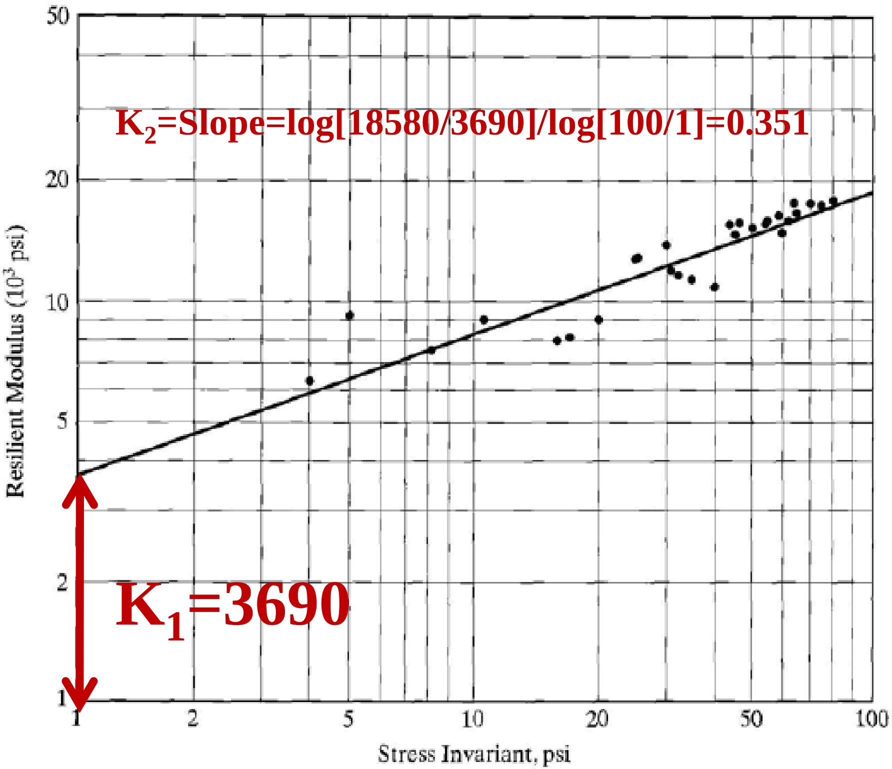
Confining pressure σ_3 (psi)	Deviator stress σ_d (psi)	Recoverable deformation (0.001 in.)	Recoverable strain ϵ_r ($\times 10^{-3}$)	Resilient modulus M_R ($\times 10^3$ psi)	Stress invariant θ (psi)
20	1	0.264	0.066	15.2	61
	2	0.496	0.124	16.1	62
	5	1.184	0.296	16.9	65
	10	2.284	0.571	17.5	70
	15	3.428	0.857	17.5	75
	20	4.420	1.105	18.1	80
15	1	0.260	0.065	15.4	46
	2	0.512	0.128	15.6	47
	5	1.300	0.325	15.4	50
	10	2.500	0.625	16.0	55
	15	3.636	0.909	16.5	60
	20	4.572	1.143	17.5	65
10	1	0.324	0.081	12.3	31
	2	0.672	0.168	11.9	32
	5	1.740	0.435	11.5	35
	10	3.636	0.909	11.0	40
	15	3.872	0.968	15.5	45
5	1	0.508	0.127	7.9	16
	2	0.988	0.247	8.1	17
	5	2.224	0.556	9.0	20
	10	3.884	0.971	10.3	25
	15	5.768	1.442	10.4	30
1	1	0.636	0.159	6.3	4
	2	0.880	0.220	9.1	5
	5	2.704	0.676	7.4	8
	7.5	3.260	0.815	9.2	10.5
	10	4.444	1.111	9.0	13

$$M_R = \frac{\sigma_d}{\epsilon_r}$$

$$\theta = \sigma_1 + 2\sigma_3 = \sigma_d + 3\sigma_3$$

Material Characterization

Equipment-Resilient modulus for Granular Materials-Numerical Problem



K_2=Slope=log[18580/3690]/log[100/1]=0.351

K_1=3690

$$E = K_1\,\theta^{K_2}$$

$$M_R = 3690\theta^{0.351}$$

Material Characterization

Equipment-Resilient modulus for fine grained soils

Please do yourself Section 7.1.4

Material Characterization

Equipment-Resilient modulus for Asphalt Mixtures

The specimens used for compression tests are usually 4 in. in diameter and 8 in. high, while those for indirect tensile tests are 4 in. in diameter and 2.5 in. thick. The advantage of indirect tensile tests is to use specimens of Marshall size, which can be easily fabricated in the laboratory or cored from the pavements.

Sample conditioning is required before the recoverable deformation is recorded. The conditioning can be affected by applying a repeated load to the specimen without impact for a minimum period sufficient to obtain uniform deformation readout.

Depending upon the loading frequency and temperature, a minimum of 50 to 200 load repetitions is typical; however, the minimum for a given situation must be determined so that the resilient deformations are stable. Tests on the same specimen are usually made at three temperatures-41, 77 and 104°F to generate design values over the range of temperatures normally encountered in pavements.

Equipment-Resilient modulus for Asphalt Mixtures

The resilient modulus of compression specimens is determined from Eq.

$$M_R = \frac{\sigma_d}{\epsilon_r}$$

A 20-psi haversine loading with a duration of 0.1 s and a rest period of 0.9 s has been most frequently used. The resilient modulus of indirect tension specimens is computed by Eq.

$$M_R = \frac{P(\nu + 0.2734)}{\delta t}$$

Dynamic load amplitudes of 40 to 60 lb with a load duration of 0.1 s applied every 3 s are typical. The test is specified by ASTM (1989b) in "D4123-82 Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures."

Material Characterization

Correlations-Subgrade soils

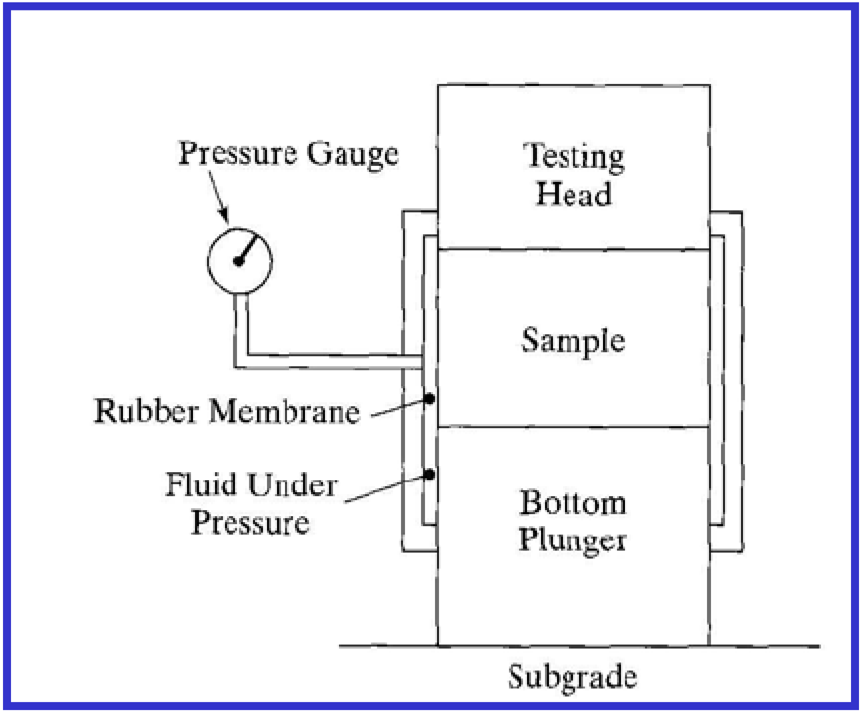
R Value-The R value is the resistance value of a soil determined by a stabilometer. The stabilometer test was developed by the California Division of Highways and measures basically the internal friction of the material the cohesion for bonded materials is measured by the cohesiometer test.

Figure is a schematic diagram of stabilometer, which is a closed-system triaxial test. A vertical pressure of 160 psi is applied to a sample, 4 in. in diameter and about 4.5 in. in height, and the resulting horizontal pressures induced in the fluid within the rubber membrane are measured.

Material Characterization

Correlations-Subgrade soils

Stabilometer



Material Characterization

Correlations-Subgrade soils

R Value-The resistance value is computed as

$$R = 100 - \frac{100}{(2.5/D_2)(p_v/p_h - 1) + 1}$$

in which R is the resistance value; p_v is the applied vertical pressure of 160 psi; p_h is the transmitted horizontal pressure at p_v of 160 psi; and D_2 is the displacement of stabilometer fluid necessary to increase horizontal pressure from 5 to 100 psi, measured in revolutions of a calibrated pump handle. The value of D_2 is determined after the maximum vertical pressure of 160 psi is applied. If the sample is a liquid with no shear resistance, then $p_h = p_v$, or from above Eq., $R = 0$. If the sample is rigid with no deformation at all, then $p_h = 0$, or $R = 100$. Therefore, the R value ranges from 0 to 100. To ensure that the sample is saturated, California used an exudation pressure of 240 psi, whereas Washington used 300 psi.

Material Characterization

Group Index

$$GI = (F-35)[0.2+0.005(LL-40)]+[0.01(F-15)(PI-10)]$$

Where

F = Percentage passing No. 200 sieve, expressed as a whole number

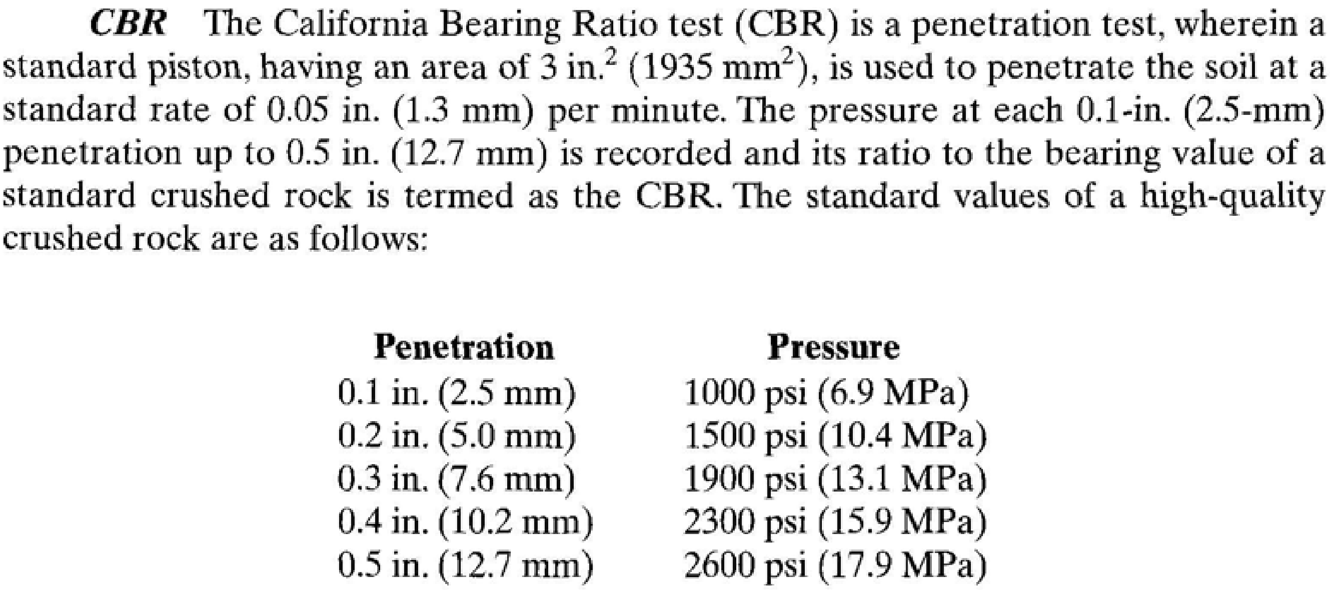
LL = Liquid limit

PI = Plasticity index

The GI is a positive whole number which rates the performance of soil in road construction. It is inversely proportional to the strength of the subgrade material.

Material Characterization

California Bearing Ratio (CBR)



CBR The California Bearing Ratio test (CBR) is a penetration test, wherein a standard piston, having an area of 3 in.^{2} (1935 mm^2), is used to penetrate the soil at a standard rate of 0.05 in. (1.3 mm) per minute. The pressure at each 0.1-in. (2.5-mm) penetration up to 0.5 in. (12.7 mm) is recorded and its ratio to the bearing value of a standard crushed rock is termed as the CBR. The standard values of a high-quality crushed rock are as follows:

Penetration	**Pressure**
0.1 in. (2.5 mm)	1000 psi (6.9 MPa)
0.2 in. (5.0 mm)	1500 psi (10.4 MPa)
0.3 in. (7.6 mm)	1900 psi (13.1 MPa)
0.4 in. (10.2 mm)	2300 psi (15.9 MPa)
0.5 in. (12.7 mm)	2600 psi (17.9 MPa)

Material Characterization

Layer Coefficient

In the AASHTO design method, the quality of the HMA, base, and subbase is indicated by their structural layer coefficients.

The correlation charts, shown on the following slides, were originally developed to determine the layer coefficients, but can also be used to determine the resilient modulus.

Material Characterization

Soil Support Value, *S*

Soil support value is an innovation of AASHO Design Committee. It is scalar parameter (1-10), i.e., it is dimensionless and can not be quantified by physical measurement.

The AASHO Road Test soil (subgrade) was assigned a Soil Support Value of 3, crushed stone base was assigned a value of 10.

Material Characterization

Marshal Test

The Marshall test is performed on cylindrical specimens, 4 in. (102 mm) in diameter and 2.5 in. (64 mm) in height, at a temperature of 140°F (60°C) and a rate of loading of 2 in. (51 mm) per minute.

Two values are measured: the stability, which is the required load to fail the specimen, and the flow index, which is the vertical distortion at the time of failure.

Due to the very fast rate of loading, the stability is a measure of the cohesion, while the flow index is a measure of the internal friction.

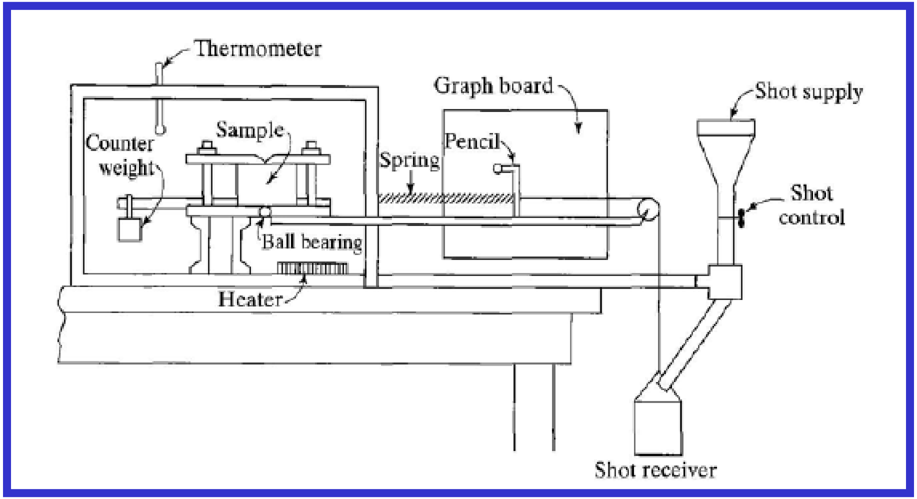
Material Characterization

Cohesiometer Test

The cohesiometer test is used to measure the cohesion of HMA or rigidly cemented materials. Figure is a schematic diagram of the cohesiometer setup. The load is applied at a control rate by the weight of shot until the sample breaks. The cohesiometer value is computed as:

$$C = \frac{L}{W(0.2t + 0.044t^2)}$$

in which *C* is the cohesiometer value in grams per inch width corrected to 3 in. (76 mm) height, *L* is the weight of lead shot in grams, *W* is the diameter or width of specimen in *L* inches, and *t* is the thickness of the specimen in inches. Note that when *t* = 3 in. (76 mm), *C* = *L* / *W*.

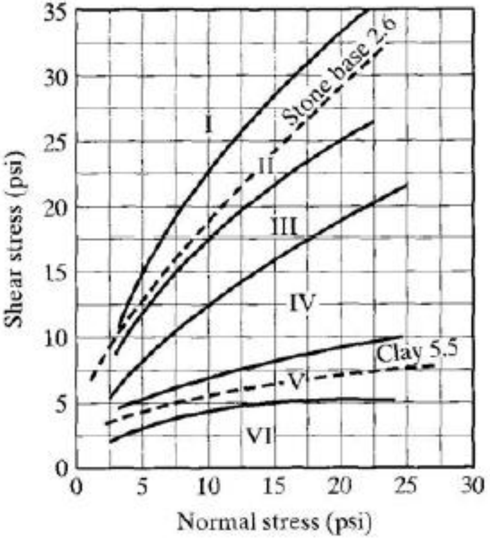


Material Characterization

Texas Triaxial Classification

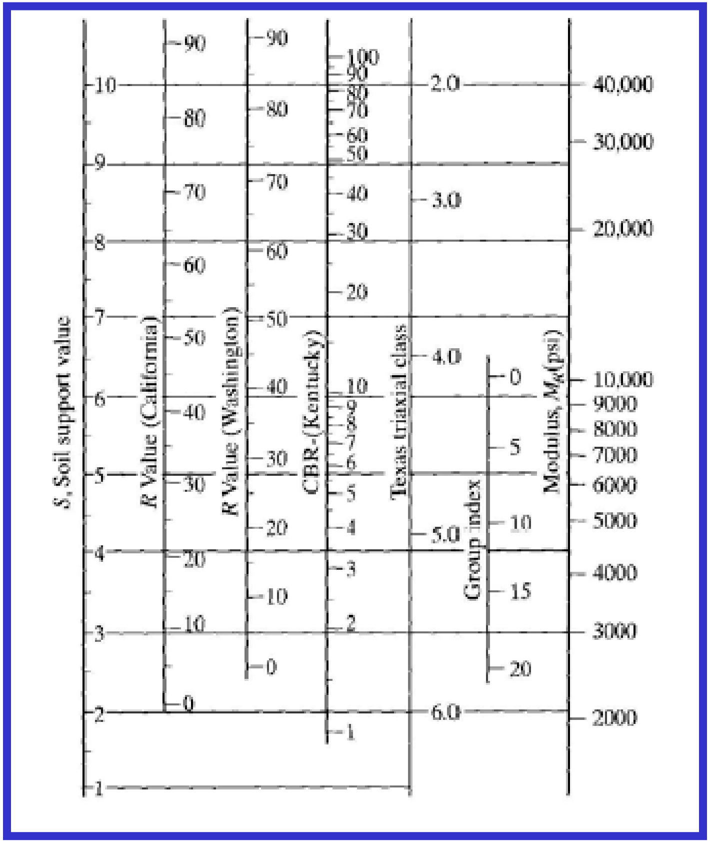
The Texas triaxial test is used to classify soils on the basis of the location of Mohr's envelope. The apparatus consists of a stainless cylinder with an inside diameter of 64 in. (171 mm) fitted with a tubular rubber membrane 6 in. (152 mm) in diameter. The lateral pressure is applied by compressed air between the cylinder and the rubber membrane. The major principal stress is the applied stress because the confining pressure is not applied to the top of the specimen.

From the principal stresses at the time of failure, Mohr's circles for several tests with different confining pressures are constructed. Mohr's failure envelope is transferred to a classification chart, as shown in Figure, and the strength class of the material is determined to the nearest tenth.



Material Characterization

Correlations-Subgrade soils



Material Characterization

Correlations-Subgrade soils

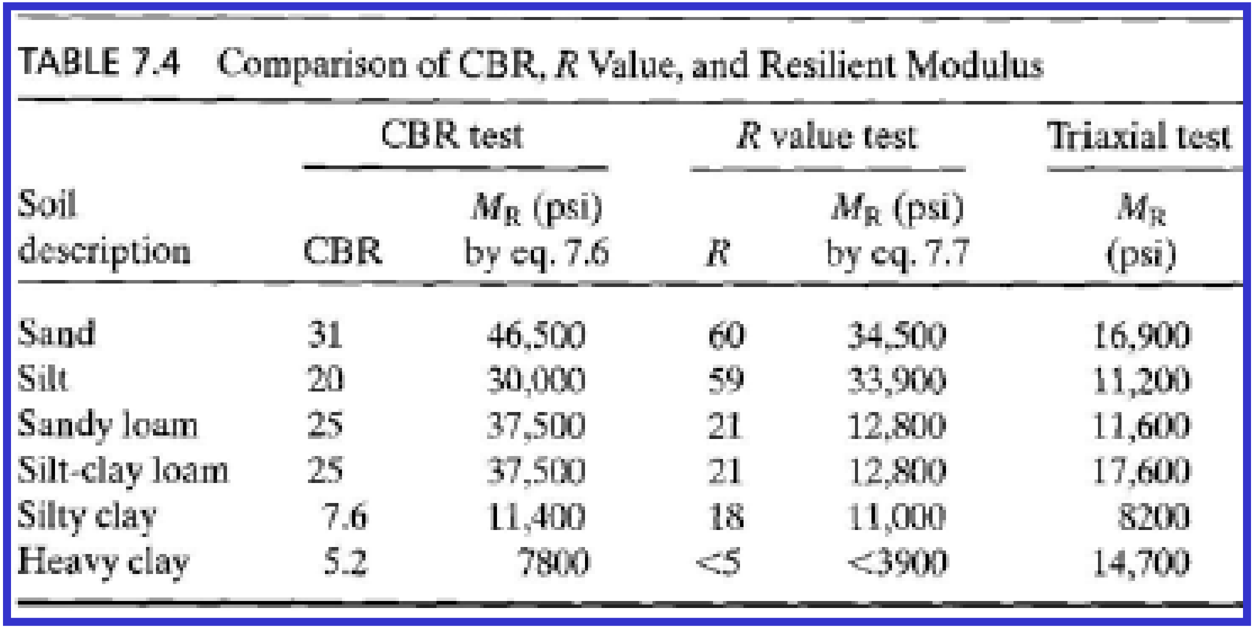


TABLE 7.4 Comparison of CBR, R Value, and Resilient Modulus

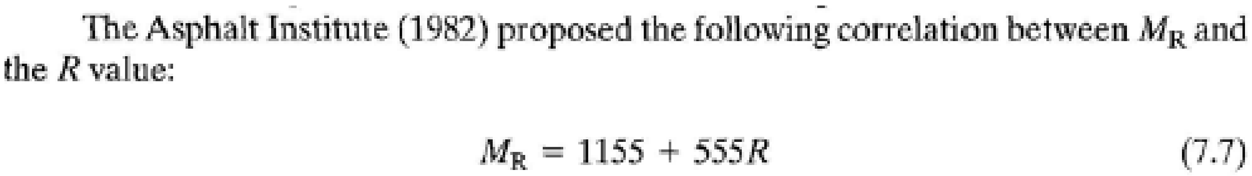
	CBR test		R value test		Triaxial test
Soil description	CBR	M_R (psi) by eq. 7.6	R	M_R (psi) by eq. 7.7	M_R (psi)
Sand	31	46,500	60	34,500	16,900
Silt	20	30,000	59	33,900	11,200
Sandy loam	25	37,500	21	12,800	11,600
Silt-clay loam	25	37,500	21	12,800	17,600
Silty clay	7.6	11,400	18	11,000	8200
Heavy clay	5.2	7800	<5	<3900	14,700

Material Characterization

Correlations-Subgrade soils

Heukelom and Klomp (1962) show that

$$M_R = 1500\,(\text{CBR})$$

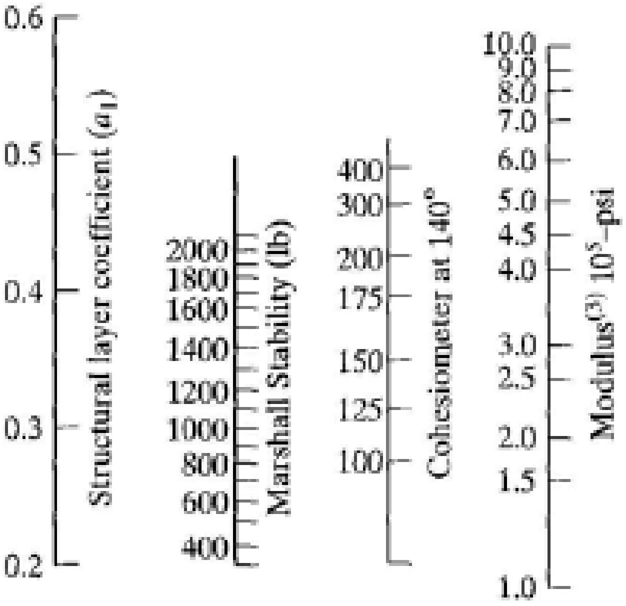


The Asphalt Institute (1982) proposed the following correlation between M_R and the R value:

$$M_R = 1155 + 555R \tag{7.7}$$

Material Characterization

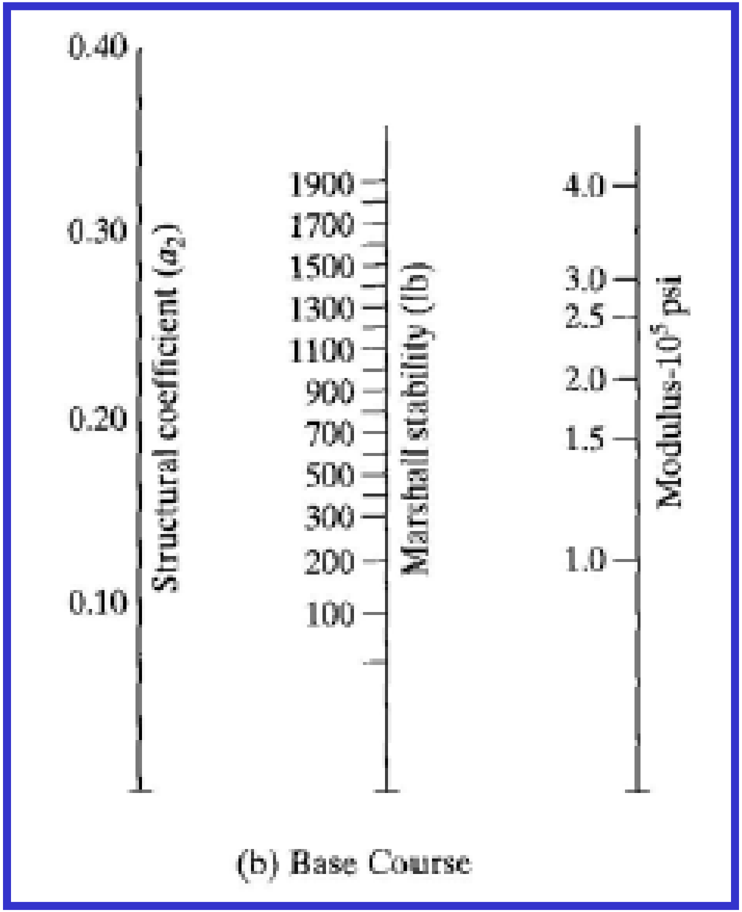
Correlations



(a) Surface Course

Material Characterization

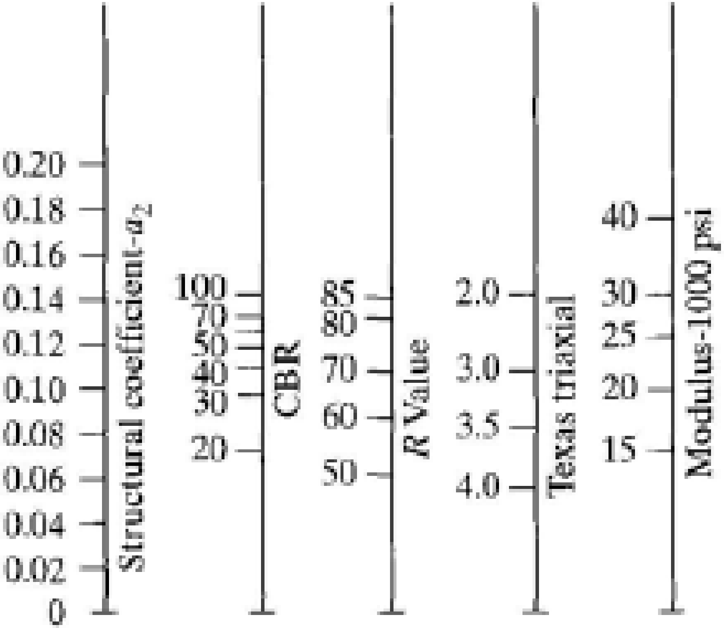
Correlations



(b) Base Course

Material Characterization

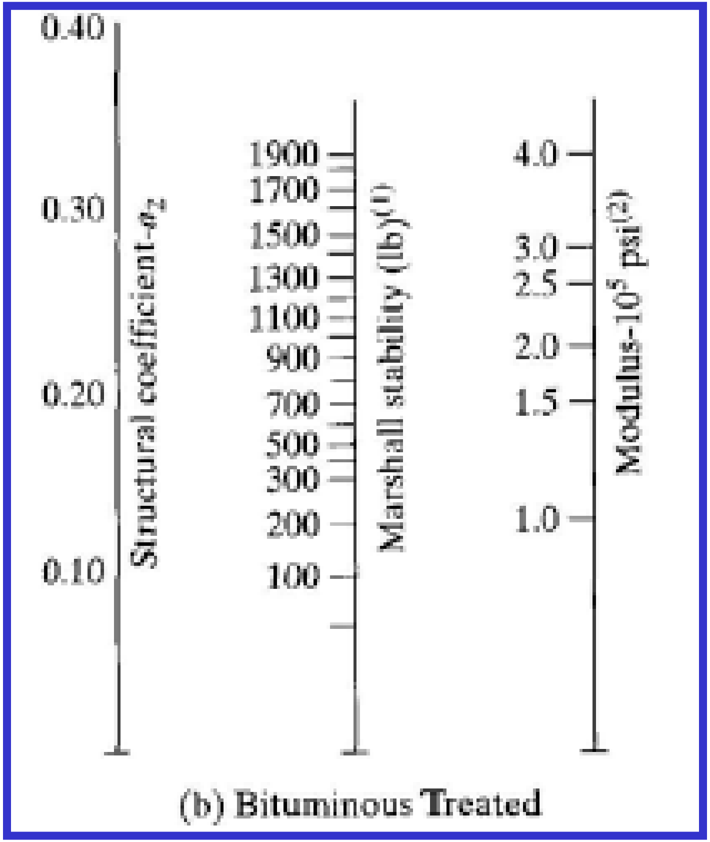
Correlations



(a) Untreated

Material Characterization

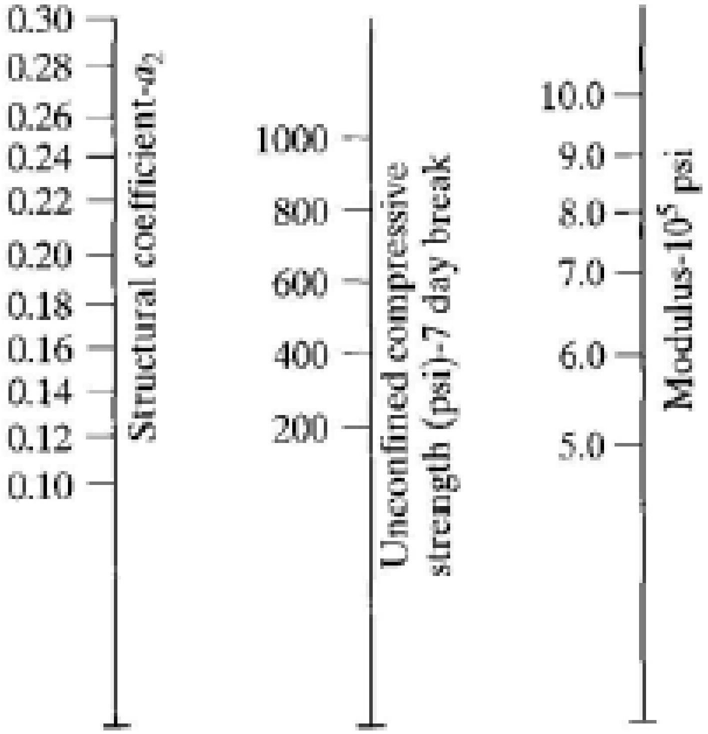
Correlations



(b) Bituminous Treated

Material Characterization

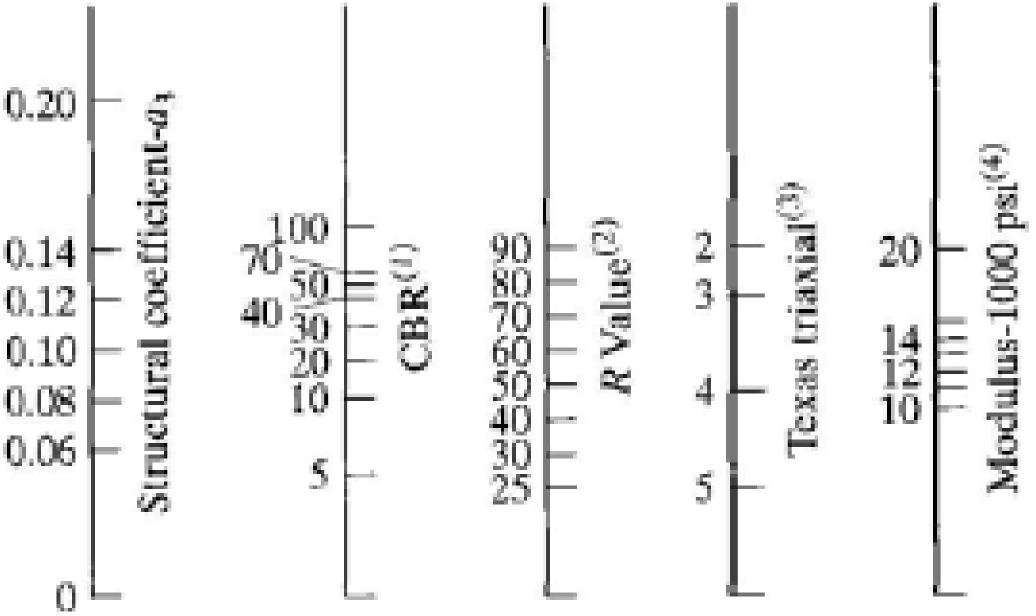
Correlations



(c) Cement Treated

Material Characterization

Correlations

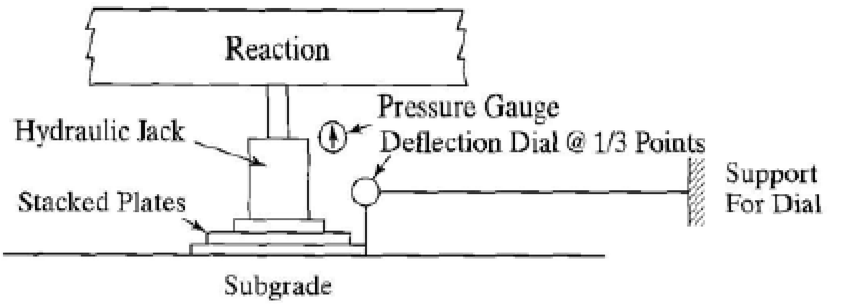


Material Characterization

Modulus of Subgrade Reaction

The modulus of subgrade reaction *k* is determined from the loading test on a circular plate, 30 in. (762 mm) in diameter. To minimize bending, a series of stacked plates should be used. The load is applied to the plates by a hydraulic jack. A steel beam tied to heavy mobile equipment can be used as the reaction for the load. Deflections of the plate are measured by three dial gauges located at the outside edge about 120° apart.

The support for the deflection dials must be located as far from the loaded area as possible, usually not less than 15 ft (4.5 m). Figure is a schematic diagram of the plate loading test.



Material Characterization

Modulus of Subgrade Reaction

The load is applied at a predetermined rate until a pressure of 10 psi (69 kPa) is reached. The pressure is held constant until the deflection increases not more than 0.001 in. (0.025 mm) per minute for three consecutive minutes. The average of the three dial readings is used to determine the deflection. The modulus of subgrade reaction is given by:

$$k = \frac{p}{\Delta}$$

in which *P* is the pressure on the plate, or 10 psi, and Δ is the deflection of plate in in.

Since the *k* value is determined from a field test, it cannot be conducted at various moisture contents and densities to simulate the different service conditions or the worst possible condition during the design life. To modify the *k* value for conditions other than those during the field test, laboratory specimens can be fabricated, one having the same moisture content and density as those in the field and the other having a different moisture content and density to simulate the service conditions. The specimens are subjected to a creep or consolidation test under a pressure of 10 psi (69 kPa), and the deformations *d* at various times are measured until the increase in deformation becomes negligibly small.

Material Characterization

Modulus of Subgrade Reaction

The modified k value can be computed as:

$$k_s = \frac{d_u}{d_s} k_u$$

in which subscript *s* indicates the service or saturated condition and *u* indicates the un saturated or field condition.

Material Characterization

Elastic Modulus

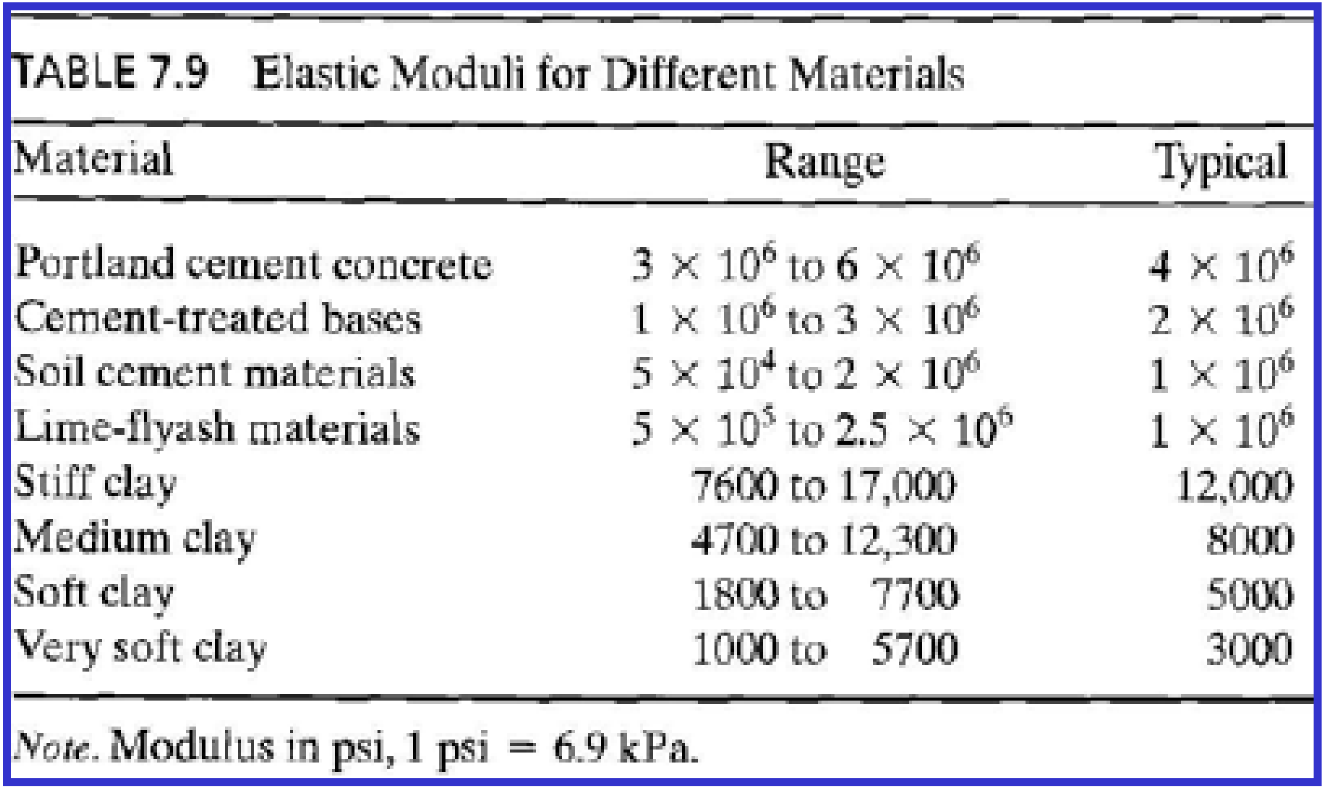


TABLE 7.9 Elastic Moduli for Different Materials

Material	Range	Typical
Portland cement concrete	3×10^6 to 6×10^6	4×10^6
Cement-treated bases	1×10^6 to 3×10^6	2×10^6
Soil cement materials	5×10^4 to 2×10^6	1×10^6
Lime-flyash materials	5×10^5 to 2.5×10^6	1×10^6
Stiff clay	7600 to 17,000	12,000
Medium clay	4700 to 12,300	8000
Soft clay	1800 to 7700	5000
Very soft clay	1000 to 5700	3000

Note. Modulus in psi, 1 psi = 6.9 kPa.

Material Characterization

Poisson's Ratio

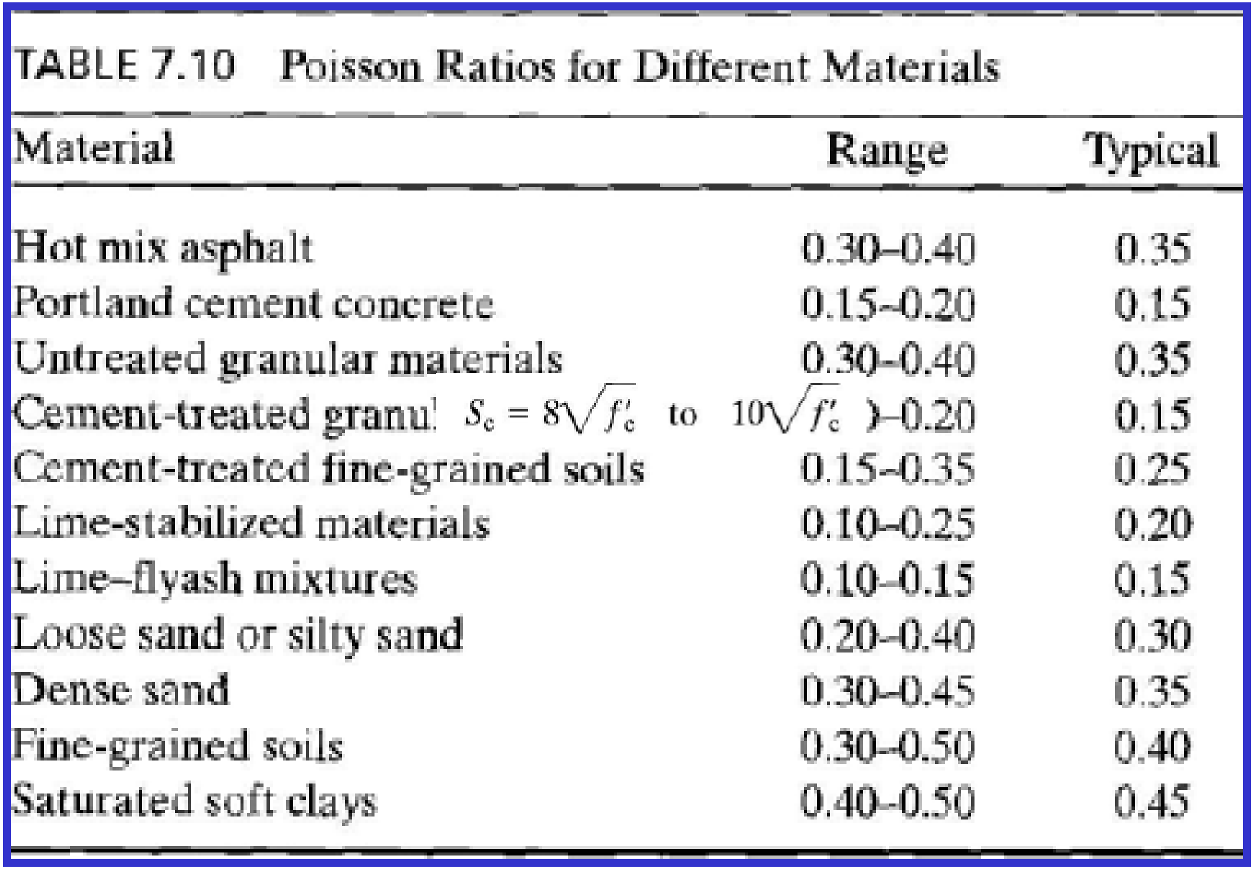


TABLE 7.10 Poisson Ratios for Different Materials

Material	Range	Typical
Hot mix asphalt	0.30–0.40	0.35
Portland cement concrete	0.15–0.20	0.15
Untreated granular materials	0.30–0.40	0.35
Cement-treated granu $S_c = 8\sqrt{f'_c}$ to $10\sqrt{f'_c}$	)–0.20	0.15
Cement-treated fine-grained soils	0.15–0.35	0.25
Lime-stabilized materials	0.10–0.25	0.20
Lime–flyash mixtures	0.10–0.15	0.15
Loose sand or silty sand	0.20–0.40	0.30
Dense sand	0.30–0.45	0.35
Fine-grained soils	0.30–0.50	0.40
Saturated soft clays	0.40–0.50	0.45

Material Characterization

Portland Cement Concrete

$$S_c = 8\sqrt{f'_c} \quad \text{to} \quad 10\sqrt{f'_c}$$

$$f_t = 6.5\sqrt{f'_c}$$

$$S_c = \frac{43.5E_c}{10^6} + 488.5$$

$$E_c = (S_c - 488.5) \times 2.3 \times 10^4$$

$$E_c = 57{,}000\sqrt{f'_c}$$