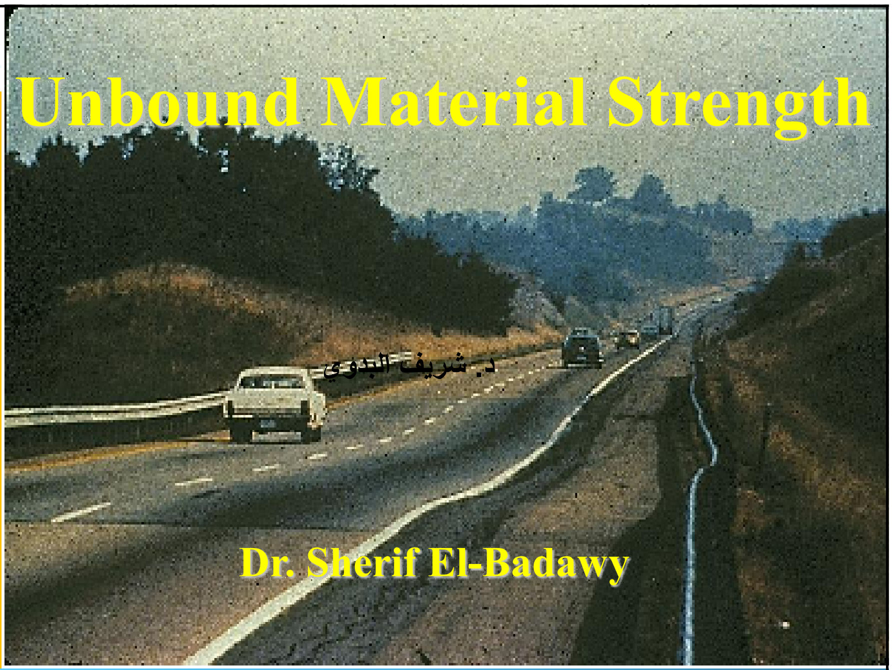

Unbound Material Strength

د. شريف البدوي

Dr. Sherif El-Badawy

Material Types

- Unbound
  - Natural (i.e., subgrade)
  - Select (i.e., subbase, base)
- Asphalt concrete
- Portland cement concrete
- Stabilized materials
  - Cement stabilized
  - Bituminous stabilized
- Bedrock
- Recycled

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Material Properties Needed for Design

- Pavement response model material inputs
  - Modulus (stiffness)
  - Poisson's ratio
- Materials-related pavement distress criteria
  - Permanent deformation resistance
  - Fatigue resistance
  - Strength
- Other materials properties
  - Density
  - Permeability
  - Thermal expansion coefficient

Material Models

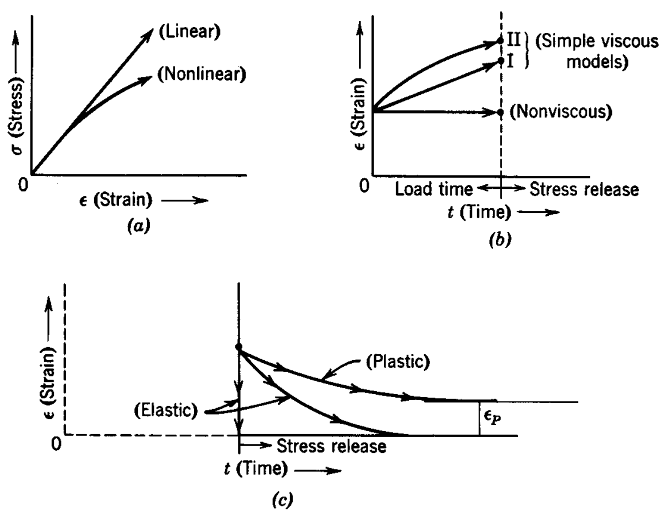

Figure 2.2. Material characteristics. (*a*) linearity; (*b*)viscous effects; (*c*) recoverable effects.

(Yoder and Witczak, 1974)

Material Models

- Linear elasticity
  - Asphalt
  - Stabilized layers
  - Unbound layers
- Linear viscoelasticity
  - Asphalt
- Nonlinear (all materials, to some extent)
  - Nonlinear elasticity
  - Plasticity
  - Nonlinear viscoelasticity
  - Viscoplasticity

Subgrade/Base/Subbase Strength/Stiffness

- California Bearing Ratio (CBR)
- Resistance Value (R-Value)
- Resilient Modulus (M_R)
- Modulus of Subgrade Reaction (K)

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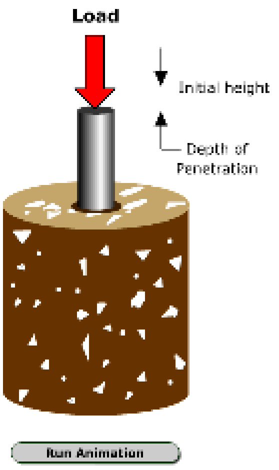
California Bearing Ratio (CBR)

- **CBR: California Bearing Ratio Test.**
- Developed by The California State Highways Department in 1930.
- Resistance of the material to uniaxial penetration.
- Measure of soil shear strength relative to standard crushed stone material.
- Field and laboratory test.

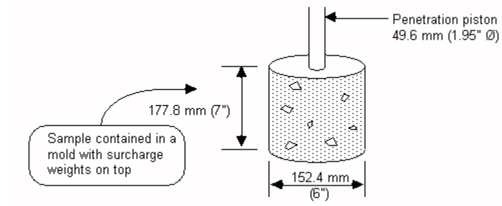
California Bearing Ratio (CBR)

- **Used in Pavement Design**
- **Performed on unbound layers:**
  - **Subgrade layer,**
  - **Subbase layer**
  - **base layer.**

California Bearing Ratio (CBR)

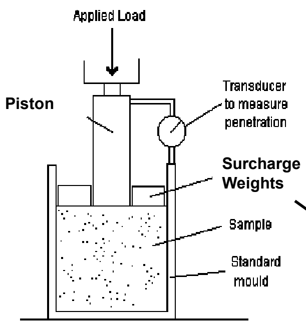


- Load a piston (area = 3 in^2) at a constant rate (0.05 in/min)
- Record Load every 0.1 in penetration
- Total penetration not to exceed 0.5 in.
- Draw Load-Penetration Curve.



Typical Testing Machine

CBR Test Equipment

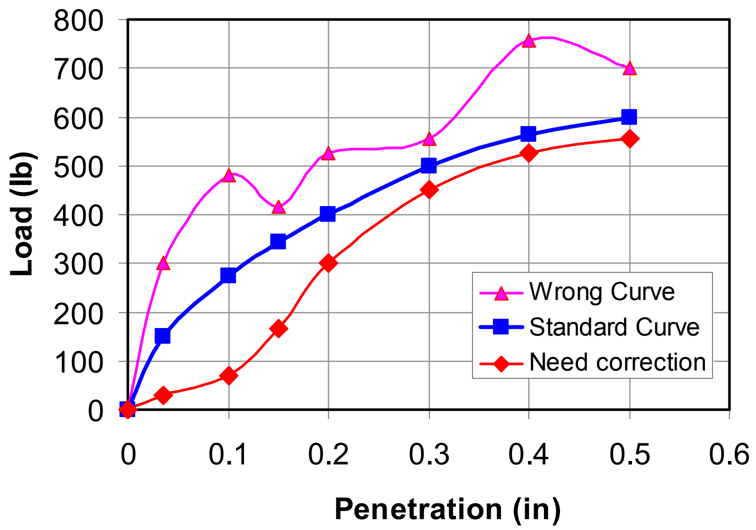


•Surcharge weights are added during testing and soaking to:

- Simulate the weight of pavement.
- Prevent heaving up around the piston.

Soaking Samples for 4 days measure swelling and CBR

CBR Curves



CBR Calculation

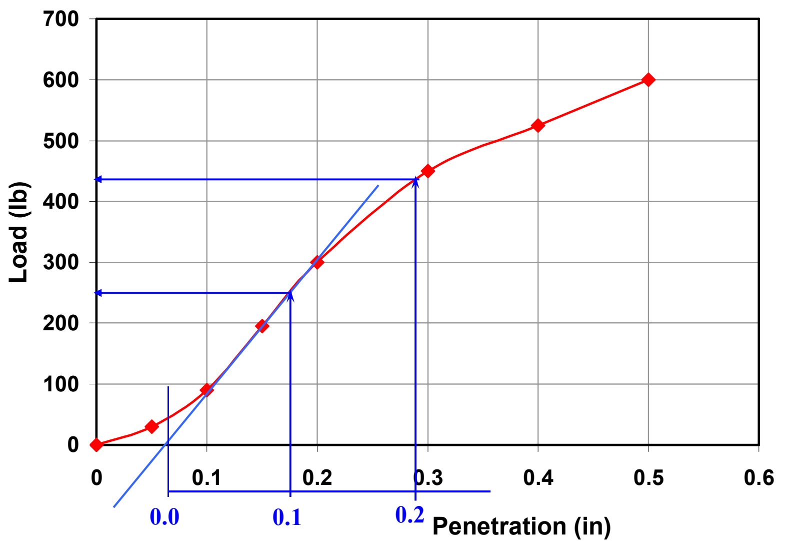
$$CBR = 100\left(\frac{\text{Load or Stress of Soil}}{\text{Load or Stress of Standard Rocks}}\right)$$

Loads and Stresses Corresponding to 0.1 and 0.2 inches Penetration for the Standard Rocks

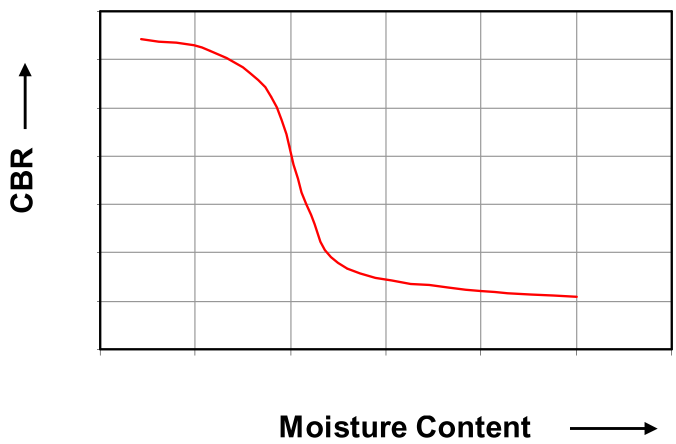
Penetration	0.1” (2.5 mm)	0.2” (5.0 mm)
Load of Standard Rocks (lb)	3000	4500
Load of Standard Rocks (kN)	13.24	19.96
Stress of Standard Rocks (KPa)	6895	10342
Stress of Standard Rocks (psi)	1000	1500

Calculate CBR at 0.1 in (2.5 mm) and 0.2 in (5.0 mm) deformation then use the Maximum value as the design CBR.

CBR Curve Correction



Influence of Moisture upon CBR

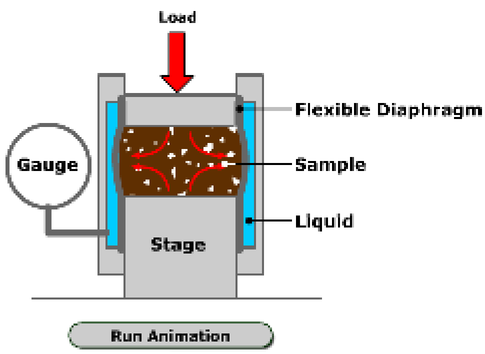


Use relevant value of moisture content when assessing soils under laboratory conditions.

Resistance Value (R-Value)

- Developed by California Division of Highways: 1940s
- Measures frictional resistance of granular material to deformation
- Uses the Hveem Stabilometer
- Tests material in a saturated condition (worst case scenario

Resistance Value (R-Value)



Stabilometer

HAPI HAWAII ASPHALT PAVING INDUSTRY

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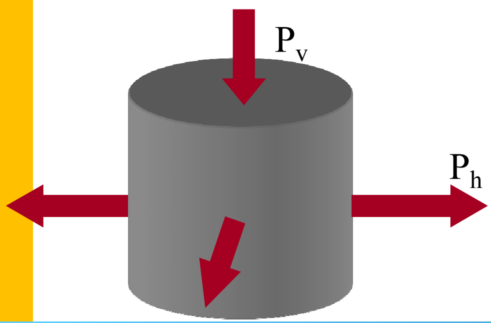
R-value Test (ASTM D2844)

$$R = 100 - \frac{100}{\left(\frac{2.5}{D_2}\right)\left(\frac{P_v}{P_h} - 1\right) + 1}$$

P_v = applied vertical pressure (typically 160 psi)

P_h = transmitted horizontal pressure

D_2 = displacement of stabilometer fluid necessary to increase horizontal pressure from 5 to 100 psi.



Typical R-Value Ranges

General Soil Type	USCS Soil Type	R-Value Range
Clean gravels	GW GP	30 – 80
Gravels with fines	GM GC	30 – 80
Clean sands	SW SP	10 – 50
Sands with fines	SM SC	20 – 60
Silts and clays	ML	5 – 20
	CL	5 – 20
	OL	< 7
	MH	5 – 20
	CH	5 – 20
	OH	< 7

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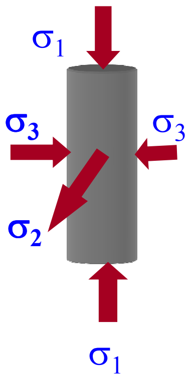
Resilient Modulus (M_R)

- Measures "stiffness" of the material under repeated load.

$$M_R = \frac{\text{Deviator stress}}{\text{Recoverable strain}} = \frac{\sigma_1 - \sigma_3}{\varepsilon_r}$$



- Determines the load carrying capacity of the material.
- Used for HMA as well as unbound materials
- Uses a repeated load triaxial test.
- Used in most modern methods of pavement design.

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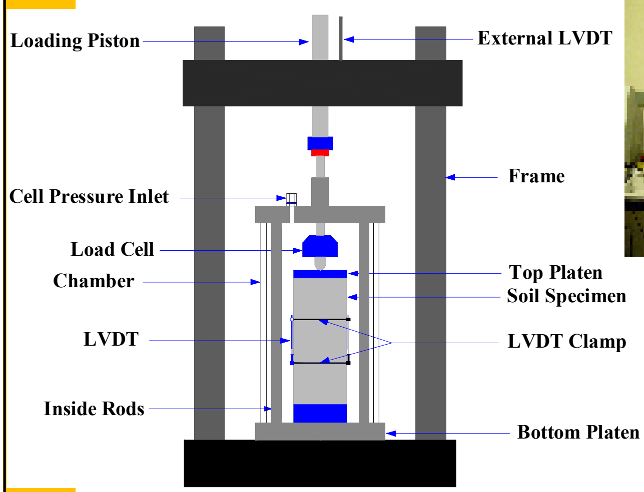
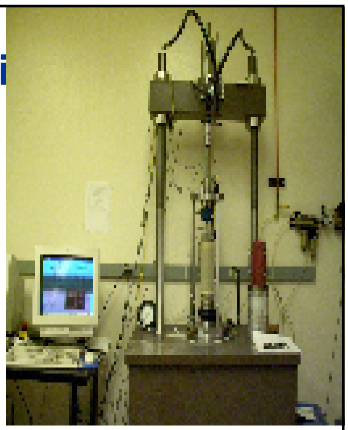
Triaxial Test Equi





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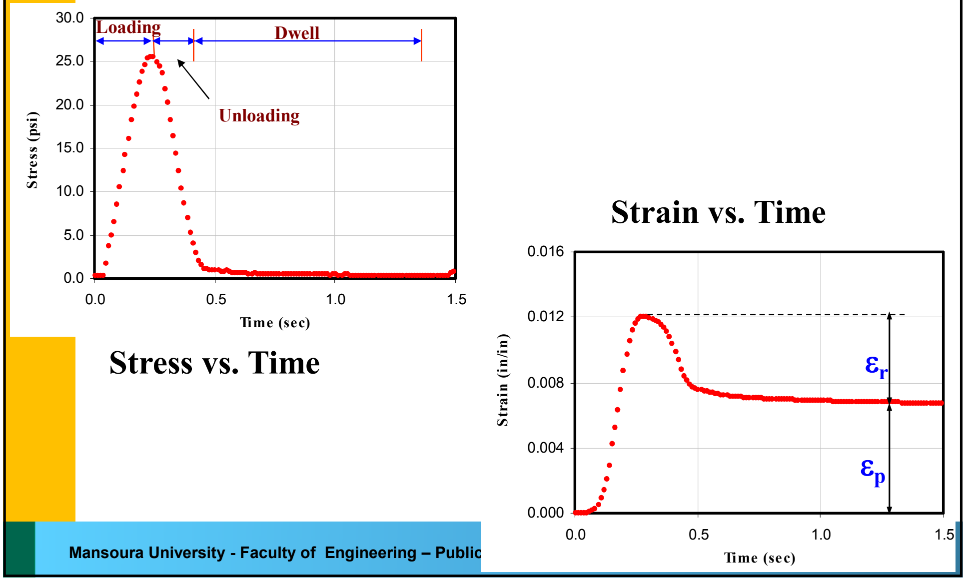
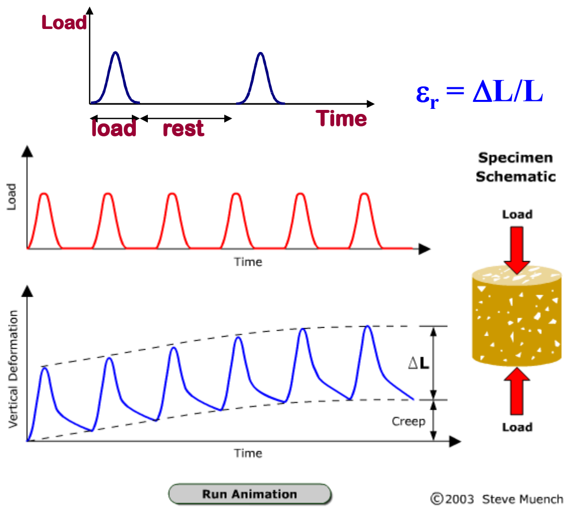
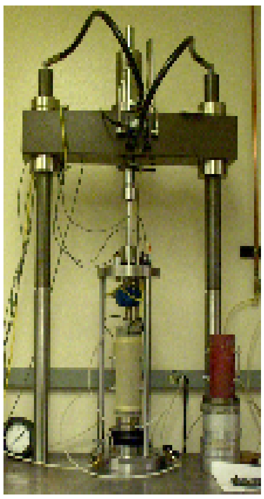
Typical Stress Strain Response During one Loading Cycle



Resilient Modulus



Animation from University of Tokyo Geotechnical Engineering Lab

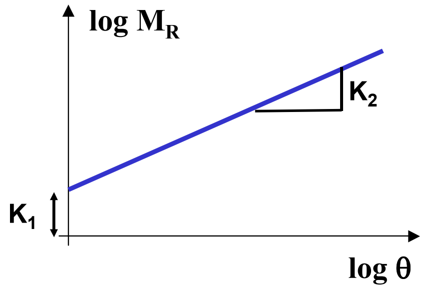


ASU Advanced Pavement Laboratory

Nonlinear Material Behavior: Coarse-Grained Soils

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

- Bulk stress: $\theta = \sigma_1 + \sigma_2 + \sigma_3$
- K_1, K_2 are material constants
  - $K_1 > 0$
  - $K_2 \geq 0$ (stress-stiffening)



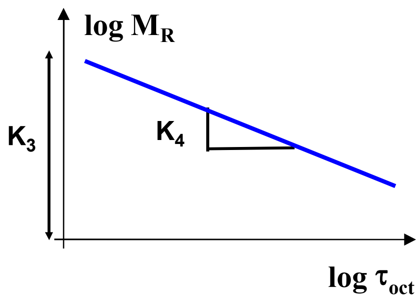
Nonlinear Material Behavior: Fine-Grained Soils

$$M_R = K_3 \tau_{oct}^{K_4}$$

- Octahedral shear stress:

$$\tau_{oct} = \frac{\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}}{3}$$

- K_3, K_4 are material constants
  - $K_3 > 0$
  - $K_4 \leq 0$ (stress-softening)



Combined Stress Dependence of M_R

$$M_R = k_1 p_a \left(\frac{\theta}{P_a} \right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1 \right)^{k_3}$$

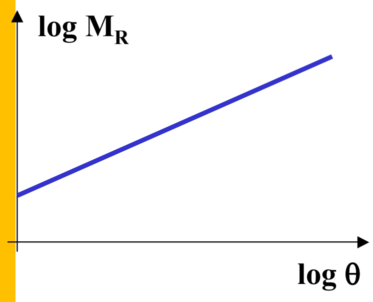
(NCHRP 1-37A)

Bulk (Confining) Stress
- Stiffening term ($k_2 \geq 0$)
- Dominates for coarse granular soils (base, subbase)

Shear (Deviatoric) Stress
- Softening Term ($k_3 \leq 0$)
- Dominates for fine-grained soils (subgrade)

Effect of Stress on M_R

Coarse Materials

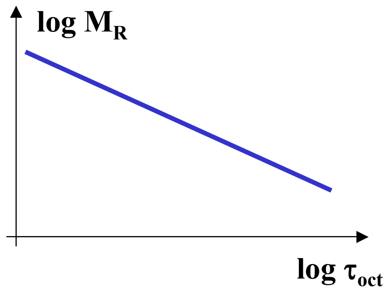


Bulk Stress↑ ➔ Stiffening

$$\theta = \sigma_1 + \sigma_2 + \sigma_3$$

$\theta = I$ = Bulk stress = First stress invariant

Fine Materials



Shear Stress↑ ➔ Softening

$$\tau_{oct} = \frac{\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}}{3}$$

τ_{oct} = Octahedral shear stress

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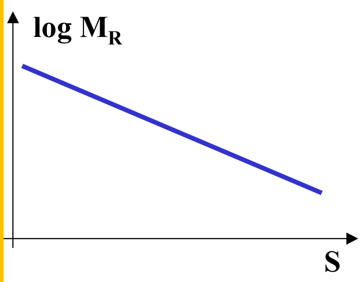
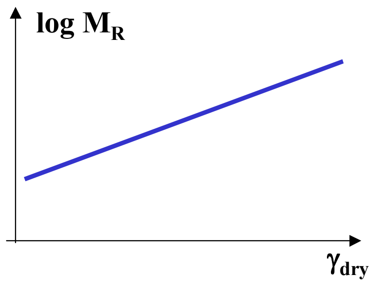
Effect of Moisture/Density on M_R





Moisture↑ ➔ Softening

Density↑ ➔ Stiffening

M_R Model Including Moisture and Density

$$M_R = F_{moisture} \cdot F_{density} \cdot k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$

$$F_{moisture} = a + \frac{b-a}{1 + EXP\left(\ln_e\left(\frac{-b}{a}\right) + k_S \cdot \left(S - S_{opt}\right)\right)}$$

$$F_{density} = \left(\frac{\gamma_d}{\gamma_{d\max}}\right)^{k_\gamma}$$

S = degree of saturation
γ_d= dry unit weight
k_S, k_γ= regression coefficients
a,b = constants (function of soil type)
P_a = atmospheric pressure

(NCHRP 1-37A)

Correlations

- **Conversions between CBR, R-value, M_R**
- **Important points:**
  - **No direct correlation**
  - **Each test measures a fundamentally different property**
  - **Developed correlations are only for limited data sets**

Correlations (CBR → M_R)

$$M_R = 1500(CBR)$$

Origin: Heukelom and Klomp (1962)
Limitation: Fine-grained non-expansive soils with soaked CBR ≤ 10

$$M_R = 2555(CBR)^{0.64}$$

Origin: NCHRP 1-37A – Mechanistic Design Guide
Limitation: No Limitation

Units for Both Models: CBR → % EX: 80% use 80

M_R → psi

Correlations

$$\text{R} - \text{Value} = \frac{1500(CBR) - 1155}{555}$$

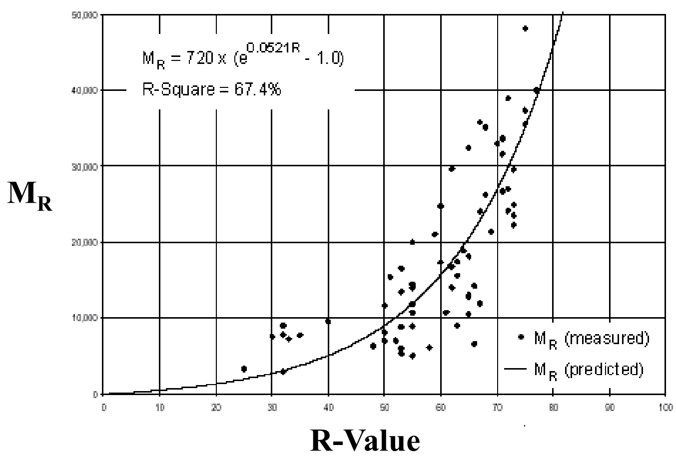
Origin: HDOT
Limitation: Fine-grained non-expansive soils with soaked CBR ≤ 8

$$M_R = 1000 + 555(\text{R Value})$$

Origin: 1993 AASHTO Guide
Limitation: Fine-grained non-expansive soils with R ≤ 20

Correlation Example

M_R vs. R-value for some Washington State soils



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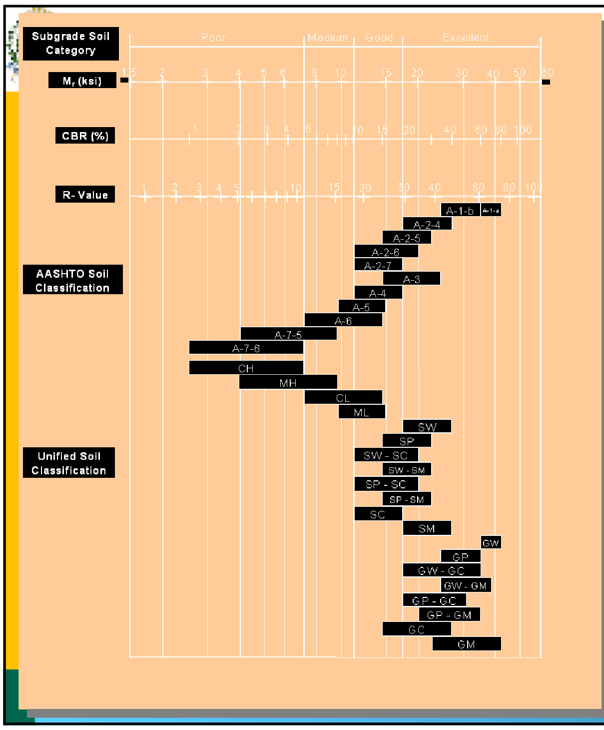

M_R Correlations w/ Index Properties and Soil Classification

(NCHRP 1-37A)

Default M_R for USCS Classes

USCS Symbol	Typical CBR Range	M_R Range (ksi)	M_R Default (ksi)
CH	1 – 5	2.5 – 7	4
MH	2 – 8	4 – 9.5	6
CL	5 – 15	7 – 14	9
ML	8 – 16	9 – 15	11
SW	20 – 40	17 – 28	21
SP	15 – 30	14 – 22	17
SW-SC	10 – 25	12 – 20	15
SW-SM	15 – 30	14 – 22	17
SP-SC	10 – 25	12 – 20	15
SP-SM	15 – 30	14 – 22	17
SC	10 – 20	12 – 17	14
SM	20 – 40	17 – 28	21
GW	60 – 80	35 – 42	38
GP	35 – 60	25 – 35	29
GW-GC	20 – 60	17 – 35	24
GW-GM	35 – 70	25 – 38	30
GP-GC	20 – 50	17 – 32	23
GP-GM	25 – 60	20 – 35	26
GC	15 – 40	14 – 28	20
GM	30 – 80	22 – 42	30

(NCHRP 1-37A)

Default M_R for AASHTO Classes

AAHSTO Symbol	Typical CBR Range	M_R Range (ksi)	M_R Default (ksi)
A-7-6	1 – 5	2.5 – 7	4
A-7-5	2 – 8	4 – 9.5	6
A-6	5 – 15	7 – 14	9
A-5	8 – 16	9 – 15	11
A-4	10 – 20	12 – 18	14
A-3	15 – 35	14 – 25	18
A-2-7	10 – 20	12 – 17	14
A-2-6	10 – 25	12 – 20	15
A-2-5	15 – 30	14 – 22	17
A-2-4	20 – 40	17 – 28	21
A-1-b	35 – 60	25 – 35	29
A-1-a	60 – 80	30 – 42	38

(NCHRP 1-37A)

Plate Loading Test

- Measure supporting power of subgrades, subases, bases and a complete pavement.
- Field test.
- Data from the test are applicable for design of both flexible and rigid pavements.
- Results might need some corrections.

Plate Loading Test

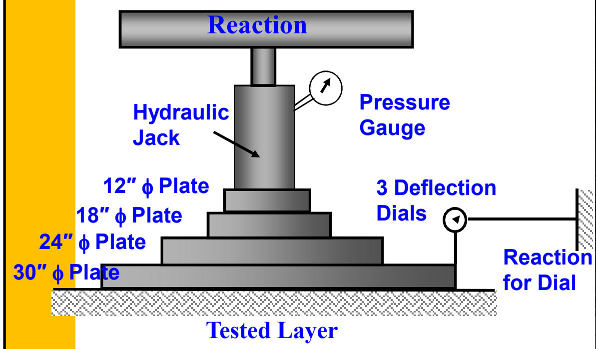

Plate Loading Test Schematic

Plate Loading Test

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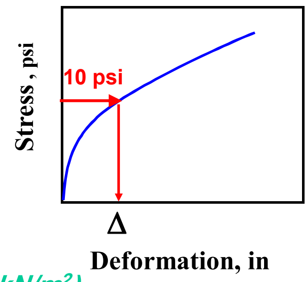
Modulus of Subgrade Reaction (k)

- Required for rigid pavement design.

$$K = \frac{P}{\Delta}$$

K = modulus of subgrade reaction
P = unit load on the plate (stress) (psi)
Δ = deflection of the plate (in)



- *For design use stress P = 10 psi (68.95 kN/m²)*

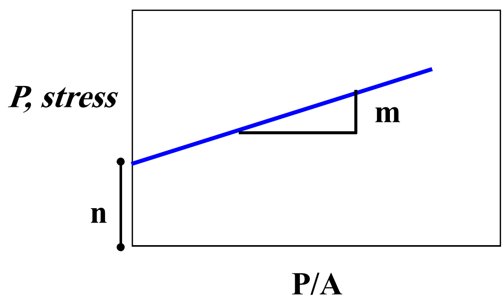
Effect of Plate Size

$$p = n + m\,(P/A)$$

p = Unit load (stress)

n, m = Empirical values obtained by test

P/A = Perimeter over area



To determine m, n tests must be made on each soil using two different sizes of bearing plates using same deflection

Corrections for K

- **Correction due to saturation (worst case scenario).**
- **Correction due to bending of the plates.**

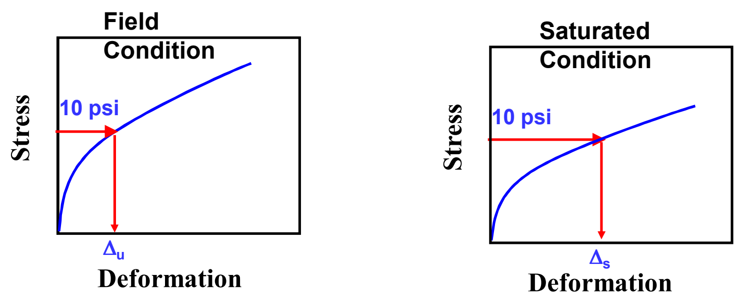
Correction Due to saturation

$$K_s = \frac{\Delta_u}{\Delta_s} K_u$$

K_s = modulus of subgrade reaction corrected for saturation

K_u = field modulus of subgrade reaction

Δ_u/Δ_s = ratio of the deflection in the unsaturated and saturated tests



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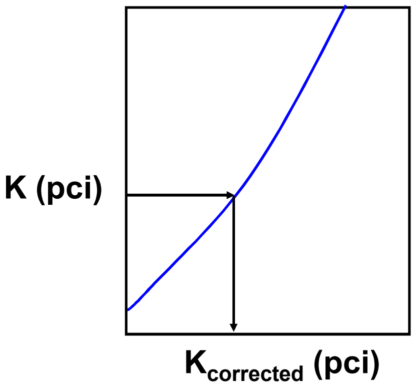
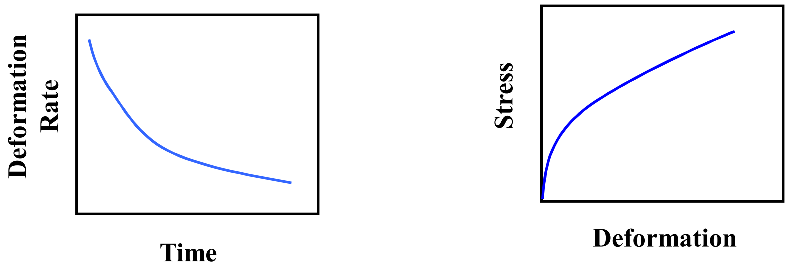
Correction due to Bending of the Plates

- Some bending of the plates might occur When materials of high modulus are tested.
- Use chart for correction of k for plate bending.



Basic Plate Loading Test Types



Static Load

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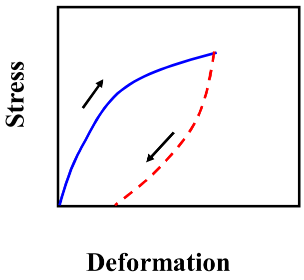
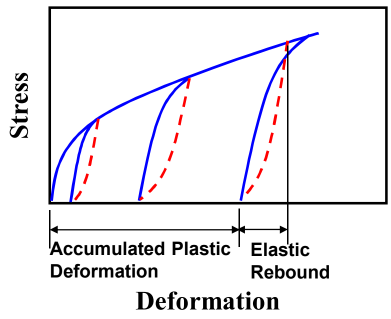
Basic Plate Loading Test Types





Repeated Load