Lecture 7
Constitutive Behavior of Asphalt Concrete
What is a Constitutive Model?

A *constitutive model* or *constitutive equation* is a relation between two physical quantities that is specific to a material or substance and approximates the response of that material to *external* stimuli.

(Wikipedia)
Simple Case: 1-D Linear Elasticity

\[ \sigma = E \varepsilon \]

or

\[ \varepsilon = \frac{\sigma}{E} \]
Uniaxial Test

\[ \sigma = \frac{F}{A_0} \]
\[ \epsilon = \frac{u}{L_0} \]

- \( \sigma \) = axial force
- \( A_0 \) = initial cross-sectional area
- \( \sigma \) = engineering stress
- \( \epsilon \) = axial displacement
- \( L_0 \) = initial gage length
- \( \epsilon \) = engineering strain
Viscoelastic Material Characterization Challenges

- **Asphaltic** materials are *Visco-Elasto-Plastic* heterogeneous composites.
- Asphalt binders behave as:
  - viscous fluids at high temperatures
  - elastic solids at very low temperatures
  - viscoelastic at intermediate temperatures
- Aggregate skeleton behaves as an assemblage of **elastic solids** with cohesive/frictional contacts.
Challenges
“Asphaltic Material”

New pavement ≠ 20 year old pavement

+64°C ≠ -22°C
Viscoelastic Material Characterization Challenges

- Standard “strength of materials” approach is often inadequate.
- Need to account for:
  - Effects of time and load history
  - Effects of temperatures
  - Effect of aging
  - Effects of heterogeneity
  - Effects of damage and failure (fatigue, fracture, etc.)
Strain Decomposition

\[ \varepsilon_{Total} = \varepsilon_{Viscoelastic} + \varepsilon_{Viscoplastic} \]

\[ \dot{\varepsilon}_{Total} = \dot{\varepsilon}_{Viscoelastic} + \dot{\varepsilon}_{Viscoplastic} \]

\[ \varepsilon_{Total} = \left( \varepsilon_{LinearViscoelastic} + \varepsilon_{Damage} \right) + \varepsilon_{Viscoplastic} \]
Linear Viscoelasticity
Superposition: *Linear Elasticity*

- First let’s examine what happens to a “*Linear Elastic*” material when we add (or subtract) new loads (or deformation).
For a linear time dependent or viscoelastic solid, we cannot just scale and add the strains.

Superposition: *Linear Elasticity*
Superposition: *Linear Elasticity*

- For a linear *time dependent or viscoelastic* solid, we cannot just scale and add the strains.

\[ \sigma_1, \sigma_2, \Delta \sigma_2 \]

\[ \varepsilon = D \sigma_1, \varepsilon = D \sigma_2 \]

\[ \varepsilon_t = D(t) \sigma_1 + D(t-x) \Delta \sigma_2 \]

This is only when \( t > x \) seconds.
Superposition: *Linear Viscoelasticity*

What about an “*arbitrary loading history*”?

Recall \( \varepsilon_t = D(t)\sigma_1 + D(t-x)\Delta \sigma_2 \)

Simply put, the above idea is extended in the form of a summation of finite stresses:

\[ \varepsilon(t) = \sum_{i=1}^{n} H(t-x_i)D(t-x_i)\Delta \sigma_i \]

A more common way to expressing the above is in its integral form:

\[ \varepsilon(t) = \int_0^t D(t-\xi) \frac{\partial \sigma(\xi)}{\partial \xi} d\xi \]

“*Boltzmann’s Convolution Integral*”
Common Test Methods

"Choice of Unit Response Functions"

- Creep Compliance “D(t)"
  - Constant stress

- Relaxation Modulus “E(t)"
  - Constant strain

- Complex Modulus “|E*|”
  - Sinusoidal load with constant stress or strain amplitude
Inter-conversion of Unit Response Functions
Rate Dependent Stiffness
Temperature Dependent Stiffness

Input

Strain

\( \dot{\varepsilon}_2 \)

Time

Response

Stress

\( T_1 \)
\( T_2 \)
\( T_3 \)
\( T_4 \)

Strain
Viscoelastic Response: **Cyclic Loading**

**Complex Modulus**

\[
E^* = \frac{\sigma_0}{\varepsilon_0} e^{i\phi} = \frac{\sigma_0}{\varepsilon_0} \left[ \cos \phi + i \sin \phi \right] = E' + iE''
\]

**Dynamic Modulus**

\[
|E^*| = \frac{\sigma_0}{\varepsilon_0}
\]

**Phase Angle**

\[
\phi = \omega t
\]
Viscoelastic Response: **Cyclic Loading**

- Elastic Solids
  - Phase angle, $\phi = 0^\circ$

- Viscous Fluids
  - Phase angle, $\phi = 90^\circ$

- Viscoelastic
  - $0^\circ < \phi < 90^\circ$
Viscoelastic Response: Creep

- Load, $P$
- Deformation, $\varepsilon$

Elastic Solids

Viscous Fluids

Viscoelastic

Excitation
”Load”

Response
”Deformation”
Creep Test

Input

\[ \sigma \]

\[ \sigma_0 \]

Response

\[ \varepsilon \]

\[ \varepsilon(t) / \sigma_0 \]

D(t) = \varepsilon(t) / \sigma_0

log D(t)

Time

log Time

n
Viscoelastic Response: Relaxation

- Deformation, $\varepsilon$
- Reaction, $\sigma$

Elastic Solids

Viscous Fluids

Viscoelastic

Excitation
“Deformation”

Response
“Reaction”
Relaxation Test

Input

$\varepsilon_0$

Response

$\sigma$

$E(t) = \sigma(t)/\varepsilon_0$

$E(t)$

$\log E(t)$

$n$

$log time$
Mechanical Models

(a) Elastic
(b) Viscous
(c) Maxwell
(d) Kelvin
(e) Burgers
(f) Generalized Model
**Basic Material Responses**

- **Elastic Response**
  - Stress vs. time graph with a constant stress level from time $t_0$ to $t_r$.
  - Strain vs. time graph showing a constant strain rate.

- **Viscous Response**
  - Stress vs. time graph with a linearly increasing stress level from time $t_0$ to $t_r$.
  - Strain vs. time graph showing a linearly increasing strain rate.

- **Plastic Response**
  - Stress vs. time graph with a sudden increase in stress at time $t_0$.
  - Strain vs. time graph showing a sudden increase in strain at time $t_0$.

Material Equations:

1. **Elastic Region**
   
   \[
   \sigma = E \varepsilon
   \]

2. **Viscous Region**
   
   \[
   \sigma = \mu \dot{\varepsilon}
   \]

3. **Plastic Region**
   
   \[
   \sigma_{\text{max}} = \sigma_{\text{yield}}
   \]
Viscoelastic Behavior

Viscoelastic Response = Immediate Elastic Response + Time Dependent Viscous Response
Mechanical Models

Maxwell Model

Kelvin Model
Maxwell Model

Maxwell model is a combination of spring and dashpot in series. Under constant stress, the total strain is the sum of the strains in both spring and dashpot.

\[ \varepsilon_{\text{total}} = \varepsilon_s + \varepsilon_d \]

\[ \dot{\varepsilon}_{\text{total}} = \frac{\dot{\sigma}}{E} + \frac{\sigma}{\mu} \]

**Constant Stress (Creep)**

- Strain vs. time
- Stress vs. time

**Constant Strain (Relaxation)**

- \( \sigma = \sigma_0 e^{-Et/\mu} \)
Maxwell Model

If a stress is applied instantaneously to the model, the spring will experience an instantaneous strain of $\sigma_0/E_0$. If the strain is kept constant, the stress will gradually relax and after a long period of time will be zero.

- When $t = 0$, then $\sigma = \sigma_0$; when $t = \infty$, then $\sigma = 0$; and when $t = T$, then $\sigma = 0.368 \sigma_0$.
- Relaxation time is the time required for stress to relax to 36.8% of the original value.
- Maxwell is a good model for relaxation behavior.
- It is more convenient to specify relaxation times than viscosity, because of its physical meaning.

\[
\sigma = \sigma_0 \exp\left(-\frac{\mu}{E} t\right) = \sigma_0 \exp\left(-\frac{t}{T}\right)
\]
Maxwell is a **not** a good model for retardation.
Kelvin Model

Combination of spring and dashpot in parallel. Both spring and dashpot have the same strain but the total stress is the sum of the two stresses.

\[ \sigma_{\text{total}} = E \varepsilon + \mu \dot{\varepsilon} \]

\[ \sigma_{\text{total}} = \sigma_s + \sigma_d \]
Kelvin Model

\[ \varepsilon = \frac{\sigma_0}{E} \left[ 1 - \exp\left( -\frac{E}{\mu} t \right) \right] = \frac{\sigma_0}{E} \left[ 1 - \exp\left( -\frac{t}{T} \right) \right] \]

\[ T = \frac{\mu}{E} \]

- \( T \) is the retardation time, the time to reach 63.2\% of the total retarded strain (i.e., when \( T \) tends to infinite)

- **Kelvin** is a good model for retardation.
Kelvin is a not a good model for relaxation.
Burger Model

\[ \varepsilon = \frac{\sigma}{E_0} \left( 1 + \frac{t}{T_0} \right) + \frac{\sigma}{E_1} \left[ 1 - \exp \left( -\frac{t}{T_1} \right) \right] \]

Maxwell

\[ T_0 = \frac{\mu_0}{E_0} \]

Kelvin

\[ T_1 = \frac{\mu_1}{E_1} \]

Constant Stress (Creep)

Strain

Time
Generalized Model

\[ \varepsilon = \frac{\sigma}{E_0} \left( 1 + \frac{t}{T_0} \right) + \sum_{i=1}^{n} \frac{\sigma}{E_i} \left[ 1 - \exp \left( -\frac{t}{T_i} \right) \right] \]
Creep Compliance

A common method to characterize viscoelastic materials is the measurement of the compliance at various times \(D(t)\):

\[
D(t) = \frac{\varepsilon(t)}{\sigma}
\]

\(\varepsilon(t)\) is the strain under \textit{constant stress}

For the generalized model:

\[
D(t) = \frac{1}{E_0} \left(1 + \frac{t}{T_0}\right) + \sum_{i=1}^{n} \frac{1}{E_i} \left[1 - \exp\left(-\frac{t}{T_i}\right)\right]
\]
Creep Compliance

- If a creep compliance curve is given, it is possible to determine the constants of the generalized model by two ways:
  - By minimizing the error using a Dirichlet Series.
  - By the collocation of creep compliances.
Creep Compliance

Dirichlet Series.

\[ D(t) = \sum_{i=1}^{n} G_i \exp\left(-\frac{t}{T_i}\right) \]

By comparing this equation with the previous:

\[ D(t) = \frac{1}{E_0} + \sum_{i=1}^{n} \frac{1}{E_i} \left[ 1 - \exp\left(-\frac{t}{T_i}\right) \right] \]

\[ G_i = -\frac{1}{E_i} \quad G_n = \frac{1}{E_0} + \sum_{i=1}^{n} \frac{1}{E_i} \]
Creep Compliance

- Collocation of Creep Compliances.
  - A creep test is performed and $x$ compliances are measured at $x$ different times (e.g. $x = 10 \{0.001, 0.003, 0.01, 0.03, 0.1, 0.3, 1, 3, 10, 13\}$ according to FHWA)

- $x$ number of “retardations time” are assumed (fixed parameters) and the values of $G_1$ to $G_x$ are determined following the equation in the next slide.

- Then, a linear system of $x$ by $x$ equations can be solved.
Creep Compliance

Collocation of Creep Compliances. 

\[ D(t) = \sum_{i=1}^{n} G_i \exp\left(-\frac{t}{T_i}\right) \]

\[ D(t_1) = G_1 \exp\left(-\frac{t_1}{T_1}\right) + G_2 \exp\left(-\frac{t_1}{T_2}\right) + G_3 \exp\left(-\frac{t_1}{T_3}\right) + \ldots + G_x \exp\left(-\frac{t_1}{T_x}\right) \]

\[ D(t_2) = G_1 \exp\left(-\frac{t_2}{T_1}\right) + G_2 \exp\left(-\frac{t_2}{T_2}\right) + G_3 \exp\left(-\frac{t_2}{T_3}\right) + \ldots + G_x \exp\left(-\frac{t_2}{T_x}\right) \]

\[ D(t_3) = G_1 \exp\left(-\frac{t_3}{T_1}\right) + G_2 \exp\left(-\frac{t_3}{T_2}\right) + G_3 \exp\left(-\frac{t_3}{T_3}\right) + \ldots + G_x \exp\left(-\frac{t_3}{T_x}\right) \]

\[ D(t_x) = G_1 \exp\left(-\frac{t_x}{T_1}\right) + G_2 \exp\left(-\frac{t_x}{T_2}\right) + G_3 \exp\left(-\frac{t_x}{T_3}\right) + \ldots + G_x \exp\left(-\frac{t_x}{T_x}\right) \]
Colocation of Creep Compliances

\[ D(t_j) = G_1 \exp\left( -\frac{t_j}{T_1} \right) + G_2 \exp\left( -\frac{t_j}{T_2} \right) + G_3 \exp\left( -\frac{t_j}{T_3} \right) + \ldots + G_x \exp\left( -\frac{t_j}{T_x} \right) \]

\[ D(t_2) = G_1 \exp\left( -\frac{t_2}{T_1} \right) + G_2 \exp\left( -\frac{t_2}{T_2} \right) + G_3 \exp\left( -\frac{t_2}{T_3} \right) + \ldots + G_x \exp\left( -\frac{t_2}{T_x} \right) \]

\[ D(t_3) = G_1 \exp\left( -\frac{t_3}{T_1} \right) + G_2 \exp\left( -\frac{t_3}{T_2} \right) + G_3 \exp\left( -\frac{t_3}{T_3} \right) + \ldots + G_x \exp\left( -\frac{t_3}{T_x} \right) \]

\[ \vdots \]

\[ D(t_x) = G_1 \exp\left( -\frac{t_x}{T_1} \right) + G_2 \exp\left( -\frac{t_x}{T_2} \right) + G_3 \exp\left( -\frac{t_x}{T_3} \right) + \ldots + G_x \exp\left( -\frac{t_x}{T_x} \right) \]

\[ \vec{D}(t) = \begin{bmatrix}
\exp(-t_1 / T_1) & \exp(-t_1 / T_2) & \ldots & \exp(-t_1 / T_x) \\
\exp(-t_2 / T_1) & \exp(-t_2 / T_2) & \exp(-t_2 / T_x) \\
\ldots & \ldots & \ldots & \ldots \\
\exp(-t_x / T_1) & \exp(-t_x / T_2) & \ldots & \exp(-t_x / T_x)
\end{bmatrix} \begin{bmatrix}
G_1 \\
G_2 \\
\ldots \\
G_x
\end{bmatrix} = \begin{bmatrix}
D_1 \\
D_2 \\
\ldots \\
D_x
\end{bmatrix} \]
Colocation of Creep Compliances

$$\vec{D}(t) = \begin{bmatrix} \exp(-t_1/T_1) & \exp(-t_1/T_2) & \ldots & \exp(-t_1/T_x) \\ \exp(-t_2/T_1) & \exp(-t_2/T_2) & \ldots & \exp(-t_2/T_x) \\ \vdots & \ddots & \ddots & \vdots \\ \exp(-t_x/T_1) & \exp(-t_x/T_2) & \ldots & \exp(-t_x/T_x) \end{bmatrix} \begin{bmatrix} G_1 \\ G_2 \\ \vdots \\ G_x \end{bmatrix} = \begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_x \end{bmatrix}$$

Then

$$\vec{G} = A^{-1} \vec{D}$$
Colocation for Viscoelastic Solutions

Similar procedure can be used to calculate the approximate viscoelastic response (vertical displacement) $R$ of a viscoelastic material:

$$R(t) = \sum_{i=1}^{n} c_i \exp\left(-\frac{t}{T_i}\right)$$

If the responses at $n$ number of time durations are obtained from elastic solutions, the coefficients $c_1$ through $c_n$ can be obtained (some values of $T_i$ can be selected from the beginning to obtain a matrix expression)
Time-Temperature Superposition

- Viscoelastic properties: function of time and temperature.

- Most asphalt binders: *thermorheologically simple*: Time-Temperature Superposition applies.

<table>
<thead>
<tr>
<th>Time-Temperature Superposition Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>The effect of time on material properties can be replaced by the effect of temperature, and vice versa.</td>
</tr>
</tbody>
</table>
Time-Temperature Dependency of Asphalt

![Graph showing the relationship between modulus (E') and temperature or loading rate. The graph is a log-log plot with markers for two loading rates: slow and fast, and two temperatures: high and low. The modulus increases significantly with decreasing temperature or increasing loading rate.]
Time-Temperature Superposition

- Time-temperature superposition principle:

\[ E(t_1, T_1) = E(t_2, T_2) \]

where:

\[ t_1 < t_2, \text{ and } \]
\[ T_1 > T_2 \]

If \( E(t) \) is needed at low temperature \( (T_2) \) and long loading time \( (t_2) \), is possible to increase the temperature \( (T_1) \) and decrease the loading time \( (t_1) \) to obtain such a value.
Time-Temperature Superposition

- The time-temperature superposition principle is used on experimental data to obtain:
  - **Master curve:** describing the viscoelastic properties at a reference temperature and over a range of time or frequency, and
  - **Shift function-temperature curve:** describing the ratio between the actual time at which the test was conducted and the reference time to which the data is shifted vs. the temperature at the actual time.
Time-Temperature Superposition

- To describe master curve: assume that relaxation modulus, \( E(t) \), is described by a simple power function as:

\[
E(t) = E_1 \ t^{-m}
\]

Taking “log” from both sides of the equation:

\[
\log(E(t)) = \log E_1 - m \log t
\]

If relaxation modulus is conducted at different temperatures:

![Diagram showing logarithmic plot with different lines at temperatures \( T_1, T_2, T_3, T_4 \).]
Time-Temperature Superposition

- The curves can be horizontally shifted to a reference temperature, let’s say $T_2$

Note: $t_r=$ reduced time, not the actual (but the shifted) time
Mathematically we can express the shift of modulus data as:

\[ E(T,t) = E(T_2, t/a_T) \]

The effect of changing temperature (T_2 instead of T (reference) is the same as applying a multiplicative factor to the time scale
Time-Temperature Superposition

- The shifting function gives the relationship between the actual time, $t$, and the reduced time, $t_r$, for each temperature:

\[ \alpha_T = \frac{t}{t_r} \]
Solution (simplified methodology)

1. Assume shift factors for each temperature \((a_T(T_i))\).
2. Compute the reduced frequency, \(f_R\), for each temperature \((f_R=a_T(T_i) \times f)\).
3. Check if the plot of \(|G^*|\) vs. \(f_R\) follows the expected tendency of the curve at the reference temperature.
4. If not, repeat follows 2 to 3 as necessary.
5. Fitted the shift factors to a William-Landel-Ferry (WLF) equation:

\[
\log(a_T) = \frac{C_1(T - T_R)}{C_2 + T - T_R}
\]
Time-Temperature (t-T) Superposition
Example

Complex shear modulus (G*) versus frequency and reduced frequency obtained from DSR tests

Reference temperature (Tr)

shifting direction

Original data
Master curve for the complex shear modulus (G*) at a 25°C reference temperature

Log Complex modulus, G* (Pa)

Log frequency (rad/sec)
Dynamic Modulus-AASHTO TP62

- AASTHO provisional standard TP62: measure $|E^*|$ of HMAs at different temperatures and loading frequencies (uniaxial or triaxial, tension or compression).
- If a compression test is used: specimen also creeps. A decomposition of the responses is needed.
- However, the creep response is typically ignored and $|E^*|$ is computed as the ratio between the amplitude of the stress function to the amplitude of the strain function.
Dynamic Modulus

Decomposition of loading and strain response into dynamic and creep:

Total Applied Stress  =  Dynamic Stress  +  Creep Stress

Total Response  =  Dynamic Response  +  Creep Response
Dynamic Modulus

- Peak stress level: chosen to maintain total measured strain per cycle between 50-150 microstrain (linear viscoelastic behavior),
- 3 LVDTs used to measure response,
- test conducted from lowest to highest temperature and from highest to lowest frequency of loading.
Dynamic Modulus

- Data from *Dynamic Modulus Test*: used to compute the master curve of HMA.
- One recommended procedure to mathematically represent the master curve: sigmoidal function,

\[
\log |E^*| = \lambda + \frac{\alpha}{1 + e^{\beta + \gamma \log t_r}}
\]

where
- \( t_R \): reduced time at reference temperature,
- \( \lambda \): minimum value of \(|E^*|\),
- \( \lambda + \alpha \): maximum value of \(|E^*|\)
- \( \beta, \gamma \): shape parameters (gradation and volumetrics)
Dynamic Modulus Master Curves

![Graph showing dynamic modulus master curves with various markers and colors representing different materials and conditions.](image)
Axial compression sinusoidal load on 100 mm diameter, 150 mm tall cylinders.

Axial deformations measured by LVDTs mounted at different locations using 4 inch gauge length.

Loading frequencies and temperatures:

- $-10^\circ, 4^\circ, 21^\circ, 37^\circ, \text{ and } 54^\circ \text{C (14^\circ, 40^\circ, 70^\circ, 100^\circ, \text{ and } 130^\circ \text{F})}$
- Loading frequencies of 0.1, 0.5, 1.0, 5, 10, and 25 Hz
Dynamic Modulus ($|E^*|$), Saw-Cut Samples
$|G^*|\text{-Based Witczak’s Predictive Equation}$

$$\log_{10} |E^*| = -0.349 + 0.754 \left( |G^*|_b^{-0.0052} \right) \left\{ 6.65 - 0.032 p_{200} - 0.0027 (p_{200})^2 + 0.011 p_4 
- 0.0001 (p_4)^2 + 0.006 p_{3/8} - 0.00014 (p_{3/8})^2 
- 0.08 V_a - 1.06 \left( \frac{V_{\text{beff}}}{V_{\text{beff}} + V_a} \right) \right\}$$

$$2.558 + 0.032 V_a + 0.713 \left( \frac{V_{\text{beff}}}{V_{\text{beff}} + V_a} \right) + 0.0124 p_{3/8} - 0.0001 (p_{3/8})^2 - 0.0098 p_{3/4}$$

$$+ \frac{1}{1 + \exp(-0.7814 - 0.5785 \log |G^*|_b + 0.8834 \log \delta_b)}$$

where $|G^*|_b = \text{dynamic shear modulus of asphalt binder (psi)}$; and $\delta_b = \text{binder phase angle associated with } |G^*|_b \text{ (degrees)}$. 
Viscosity-Based Witczak’s Predictive Equation

\[ \log |E^*| = -1.249937 + 0.029232 \cdot p_{200} - 0.001767 \cdot (p_{200})^2 - 0.002841 \cdot p_4 \\
- 0.058097 \cdot V_a - 0.082208 \cdot \frac{V_{b_{eff}}}{(V_{b_{eff}} + V_a)} \\
+ 3.871977 - 0.0021 \cdot p_4 + 0.003958 \cdot p_{38} - 0.000017 \cdot (p_{3/8})^2 + 0.005470 \cdot p_{3/4} \\
+ \frac{3.871977 - 0.0021 \cdot p_4 + 0.003958 \cdot p_{38} - 0.000017 \cdot (p_{3/8})^2 + 0.005470 \cdot p_{3/4}}{1 + e^{(-0.603313 - 0.313351 \cdot \log(f) - 0.393532 \cdot \log(\eta))}} \]

where  
\( |E^*| \) = asphalt mix dynamic modulus in 10^5 psi;  
\( \eta \) = bitumen viscosity in 10^6 poise (at any temperature, degree of aging);  
\( f \) = load frequency in Hz;  
\( V_a \) = % air voids in the mix, by volume;  
\( V_{b_{eff}} \) = % effective bitumen content, by volume;  
\( P_{3/4} \) = % retained on the ¾ inch sieve, by total aggregate weight (cumulative);  
\( P_{3/8} \) = % retained on the 3/8 inch sieve, by total aggregate weight (cumulative);  
\( P_4 \) = % retained on the No. 4 sieve, by total aggregate weight (cumulative); and  
\( P_{200} \) = % passing the No. 200 sieve, by total aggregate weight.
## Typical Moduli Values

<table>
<thead>
<tr>
<th>Material</th>
<th>E (psi)</th>
<th>E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt Concrete (32°F)</td>
<td>3 million</td>
<td>21,000</td>
</tr>
<tr>
<td>Asphalt Concrete (70°F)</td>
<td>500,000</td>
<td>3,500</td>
</tr>
<tr>
<td>Asphalt Concrete (120°F)</td>
<td>20,000</td>
<td>150</td>
</tr>
<tr>
<td>Crushed Stone</td>
<td>20,000-100,000</td>
<td>150-750</td>
</tr>
<tr>
<td>Sandy Soils</td>
<td>5,000-30,000</td>
<td>35-210</td>
</tr>
<tr>
<td>Silty Soils</td>
<td>5,000-20,000</td>
<td>35-150</td>
</tr>
<tr>
<td>Clayey Soils</td>
<td>5,000-15,000</td>
<td>35-100</td>
</tr>
<tr>
<td>Cement-Treated Base</td>
<td>1-3 million</td>
<td>7,000-21,000</td>
</tr>
<tr>
<td>Stabilized Soils</td>
<td>50,000-2 million</td>
<td>345-14,000</td>
</tr>
<tr>
<td>PCC</td>
<td>3-8 million</td>
<td>21,000-56,000</td>
</tr>
</tbody>
</table>
## Typical Poisson’s Ratio Values

<table>
<thead>
<tr>
<th>Material</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC</td>
<td>0.15- 0.20</td>
</tr>
<tr>
<td>Asphalt Concrete (32°F)</td>
<td>0.20</td>
</tr>
<tr>
<td>Asphalt Concrete (70°F)</td>
<td>0.35</td>
</tr>
<tr>
<td>Asphalt Concrete (120°F)</td>
<td>0.40</td>
</tr>
<tr>
<td>Crushed Stone</td>
<td>0.40</td>
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<tr>
<td>Fine-Grained Soils</td>
<td>0.45</td>
</tr>
<tr>
<td>Sandy Soils</td>
<td>0.35</td>
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<tr>
<td>Cement-Treated Base</td>
<td>0.15</td>
</tr>
<tr>
<td>Cement-Treated Soils</td>
<td>0.25</td>
</tr>
<tr>
<td>Lime-Stabilized Soils</td>
<td>0.20</td>
</tr>
<tr>
<td>Lime-Fly Ash Mixtures</td>
<td>0.15</td>
</tr>
</tbody>
</table>