Ashok Gurjar is a visiting assistant professor of Civil Engineering at the Michigan State University since 1996. He received his Ph.D. from Texas A&M University specializing in Materials Engineering. His research interest relates to the pavement design, behavior and performance, properties of concrete and asphalt, fracture mechanics and viscoelasticity.

Tianxi Tang is an assistant research engineer at Texas Transportation Institute, the Texas A&M University System, and a professional engineer licenced in Texas. He is a memebr of ACI committee 446, Fracture Mechanics, and an associate memeber of ACI committee 504, Joint Sealant and Joint System.

INTRODUCTION

Joints, transverse and longitudinal, in concrete pavements are constructed to allow movements of pavement slabs so that stress levels and therefore the resulting distresses in the pavement are reduced. These joints are formed by long, straight notches on the surface of the pavement. Maintenance of joints is more convenient, because of their standard size, shape, and location, than the repair of random distresses. To prevent intrusion of foreign objects and moisture, sealant materials are applied to seal the notches.

Since pavement movements may cause large openings and closing of the joint, sealant materials are usually required to have low modula for low stresses. Polymer-modified asphalt, silicone and polyurethane are some of the most commonly used material for sealing purpose. In addition to low modulus, these materials exhibit strong viscous properties such as relaxation and creep. Hence, properties of these materials are time dependent. Furthermore, it has been observed that these viscoelastic properties are sensitive to temperature, solar radiation and material age. Sealants with such complex properties are also subjected to cyclic movements of joint boundaries due to traffic load and change in ambient temperature. The two failure mechanism that often occur in joint sealants are cohesive failure (cracking inside the sealant) and adhesive failure (debonding between the sealant and the concrete interface).

In the view of above factors a more reliable analysis procedure is required for designing durable joints of concrete pavement. A first step toward achieving this is to develop a material model that truly represents the sealant material and its behavior. For this purpose, viscoelastic properties of the sealant material was experimentally studied. A theoretical viscoelastic material model is proposed based on the laboratory experimental results, which can be easily applied to finite element programs for stress analysis of joint system.

RESEARCH SIGNIFICANCE

It is of essential importance to understand long-term behavior of joint sealant material in order to properly design a durable joint in concrete pavements. A systematic study consisting of laboratory tests and theoretical modeling was carried out to better predict the behavior of joint sealant material under various conditions. Understanding and information obtained from this study will help establish better criterias to select sealant material and joint geometry for specific locations. Often, joints sealants are subjected to very large deformation compared to their initial geometry and accordingly, true stress and finite strain definitions were used. The resulting stress analysis based on such model is expected to provide more reliable results.

BASIC IDEA

Joint sealant are constantly exposed to many degrading factors which generally have an adverse effect on their material properties. Environmental conditions such as daily and seasonal temperature changes, humidity changes, and solar radiation (UV radiation) degrades (ages) the material and makes them more rigid or stiffer with time. In order to analyze joint sealants, it is pertinent to develop a material model which accounts all the effects of these factors mentioned on material behavior. In the past temperature dependence has been studied and successfully incorporated in the material model. This was done through the use of superposition principle. The relationship for shift factor while generating master curve was first proposed by William, Landel and Ferry (WLF equation) (1, 2). In this study, the superposition principle is used to normalize the deformation (unit extension) dependence and age dependence through the development of the master relaxation modulus curve. Development of master curve is discussed in the latter section.

EXPERIMENTAL PROCEDURE

Tensile relaxation tests were conducted at different unit extension and age levels to determine the viscoelastic parameters of the material. Different age levels of specimens were obtained by subjecting the material to accelerated weathering. The sealant specimens were prepared by pouring the silicone sealant material into a 300 x 225 x 12.7 mm mold. After the curing period suggested by manufacturer, strips of 6.35 mm width were cut from the demolded sheet with a band saw. These resulting strips of cross-sectional area 12.7 x 6.35 mm were tested to provide properties of unaged material (0 hours of weathering). The remaining uncut sheet of the sealant material was then artificially weathered to the three desired levels using Ci65A Atlas Weather-Ometer. Relaxation tests were carried out on both unaged and aged specimens at different unit extension levels with an Instron machine, where data were acquired through an Instron series IX automated material testing system (version 5.02).

Unit Extension

Field studies of pavement joints have suggested that a joint sealant may experience joint opening or closing up to 50-100%. To study the effects of these movements, the six levels of unit extensions used in the laboratory investigation were;

- 5% (2.55mm)
- 10% (5.1mm)
- 20% (10.2mm)
- 30% (15.3mm)
- 50% (25.4mm)
- 100% (51mm)

Numbers in the parenthesis above represent the actual amount of deformation (δL) applied to test specimen with a gauge length of 51mm. The range of unit extensions used in this study attempted to cover the response of sealant material to wide spectrum of deformation to which they are typically subjected in field.

Accelerated Weathering

To monitor effects of aging on the properties of sealant materials, Ci65A Atlas Weather-Ometer was employed for accelerated weathering. Ci65A Weather-Ometer is a controlled irradiance Xenon exposure system. It reproduces and accelerates the natural degradation process by controlling five separate parameters. These controlled parameters are black panel temperature, dry bulb temperature, humidity, light, and water spray (3). Material specimens undergo repeated exposure of accelerated weather cycles. The weather cycle in this study consisted of 102 minutes of light followed by 18 minutes of light and specimen spray. The radiant energy is provided by a single water cooled xenon arc lamp whose filtered spectral output closely simulates natural sunlight. Once the predetermined levels of exposure were completed, 6.35mm wide strips were cut for laboratory testing. Hence, the levels of exposure (age) to which the sealant material were subjected in Ci65A Weather-Ometer and studied were:

- 0 hrs
- 1000 hrs
- 2000 hrs
- 2500 hrs

Relaxation Test

Relaxation test, where the specimens are subjected to instantaneous strain and held constant over time can be used to determine the viscoelastic parameters of the material. Since volumetric movements of sealant depend on the movements of the pavement slabs, the boundary conditions of the sealant are well specified by displacement rather then traction. Therefore, the relaxation test was employed for more accurate results.

In this laboratory investigation, an Instron model 4505 was used to perform the relaxation tests. A 100 lb load cell was used and the displacement was applied at a constant rate of 51 mm/min rate. The displacement rate of 51 mm/min applied met the specification of ASTM D2991 (4). The specimens were stretched to various desired unit extension levels and then held in that displaced position with time. Due to viscoelastic nature of the material, the specimen immediately starts to relax and the stress in the specimen decays with time. The decaying load required to maintain the specimen in deformed position was recorded over test duration. The data were acquired automatically with an Instron Series IX automated material testing system and analyzed.

ANALYSIS OF EXPERIMENTAL DATA

Due to large deformation involved in the experimental work, it was necessary to translate the acquired data to true stress-true strain form. The true stress and relaxation modulus was obtained with the assumption that the material is incompressible, i.e., the total volume of the specimen remains constant during the test. The cross sectional area once the specimen is brought to the desired unit extension level can be calculated as:

$$A_i \; L_i = A_f \; L_f \qquad 1$$

$$A_f = \frac{A_i L_i}{L_f} = \frac{W_i \; T_i \; L_i}{L_i + \delta L} \qquad 2$$

where,

A_i = initial cross sectional area of test specimen = Wi · Ti,
A_f = cross sectional area after application of desired unit extension,
L_i = initial gauge length of the test specimen,
L_f = length of the test specimen after application of desired unit extension,
δL = unit extension applied,
W_i = initial width of the test specimen,
T_i = initial thickness of the test specimen.

Finally, the true stress is calculated as:

$$\sigma(t) = \frac{P(t)}{A_f} \qquad 2$$

where,

$\sigma(t)$ = true stress in the specimen,
$P(t)$ = load required to maintain the desired unit extension.

Finite strain definitions were used in this study. The component of finite strain tensor in the relaxation test can be expressed as(5,6):

$$E_{11} = \frac{1}{2}(\lambda^2 - 1) \qquad 3$$

where,

λ = L_f/L_i,
L_i = Initial gauge length of the test specimen,
L_f = Length of the test specimen at any time t.

The relaxation modulus is then easily calculated by dividing true stress by the finite strain calculated for the unit extension level as:

$$E_R(t) = \frac{\sigma(t)}{E_{11}} \qquad 4$$

where,

$E_R(t)$ = relaxation modulus,
E_{11} = finite strain as calculated in Equation 4.

The procedure was applied to obtain relaxation modulus for all the age and unit extension levels. The plots of relaxation modulus of the silicone material for different age levels are shown in Figures 1-4.

Master Curve Generation

As seen in Figures 1-4, the modulus of the silicone changes with time and age. Effect of unit extension is also apparent. To combine effects of unit extension and age in a single material model, the superposition principle was utilized. This principle has been used to account the effect of temperature through the use of WLF equation first suggested by William, Landel and Ferry (1, 7, 8).

Time-Temperature Shift Principle

Various studies have demonstrated that temperature plays an important role in behavior of viscoelastic materials, particularly polymer-based materials such as rubbers and sealants (8). The effect of temperature on the constitutive equation can be studied by assuming the relaxation modulus to be a function of temperature as:

$$E_R = E_R(T, t) \qquad \mathbf{5}$$

where,

E_R = relaxation modulus,
T = temperature,
t = time.

This function can be derived, in principle, through a number of relaxation tests. Theoretical and experimental studies have shown that for certain categories of materials such as polymers, the effects of time and temperature can be combined into single parameter through the concept of the time-temperature superposition principle. It implies that temperature will affect material response simply through a change in its real time-scale (8). This principle defines the association between time and temperature which reflects quantitatively the observation that behavior at high temperatures and high strain rates is similar to that at low temperatures and low strain rates (8).

Hence,

$$E_R(T, t) = E_R(T_0, \tau) \qquad \mathbf{6}$$

where,

- t = actual time of observation measured from the application of unit extension,
- T = test temperature,
- T_0 = reference temperature,
- τ = reduced time.

The reduced time, τ is given by the following relationship between t and a_T as:

$$\tau = \frac{t}{a_T(T)} \qquad 7$$

where,

- $a_T(T)$ = temperature shift factor,
- T_0 = reference temperature.

The usual form of the relationship between shift factor and temperature proposed by Williams, Landel, and Ferry (1,2) and well known as the WLF equation, is of following form:

$$\log_{10} a_T(T) \equiv \log\frac{t}{\tau} = \frac{-C_1\ (T - T_o)}{C_2 + (T - T_0)} \qquad 8$$

where,

- C_1, C_2= material constants,
- T_0 = reference temperature.

C_1 and C_2 can be experimentally determined by knowing at least two different $a_T(T)$ at two different temperatures.

Time-Strain Shift and Time-Age Shift Relationship

The time-temperature superposition principle discussed above assumes that temperature alone affects the material behavior, but, in practice, the sealant behavior is also affected by unit extension and its age. The superposition principle outlined in the previous section was used for normalizing the effects of unit extension and age. Accordingly, time-strain shift factor, $a_E(E)$, and time-age shift factor, $a_A(A)$, are proposed in this paper. Therefore, effects of temperature, unit extension and age on the material response, $E_R = E_R(T, E, A, t)$, can be uniformly expressed by changing the time scale as:

$$E_R = E_R(T, E, A, t) = E_R\left(T_0, E_0, A_0, \frac{t}{a(T, E, A)}\right) \quad 9$$

where,

$$\frac{t}{a(T, E, A)} = \tau \quad 10$$

is now defined as the reduced time and the material shift factor a(T, E, A) is a combination of separate shift factors $a_T(T)$, $a_E(E)$ and $a_A(A)$:

$$a(T, E, A) = a_T(T) \cdot a_E(E) \cdot a_A(A) \quad 11$$

where,

a(T,E,A) = material shift factor.

The form of shift factor relationships $a_E(E)$ and $a_A(A)$ proposed in this paper are similar to Equation 9 and can be expressed as follows:

$$\text{Log}\, a_E(E) = \frac{-K_1 (E - E_0)}{K_2 + E - E_0} \quad 12$$

$$\text{Log}\, a_A(A) = \frac{-K_3 (A - A_0)}{(K_4 + A - A_0)} \quad 13$$

where,

a_E (E) = time-strain shift factor,
a_A (A) = time-age shift factor,
K_1, K_2 = material constants depending on unit extension effect,
K_3, K_4 = material constant depending on age effect,
E_0 = reference strain (5% in this study),
A_0 = reference age (2500 hours of exposure in this study).

Time-Strain Shift Factor, $a_E(E)$

Relaxation modulus measured for various strain levels are shown in Figures 1to 4. These figures clearly demonstrate the influence of unit extension on material response at room temperature. It was also noted that none of the specimen failed during the tests. A master relaxation modulus curve can be generated by horizontally moving the individual curves to the right to superimpose on the reference strain curve. Unit Extension of 5% was chosen as the reference strain level, E_0 in this study, for the purpose of generating master curves. These horizontal movements obtained by superimposing different curves are called "shifts". A plot of time-strain shift factor is shown on a log scale in Figure 9. The abscissa represent ($E - E_0$), where reference unit extension E_0 is 5%.

Using this approach, the master relaxation curve were obtained for all four age groups, namely, 0 hrs, 1000 hrs, 2000 hrs, 2500 hrs and are shown in Figures 5 to 8. From the time-strain shift factors observed, a_E (E) was deduced. Table I shows the values of K_1 and K_2 corresponding to the age level of specimens.

Following equation provides the best fit curve to these shift factors for various age.

$$\text{Log}\, a_E(E) = \frac{-3.534\,(E - E_0)}{12.986 + E - E_0} \qquad \textbf{15}$$

where,

E_0 = reference unit extension,
E = unit extension under consideration.

Figure 9 shows the plot of various log time-strain shift factor along with a curve representing Equation 15.

Time-Age Shift Factor, $a_A(A)$

Figure 10 shows the master relaxation modulus curves after normalizing for unit extension for different age levels. As seen from this figure, the modulus of the material appreciably increases with an increase in exposure time, implying that the material becomes stiffer resulting in larger stresses for same unit extension. It can be easily observed that these curves can be normalized for the age effect by reducing these curves to a new master curve. The form of the relationship between age and shift factor is given by Equation 14. The time-age shift factor relationship for the material tested was found to be of following form:

$$\text{Log}\, a_A(A) = \frac{-1.878\,(A - A_0)}{-512.59 + A - A_0} \qquad \textbf{16}$$

Equation 16 is plotted in Figure 11 along with observed values of the time-age shift factor values. The master relaxation modulus curve obtained and shown in Figure 12 includes the effects of unit extension and age. The relaxation modulus is plotted against reduced time. This reduced time is obtained from real time from following relationship:

$$\tau = \frac{t}{a(\varepsilon, A)} \tag{17}$$

where,

a(E, A)	$= a_E(E) \cdot a_A(A)$,
t	= actual time in seconds,
τ	= reduced time in seconds.

The time temperature shift factor $a_T(T)$ will be determined after relaxation tests are conducted at different temperatures. This factor can be easily incorporated in to the material model through Equations 11 and 12.

ANALYTICAL MATERIAL MODEL

To develop analytical capabilities for a specific system, an appropriate material model which represents the behavior of the material is needed. Certain materials referred to as viscoelastic show intermediate behavior between elastic and viscous. This difference in response is attributed to the difference of the internal constitution of the materials. Equations characterizing the individual material and its reaction to external excitations are called "constitutive equations". In other words, constitutive equations describe the relationship between stress, strain and time in terms of the material properties (8).

Generalized Maxwell Model

Generalized Maxwell models connected in parallel with a single spring element represents instantaneous elasticity, delayed elasticity with various retardation times, stress relaxation with various relaxation times and also viscous flow. To predict stress associated with a prescribed strain variation, the generalized Maxwell model, as shown in Figure 13 is more convenient since the same prescribed strain is applied to each individual element, and also resulting stress is the sum of the individual contributions. Contribution of one element is given as:

$$\sigma(\tau) = E_i \; \varepsilon_o \; e^{\frac{-E_i \, \tau}{\eta_i}} \tag{18}$$