Verification of Resilient Modulus Prediction of Asphalt Mixtures

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Abstract: Resilient modulus of asphalt mixtures is important parameter for flexible pavement design and evaluation. In Indonesia, the availability of modulus testing apparatus is very limited. As routine testing would be impractical, the accuracy of its prediction is important. This study compares the predictions from Asphalt Institute formula and value obtained in laboratory testing for one type of asphalt mixtures used in Indonesia. Results from indirect tensile test, for modulus less than 2000 MPa, the actual modulus is between 0.7 to 1.1 of the prediction. For modulus greater than 2000 MPa, the actual modulus is between 1.19 to 1.6 of the prediction. Results from four point bending, for modulus greater than 2000 MPa, the actual modulus ranged from 0.8 to 1.23 of the prediction. It concludes that predicted modulus gives a deviation from the actual value within an acceptable level and it can be used for practical purposes.

Keywords: resilient modulus, asphalt mixtures, verification

1. INTRODUCTION

Resilient modulus of asphalt mixture depends on many variables such as aggregate gradation, aggregate size, asphalt viscosity, temperature and frequency of loading. In practise, resilient modulus of asphalt mixture is predicted using available formulas, i.e. Claessen, et al. (1977), Shell (1978), Asphalt Institute (1982), Miller, et al. (1983). The predicted value from formula is usually assumed accurate as the actual resilient modulus that requires special testing apparatus that rarely available in Indonesia. The modulus will be the inputs for further analysis of either design a new pavement or pavement evaluation. The accuracy of further analysis depends on the accuracy of the predicted resilient modulus. This research compares actual resilient modulus obtained from laboratory testing to the predicted resilient modulus from formula of the Asphalt Institute (1982). The comparisons will give confidence on the practical engineers in using the formula.

2. RESILIENT MODULUS

Resilient modulus is used as an elastic modulus in theory of elasticity, for materials shows indication of non-elasticity as there is very small permanent deformation after the load application. However, as the applied load is much less than the strength of materials, deformation caused by each load application almost everything back to its original condition and can be considered the material as an elastic. As the load applied repeatedly, later the permanent deformation can be detected. Figure 1 shows both elastic strains and total strains due to load repetitions. Plastic strain is the difference between total strain and elastic strain. After 100 – 200 load repetitions, plastic strain is hardly visible anymore. For this kind of material, its modulus of elasticity due to load repetition is referred to as resilient modulus, M_r, and is calculated by Equation 1.

$$M_r = \frac{\sigma_d}{\epsilon_r} \tag{1}$$

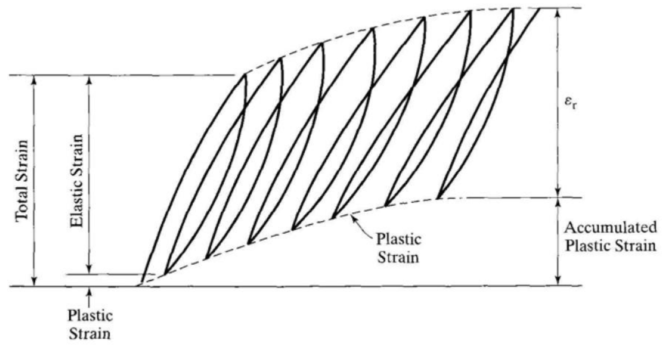

Figure 1. Elastic strain and total strain for repeated loading (Huang, 2004)

Since the resilient modulus depends on the loading pattern and time of loading, the two should be represent of the loading of a moving vehicle on pavement. When the load axle is far distance from a point on wheel track, the stress is not detected. As the axle approaches, the stress increases and becomes maximum as the load is at that point (see Fig. 2). The shape of approaching loading is known as haversine. Mathematically it is expressed by Equation 2. The time of haversine loading is related to the speed of the moving axle or vehicle, and is calculated as Equation 3.

$$\sigma_v(t) = \sigma_{max} sin^2\left(\frac{\pi}{2} + \frac{\pi t}{d}\right) \tag{2}$$

$$d = \frac{12a}{s} \tag{3}$$

According Barksdale (1971), time of loading depends on vehicle speed and depth in pavement as shown in Figure 3. For practical purposes, Huang (2004) suggested time of loading 100 ms. Load repetitions are expressed as rest period of 900 ms in haversine loading pattern.

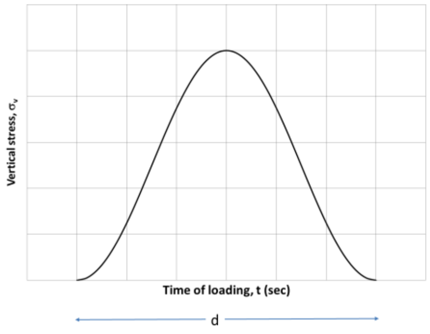

Figure 2. Model of approaching load

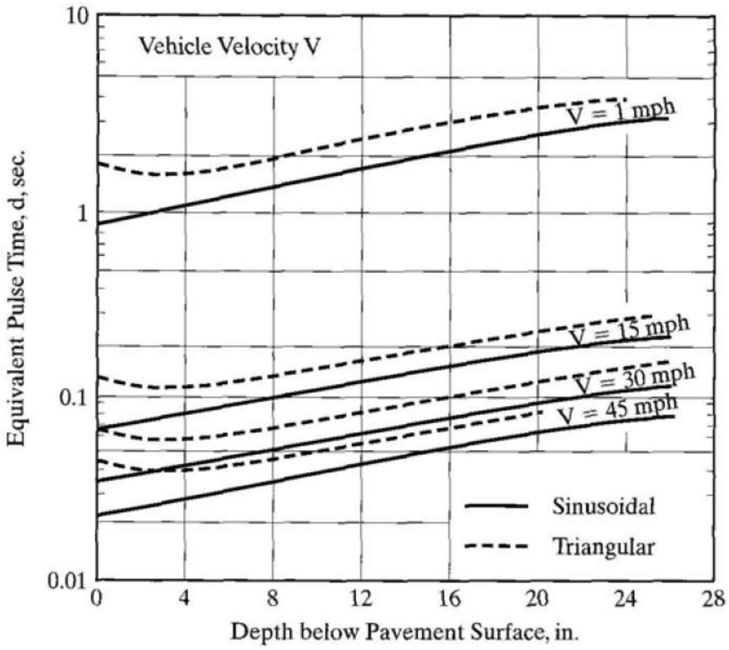

Figure 3. Time of loading as a function of depth in the pavement (Barksdale, 1971)

In addition to resilient modulus, dynamic complex modulus and dynamic stiffness modulus is also used in pavement design. Resilient modulus is based on any loading pattern and rest period, whereas complex modulus, E*, based on sinusoidal or haversine loading pattern with no rest period. Complex modulus is a way to describe the relationship of stress to strain in viscoelastic materials such as asphalt mixture. The real value of this modulus represents the elastic stiffness and the imaginary part describes the damping characteristics of internal damping. The absolute value of the complex modulus is known as dynamic modulus, |E*| as written in Equation 4. Prediction of resilient modulus based on the Asphalt Institute research results is in Equation 5 (Asphalt Institute, 1982) as well as in AASHTO (1993).

$$E^* = |E^*|cos\varphi + i|E^*|sin\varphi \tag{4}$$

$$log|E^*| = 5.553833 + 0.028829\left(\frac{P_{200}}{F^{0.17033}}\right) - 0.03476V_v + 0.070377\eta_{70F,10^6} + 0.000005t_p^{(1.3+0.49825logF)}P_{ac}^{0.5} - \frac{0.00189}{F^{1.1}}t_p^{(1.3+0.49825logF)}P_{ac}^{0.5} + 0.931757\left(\frac{1}{F^{0.02774}}\right) \tag{5}$$

3. BENEFITS OF RESILIENT MODULUS

Pavement thickness design and evaluation of existing pavement based on mechanistic empirical approach requires resilient modulus of each pavement layers. These values are input for the calculation of strain that occurs in the pavement due to the traffic loading. Later the obtained strain will be used in the design and evaluation of the remaining life of the pavement. It is worth to note however that with the transition from the AASHTO (1993) to the new Mechanistic-Empirical Pavement Design Guide (MEPDG) of the American Association of

State Highway and Transportation Officials (AASHTO), the resilient modulus has been replaced with dynamic modulus (Shu, et al. 2010). Relation between modulus resilient and dynamic modulus is discussed in Flintsch, et al. (2005) and Loulizi, et al. (2006).

4. RESILIENT MODULUS TEST FOR ASPHALT MIXTURE

The value of resilient modulus of pavement layers can be obtained by laboratory testing or in some cases with backcalculation approach. For the pavement design the resilient modulus obtained from laboratory test. Various test methods have been standardized in the laboratory include:

1) ASTM D4123-82 (1995) Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures (Withdrawn 2003). This test intially introduced by Schmidt (1972), and Brown and Cooper (1993) who introduced the controlled strain rate in the test protocol.
2) ASTM D7369 - 11 Standard Test Method for Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension Test
3) AASHTO T 321 Determining the Fatigue Life of compacted Hot-Mix Asphalt (HMA) subjected to Repeated Flexural Bending
4) ASTM D3497-79 (2003) Standard Test Method for Dynamic Modulus of Asphalt Mixtures (Withdrawn 2009)

and related to Superpave:

5) ASTM D7312 - 10 Standard Test Method for Determining the Permanent Shear Strain and Complex Shear Modulus of Asphalt Mixtures Using the Superpave Shear Tester (SST), and
6) ASTM D7552 - 09 Standard Test Method for Determining the Complex Shear Modulus (G*) of Bituminous Mixtures Using Dynamic Shear Rheometer.

5. VERIFICATION OF RESILIENT MODULUS PREDICTION

Predicted resilient modulus from the Asphalt Institute formula (1982) will be verified by the results obtained from laboratory test on the asphalt mixture. The mixture with gradation and asphalt cement that commonly used in Indonesia.

Table 1. Gradation of the aggregates for the mixture

Sieves		% Passing (by weight)	
ASTM	mm	Specification	Actual
1”	25	100	100
¾”	19	90-100	94.58
½”	12.5	71-90	78.01
3/8”	9.5	58-80	68.76
No. 4	4.75	37-56	49.99
No. 8	2.36	23-34.6	32.77
No.16	1.18	15-22.3	19.9
No.30	0.6	10-16.7	12.23
No.50	0.3	7-13.7	8.68
No.100	0.15	5-11	5.77
No.200	0.075	4-8	4

A dense graded asphalt mixture with gradation of the aggregates as specified in Table 1. The properties of the asphalt cement is given in Table 2. The asphalt content is obtained based on Marshall test procedure. The optimum asphalt content for this mixture is 6.25%. Other mixture parameters is given in Table 3.

Table 2. Asphalt cement properties

No	Testing	Specification	Result
1	Penetration 25 ^oC (0.1 mm)	60 – 70	65
2	Softening point (^oC)	≥ 48	49
3	Penetration index	≥ -1.0	-0.711
4	Ductility at 25 ^oC (cm)	≥ 100	≥ 140
5	Flash point COC (^oC)	≥ 232	326
6	Solubility in Trichloroethylene (%)	≥ 99	99.79
7	Specific gravity	≥ 1.0	1.035
8	Loss on heating (TFOT) (%)	≤ 0.8	0.032
9	Penetration after TFOT 25 ^oC (%)	≥ 54	87
10	Ductility after TFOT (cm)	≥ 100	≥ 140
11	Penetration index after TFOT	≥ -1.0	-0.539

Table 3. Asphalt mixtures properties

Parameter	Spesification	Result
Asphalt content (%)		6.25
Unit weight (t/m^3)		2.35
Voids in Mix (%)	3 - 5	4.49
Voids in Mineral Aggregates (%)	> 14	17.08
Voids Filled with Bitumen (%)	> 63	73.71
Marshall Stability (kg)	> 800	1071
Flow (mm)	> 3	3.50
Marshall Quotient (kg/mm)	> 250	308.58

6. THE TEST RESULTS

In this research there are two test methods for resilient modulus testing, i.e. indirect tensile test (ASTM D7369 - 11), and four point bending test (AASHTO T 321). The above asphalt mixture was subjected to both tests. Cylindrical specimens with diameter of 4 in. (102 mm) and height of 63 mm for indirect tensile test. Indirect tensile test apparatus is shown in Figure 4. Four point bending specimens are beams with dimensions 67 x 51 x 380 mm (width x height x length). The plate-shaped compacted asphalt mixture is cut to get the desired dimension. The testing apparatus is shown in Figure 5.

Figure 4. Indirect tensile test apparatus

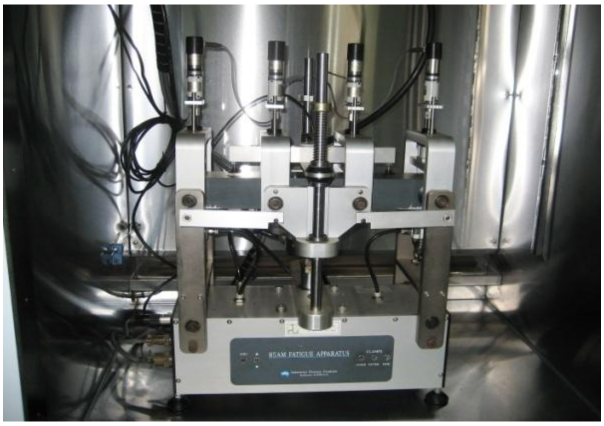

Figure 5. Four point bending test apparatus

Indirect tensile resilient modulus test was subjected to haversine loading shape. The test has three different time of loading (i.e. 100, 250, and 400 ms) with rest period of 900 ms, and three different temperatures (i.e. 25, 33, and 40^{o}C). Figure 6 shows the output of the test with 400 ms time of loading and 900 ms rest period. Five pulsating loadings are applied to each specimens, as "Pulse 1" for the first loading, "Pulse 2" for the second and so on.

At the beginning of the test, peak load was specified and seating force is 10% of peak load. For testing at 40°C, peak load was 690 N, and seating force was 69 N. As load is applied the specimen deformed, and horizontal deformation is measured. Fig. 6 shows phase lag phenomenon as maximum deformation shifted to the right after maximum load. Recoverable horizontal deformation is used to calculate resilient modulus as given in Eq. 6.

$$M_r = P_{max}\frac{(\mu + 0.27)}{L \times H} \quad (6)$$

As the results, the peak load, recoverable horizonal deformation, and seating force caused by loading pulse is 683 N (14.83 μm, 73 N), 691 (15.50, 69), 691 (15.72, 69), 693 (15.76, 69), and 691 (15.76, 69). Resilient modulus was calculated (based on specimen thickness of 63 mm, and μ=0.35) as 453, 439, 433, 433, and 431 MPa respectively. The average value of the 5 pulse was 438 MPa with a standard deviation of 8.27. The average peak load 690 N with a standard deviation of 3.31, and the average force 70N seating with standard deviation 1.58. At the time of the test, actual specimen core temperature is 40.3°C and the skin temperature is 40.7° C, or the average temperature of 40.5°C. Resilient modulus of the same mixture is predicted by Eq. 5. Both resilient moduli are compared and some of the results are shown in Table 4. The complete results are shown in Fig. 7. Four point bending test is performed at 20 and 25^{o}C with time of loading of 100 and 200 ms with sinusoidal type of loading without any rest period. At the same condition, the predicted resilient modulus is obtained from Eq. 5. Both resilient moduli is compared and shown in Fig. 7 with legend in red. Ratio of actual resilient modulus to the predicted value is shown in Fig. 8.

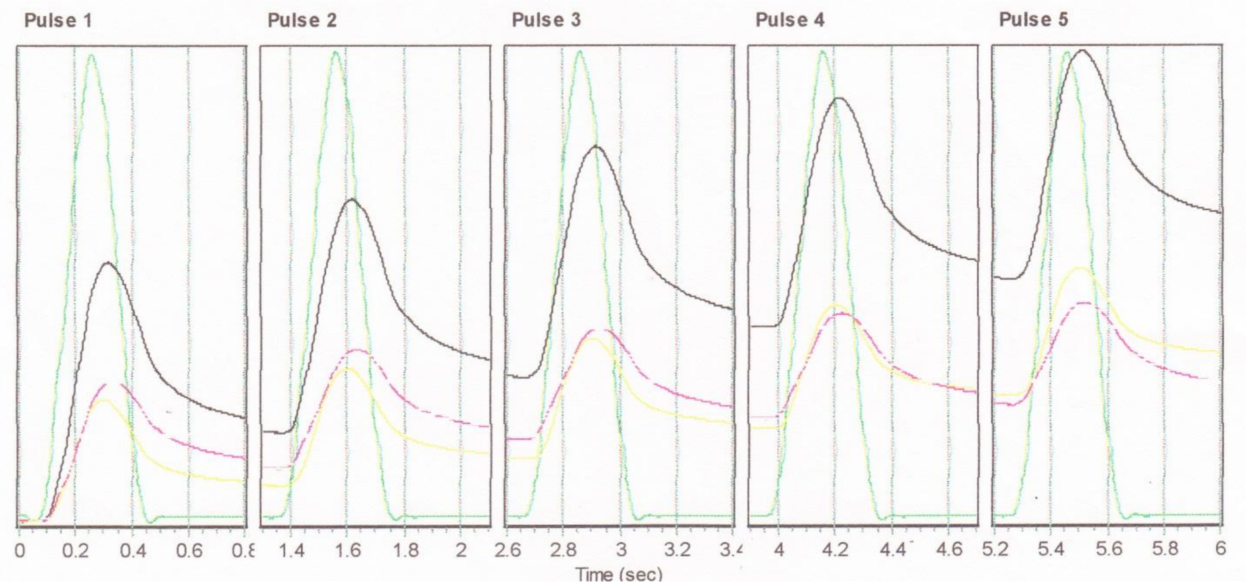

Figure 6. Sample output indirect tensile test with 400 ms loading and 900 ms rest period

Table 4. Indirect tensile test results

Temperature		Time of Loading	Peak of loading	Seating force	Recoverable horizontal deformation	Resilient Modulus	
Target	Actual					Result	Prediction
(°C)		(ms)	(N)	(N)	(μm)	(MPa)	
25	25.15	100	1,906	200	3.81	4,923	3,206
25	25.15	100	1,906	200	4.08	4,597	3,206
25	25.15	100	1,921	187	4.17	4,534	3,206
25	25.15	100	1,924	183	4.29	4,414	3,206
25	25.15	100	1,916	181	4.29	4,395	3,206
..	..	..	..	..	..	..	..
40	40.5	400	683	73	14.83	453	434
40	40.5	400	691	69	15.50	439	434
40	40.5	400	691	69	15.72	433	434
40	40.5	400	693	69	15.76	433	434
40	40.5	400	691	69	15.76	431	434

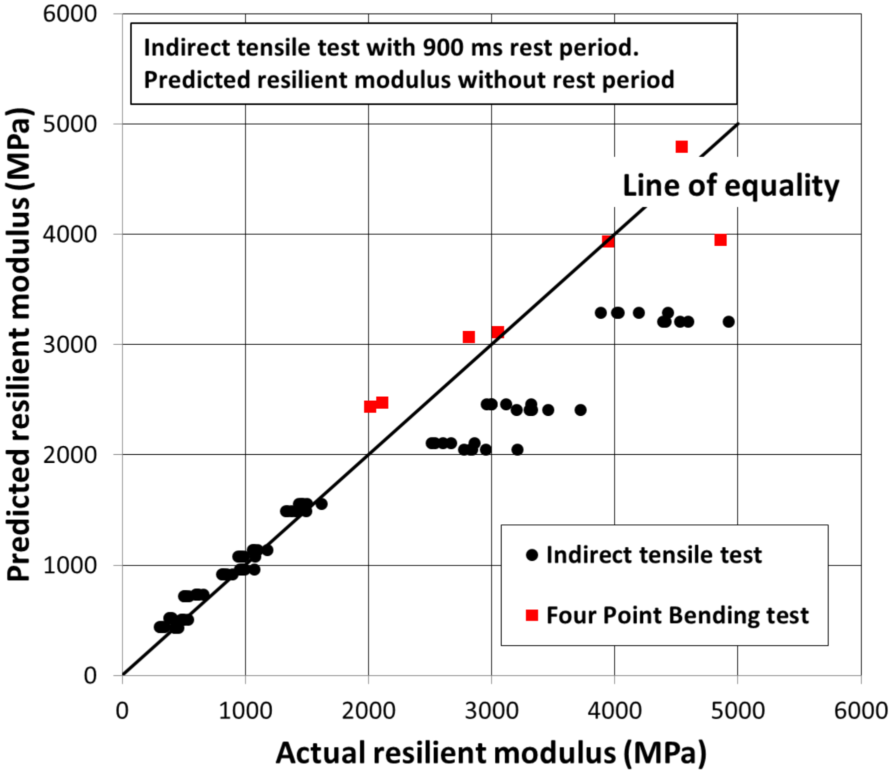

Figure 7. Comparison of actual and predicted resilient modulus

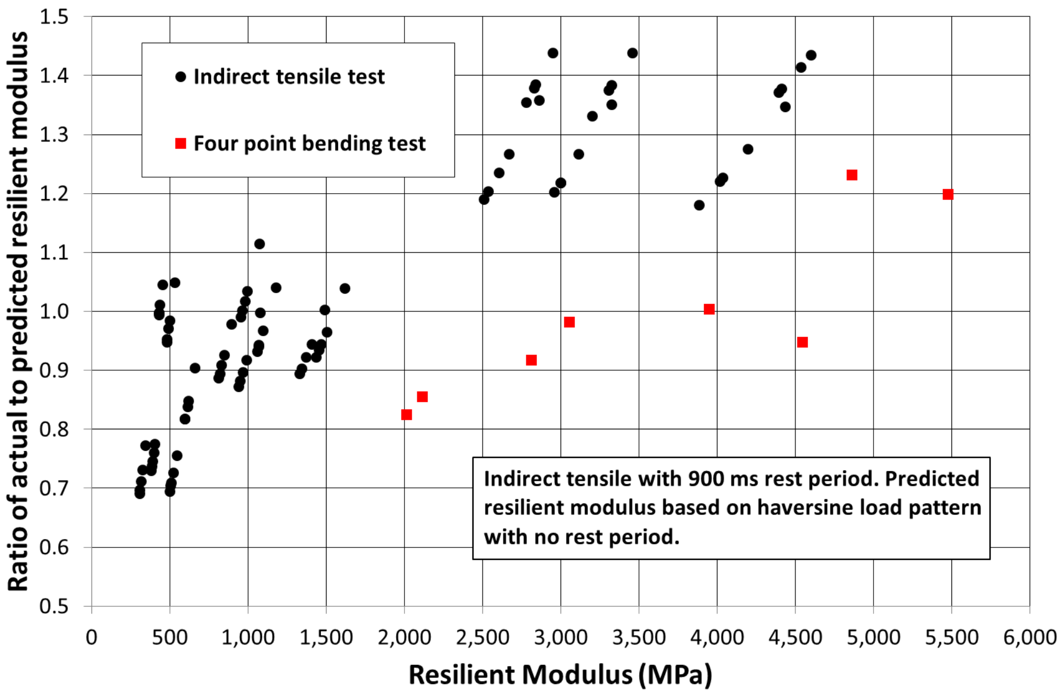

Figure 8. Ratio of actual to predicted resilient modulus

7. CONCLUSIONS

1) The values of resilient moduli less than 2000 MPa that obtained from indirect tensile test with haversine load pattern and 900 ms rest period are between 0.7 to 1.1 of the predicted modulus from the formula. For moduli greater than 2000 MPa, are between 1.19 to 1.6 of the predicted value.
2) The value of resilient moduli greater than 2000 MPa that obtained from four point bending test, are between 0.8 to 1.23 of the predicted modulus.
3) It can be concluded when the apparatus for resilient modulus test is not available, with deviation as described, the predicted resilient modulus from the Asphalt Institute formula can be used.

NOTATIONS

a	=	radius of contact pressure
COC	=	Cleveland Open Cup
d	=	time of loading
E*	=	complex modulus
$\|E^*\|$	=	dynamic modulus
F	=	loading frequency (Hz)
H	=	recoverable horizontal deformation, mm
L	=	thickness of cyclindrical specimen, mm
M_r	=	resilient modulus, MPa
P_{200}	=	ratio by weight of aggregates passing sieve #200 to total aggregates (%)
P_{ac}	=	ratio by weight of asphalt to total mixture (%)
P_{max}	=	peak load
s	=	vehicle speed
t	=	time of loading from 0 upto d
t_p	=	pavement temperature (^oF)
TFOT	=	Thin Film Oven Test
V_v	=	ratio by volume of voids to total mixture (%)
ε_r	=	recoverable strain
σ_d	=	deviator stress
σ_{max}	=	maximum stress
$\sigma_{v(t)}$	=	stress at time t
φ	=	phase angle
$\eta_{70F,10^6}$	=	asphalt viscosity at 70^{o}F (million poise)
μ	=	poisson'r ratio

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