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다양한 Sinusoidal 하중을 받는 아스팔트콘크리트 혼합물의 Moduli 값에 대한 비교연구

Fundamental Comparison of Moduli Values in Asphalt Concrete Mixture due to Various Sinusoidal Loadings

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Abstract

A laboratory investigation was performed to estimate the moduli values of asphalt concrete mixture due to various sinusoidal loadings in compression and tension. Total five modes of loading were used under five testing temperatures of 32, 50, 68, 86, and 104°F (0, 10, 20, 30, and 40°C); repeated compressive haversine loading with rest period, repeated tensile haversine loading with rest period, cyclic compressive loading, cyclic tensile loading, and alternate tensile-compressive loadings. The test results showed that, due to the repeated haversine loading with rest period, asphalt concrete demonstrated similar moduli in tension and compression at low temperatures,(0 and 10 °C) while those moduli were different at high temperatures (20, 30, and 40 °C). At high temperatures the compressive moduli were always higher than the tensile moduli. The uniaxial tensile moduli were higher than indirect tensile moduli at low temperatures. However, those moduli were similar at high temperatures. In uniaxial cyclic tension, compression, and alternate tension-compression tests, compressive moduli were higher than tensile and alternate tensile-compressive moduli throughout the temperatures. Generally, the moduli from the repeated haversine loading with rest period were always lower than those from the cyclic sinusoidal loading. The difference in moduli from the repeated haversine loading with rest period and cyclic sinusoidal loading becomes more significant as the temperature decreases.

key words : asphalt concrete mixture, resilient modulus, dynamic modulus, sinusoidal loading, rest period

요 지

본 시험은 다양한 sine파형을 가진 인장 및 압축 하중 하에서 아스팔트 혼합물의 모듀율값 을 비교평가하기 위하여 수행되었다. 즉, 휴식시간을 가진 반복 인장 haversine 하중, 휴식시간을 가진 반복 압축 haversine 하중, 주기적 인장하중, 주기적 압축하중, 그리고 주기적 인장-압축 반복하중이라는 총 5개의 하중형태가 32, 50, 68, 86, 104 °F (0, 10, 20, 30, 40 °C) 라는 5개의 온도하에서 평가되었다. 시험결과, 휴식시간을 가진 반복 haversine 하중으로 인한 아스팔트 콘크리트의 인장 및 압축 모듀율 값은 저온에서 유사한 값을 나타내었지만, 고온에서는 상이한 값을 보였다. 특히, 고온에서 압축 모듀율 값은 인장 모듀율

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값보다 높은 수치를 보였다. 또한, 저온에서 일축 직접인장 시험으로부터 구한 모듀율 값은 간접 인장시험으로부터 구한 모듀율 값보다 높은 값을 나타내었다. 그러나, 고온에서는 서로 유사한 값을 보였다. 일반적으로, 휴식시간을 갖는 반복 haversine 하중을 이용하여 얻은 모듀율 값은 주기적 sine파형을 가진 하중으로부터 구한 모듀율 값보다 항상 낮은 값을 나타내었으며 그 두 가지 하중으로부터 구한 모듀율 값의 차이는 온도가 감소함에 따라 더욱 증가되었다.
핵심용어 : 아스팔트 콘크리트 혼합물, 회복 탄성계수, 동 탄성계수, sine파형 하중, 휴식시간

1. Introduction

Material characterization is an important part of the pavement design and analysis process irrespective of the method of design or analysis used. In particular, among the component materials of a flexible pavement, asphalt concrete mixture is considered as the most important materials to be accurately characterized, not only because of its higher cost but also because of its contribution to pavement performance (Kim and Lee, 1992). Material characterization is the measurement and analysis of the response of asphalt concrete mixtures to load, deformation, and the environment at various rates of loading and temperatures. These material properties are input to constitutive models of different design analyses to predict stresses, strains, and deflections induced in a layered pavement structure under moving wheel loads.

The use of a single modulus value for asphalt concrete would be justified if the asphalt concrete layer under the action of the traffic loads would undergo either tensile stress only or compressive stress only throughout the thickness of the layer. This would also be justified if the asphalt concrete has the same modulus values in both tension and compression. However, neither of these cases is true. The asphalt concrete layer under the action of vehicular loads is partly in tension and partly in compression. Also, it has been reported as early as 1960's that the material behaves differently in tension and compression (Monismith and Secor, 1962 ; Pister and Westman, 1962). It is, therefore, more realistic to use different modulus and phase angle values in tension and compression for the asphalt concrete in the analysis and design of pavements (Khanal and Mamlouk, 1995).

The principal objective of this study is to compare the various moduli and the corresponding phase angles of asphalt concretes under different loading and temperature conditions. The resilient moduli and the phase angles under repeated tensile and compressive loadings with rest period, and the dynamic moduli and the phase angles under sinusoidal loading conditions without rest period were determined in the laboratory. Also, the effect of testing method on resilient modulus will be investigated from the uniaxial direct tension test and diametral tension test.

2. Materials and Specimen Preparation

The asphalt cement used in this research was AC-20 asphalt, and the level of asphalt content for the asphalt cement was determined by Blythe Industries, Inc., Staley, North Carolina. According to the construction record maintained by the North Carolina Department of Transportation (NCDOT), the optimum asphalt content of the heavy duty surface (HDS) course was determined using the U.S. Army Corps of Engineers (Marshall) 75-blow procedure (ASTM D 1559). The procedure required a minimum 1,500 lbs (681 kgf) Marshall stability. Selected optimum asphalt content of the asphalt concrete was 5.5 percent by weight of aggregate.

The aggregates used in this research were #78M, SCRG., and Sand. To get the HDS mixture, these aggregates were blended properly in certain proportions. The aggregate sources and blending percentages of each aggregate are shown in Table 1. The selected aggregate gradation with North Carolina specification limits of the mixture is also presented in Table 2. More detailed information on aggregate and asphalt binder can be found elsewhere (Kim, N., 1994 ; Kim, N., 1999).

The sample preparation procedures for heating of aggregate and asphalt, mixing, and curing were conducted according to the "Asphalt Concrete Specimen Preparation Protocol" (Harvey, J., 1990) prepared at the University of California, Berkeley as a part of the SHRP Project A-003A. Following the construction record maintained by the NCDOT, the selected mixing temperature for the HDS mixture was 285°F (140.6°C).

The mixture was placed in pans in a forced air oven for a minimum of about 90 minutes to reach uniform temperature. The mixture was heated to a mixing temperature of 285°F (140.6°C). Mixtures not used within 3.5 hours after being placed in the oven were discarded. The heating of the mixture was continuous, and was done only once. All molds and tools that came in contact with the mixture during compaction were maintained at the compaction temperature as far as possible.

The mixture was compacted using Gyratory Testing Machine (GTM) designed by the United State Army Corps of Engineers (COE). One and two degrees of gyratory angles were used to produce the Marshall (4"x2.6") and 4"x8" specimens, respectively. One level of compaction effort was imparted to the mixture in order to produce specimens with 6% air void content regardless of the specimen size. This target air void content of the specimen was selected based upon the air void content measurements from the field core specimens. The method used for measurement of the air void data presented in this paper was wet-with parafilm (WWP) method (Harvey et al., 1991 ; Kim and Im, 1996).

3. Laboratory Testing

3.1 Resilient Modulus and Phase Angle

An MTS Model 643.01A Resilient Modulus Fixture was used in this study. The fixture can

Table 1. Aggregate sources and blending proportions for HDS mixture

Shipping Point	Materials	Amount(%)
E. Forsyth Quary	#78M	45.0
E. Forsyth Quary	SCRG.	35.0
Kelly Pit	Sand	20.0

Table 2. Selected aggregate gradations

JMF Combined sieve size	Percent passing(%)	
	NC Spec. Limits	Selected gradation
3/4(in)	100	100
1/2(in)	96-100	98
#4	55-80	67
#8	40-60	51
#40	11-38	25
#80	4-20	11
#200	2-8	4.1

be installed in a load unit having either a crosshead or a baseplate mounted actuator. This resilient modulus fixture is small and simple enough to be used in a small environmental chamber akin the one at North Carolina State University (NCSU). The schematic presentations of the indirect tensile resilient modulus fixture and the uniaxial modulus fixture are shown in Figs. 1 and 2, respectively. In this study, the resilient moduli under three types of loadings with rest period were measured. Those are uniaxial compression (UCWR), uniaxial tension (UTWR), and indirect tension (ITWR).

In addition, the phase angles under the uniaxial compression (UCWR) and the uniaxial tension with rest period (UTWR) were determined. The phase angle is defined as the angle between the stress and strain wave signals at a certain load repetition. The phase angle between the stress and strain wave signals stems from the intrinsic time dependent asphalt mixture behavior. The phase angle is zero for a purely elastic material and 90 degrees for a purely viscous body.

The elastic modulus based on the recoverable strain (ε_r) under repeated loads is called the resilient modulus, Mr, defined as

$$Mr = \sigma_d / \varepsilon_r \quad (1)$$

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 specimen can be used for many tests under different loading and environmental conditions.

3.2 Dynamic Modulus and Phase Angle

The complex modulus test may be used to determine both the linear viscoelastic and elastic properties of pavement materials. The complex modulus, E^*, is defined as a complex number that relates stress to strain for a linear viscoelastic material subjected to a sinusoidal loading. The absolute value of the complex modulus, $|E^*|$, is commonly referred to as the dynamic modulus.

Dynamic moduli values of asphaltic materials are normally conducted on unconfined specimens using a uniaxially applied sinusoidal (haversine) stress pattern. Through recording equipment, axial strains are continuously monitored throughout the test. In this study, the dynamic

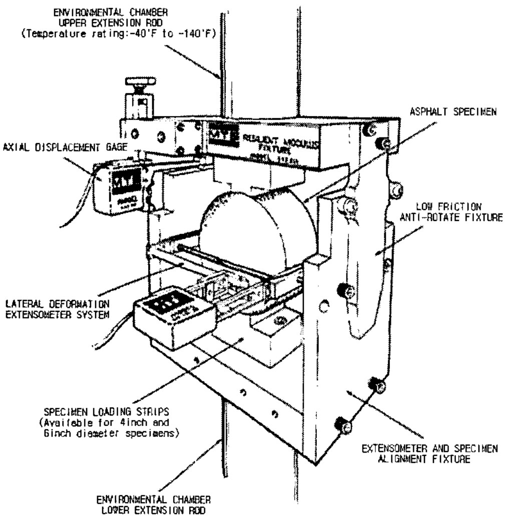


Fig. 1. Schematic drawing of indirect tensile resilient modulus fixture

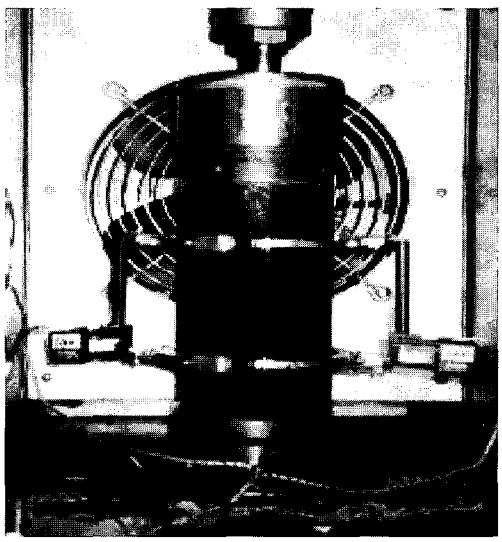


Fig. 2. Uniaxial modulus fixture

moduli under three types of loadings without rest period were determined. Those are uniaxial cyclic compression (UCNR), uniaxial cyclic tension (UTNR), and alternate tension–compression (TCNR). In addition, the three corresponding phase angles were measured.

The sinusoidal stress σ is:

$$\sigma = \sigma_0 \sin(\omega t) \qquad (2)$$

where σ_0 = Stress amplitude (psi),
ω = Angular frequency (radian per second), and
t = Time (second).

The resultant sinusoidal strain ε is:

$$\varepsilon = \varepsilon_0 \sin(\omega t - \varphi) \qquad (3)$$

where ε_0 = Recoverable strain and
φ = Phase angle (degree).

By definition, the complex modulus E^* is:

$$E^* = E' + i E'' \qquad (4)$$

where E'= Real portion of the complex modulus and
E''= Imaginary portion of the complex modulus.

Therefore, the dynamic modulus is defined as:

$$|E^*| = \sqrt{(E')^2+(E'')^2} \qquad (5)$$

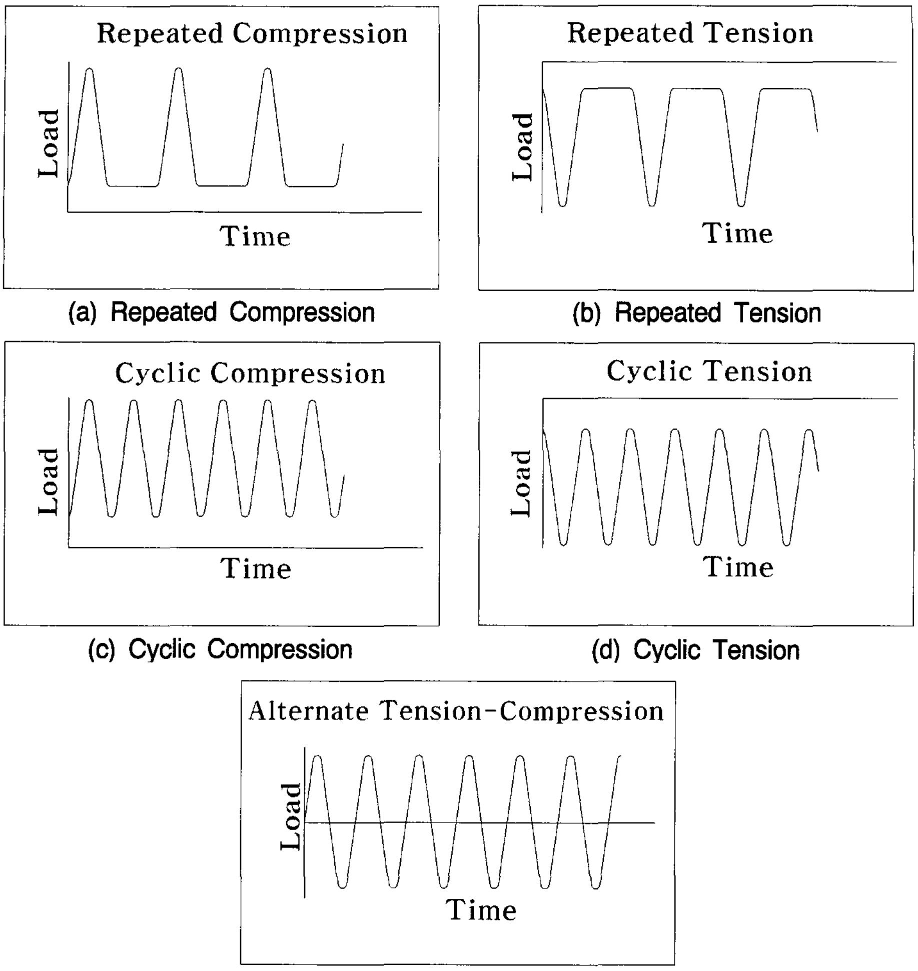
3.3 Experimental Design

The effect of five loading patterns on asphalt concrete moduli at different temperatures were investigated in this research: repeated uniaxial compression (UCWR), repeated uniaxial tension (UTWR), uniaxial cyclic compression (UCNR), uniaxial cyclic tension (UTNR), and alternate tension–compression (TCNR). In addition, the indirect tension test with rest period (ITWR) was conducted to evaluate the effect of testing method on moduli. Fig. 3 shows the five loading patterns used in the laboratory. The experimental design is presented in Table 3. Two specimens were used for each test combination and the moduli tests were replicated for each specimen. Therefore, a total of 12 specimens was used and 120 moduli tests were performed in this study. The tests were conducted from low to high temperature to minimize the possible specimen damage.

Haversine load with a 0.1 second load duration and a 0.9 second rest period was repeated for the repeated loading tests. The frequency for the cyclic and alternate loadings was 10Hz. The stress amplitude was kept constant throughout testing, and the corresponding deformations were recorded at the 200th cycle. The load levels used in this research were in the range of 5 to 30% of the indirect tensile strength at 68°F (20°C). That is, about 30% of the indirect tensile strength at 68°F (20°C) was used for the moduli tests at the low temperature (32°F (0°C)) and about 5% of the indirect tensile strength at 68°F (20°C) was used for the moduli tests at the high temperature (104°F (40°C)).

4. Test Results and Discussions

In uniaxial tension and compression tests due to the repeated haversine loading with rest period, asphalt concrete demonstrated similar moduli and phase angles in tension (UTWR) and compression (UCWR) at low temperatures (0 and 10°C (32 and 50°F)), but those moduli were different at high temperatures (20, 30, and 40°C (68, 86, and 104°F)). This can be attributed to the fact that at low temperatures, the asphalt binder has a high stiffness, and hence the modulus and phase angle, of the asphalt aggregate mixture. Thus, at low temperatures, asphalt concrete seems to behave similarly in tension and compression with rest periods. Figs. 4(a) and (b) present moduli comparisons



(a) Repeated Compression (b) Repeated Tension

(c) Cyclic Compression (d) Cyclic Tension

(e) Alternate Tension-Compression

Fig. 3. Loading patterns used in laboratory testings

Table 3. Experimental design for modulus and phase angle determination

Loading \ Parameter type	Resilient modulus	Dynamic modulus	Phase angle
UCWR	x		x
UTWR	x		x
ITWR	x		
UCNR		x	x
UTNR		x	x
TCNR		x	x

in asphalt concrete mixture under various sinusoidal loadings with and without rest period, respectively. Figs. 5(a) and (b) demonstrate phase angle comparisons with and without rest period, respectively.

In particular, the compressive moduli at high temperatures were always higher than the tensile moduli. However, the phase angles were vise versa though the differences were negligible. The difference between the tensile and compressive moduli and phase angles became more significant as the temperature increases. The reason for obtaining compressive moduli values higher than the corresponding tensile values at high temperatures can be explained by the fact that the tensile stiffness of the mixture is contributed mostly by the tensile resistance of the asphalt binder, whereas

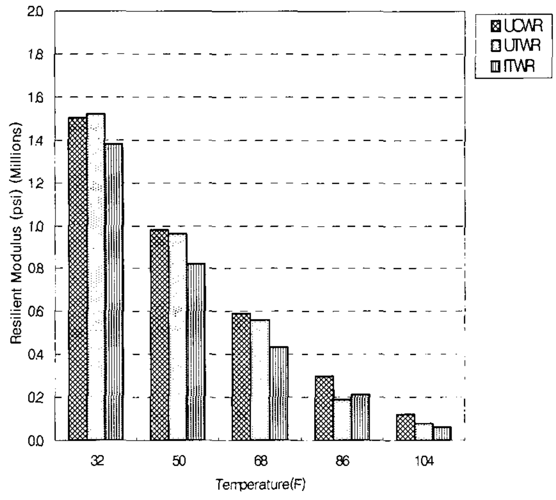


Fig. 4(a) Resilient modulus comparisons of loading with rest period

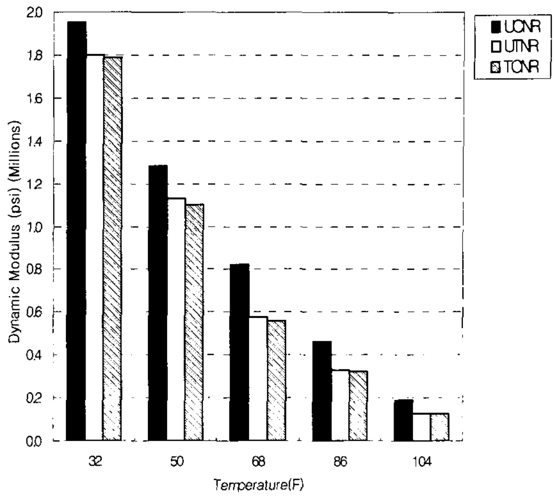


Fig. 4(b) Dynamic modulus comparisons of loadings without rest period

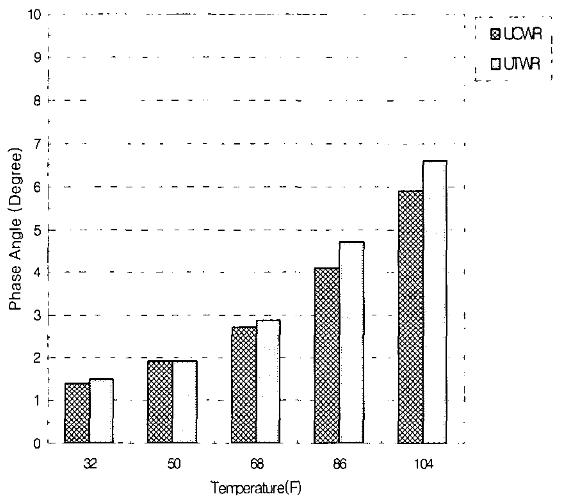


Fig. 5(a) Phase angle comparisons of loading with rest period

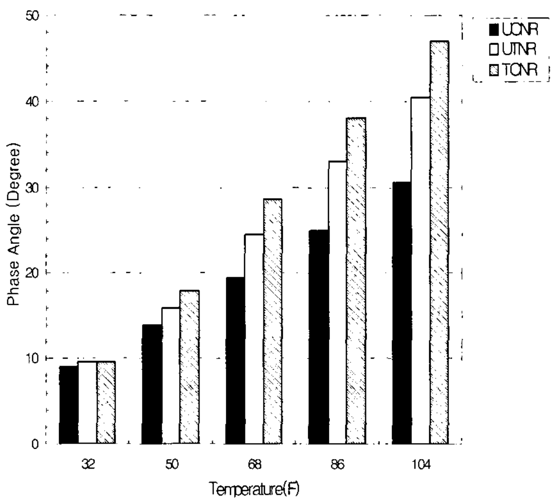


Fig. 5(b) Phase angle comparisons of loading without rest period

aggregate particles contribute very little. Since the stiffness of the asphalt is largely reduced at high temperature, the tensile modulus is also reduced. On the other hand, most of the load is carried by the aggregate particles when the mixture is subjected to compression, while the time-dependent viscoelastic material, asphalt binder, has little contribution. As a result, at high temperatures the copmpressive modulus was not largely reduced when compared to the tensile modulus. The comparison between the uniaxial tensile moduli and the indirect tensile ones showed that the uniaxial tensile moduli are higher than indirect tensile moduli at low temperatures (0, 10, and 20°C (32, 50, and 68°F)). However, those moduli were similar at high temperatures (30 and 40°C (86 and 104°F)).

In uniaxial cyclic tension (UTNR), compression (UCNR), and alternate tension-compression (TCNR) tests without rest period, compressive moduli were higher than tensile and alternate tensile-compressive moduli throughout the temperatures. The compressive moduli and alternate tensile-compressive moduli demonstrated similar values throughout the temperatures. However, general trend of the phase angles due to uniaxial cyclic loadings were vise versa with negligible differences. The UTNR phase angles were always higher than the UCNR phase angles. In addition, the TCNR phase angles were highest among other ones. It should be noted that the differences between the TCNR, UTNR, and UCNR phase angles become significant as the temperature increases. General trend of the dynamic moduli due to various uniaxial cyclic loadings can be explained similar ways as those in Fig. 5. That is, the tensile dynamic moduli of the mixture is contributed mostly by the tensile resistance of the asphalt binder, whereas aggregate particles play a major role in the compressive dynamic moduli of the mixture.

In order to evaluate the effect of different sinusoidal loadings on moduli of asphalt concrete in more detail, the test data in Figs. 4 and 5 were replotted in Figs. 6 and 7, respectively. Generally, the moduli from the repeated haversine loadings with rest period were always lower than those from the cyclic sinusoidal loadings. The difference in moduli from the repeated haversine loading with rest period and cyclic sinusoidal loading becomes more significant as the temperature decreases. It is noted that the additional data on moduli and phase angles except the temperature selected in this research can be obtained through an appropriate extrapolation method.

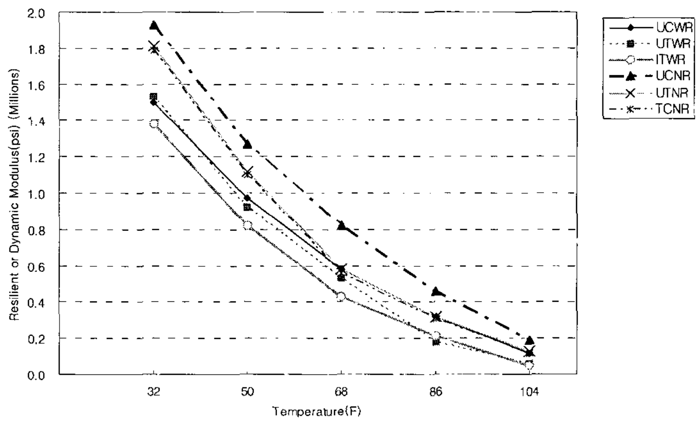


Fig. 6. Modulus comparisons of various sinusoidal loadings

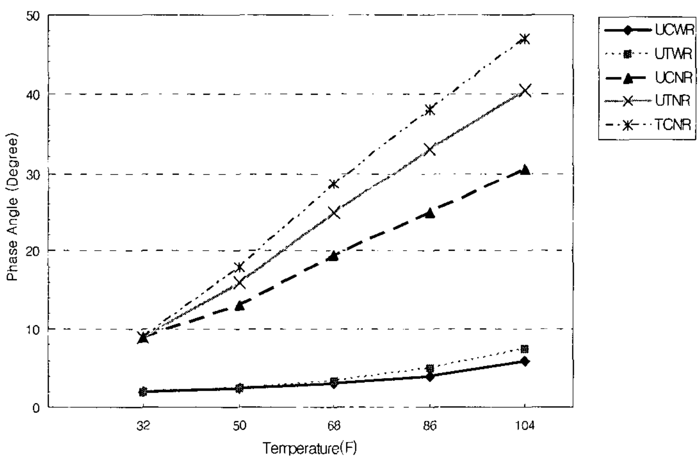


Fig. 7. Phase angle comparisons of various sinusoidal loadings

5. Conclusions

Based on the observations obtained from the various laboratory measurements, the following conclusions can be drawn:

(1) In uniaxial tension (UTWR) and compression (UCWR) tests due to the repeated haversine loading with rest period, asphalt concrete shows similar moduli in tension and compression at low temperatures, but those moduli were different at high temperatures. At high temperatures the compressive moduli were always higher than the tensile moduli. However, the phase angles were vise versa though the differences were negligible. The difference between the tensile and compressive moduli became more significant as the temperature increases.

(2) The uniaxial tensile (UTWR) moduli were higher than indirect tensile (ITWR) moduli at low temperatures. However, those moduli are similar at high temperatures.

(3) In uniaxial cyclic tension (UTNR), compression (UCNR), and alternate tension-compression (TCNR) tests without rest period, compressive moduli were higher than tensile and alternate tensile-compressive moduli throughout the temperatures. The compressive moduli and alternate tensile-compressive moduli demonstrated similar values throughout the temperatures. However, general trend of the phase angles due to uniaxial cyclic loadings were vise versa with noticeable differences.

(4) Generally, the moduli from the repeated haversine loading with rest period were always lower than those from the cyclic sinusoidal loading without rest period. The difference in moduli from the repeated haversine loading with rest period and cyclic sinusoidal loading without rest period became more significant when the temperature decreases.

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References

Harvey, J. (1990). Asphalt Concrete Specimen Preparation Protocol, SHRP Asphalt Project A-003A, Version 2.0, University of California at Berkeley.

Harvey, J., Sousa, J.B., Deacon, J.A., and Monismith, C.L. (1991). Effect of Sample Preparation and Air-Void Measurement on Asphalt Concrete Properties, 70th Annual Meeting, Transportation Research Board, Washing, D.C.

Khanal, P.P. and Mamlouk, M.S. (1995). Tensile versus Compressive Moduli of Asphalt Concrete, 74th Annual Meeting, Transportation Research Board, Washington, D.C.

Kim, N. (1994). Development of Performance Prediction Models for Asphalt Concrete Layers, Ph.D. Dissertation, North Carolina State University, Raleigh, North Carolina.

Kim, N. and Im, J.S. (1996). Factors Influencing Resilient Modulus of Asphalt- Aggregate Mixture, Journal of Korean Society of Civil Engineers, Vol.16, No.III-2, pp. 121-129.

Kim, N. (1999). Multi-Laboratory Validation Study on Resilient Modulus of Asphalt Concrete using SHRP LG Device, Journal of Korean Society of Civil Engineers, Vol.3, No.1, pp. 47-55.

Kim, Y.R. and Lee, Y.C. (1992). Characterization of Damage Growth in Asphalt Concrete, Final Report Submitted to Texas A&M Research Foundation, Department of Civil Engineering, North Carolina State University.

Monismith, C.L. and Secor, K.E. (1962).

Viscoelastic Behavior of Asphalt Concrete Pavements, Proceedings International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, MI.

Pister, K.S. and Westman, R.A. (1962). Analysis of Viscoelastic Pavements Subjected to Moving Loads, Proceedings International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, MI.

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