EVALUATION OF RESILIENT MODULUS ESTIMATION METHODS FOR ASPHALT MIXTURES BASED ON LABORATORY MEASUREMENTS

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EVALUATION OF RESILIENT MODULUS ESTIMATION METHODS FOR ASPHALT MIXTURES BASED ON LABORATORY MEASUREMENTS

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ABSTRACT

EVALUATION OF RESILIENT MODULUS ESTIMATION METHODS FOR ASPHALT MIXTURES BASED ON LABORATORY MEASUREMENTS

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Resilient modulus is a property for bound and unbound pavement materials characterizing the elastic behavior of materials under dynamic repeated loading. Resilient modulus is an important design parameter for pavement structures because it represents the structural strength of pavement layers through which the thickness design is based on. In Turkey, the layer thickness design is performed using resilient modulus determined empirically from various published sources. Determining a layer modulus using empirical methods causes inaccurate design solutions, which directly affects the structural performance and the overall cost of pavement construction. In this study, the resilient moduli of bituminous mixtures are measured in the laboratory by the indirect tensile test procedure for eight asphalt concrete samples according to NCHRP and ASTM procedures. The measured moduli of samples based on the two procedures are compared with the predicted values calculated from various empirical methods using aggregate and binder properties. An evaluation of each estimation method is presented on the basis of its accuracy level. The results show that the Witczak predictive equation produces the closest estimation to the modulus of samples for both laboratory measurement methods.

Key words: Resilient Modulus, Indirect Tension Test, Mix Stiffness

ÖZ

ESNEKLİK MODÜLÜ TAHMİN YÖNTEMLERİNİN LABORATUVAR DENEY SONUÇLARINA DAYANARAK DEĞERLENDİRİLMESİ

Demirci, Canser
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Esneklik modülü bağlayıcılı be bağlayıcısız üstyapı malzemeleri için dinamik tekrarlı yükler altında elastik davranışını gösteren bir özelliktir. Esneklik modülü üstyapı malzemelerinin kalınlık dizaynı yapılırken kullanılan yapısal dayanımını göstermesinden dolayı üstyapı için önemli bir parametredir. Türkiye'de tabaka kalınılk dizaynı yapılırken esneklik modülü yayınlanmış çeşitli kaynaklardan ampirik olarak alınır. Ampirik olarak elde edilen bir tabaka modülünün kullanılması üstyapının yapısal dayanımını ve toplam maliyetini direk olarak etkileyen hatalı dizayn sonuçlarına neden olabilir. Bu çalışmada bitümlü karışımların esneklik modülleri, sekiz farklı karışım için laboratuvarda indirek çekme deneyi ile ölçüldü. Numunelerin ölçülen modülleri agrega ve bitüm özelliklerini kullanan çeşitli ampirik yöntemlerle tahmin edilen değerlerle karşılaştırılılmıştır. Her bir tahmin yönteminin değerlendirilmesi, doğruluk derecesine bağlı olarak sunulmuştur. Sonuçlar, Witczak tahmin denklemlerinin deney ölçümlerine en yakın sonuçları verdiğini göstermektedir.

Anahtar kelimeler: Esneklik Modülü, İndirekt Çekme Deneyi, Karışım Rijitliği

To my family.

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LIST OF SYMBOLS

AASHTO:	American Association of State Highway and Transportation officials
ASTM:	American Society of Testing and Materials
HMA:	Hot Mix Asphalt
ITT:	Indirect Tension Test
LVDT:	Linear Variable Displacement Transducers
METU:	Middle East Technical University
NCHRP:	National Cooperative Highway Research Program
PMB:	Polimer Modified Bitumen
UMATTA:	Universal Materials Testing Apparatus
SMA:	Stone Mastic Asphalt
STRCT:	Scientific and Technological Research Council of Turkey
TGDH:	Turkish General Directorate of Highways

CHAPTER 1

INTRODUCTION

1.1 Background

In order to design a long lasting pavement, it is very important to estimate the actual field conditions in design phase of asphalt concrete pavements. For example, better structural performance depends on a good projection of future traffic and accurate representation of field conditions, i.e., temperature. Traffic loads are represented by cyclic loads in the performance testing of asphalt mixtures, and the resilient modulus is used to describe the stress-strain behavior of asphalt concrete under cyclic traffic loading. It is the most important material parameter in the design process of asphalt concrete pavements characterizing the entire structural performance of pavement structure. Hence, the accurate estimation of resilient modulus directly affects the layer thickness, service life and the overall cost of the pavement construction.

In Turkey, according to the Highway Flexible Pavement Design Guide published by the Turkish General Directorate of Highways, which is based on AASHTO 1993 design procedures, the resilient modulus of structural layers are used to estimate the layer coefficients hence layer thicknesses. These resilient modulus values are estimated from various nomographs or empirical relations, which are questionable in terms of reliability and accuracy. It is obvious that a deviation between the estimated and the actual modulus may easily cause inaccurate design solutions. Hence, the Turkish General Directorate of Highways (TGDH) started a research project that was funded by the Scientific Technological Research Council of Turkey's (STRCT) under the project 105G021 "Adaptation of Resilient Modulus to Mechanistic-Empirical Design Specifications of Flexible Pavements". A major portion of this project was assigned for testing resilient modulus of bound, i.e., asphalt concrete, materials. A comparison of various empirical methods is conducted based on this research outcomes, and the method leading to the closest approximation to the measured modulus values are presented accordingly.

1.2 Objective of the Study

The objective of this study is (i) to determine the resilient modulus of Hot Mix Asphalt (HMA) mixtures which are prepared by different aggregate and bitumen types suggested in the Turkish General Directorate of Highways design guidelines; (ii) to estimate the resilient modulus of the HMA mixtures by empirical methods; iii) to compare the results obtained by laboratory measurements and estimation methods and; (iv) to choose the empirical method that best approximates the laboratory measurements by comparing the results.

1.3 Scope

This study consists of three main parts: First part is the determination of resilient modulus of HMA mixtures used in the design of asphalt concrete pavements in Turkey. For this purpose, eight different types of mixtures which are used in Turkey were prepared and subjected to the resilient modulus testing in TGDH Technical Research Department Laboratories. The tests were conducted according to the NCHRP 1-28A guidelines using an UTM-100 machine under 25 ^{0}C temperature. The resilient modulus values were calculated according to both NCHRP 1-28A and ASTM D4123-82 procedures.

The second part includes the estimation of resilient modulus of bituminous mixtures by nomographs and empirical equations. The nomographs and the equations are used to calculate the resilient modulus values based on various volumetric and rheological properties of mix constituents, i.e., aggregate and asphalt binder.

Finally, in the third part, a discussion is given on the reliability and the accuracy of both empirical and graphical methods in estimating the measured resilient modulus values.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, various literatures taken from different sources about resilient modulus and materials characteristics are presented. In the first part, the definition and the determination of resilient modulus are elaborated. Then, information about the bitumen and aggregate characteristics is given. Finally, the determination of HMA mix stiffness by using bitumen stiffness is explained.

2.2 Resilient Modulus

The AASHTO Pavement Design Guide (1993), in addition to other revisions, incorporated the resilient modulus (MR) concept to characterize pavement materials subjected to moving traffic loads. MR values may be estimated directly from laboratory testing, indirectly through correlation with other laboratory/field tests, or back calculated from deflection measurements. The testing procedure for the determination of MR consists of the application of a repeated deviator stress (σ_d), under a constant cell pressure and then measuring the resilient axial strain. Under repeated load tests, it is observed that as the number of load cycles increases, the secant modulus increases. After a number of load cycles, the modulus becomes nearly constant, and the response can be presumed to be elastic. This steady value of modulus is defined as the resilient modulus (Rahim A.M., 2005).

The actual resilient response of a material under repeated loading can be determined after a certain number of load applications since there would be considerable permanent deformation within the early stages. As the number of load applications increases, the plastic strains due to load repetition decreases (Huang, 1993). Thus, the resilient modulus for a certain sequence is determined using the last 5 measurements out of 100 readings. The resilient modulus is defined as the ratio of the applied deviatoric stress to the recoverable elastic vertical strain. Figure 2.1 shows the elastic and plastic responses under the repeated loads. It can be observed from the figure that the permanent deformation rate approaches to zero with the increasing number of load repetitions (Çöleri E., 2007).

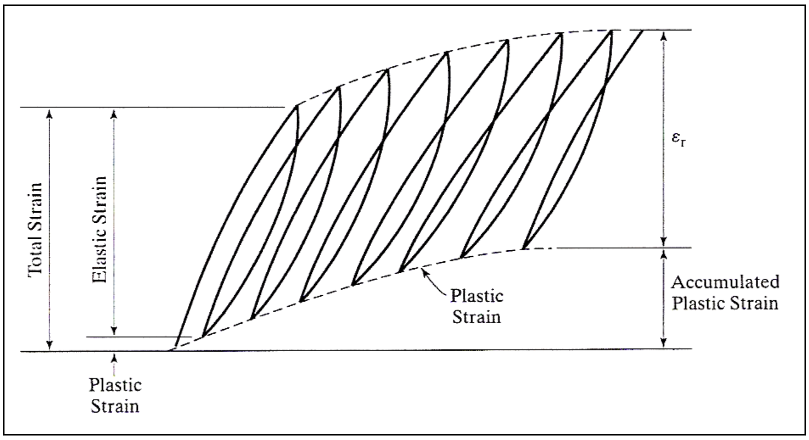


Figure 2.1 Elastic and Plastic Responses under Repeated Loads (Huang, 1993)

The resilient modulus of HMA mixtures are used to estimate layer relative strength coefficient (a) that is used for the calculation of SN number which allows for determining layer thicknesses.

2.3 Determination of Resilient Modulus

Stiffness modulus of bituminous mixes can either be measured in the laboratory or predicted from properties of mix components, namely, aggregate and bitumen. There are a number of well known empirical models that were developed by various researchers and relate resilient modulus to bituminous mix properties (Suhaibani et al., 1997). Since, carrying out resilient modulus tests is difficult and the devices are very expensive, generally empirical methods are used and published in pavement design. Both of these methods will be evaluated in the following chapters.

The resilient modulus is the elastic modulus used in the layered elastic theory for pavement design. Hot mix asphalt is known to be a viscoelastic material and, therefore, experiences permanent deformation after each application of load cycle. However, if the load is small compared to the strength of the material and after a relatively large number of repetitions (100 to 200 load repetitions), the deformation after the load application is almost completely recovered. The deformation is proportional to the applied load and since it is nearly completely recovered it can be considered as elastic.

For unbound materials, the resilient modulus is based on the recoverable strain under repeated loading and is determined as follows:

$$M_r = \frac{\sigma_\mathrm{d}}{\varepsilon_r} \tag{2.1}$$

where σ_d is the deviator stress and ε_r is the recoverable (resilient strain). Because the applied load is usually small compared to the strength of the specimen, the same specimen may be used for the same test under different loading and temperatures (Katicha W.S., 2003)

The resilient modulus can be performed on laboratory prepared specimens or field cores. For consistency in design, results obtained from laboratory prepared specimens should match with results obtained from field cores (Katicha W.S., 2003)

2.4 Resilient Modulus Test

Resilient modulus testing, developed by Seed et al. (1962), aims to determine an index that describes the nonlinear stress-strain behavior of soils under cyclic loading. Resilient modulus is simply the ratio of the dynamic deviatoric stress to the recovered strain under a standard haversine pulse loading. Mechanistic design procedures for pavements and overlays require resilient modulus of unbound pavement layers to determine layer thickness and the overall system response to traffic loads. In AASHTO specification T-274 (1982) based on the mechanistic methods, resilient modulus is considered as an important design input parameter. After this specification, AASHTO TP46, T292, T294 and T307 specifications were also published as improvements were made over the years in the test procedures (Çöleri, E., 2007)

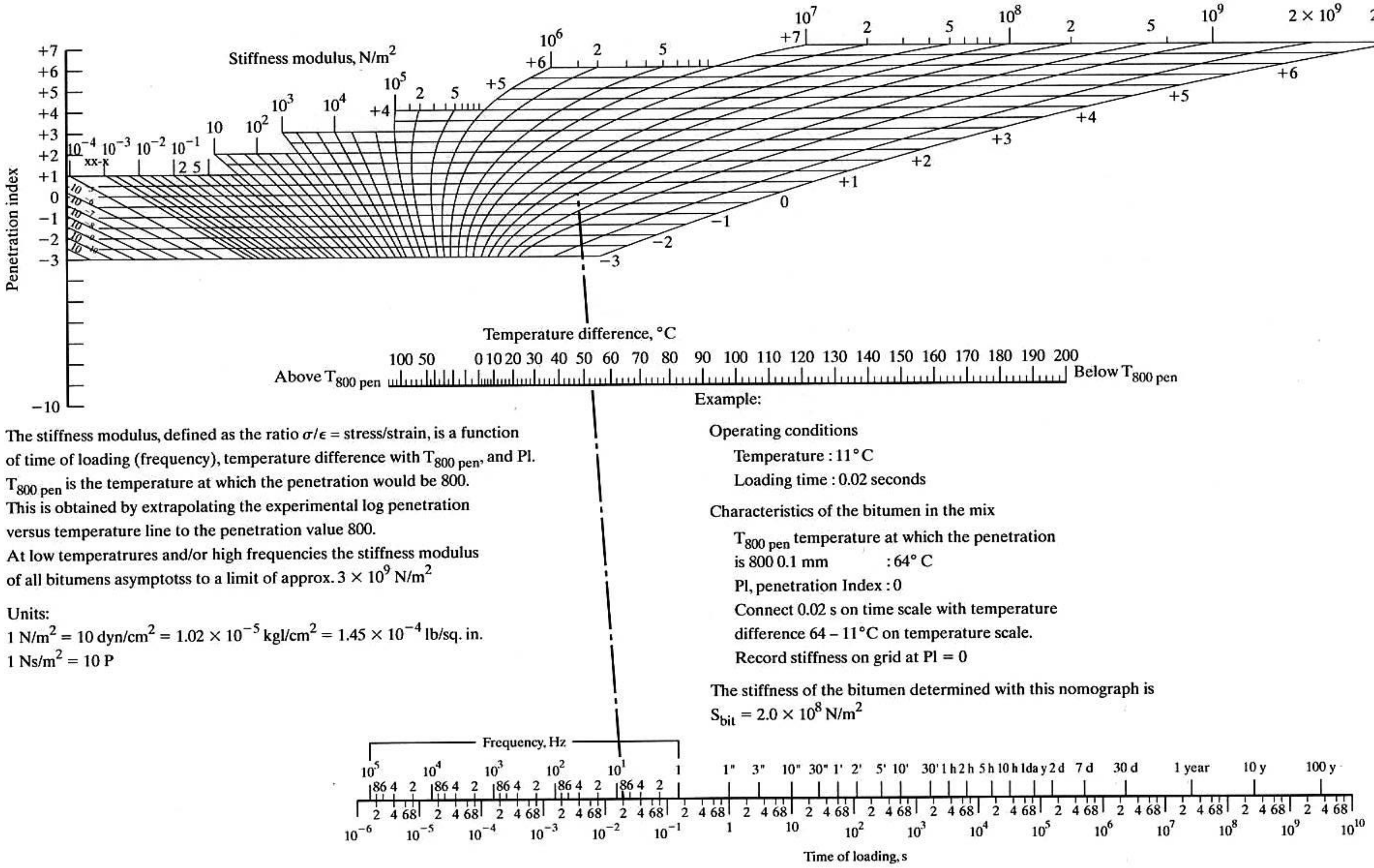
Different test methods and equipment have been developed and employed to measure these different moduli. Some of the tests employed are triaxial tests (constant and repeated cyclic loads), cyclic flexural test, indirect tensile tests (constant and repeated cyclic load), and creep test. Baladi and Harichandran indicated that resilient modulus measurement by indirect tensile test is the most promising in terms of repeatability. Resilient modulus measured in the indirect tensile mode (ASTM D 4123-82) has been selected by most engineers as a method to measure the resilient modulus of asphalt mixes (Brown et al., 1989)

NCHRP (National Cooperative Highway Research Program) Project 1-28A "Recommended Standard Test Method For Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension" is the latest method in AASHTO standard format.

2.5 Stiffness of the Bitumen

Stiffness of the bitumen used in the mix is an important parameter that affects the stiffness of the mix directly.

Van Der Poel developed one of the first stiffness prediction models for asphalt concrete (Figure 2.2). It is one of the most commonly used models to predict the stiffness modulus of bitumen as a function of time of loading, the penetration index, and the temperature at which the penetration of the bitumen is 800 (Suhaibani et al., 1997).



The stiffness modulus, defined as the ratio σ/ϵ = stress/strain, is a function of time of loading (frequency), temperature difference with $T_{800\ pen}$, and PI.
$T_{800\ pen}$ is the temperature at which the penetration would be 800.
This is obtained by extrapolating the experimental log penetration versus temperature line to the penetration value 800.
At low temperatrures and/or high frequencies the stiffness modulus of all bitumens asymptotss to a limit of approx. 3 × 10^9 N/m^2

Units:
1 N/m^2 = 10 dyn/cm^2 = 1.02 × 10^{-5} kgl/cm^2 = 1.45 × 10^{-4} lb/sq. in.
1 Ns/m^2 = 10 P

Example:

Operating conditions
Temperature : 11°C
Loading time : 0.02 seconds

Characteristics of the bitumen in the mix
$T_{800\ pen}$ temperature at which the penetration is 800 0.1 mm : 64° C
PI, penetration Index : 0
Connect 0.02 s on time scale with temperature difference 64 – 11°C on temperature scale.
Record stiffness on grid at PI = 0

The stiffness of the bitumen determined with this nomograph is
S_{bit} = 2.0 × 10^8 N/m^2

Figure 2.2 Van Der Poel Nomograph (After Huang, 2004)

Van Der Poel also developed the following equation in order to calculate the stiffness of the bitumen.

$$\mathrm{M_R} = 1.157 \times 10^{-7} \times \mathrm{t_w}^{-0.368} \times e^{-PI} \times (\mathrm{T_{RB}} - T)^5 \qquad (2.2)$$

where,
Mr : Stiffness of the bitumen,
T_w : Time of loading,
T_{RB} : Softening point,
T : Test temperature,
PI : Penetration index

In this equation, the characteristics of the bitumen are expressed as a penetration index, PI, defined as

$$\mathrm{PI} = \frac{20 - 500\mathrm{A}}{1 + 50\mathrm{A}} \qquad (2.3)$$

In which A is the temperature susceptibility, which is the slope of the straight line plot between the logarithm of penetration (abbreviated as pen) and temperature

$$\mathrm{A} = \frac{\log(\text{Pen at } \mathrm{T_1}) - \log(\, penatT_2\,)}{T_1 - T_2} \qquad (2.4)$$

If we replace T_2 by T_{RB} and write 800 instead of log (Pen at T_2), the equation becomes

$$\mathrm{A} = \frac{\log(\text{Pen at T}) - \log(800)}{T - T_{RB}} \qquad (2.5)$$

2.6 Estimation of Resilient Modulus of Asphalt Mixture

The resilient modulus of bituminous mixtures can also be determined by nomographs and some empirical equations that use stiffness of the bitumen, volume of the bitumen and the aggregate in the mixture.

Shell Nomograph (1977)

Figure 2.3 shows the nomograph for determining the stiffness modulus of the bituminous mixtures (Bonnaure et al.,1977) Three factors considered are the stiffness modulus of bitumen, the percent volume of bitumen and the percent volume of aggregate.

The percent volume of aggregate V_g is

$$V_g = \frac{(1-P_b)W/G_g}{W/G_m} \times 100 = \frac{100(1-P_b)G_m}{G_g} \tag{2.6}$$

The percent volume of bitumen V_b is

$$V_b = \frac{P_b W/G_b}{W/G_m} \times 100 = \frac{100P_b G_m}{G_b} \tag{2.7}$$

The percent volume of air void V_a is

$$V_a = 100 - V_g - V_b \tag{2.8}$$

where,

G_m : The bulk specific gravity of mixture

W : Total weight of mixture

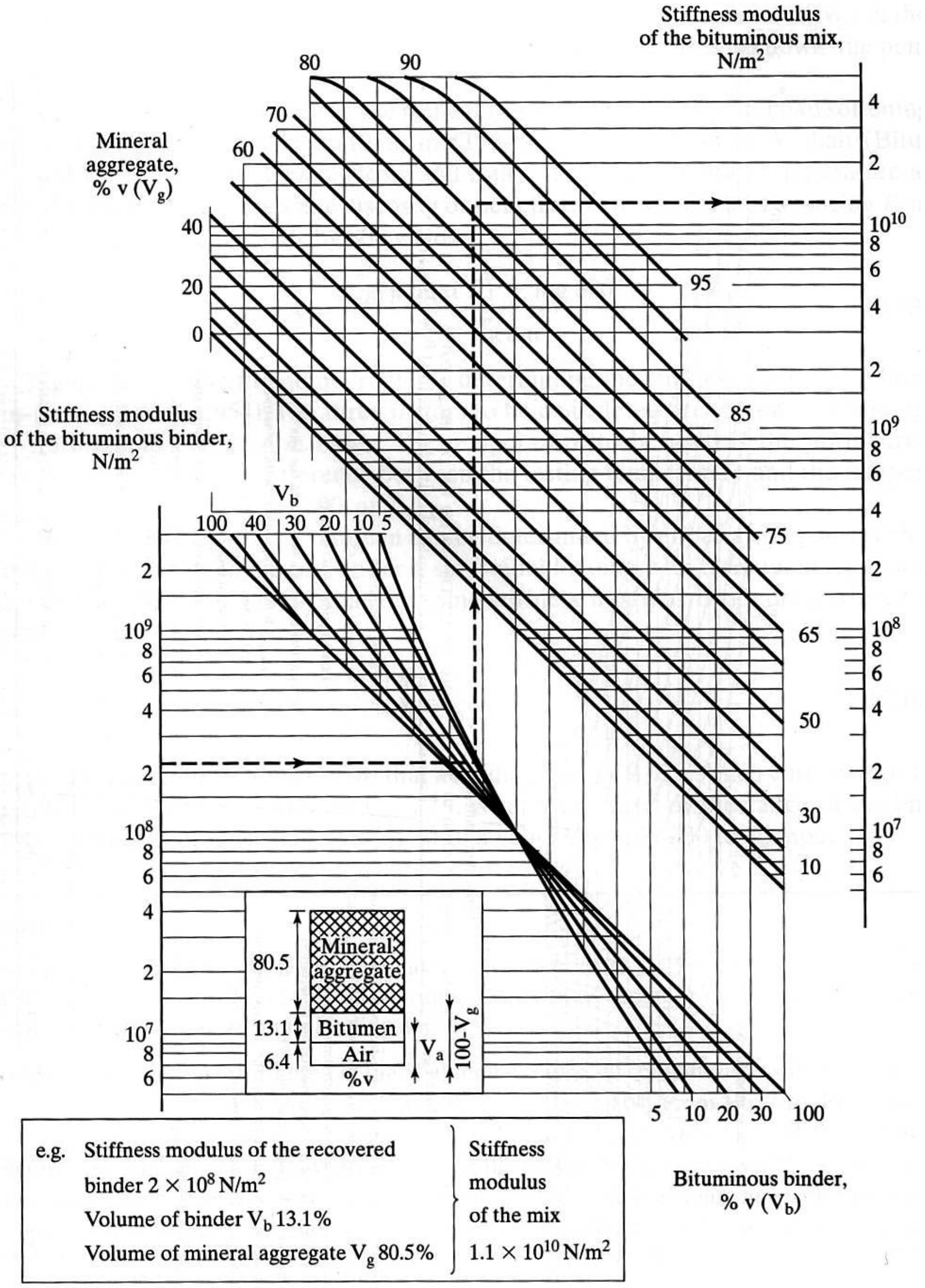


Figure 2.3 Shell Nomograph (After Huang, 2004)

Bonnaure et al. Equation (1977)

Bonnaure et al. (1977) also developed the following equation for predicting the resilient modulus of mix S_m, based on V_g, V_b, and S_b (Huang, 1993)

$$\beta_1 = 10{,}82 - \frac{1{,}342(100 - V_g}{V_g + V_b} \qquad (2.9)$$

$$\beta_2 = 8{,}0 + 0{,}0568V_g + 0{,}0002135V_g^2 \tag{2.10}$$

$$\beta_3 = 0{,}6\log(\frac{1{,}37\mathrm{V}_\mathrm{b}^2 - 1)}{1{,}33V_b - 1} \tag{2.11}$$

$$\beta_4 = 0{,}7582(\beta_1 - \beta_2) \tag{2.12}$$

For 5 x 10^6 N/m^2<S_b<10^9 N/m^2

$$\log S_m = \frac{\beta_1 + \beta_3}{2}(\log S_b - 8) + \frac{\beta_4 - \beta_3}{2}\left|\log S_b - 8\right| + \beta_2 \tag{2.13}$$

For 10^9 N/m^2<S_b<3 x 10^9 N/m^2

$$\log S_m = \beta_2 + \beta_4 + 2{,}0959(\beta_1 - \beta_2 - \beta_4)\log(S_b - 9) \tag{2.14}$$

Heukelom and Klomp Equation (1964)

Heukelom and Klomp developed the following equation by the help of Van Der Poel’s studies (Uluçaylı, 1975; Ullidtz, 1987).

$$\mathrm{E} = S_b \times [1 + 2{,}5/n) \times C_v' /(1 - C_v)]^n \tag{2.15}$$

In this equation C^1_v is the aggregate volume concentration and is calculated by equation:

$$\mathrm{C}_\mathrm{v}^1 = C_v /[0{,}97 + 0{,}01(100 - (V_g - V_b))] \tag{2.16}$$

$$\mathrm{C}_\mathrm{v} = V_g /(V_g + V_b) \tag{2.17}$$

$$\mathrm{n} = 0{,}83 \times \log(40000MP_a / S_b) \tag{2.18}$$

Asphalt Institute (1979) Equations

In developing the DAMA computer program for the Asphalt Institute, Hwang and Witzack (1979) applied the following regression formulas to determine the dynamic modulus of HMA, $|E^*|$:

$$\left|E^*\right| = 100000 \times 10^{\beta_1} \tag{2.19}$$

$$\beta_1 = \beta_3 + 0.000005\beta_2 - 0.00189\beta_2 f^{-1.1} \tag{2.20}$$

$$\beta_2 = \beta_4^{0.5} T^{\beta_5} \tag{2.21}$$

$$\begin{aligned} \beta_3 = 0.553833 + 0.028829\left(P_{200} f^{-0.1703}\right) - 0.03476 V_a + \\ 0.070377\lambda + 0.931757 f^{-0.02774} \end{aligned} \tag{2.22}$$

$$\beta_4 = 0.483 V_b \tag{2.23}$$

$$\beta_5 = 1.3 + 0.492825 \log f \tag{2.24}$$

In these equations, β_1 to β_5 are temporary constants, f is the load frequency in Hz, T is the temperature in ^{0}F, P_{200} is the percentage by weight of aggregate passing through a No.200 sieve, V_v is the volume of air void in %, λ is the asphalt viscosity at 70 ^{0}F in 10^6 poise, and V_b is the volume of bitumen in %. If sufficient viscosity data are not available to estimate λ at 70 ^{0}F, one may use the equation

$$\lambda = 29508.2\left(P_{77^0 F}\right)^{-2.1939} \tag{2.25}$$

In which P_{77^0F} is the penetration at 77 ^{0}F (25^{0}C). (Huang, 1993)

Witczak Predictive Equation (2000)

After this first study, Witczak and Fonseca (1995) propose an empirical model to predict the complex modulus of an asphalt mixture. The proposed model for complex modulus master curve was generated based on a large amount of data consisting of 1429 points from 149 separate asphalt mixtures. Improvements were made to earlier models, taking into account hardening effects from short- and long-term aging, as well as extreme temperature conditions. Based on the gradation of aggregates in the mixture and asphalt binder properties, the final dynamic modulus model developed from this statistical study is given as (Minnesota Department of Transportation, 2003):

$$\log\left|E^*\right| = -0.261 + 0.008225P_{200} - 0.00000101(P_{200})^2 + 0.00196P_4 - \\ 0.03157V_a - 0.415\frac{V_{beff}}{(V_{beff} + V_a)} + \\ \frac{\left[1.87 + 0.002808P_4 + 0.00000404P_{38} - 0.0001786(P_{38})^2 + 0.0164P34\right]}{1 + e^{(-0.716\log f - 0.7425\log\eta)}} \tag{2.26}$$

where,

|E*| = asphalt mix dynamic modulus, in 10^5 psi;

η = bitumen viscosity, in 10^6 poise;

f = load frequency, in Hz;

V_a = percent air voids in the mix by volume;

V_{beff} = percent effective bitumen content by volume;

P_{34} = percent retained on ¾-in. sieve by total aggregate weight (cumulative);

P_{38} = percent retained on 3/8-in. sieve by total aggregate weight (cumulative);

P_4 = percent retained on #4 (4.75-mm) sieve by total aggregate weight (cumulative); and

P_{200} = percent passing #200 (0.075-mm) sieve by total aggregate weight.

With the accumulation of more and more test data, Dr. Witczak developed a new predictive equation for the dynamic modulus based on Equation (2.26). The new model is shown in equation (2.27) (Minnesota Department of Transportation, 2003) where the parameters and definitions shown in Equation (2.27) are the same as for Equation (2.26).

$$\log\left|E^*\right| = -1.249937 + 0.029232P_{200} - 0.001767(P_{200})^2 + 0.002841P_4 - \\ 0.058097V_a - 0.802208\frac{V_{beff}}{(V_{beff} + V_a)} + \\ \frac{\left[3.871977 + 0.0021P_4 + 0.003958P_{38} - 0.00017(P_{38})^2 + 0.0547P_{34}\right]}{1 + e^{(-0.603313 - 0.313351\log f - 0.393532\log\eta)}} \tag{2.27}$$

CHAPTER 3

MATERIALS AND METHODS

3.1 Introduction

The main objective of this chapter is to discuss the materials and test methods involved in this study. Eight different HMA mixtures were prepared for the resilient modulus experiments. The characteristics of aggregates and bitumen used in mixtures are presented in details. The test results applied to mixtures before and after compaction are given. The method of specimen preparation and compaction is described briefly. Information about the indirect tension test that is used for the determination of resilient modulus of bituminous mixtures is discussed.

3.2 Materials Used For Experiments

In this study, Kırıkkale B50/70 bitumen and modified bitumen with 5% SBS are used as binding material. Basalt and limestone are chosen in the design of test mixtures. These materials are mixed in eight different combinations according to mixture types used in our country. Aggregates were taken from various highway construction sites in Turkey and prepared for the desired gradations. The characteristics of bitumen and aggregates are also presented in the subsequent sections.

3.2.1 Aggregate Characteristics

In this study, resilient modulus of wearing course, binder course, bituminous base course, and stone mastic asphalt layers are measured using hot mix asphalt mixtures having different gradation and different bitumen type. In this respect, in wearing course both basalt and limestone, in SMA only basalt, in binder, and bituminous base layers only limestone aggregates are used. Since basalt is a stronger aggregate type, it is generally used for surface layers and limestone is preferred bottom structural layers. The gradation and characteristics of the aggregates are shown in Table 3.1

Table 3.1 The gradation and mixture design values

DESİGN CRITERIAS			Mixture Types				
			SMA	**Basalt Wearing**	**Limestone Wearing**	**Limestone Binder**	**Limestone Bitum. Base**
Optimum bitumen content (to 100 gr dry aggregate), (%)			6.5	5.25	5.25	5	4.5
Specific Gravity, Dp, (gr/cm3)			2.458	2.473	2.356	2.360	2.348
Stability, kg			561	1140	1260	1190	920
Voids filled by asphalt, %			79	75	72.4	67	59.7
Void Ratio, Vh (%)			3.53	3.66	4.13	4.7	5.61
Flow (mm)			3.47	2.92	3.4	3.1	3.2
Voids in the mineral agg., VMA (%)			16.81	14.6	14.9	14.1	13.9
SIEVE ANALYSIS	**Sieve size**		% Passing				
	mm	**inch**					
	37.5	**1 1/2"**	100	100	100	100	100
	25.4	**1"**	100	100	100	100	86.2
	19.1	**3/4"**	100	100	100	92.7	74.3
	12.7	**1/2"**	95.2	90	90	72.7	62.4
	9.52	**3/8"**	62.0	80	78.8	61.8	55.6
	4.76	**No.4**	33	45	48.2	48.6	44
	2	**No.10**	23.7	32	27	29.6	27.3
	0.42	**No.40**	15	15	11.7	13	11.9
	0.177	**No.80**	12	9	8.3	9	7.6
	0.075	**No.200**	9	7	5.6	5.8	5.1

The specific gravities of Basalt and limestone aggregates were measured as 2.82 and 2.65, respectively. The percent volume of bitumen and aggregates given in the Table 3.1 are calculated by using Equations 2.6. and 2.7.

3.2.2 Bitumen Characteristics

For the resilient modulus tests, for the wearing and SMA mixtures both unmodified (B50/70) and modified (5% SBS) bitumens are used, and for the binder and bituminous base mixtures only base (unmodified) bitumen is used. It is known that polymers modifiers increase the penetration index of bitumen, hence the bitumen becomes generally more resistant to higher and lower service temperatures. When these preferences are made then the modified bitumen is used only for surface layers in Turkey. The characteristics of Kırıkkale B50/70 bitumen and 5% SBS added modified bitumen are given in Table 3.2. In the table, even though the performance grade of the bitumens are listed, in the following chapters the penetration index of these bitumens are also calculated.

Table 3.2 Bitumen Characteristics (Güngör A. G., Orhan F., and Kaşak S, 2009)

BITUMEN CHARACTERISTICS						
	Bitumen Type		B50/70		PMB	
Original Bitumen	Penetration (0.1mm)		63		46	
	Softening Point (°C)		48.8		81.2	
	Brookfield Viscosity 135°C,20rpm	cP	373		335	
	DSR (G*/sinδ>1kPa)	Failure temperature	66.8		80	
		Class	64		76	
RTFOT	Mass Loss	%	0.02			
	DSR (G*/sinδ >2.2 kPa)	Failure temperature	67.6		76	
		Class	64		76	
PAV	DSR (G*sinδ <5000 kPa)	Failure temperature	20.3			
		Class	22			
	BBR (Bending Beam Rheometer)		S (MPa)	m-value	S (MPa)	m-value
	Temperature (S<300MPa m>0,300)	-6 °C			85.2	0.353
		10 °C^	179	0.302	217	0.264
			136	0,338		
		i q °r^	287	0,278	403	
			272	0,274	405	
PG			**64-22**		**76-16**	

3.2.3 Specimen Preparation

The following table shows the material combinations used in the mixtures briefly. (The used materials are shown by X).

Table 3.3. Experimental design for the resilient modulus tests

	Wearing		**Stone Mastic Asphalt**		**Binder**		**Bituminous Base**	
	B 50/70	PMB (5 % SBS)	B 50/70	PMB (5 % SBS)	B 50/70	PMB (5 % SBS)	B 50/70	PMB (5 % SBS)
Basalt	X	X	X	X	-	-	-	-
Limestone	X	X	-	-	X	-	X	-

The aggregates which have various sizes are taken from highway construction sites and blended to obtain the target gradation curves.

For the sieve analysis, the weights of the necessary amount of aggregates are determined and put into the sieves (Figure 3.1). Then, the sieving operation was carried out using a shaking table. After the sieving operation the weight of aggregates remained on each sieve is measured to find the percent amount passing. By means of these percents, the gradation of the aggregates is established and inspected whether it compiles with the necessary standards.

Figure 3.1 Sieves used in the laboratory

Figure 3.2 Aggregates used in HMA design

After obtaining the desired gradations, the bitumen is mixed with aggregates by using a mixer as shown in Figure 3.3. The container of the mixer is capable of rotating around its axis and moving at a certain amount of offset relative to its axis, hence achieving a good mixing operation. During the mixing process, it is important to observe that all aggregates be coated with the bitumen.

During the mixing process, a spatula was used for removing the asphalt particles sticking at the sides of the container in order to make sure that no fine particles were lost during the mixing process. The speed of the mixer should be adjusted in such a way that it is neither too slow causing the mix to cool down nor so fast that its movement may result in throwing of asphalt particles out of the container (Gül, 2008)

The optimum bitumen contents as determined from the previous studies are used when preparing the test briquettes. The design details and gradation limits for these mixtures are given in Table 3.1.

Figure 3.3 Mixer used in preparing test mixtures

Briquettes were compacted using a gyratory compactor meeting the design criteria for 8 different mixtures. The mix is put in a cylindrical metal mold (Figure 3.4) and the mold is placed into the gyratory compactor (Figure 3.5). Gyratory compactor compacts the mix by kneading action (Figure 3.6), achieving a mixture that is more representative of field compacted mixture. One advantage of using gyratory compactor is to be able to compact mixture to a desired density.

Figure 3.4 Mold used for preparing briquettes

Figure 3.5 Gyratory compactor

Figure 3.6 the place of the mold in the gyratory compactor

After the compaction process is completed, the weights of the briquettes are measured before putting them into the water. The weights of samples in the water are also measured in order to calculate the specific gravity. The specific gravities of the briquettes are calculated in order to check whether they provide the design compaction and void ratio criteria. Figure 3.7 illustrates a sample briquette.

Before preparing the samples for resilient modulus test, 2 cm portion from upper and lower ends are cut to obtain a smooth end surfaces. From each compacted specimens, 2 cylindrical specimens are obtained with a thickness of 4 cm for SMA mixture and 5 cm for the other mixtures. As shown in Figure 3.8, the specimens are cut by using a diamond saw cutting machine. The specimen is fixed during the cutting process using a special apparatus. To prevent overheating, water is used during cutting hence preventing any possible damage to test samples.

Figure 3.7 A picture of 15 cm height specimen

Figure 3.8 Cutting Machine

The height of specimens is measured from 4 different points, and the average of these measurements is taken as the specimen height. A total of 48 specimens were prepared for the resilient modulus experiments. A picture of a cut specimen is shown in Figure 3.9.

Figure 3.9 Specimen after cutting

3.3 Indirect Tension Test for Determining Resilient Modulus of Bituminous Mixtures

Resilient modulus values of bituminous mixtures are determined by indirect tension test in this study. There are four main steps in the indirect tension test:

i) Calibration of the machine and LVDTs (Linear Variable Differential Transformer)
ii) Conducting the test
iii) Evaluation of the test results.

3.3.1 Test Equipment

In this study, an UTM-100 machine capable of applying 100 kPa of loading is used. The machine has an environmental chamber that can provide condition temperatures between -10 ^{o}C and 60 ^{0}C. The temperature can be easily controlled by the digital gages attached onto the chamber. The loading piston of the machine is installed inside the environmental chamber to apply vertical loading under a certain test temperature. The vertical load applied is measured using a load cell calibrated specially for typical test temperatures. The test device can apply dynamic, repeated, sinusoidal or static loadings while monitoring the deformation and temperature sensors simultaneously. All the test outputs are sent to a desktop computer and the test sequence can be monitored and controlled through a user-friendly interface program. By specification requirements according to both ASTM and NCHRP procedures, repeated haversine loading is applied in the resilient modulus tests.

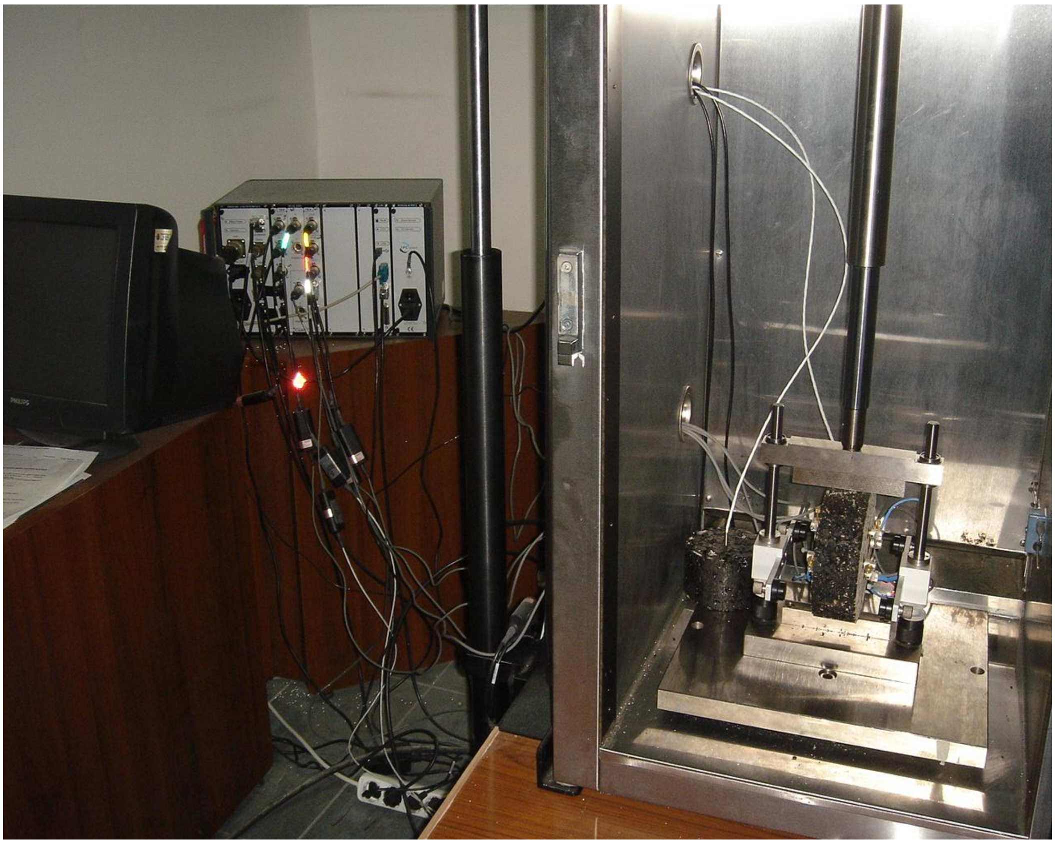


Figure 3.10 Universal testing machine (UTM-100) used for the resilient modulus tests

3.3.2 Test Procedure

The resilient modulus test was conducted according to the NCHRP Project 1-28A procedures "Laboratory Determination of Resilient Modulus for Flexible Pavement Design". In the testing process, first one of the specimens are chosen from each layer and its indirect tension resistance is determined. The indirect tension resistance test is performed by applying a vertical load at a rate of 50 mm/min according to SHRP Protocol P07 "Test Method for Determining the Creep Compliance, Resilient Modulus and Strength of Asphalt Materials Using the Indirect Tensile Test Device". The maximum load reached before the specimen starts to break is taken as the indirect tension resistance.

After this operation, 3 specimens are chosen from each mixture for testing, On each specimen surface, 4 small metallic LVDT installation fixtures (Figure 3.11-12) are glued perpendicular to each other with 5 cm distance between them and left for curing at least 6 hours. Then the horizontal and vertical LVDTs are installed through the fixtures (Figure 3.13) and the specimen is placed into the testing device for testing. The upper loading plate is placed onto the specimen and conditioned under 25 ^{o}C for 6 hours together with the test specimen. The test temperature is also checked by the condition temperature of a dummy specimen located inside environmental chamber.

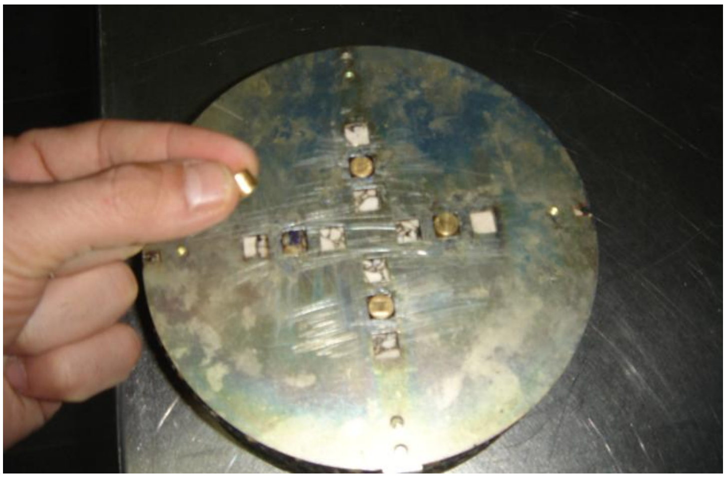


Figure 3.11 Gluing of LVDT installation fixtures onto the test specimen by the help of a mould

Figure 3.12 Installation fixtures glued onto the specimen

Figure 3.13 LVDTs installed on the specimen

During the test, repeated haversine loading (Figure 3.14-3.15) is applied at 1 Hz to the specimen with 0.1 sec loading and 0.9 sec rest period. After 100 conditioning loadings, 5 loadings are applied and the average values of these loadings are taken as the resilient modulus of the specimen under testing.

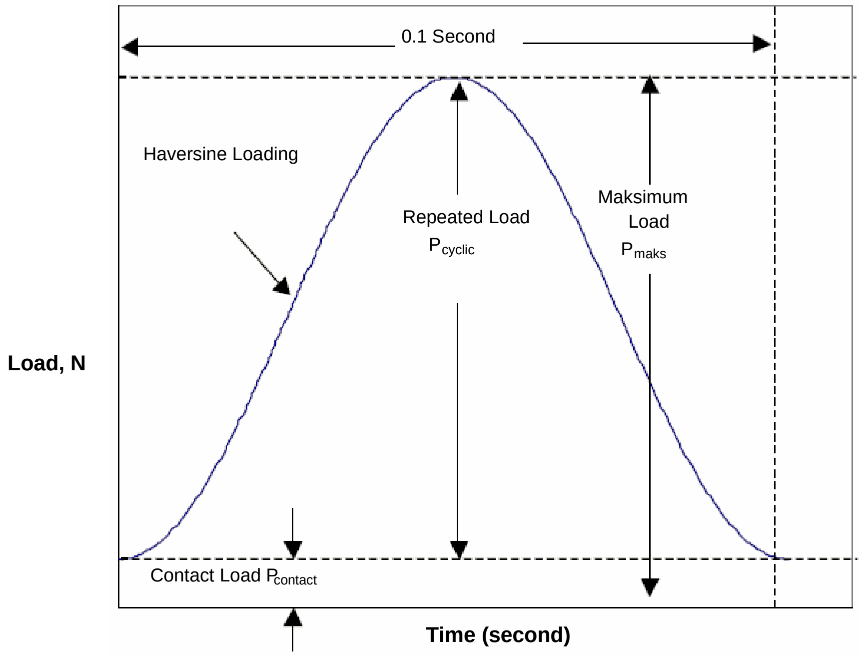


Figure 3.14 Haversine Loading [NCHRP 1-28A, 2004]

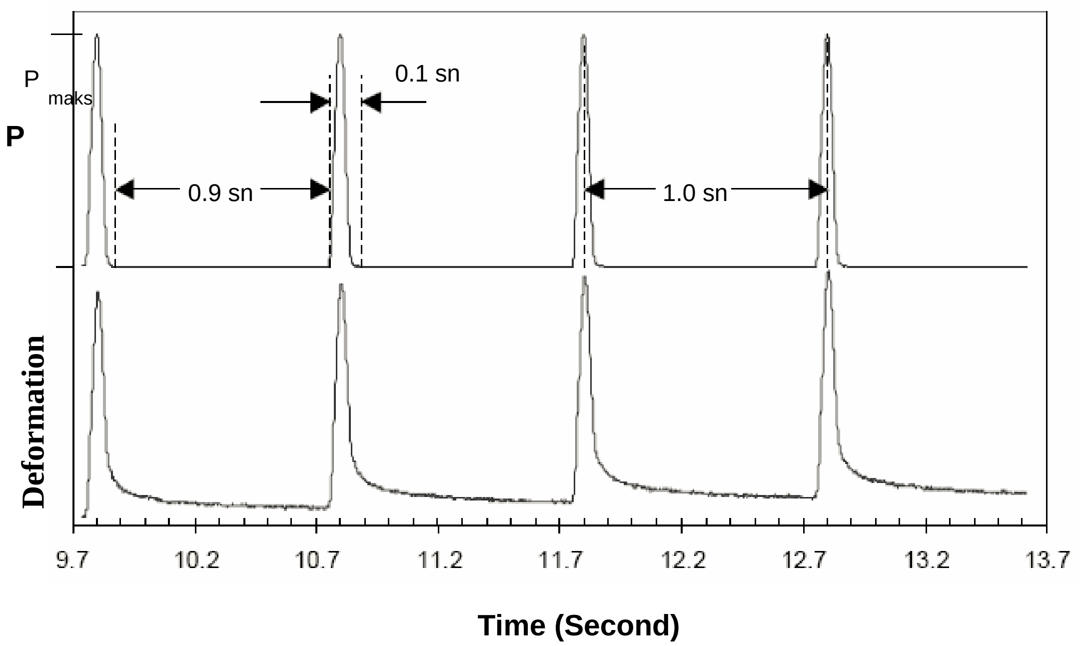


Figure 3.15 Load and deformation graphs of resilient modulus test

In each loading sequence, the total load applied is the sum of the cyclic (deviatoric) load and the contact load. The contact load makes the specimen to stay in touch with the loading pad of the test device. The cyclic deviatoric load is taken as the 15 % of the indirect tension resistance and the contact load as the 4 % of the deviatoric load.

After completing the all loading sequences, the specimen is rotated 90^0 and the same test sequence is applied one more time. The average of the resilient moduli determined from these two steps is taken as the measured resilient modulus of test specimen. Furthermore, the Poisson ratio of the specimen is established by using the horizontal and vertical deformations.

The resilient modulus and the Poisson's ratio are calculated by the user software using the loading and the measured deformations during testing according to NCHRP 1-28A as follows:

Poisson Ratio:

$$\mu = \frac{-1.0695 - 0.2339\dfrac{\delta_v}{\delta_h}}{0.3074 + 0.7801\dfrac{\delta_v}{\delta_h}} \tag{3.1}$$

where;

μ : Poisson ratio

δ_V : Recoverable vertical deformation

δ_h : Recoverable horizontal deformation

Resilient Modulus:

$$M_R = \frac{P_{cyclic}}{\delta_h t}(0.2339 + 0.7801\mu) \tag{3.2}$$

where,

M_R : Resilient modulus

δ_h : Recoverable horizontal deformation

P_{cyclic} : Applied cyclic deviatoric load ($P_{cyclic} = P_{max} – P_{contact}$)

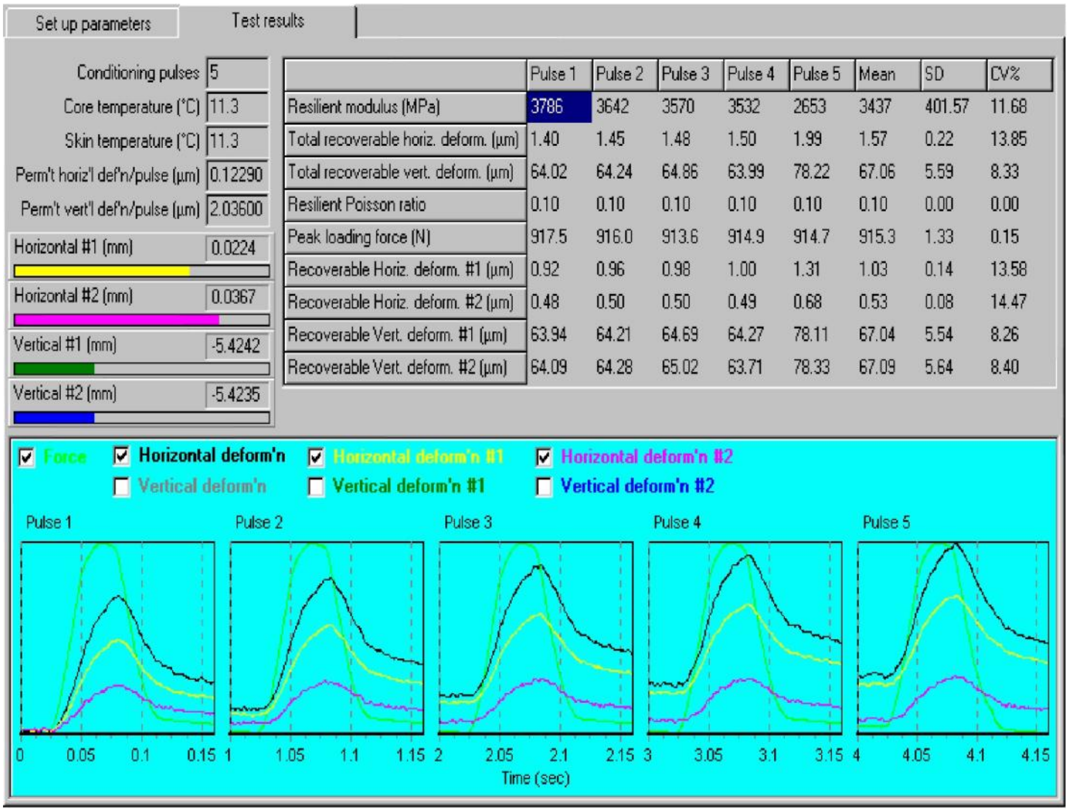
P_{max} : Applied maximum load

$P_{contact}$: Contact load (Pmax*0.04)

t : Thickness of the specimen

μ : Poisson's ratio

The calculated resilient modulus, Poisson's ratio can be seen on the computer as illustrated in Figure 3.16.



Conditioning pulses: 5
Core temperature (°C): 11.3
Skin temperature (°C): 11.3
Perm't horiz'l def'n/pulse (µm): 0.12290
Perm't vert'l def'n/pulse (µm): 2.03600
Horizontal #1 (mm): 0.0224
Horizontal #2 (mm): 0.0367
Vertical #1 (mm): -5.4242
Vertical #2 (mm): -5.4235

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	SD	CV%
Resilient modulus (MPa)	3786	3642	3570	3532	2653	3437	401.57	11.68
Total recoverable horiz. deform. (µm)	1.40	1.45	1.48	1.50	1.99	1.57	0.22	13.85
Total recoverable vert. deform. (µm)	64.02	64.24	64.86	63.99	78.22	67.06	5.59	8.33
Resilient Poisson ratio	0.10	0.10	0.10	0.10	0.10	0.10	0.00	0.00
Peak loading force (N)	917.5	916.0	913.6	914.9	914.7	915.3	1.33	0.15
Recoverable Horiz. deform. #1 (µm)	0.92	0.96	0.98	1.00	1.31	1.03	0.14	13.58
Recoverable Horiz. deform. #2 (µm)	0.48	0.50	0.50	0.49	0.68	0.53	0.08	14.47
Recoverable Vert. deform. #1 (µm)	63.94	64.21	64.69	64.27	78.11	67.04	5.54	8.26
Recoverable Vert. deform. #2 (µm)	64.09	64.28	65.02	63.71	78.33	67.09	5.64	8.40

☑ Force ☑ Horizontal deform'n ☑ Horizontal deform'n #1 ☑ Horizontal deform'n #2
☐ Vertical deform'n ☐ Vertical deform'n #1 ☐ Vertical deform'n #2

Figure 3.16 Sample output of the user software from a resilient modulus test

Using the test outputs, the resilient modulus can also be calculated according to the ASTM D4123-82 method. In the following section, the calculated moduli values using this procedure are also introduced.

3.3.3 Test Results

- According to NCHRP 1-28A

The results of resilient modulus test applied to 3 specimens from each mixture types according to NCHRP 1-28A are given in Table 3.4 and Figure 3.17. In addition to resilient modulus values, all Poisson's ratios, maximum loads, and contact loads are shown. Since the test is repeated after rotating the specimen 90^0, the results are given both for horizontal and vertical position of the specimen. The resilient modulus of a specimen is the average of the moduli calculated from vertical and horizontal directions. Figure 3.18 illustrates the layer resilient modulus values.

Table 3.4 Indirect tension test results according to NCHRP 1-28A

Sample Name	No	Dp (gr/cm^3)	Ave. Sample height (mm)	Indirect tensile strength (N)	Peak load (N)	Contact load (N)	Direction	Temperature ^{0}C	Resilient Modulus (MPa)	Average Resilient Modulus (MPa)	Poisson Ratio	Mixture Resilient Modulus (MPa)
B 50/70 Bitumen Basalt SMA	C1a	2436	41.5	4986	748	30	Horizontal	24.9	3593	3545.5	0.29	3976
							Vertical	24.7	3498		0.43	
	C2a	2438	40.8				Horizontal	25	4645	4021.5	0.5	
							Vertical	25	3398		0.46	
	C4a	2436	41.6				Horizontal	24.7	5374	4361	0.42	
							Vertical	24.9	3348		0.1	
Modified Bitumen Basalt SMA	D1a	2441	40.9	5046	757	30	Horizontal	25.3	5087	4298.5	0.49	4312.5
							Vertical	25.2	3510		0.17	
	D3a	2443	41.0				Horizontal	24.7	4721	3784.5	0.38	
							Vertical	24.9	2848		0.12	
	D4b	2443	44.2				Horizontal	24.7	5412	4854.5	0.26	
							Vertical	25	4297		0.13	
B 50/70 Bitumen Basalt Wearing	N1b	2434	51.38	4750	713	29	Horizontal	25.3	5749	4699.5	0.43	4338.3
							Vertical	25.1	3650		0.12	
	N2a	2437	50.63				Horizontal	24.8	4281	4041.5	0.46	
							Vertical	24.8	3802		0.12	
	N2b	2438	48.63				Horizontal	25.2	4898	4274	0.1	
							Vertical	25.1	3650		0.33	
Modified Bitumen Basalt wearing	M1a	2429	52.60	5723	858	34	Horizontal	24.8	4425	4770.5	0.13	4766.8
							Vertical	25.1	5116		0.37	
	M2a	2434	52.48				Horizontal	25	4098	4086.5	0.2	
							Vertical	25.2	4075		0.23	
	M3a	2442	50.13				Horizontal	24.9	6475	5443.5	0.41	
							Vertical	24.9	4412		0.1	

B 50/70 Bitumen Limestone Wearing	A1b	2284	49.78	7196.4	1079	43	Horizontal	26.1	3969	3827.5	0.2	5244.8
							Vertical	25.9	3686		0.17	
	A2a	2308	49.05				Horizontal	25.4	6914	6462	0.18	
							Vertical	25.5	6010		0.15	
	A3b	2292	50.25				Horizontal	24.9	6065	5303.5	0.29	
							Vertical	24.7	4542		0.1	
Modified Bitumen Limestone Wearing	B2b	2299	47.95	6433.6	965	39	Horizontal	24.4	6367	7408.5	0.13	5970.2
							Vertical	25.5	8450		0.34	
	B3b	2317	48.88				Horizontal	25.1	7409	7747.5	0.13	
							Vertical	25	8086		0.28	
	B4b	2236	51.43				Horizontal	25.2	2879	2754.5	0.12	
							Vertical	25	2630		0.18	
B 50/70 Bitumen Limestone Binder	E2a	2.291	50.8	6280	942	38	Horizontal	25.3	2643	4419.5	0.1	4487
							Vertical	25.2	6196		0.48	
	E3a	2.294	49.3				Horizontal	24.9	4382	4691.5	0.15	
							Vertical	24.9	5001		0.22	
	E3b	2.294	52.6				Horizontal	25.3	4039	4350	0.17	
							Vertical	25.1	4661		0.34	
B 50/70 Bitumen Limestone Bit. Base	F1a	2.297	51.9	6278	942	38	Horizontal	25.1	4369	4397.5	0.26	4306.3
							Vertical	25	4426		0.29	
	F3a	2.319	50.7				Horizontal	25.1	3299	4387	0.1	
							Vertical	25.4	5475		0.45	
	F4a	2.299	50.0				Horizontal	25.2	4219	4134.5	0.29	
							Vertical	25.1	4050		0.13	

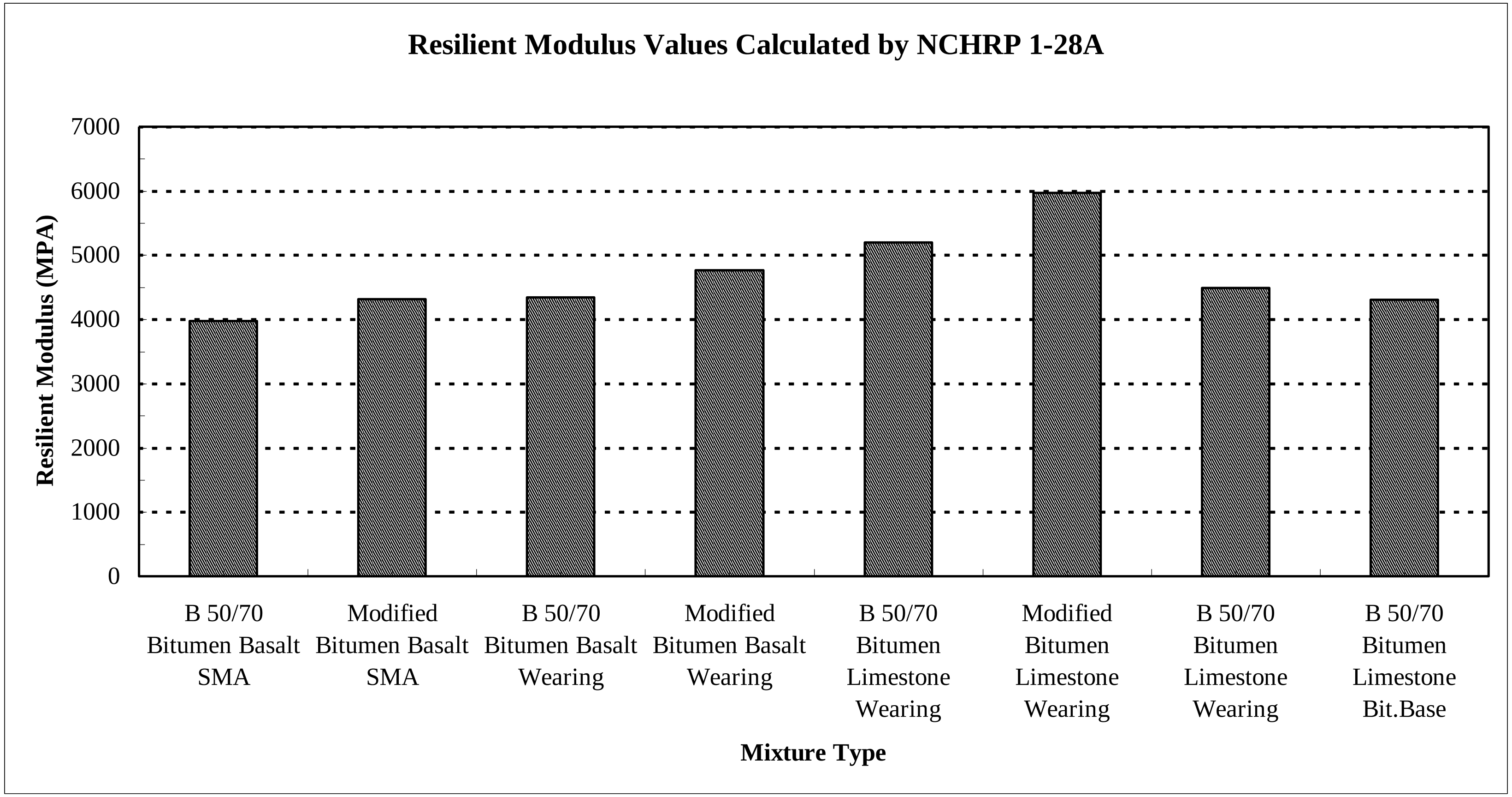


Figure 3.17 Resilient modulus values calculated by NCHRP 1-28A

Table 3.5 Average resilient modulus values of HMA mixtures

HMA MIXTURE	Resilient Modulus (MPa)
Wearing	5080
Binder	4487
Bitum. Base	4306
Stone Mastic Asphalt	4144

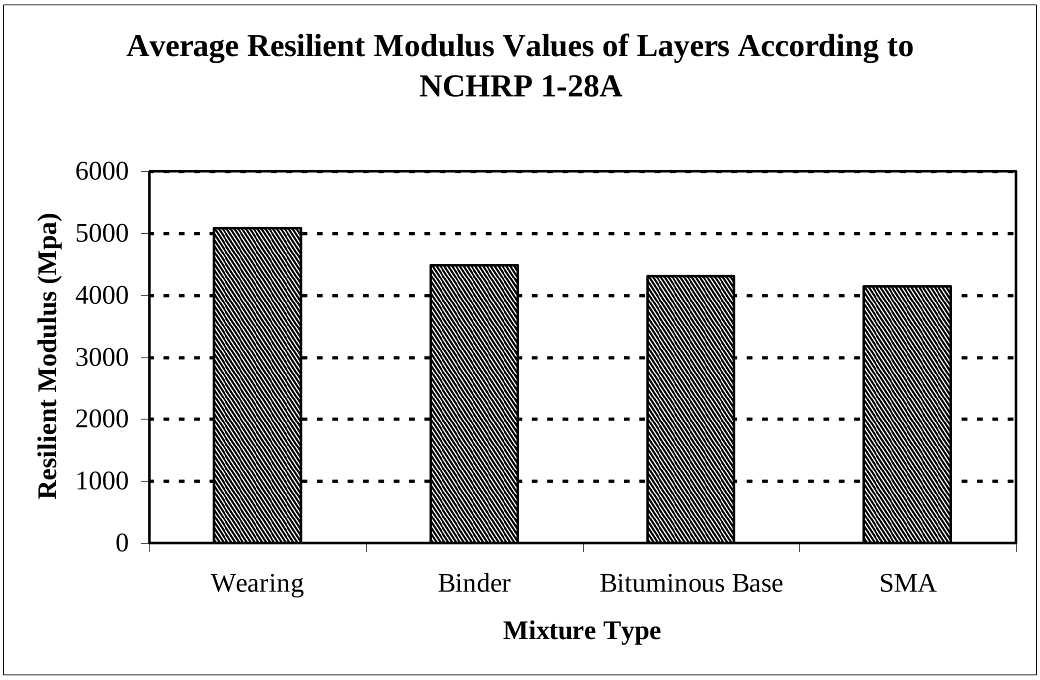


Figure 3.18 Graph of Average Resilient Modulus Values for HMA Mixtures

- According to ASTM D4123-82

As stated before, the indirect tensile test was applied according to NCHRP Project 1-28A. Another standard for this method is ASTM D4123-82 “Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures”. There are some differences between these two methods for calculating the resilient modulus of mixtures: According to NCHRP Project 1-28A procedure, the resilient modulus is calculated as;

$$M_R = \frac{P_{cyclic}}{\delta_h t}(0.2339 + 0.7801\mu)$$

but according to ASTM D4123-82, it is calculated as;

$$M_R = \frac{P_{cyclic}}{\delta_h t}(0.27 + \mu) \tag{3.3}$$

The results obtained by the ASTM method are shown in Table 3.6 and Figure 3.19, respectively. Figure 3.20 represents the comparison of the resilient modulus values obtained by the NCHRP and ASTM methods.

In general, it is accepted that the deformations measured according to the NCHRP method offer higher accuracy than do the ASTM method. In the ASTM method, the LVDTs can be installed onto the specimen surface as described in the NCHRP method, however, it is also common practice to measure only horizontal deformations from the specimen surface using two LVDTs that are 180^o radially located from each other. Because deformations are measured only in one direction, the true Poisson’s ratio cannot be calculated and must be assumed in the calculation of resilient modulus as evidenced by Equation (3.3). Because of this deficiency in the ASTM method, it results in reduced reliability and less accuracy in the measured resilient modulus as compared to the NCHRP method. In the following sections, a comparison is made on the resilient modulus of the test mixtures calculated according to the NCHRP method and the ASTM method using an assumed Poisson’s ratio and the true Poisson’s ratio determined from the NCHRP method.

Table 3.6 Resilient Modulus Values According To ASTM D4123-82 Method

Sample Name	Hor. Def. (µm)	Ver. Def. (µm)	Sample Height	Peak load (N)	Contact load (N)	Resilient modulus (MPa)	Mixture Resilient Modulus (MPa)
B 50/70 Bitumen Basalt SMA	1.84	3.53	41.5	748	30	5269	5992.8
	2.29	3.75				5292	
	2.35	3.24	40.8			5770	
	2.66	4.13				4832	
	1.52	2.48	41.6			7844	
	0.92	3.21				6950	
Modified Bitumen Basalt SMA	1.84	2.81	40.9	757	30	7343	6404
	1.52	3.51				5146	
	1.66	2.86	41.0			6940	
	1.59	4.15				4347	
	1.1	2.19	44.2			7930	
	0.98	2.54				6718	
B 50/70 Bitumen Basalt Wearing	1.19	1.89	51.38	713	29	7832	7762
	0.95	2.47				5466	
	1.1	2.16	50.63			8966	
	0.85	2.27				6199	
	0.56	1.9	48.63			9294	
	1.59	2.89				5308	
Modified Bitumen Basalt Wearing	0.98	2.39	52.60	858	34	6395	8836.8
	1.39	2.4				7214	
	1.24	2.7	52.48			5953	
	1.32	2.74				5949	
	1.23	2.04	50.13			9089	
	0.82	2.41				7419	

B 50/70 Bitumen Limestone Wearing	1.73	3.72	49.78	1079	43	5656	7762
	1.73	3.92				5295	
	0.95	2.15	49.05			10008	
	0.94	2.39				9440	
	1.34	2.52	50.25			8618	
	1.01	2.96				7555	
Modified Bitumen Limestone Wearing	0.79	2.03	47.95	965	39	9783	8836.8
	0.97	1.74				12150	
	0.67	1.73	48.88			11317	
	0.89	1.73				11714	
	1.66	4.16	51.43			4233	
	2.12	4.71				3824	
B 50/70 Bitumen Limestone Binder	1.17	3.81	50.8	942	38	5635	7059.3
	1.53	2.21				8735	
	1.18	2.47	49.3			6529	
	1.08	2.62				8322	
	1.23	2.81	52.6			6147	
	1.5	2.65				6988	
B 50/70 Bitumen Limestone Bit.Base	1.5	2.96	51.9	942	38	6155	6288.2
	1.57	2.95				6213	
	1.12	3.54	50.7			5896	
	1.85	2.73				6946	
	1.69	3.2	50			5997	
	1.11	2.95				6522	

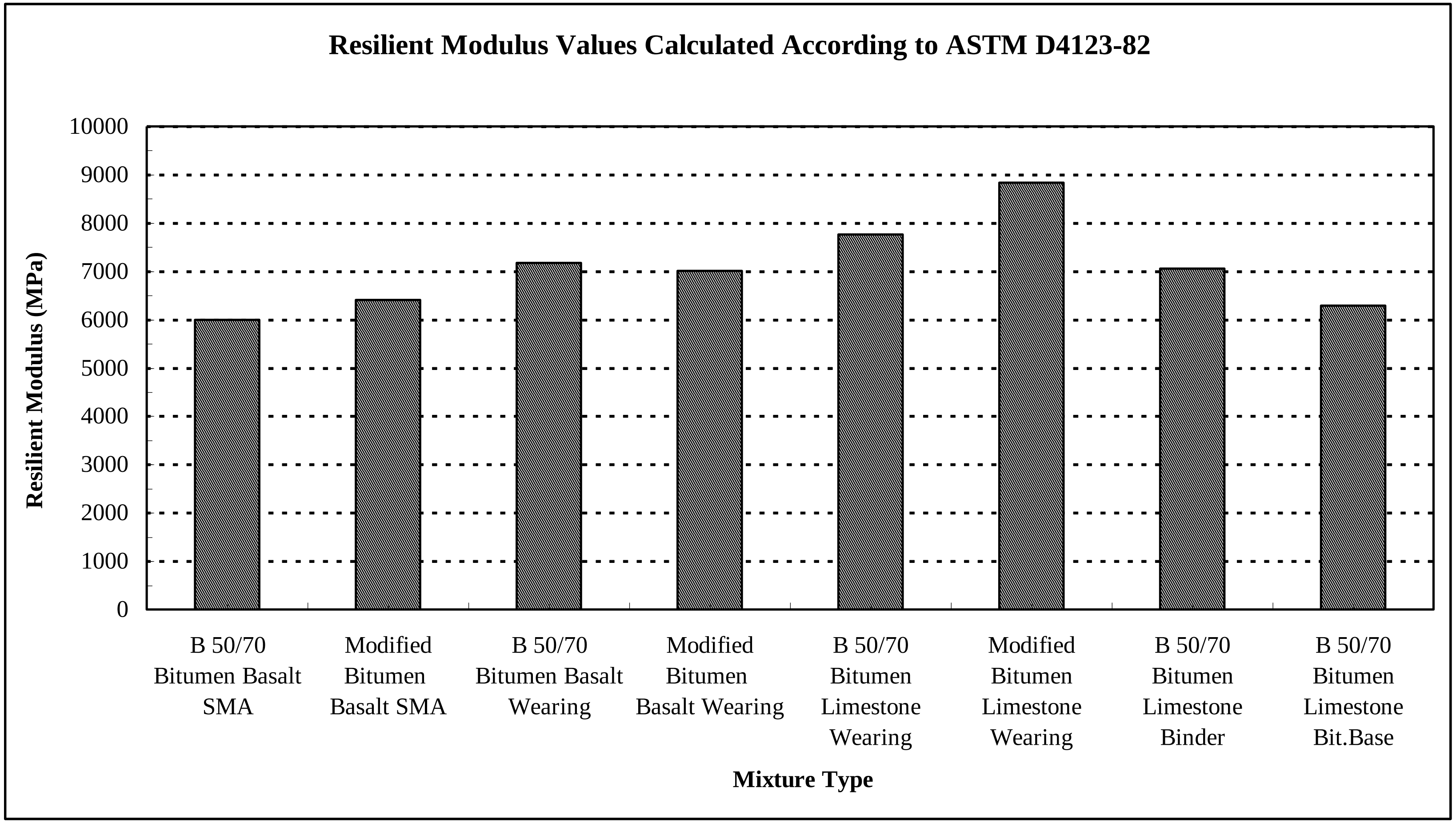


Figure 3.19 Graph of resilient modulus values according to ASTM D4123-82 Method.

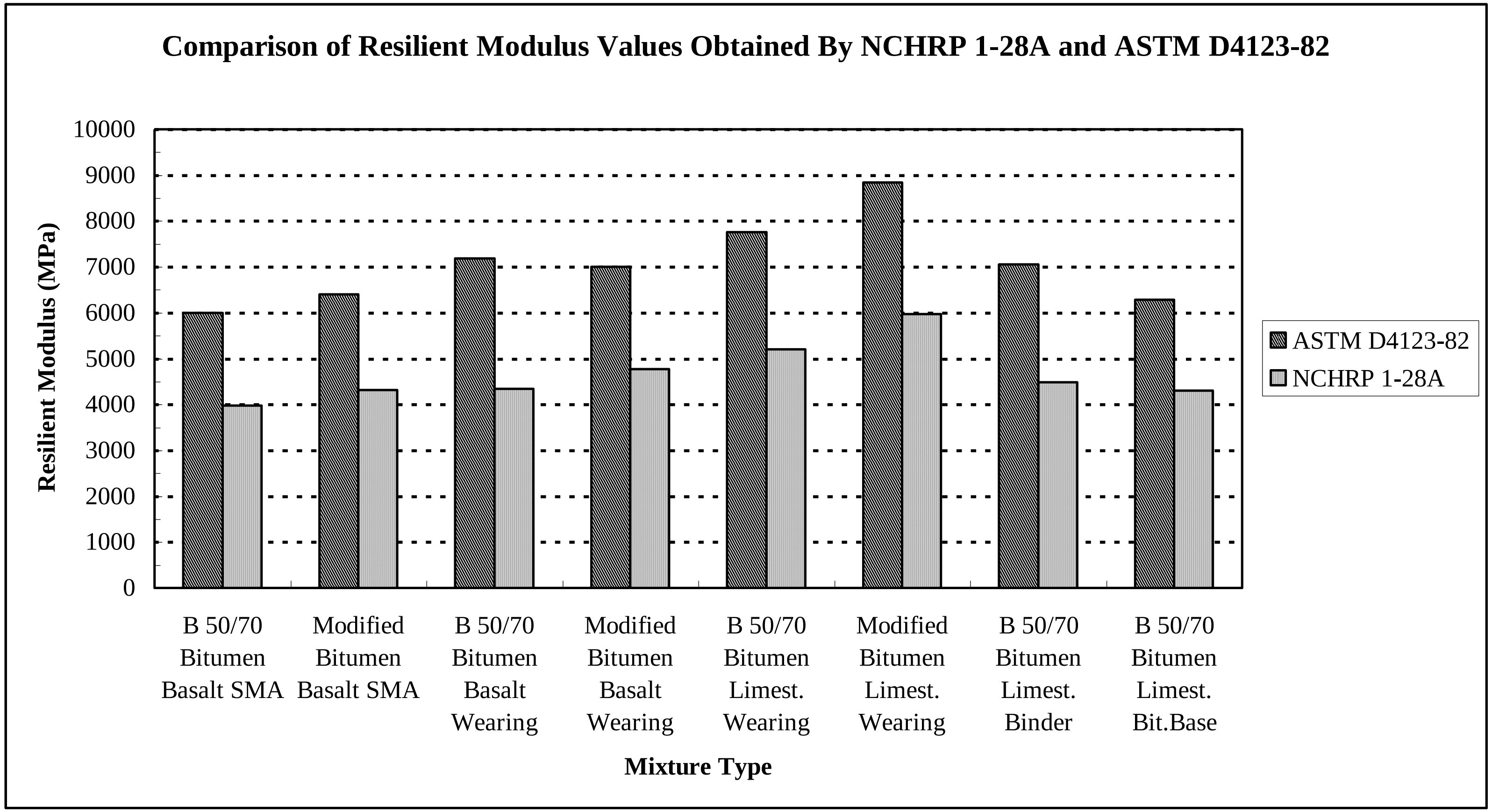


Figure 3.20 Comparison of resilient modulus values obtained by NCHRP 1-28A and ASTM D4123-82 Methods.

It is indicated in ASTM D4123-82 that the Poisson ratio can be assumed as 0.35 if vertical deformation data are not available. The resilient modulus values calculated using Poisson ratio of 0.35 are shown in Table 3.7 and Figure 3.21 below.

Table 3.7 Resilient modulus values calculated using Poisson ratio of 0.35

B 50/70 Bitumen Basalt SMA	Modified Bitumen Basalt SMA	B 50/70 Bitumen Basalt Wearing	Modified Bitumen Basalt Wearing	B 50/70 Bitumen Limest. Wearing	Modified Bitumen Limest. Wearing	B 50/70 Bitumen Limest. Binder	B 50/70 Bitumen Limest. Bit.Base
6327.3	7743.3	9025.9	4766.8	10807.8	11709.2	8766.1	7781.6

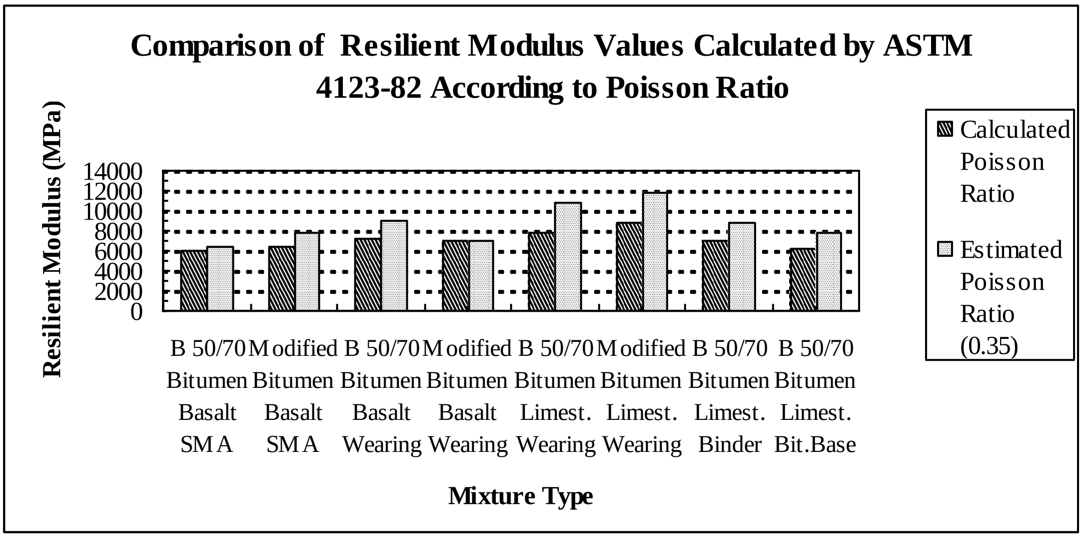


Figure 3.21 Comparison of resilient modulus values according to Poisson ratio

As it can be seen from Figure 3.21 that the resilient modulus values calculated by assumed Poisson’s ratio of 0.35 are generally greater. However, the difference between the two measurement methods seems to be insignificant. Hence, it can be concluded that the accuracy of the ASTM method is related to more on the accuracy of deformation measurements rather than the accuracy in determining the true Poisson’s ratio.

CHAPTER 4

DETERMINATION OF RESILIENT MODULUS BY NOMOGRAPHS AND E EMPIRICAL EQUATIONS

In this chapter, methods for determining resilient modulus of bituminous mixtures are presented using nomographs and various empirical equations that have still been in pavement design procedures. The methods generally use binder and aggregate stiffness properties to calculate the resilient modulus of bituminous mixtures. In the below sections, moduli values calculated using various methods are compared.

4.1 Van Der Poel and Shell Nomographs

4.1.1 Van Der Poel Nomograph

Van Der Poel Nomograph, as described in Section 2.4, is used to estimate the bitumen stiffness. The parameters needed to estimate the stiffness of bitumen from the Van Der Poel Nomograph are:

i) For B50/70 Bitumen;

T_{RB}=48.8 ^{0}C

T = 25 ^{0}C

T- T_{RB} = 23.8 ^{0}C

$$A = \frac{\log(63) - \log(800)}{25 - 48.8} = 0.046$$

$$PI = \frac{20 - 500x0.046}{1 + 50x0.046} = -0.96$$

Time of Loading = 0.1 seconds

S_b = 4.5 x 10^6 N/m^2 (estimated from the nomograph)

ii) For 5% SBS Modified Bitumen

T_{RB}=81.2 ^{0}C

T = 25 ^{0}C

$$A = \frac{\log(46) - \log(800)}{25 - 81.2} = 0.022$$

$$PI = \frac{20 - 500x0.022}{1 + 50x0.022} = 4.26$$

T- T_{RB} = 56.2 ^{0}C

PI = 4.26 (Calculated)

Time of Loading = 0.1 seconds

S_b = 4 x 10^6 N/m^2 (estimated from the nomograph)

4.1.2 Shell Nomograph

The stiffness of the bitumen was estimated as 4.5x10^6 Pa and 4x10^6 Pa, but in this study for Shell nomograph, the values are assumed as 5x10^6 Pa. In order to estimate the resilient modulus from the Shell nomograph, the percent volume of bitumen and aggregate is needed. The calculations for SMA prepared by B 50/70 bitumen and basalt are shown below. The results for the other mixtures and graph of the results are given in Table 4.1. and Figure 3.19, respectively.

S_b = 5 x10^6 N/m^2

$$V_b = \frac{100x(0.061x2.458)}{1.02} = 14.70$$

$$V_g = \frac{100x(1 - 0.061)x2.458}{2.82} = 81.77$$

S_{mix} = 1000 MPa

Table 4.1 The resilient modulus of the mixtures estimated by Shell Nomograph

	Bazalt				**Limestone**			
	SMA		**Wearing**		**Wearing**		**Binder**	**Bitum. Base**
	50/70	PMB	50/70	PMB	50/70	PMB	50/70	50/70
Vg	81.76	81.76	83.22	83.22	84.46	84.46	84.82	84.79
Vb	14.70	14.70	12.12	12.12	11.55	11.55	11.01	9.90
Sb	$5x10^6$	$5x10^6$	$5x10^6$	$5x10^6$	$5x10^6$	$5x10^6$	$5x10^6$	$5x10^6$
Smix	1000	1000	1300	1300	1400	1400	1600	1650

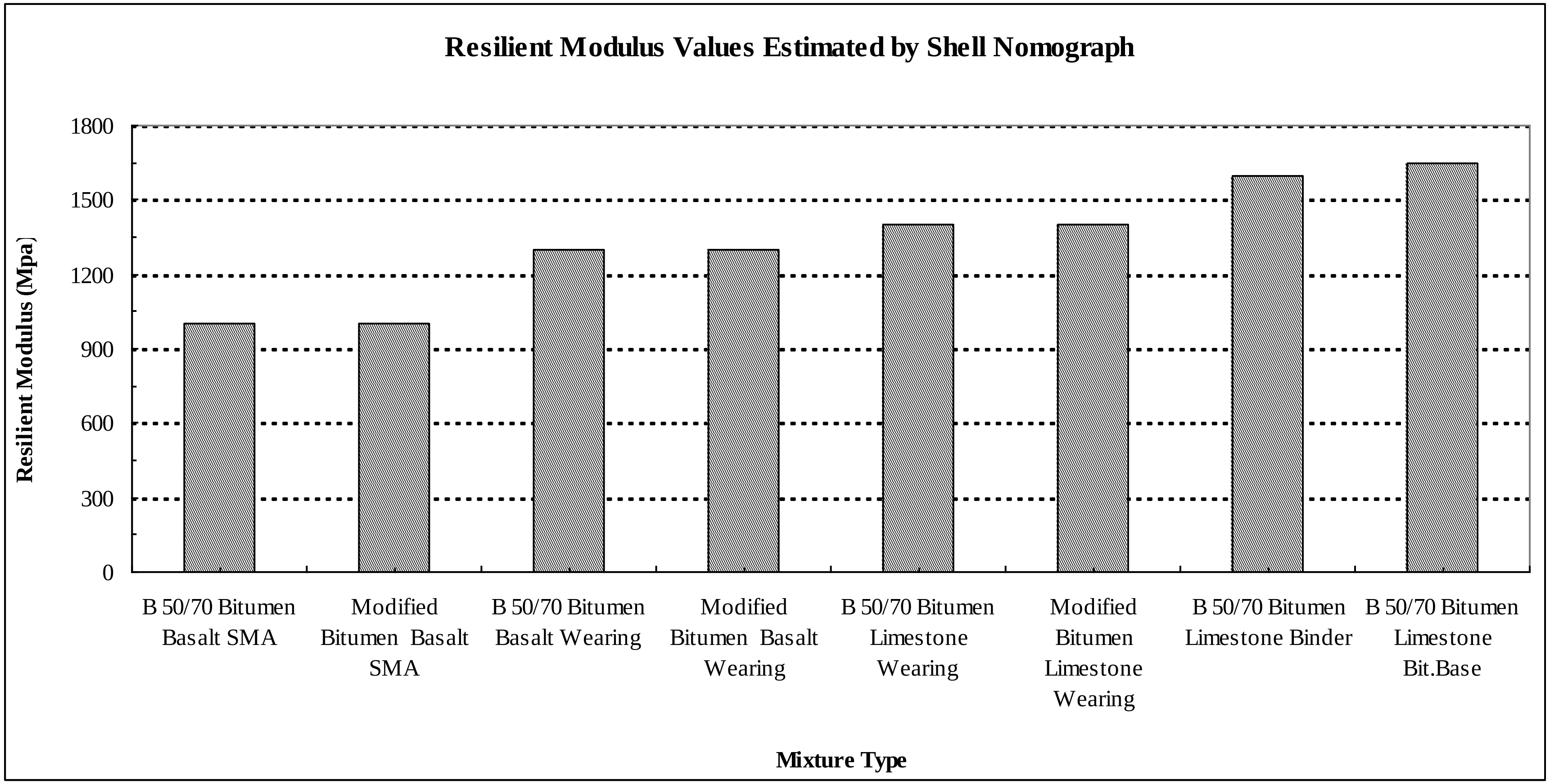


Figure 4.1 Graph of the resilient modulus values calculated by Shell Nomograph (1977).

4.2 Estimation of the Stiffness Modulus of Mixtures by Empirical Equations

Resilient modulus values can be estimated by various empirical equations. For, some of these equations, the stiffness of bitumen should be determined first. Hence, a description of the method to estimate the bitumen stiffness is given first , and then the estimation of resilient modulus using bitumen stiffness, aggregate and bitumen characteristics are explained based on various empirical methods.

4.2.1 Estimation of Bitumen Stiffness by Empirical Equations

The stiffness of the bitumen can be estimated by the Van Der Poel equation as stated in the previous sections.

$$\mathrm{S_b} = 1.157 \times 10^{-7} \times \mathrm{t_w}^{-0.368} \times e^{-PI} \times (\mathrm{T_{RB}} - T)^5$$

The determined values by Van Der Poel equation for B50/70 bitumen are given below:

i) For B50/70 bitumen

$$\mathrm{S_b} = 1.157 \times 10^{-7} \times 0.1^{-0.368} \times e^{0.96} \times (48.8 - 25)^5$$

$S_b = 5.39 \times 10^6$ MPa

ii) For Modified Bitumen

$$\mathrm{S_b} = 1.157 \times 10^{-7} \times 0.1^{-0.368} \times e^{-4.26} \times (81.2 - 25)^5$$

$S_b = 2.13 \times 10^6$ MPa

4.2.2 Estimation of the Resilient Modulus of Mixtures By Empirical Equations

The stiffness modulus of the bitumen is calculated by Bonnaure et al. (1977), Heukelom and Klomp (1964) and Witczak predictive equations (2000) as explained in the previous chapters.

Bonnaure et al. (1977) Equation :

The estimation of stiffness for SMA prepared with basalt and B 50/70 bitumen are shown below. The remaining results are shown in Table 4.2 and Figure 4.2 shows the graph of the results. V_g and V_b values are taken as 81.77 and 14.70, respectively which were calculated by Equation 2.6 and 2.7.

$$\beta_1 = 10{,}82 - \frac{1{,}342(100 - 81.77)}{81.77 + 14.70} = 10.566$$

$$\beta_2 = 8{,}0 + 0{,}0568x81.77 + 0{,}0002135x81.77^2 = 9.892$$

$$\beta_3 = 0{,}6\log(\frac{1{,}37\text{x}14.70^2 - 1)}{1{,}33x14.70 - 1} = 0.721$$

$$\beta_4 = 0{,}7582(10.566 - 9.892) = 0.512$$

the stiffness of the bitumen is assumed as $5\text{x}10^6$ MPa.

$$\log S_m = \frac{10.566 + 0.721}{2}(\log 5x10^6 - 8) + \frac{0.512 - 0.721}{2}\left|\log 5x10^6 - 8\right| + \beta 9.892$$

$$\log S_m = 8.954$$

$$S_m = 898.72\,\text{MPa}$$

Since the stiffness of the bitumen for B 50/70 and PMB are assumed to be equal, the mixture stiffness values turn out to be equal for the mixtures prepared with different types of bitumen.

Table 4.2 Resilient modulus of mixtures estimated by Bonnaure et. al (1977) equation

	Basalt				**Limestone**			
	SMA		**Wearing**		**Wearing**		**Binder**	**Bitum. Base**
	B 50/70	**PMB**	**B 50/70**	**PMB**	**B 50/70**	**PMB**	**B 50/70**	**B 50/70**
Vg	81.76	81.76	83.22	83.22	84.46	84.46	84.82	84.79
Vb	14.70	14.70	12.12	12.12	11.55	11.55	11.01	9.90
ß1	10.566	10.566	10.583	10.583	10.602	10.602	10.607	10.604
ß2	9.892	9.892	9.951	9.951	10.003	10.003	10.018	10.017
ß3	0.721	0.721	0.673	0.673	0.661	0.661	0.650	0.624
ß4	0.512	0.512	0.480	0.480	0.455	0.455	0.447	0.446
Log M_R	8.95	8.95	9.07	9.08	9.14	9.14	9.17	9.21
M_R (Pa)	898719885	898719885	1189686816	1189686816	1387712133	1387712133	1487208731	1604138764
M_R (MPa)	**898.7**	**898.7**	**1189.7**	**1189.7**	**1387.7**	**1387.7**	**1487.2**	**1604.1**

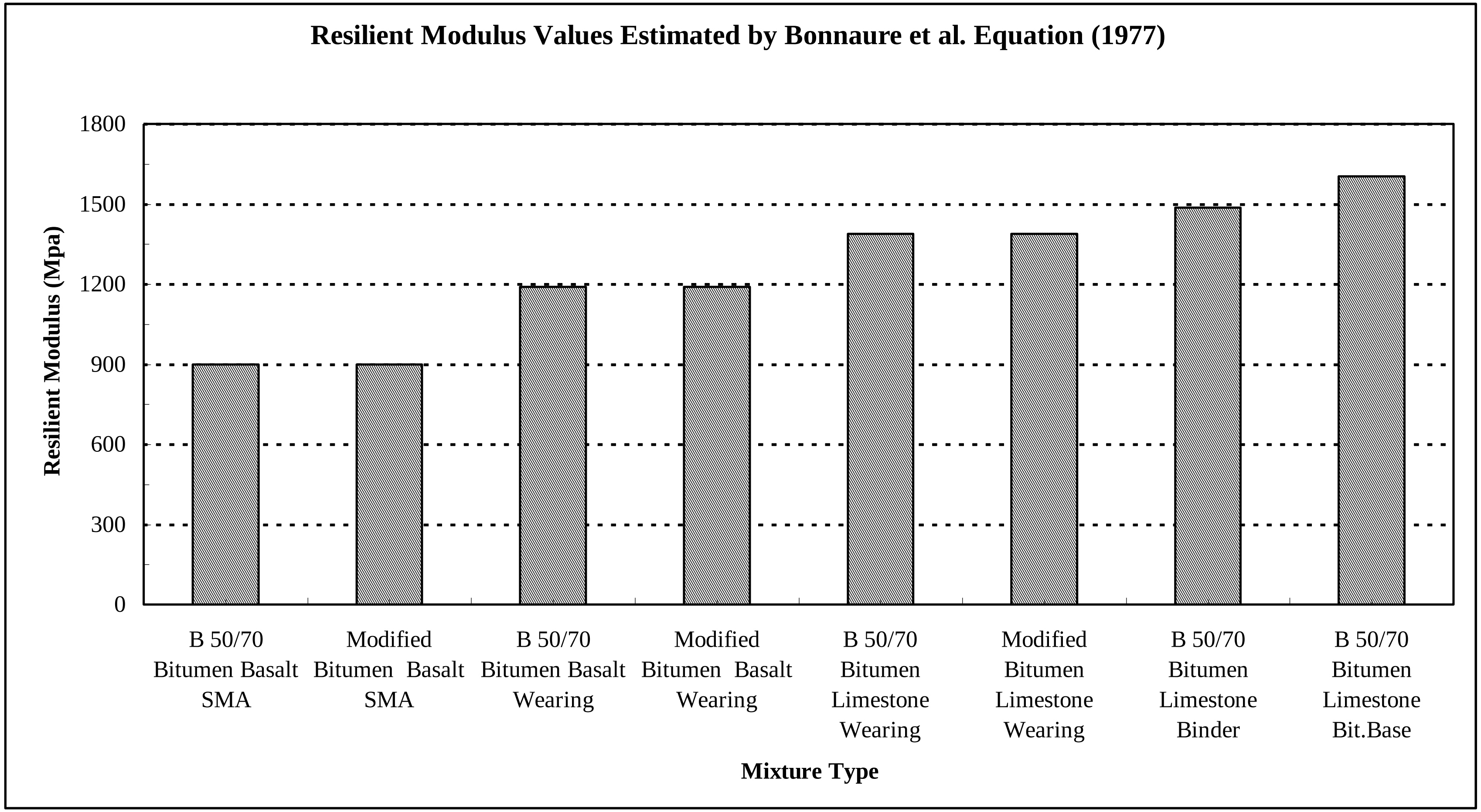


Figure 4.2 Graph of the resilient modulus values calculated by Bonnaure et. al (1977) Equation.

Heukelom and Klomp Equation :

The estimation for the SMA mixture prepared with B 50/70 bitumen is shown below.

$$\mathrm{E} = S_b \times [1 + 2.5 / n) \times C_v' /(1 - C_v)]^n$$

$$\mathrm{C_v} = 81.76/(81.77 + 14.70) = 0.848$$

$$\mathrm{C_v^1} = 0.848/[0,97 + 0,01(100 - (81.77 - 14.70))] = 0.843$$

$$\mathrm{n} = 0,83 \times \log(40000 MP_a / 5.39) = 3.213$$

Stiffness of the bitumen is assumed as 5.39x10^6 MPa, which is calculated by the Van Der Poel equation.

$$\mathrm{E} = 5.39 \times [1 + 2.5 / 3.213) \times 0.843 /(1 - 0.848)]^{3.213} = 1146.88 Mpa$$

The calculated values for the mixtures are given in the Table 4.3 below and Figure 4.3 illustrates the graph of the results.

Table 4.3 Calculated resilient modulus values by Heukelom and Klomp (1964) Equation

Specimen	**B50/70 Bitumen Basalt SMA**	**Modified Bitumen Basalt SMA**	**B 50/70 Bitumen Basalt Wearing**	**Modified Bitumen Basalt Wearing**	**B 50/70 Bitumen Limestone Wearing**	**Modified Bitumen Limestone Wearing**	**B50/70 Bitumen Limestone Binder**	**B 50/70 Bitumen Limestone Bitum. Base**
Sb	5.39x10^6	2.13x10^6	5.39x10^6	2.13x10^6	5.39x10^6	2.13x10^6	5.39x10^6	5.39x10^6
Cv	0.85	0.85	0.87	0.87	0.88	0.88	0.89	0.90
C'v	0.84	0.84	0.86	0.86	0.87	0.87	0.87	0.87
n	3.21	3.54	3.21	3.54	3.21	3.55	3.21	3.21
M_R	**1146.9**	**598.1**	**1947.3**	**1061.9**	**2353.5**	**1304.5**	**2698.5**	**3512.3**

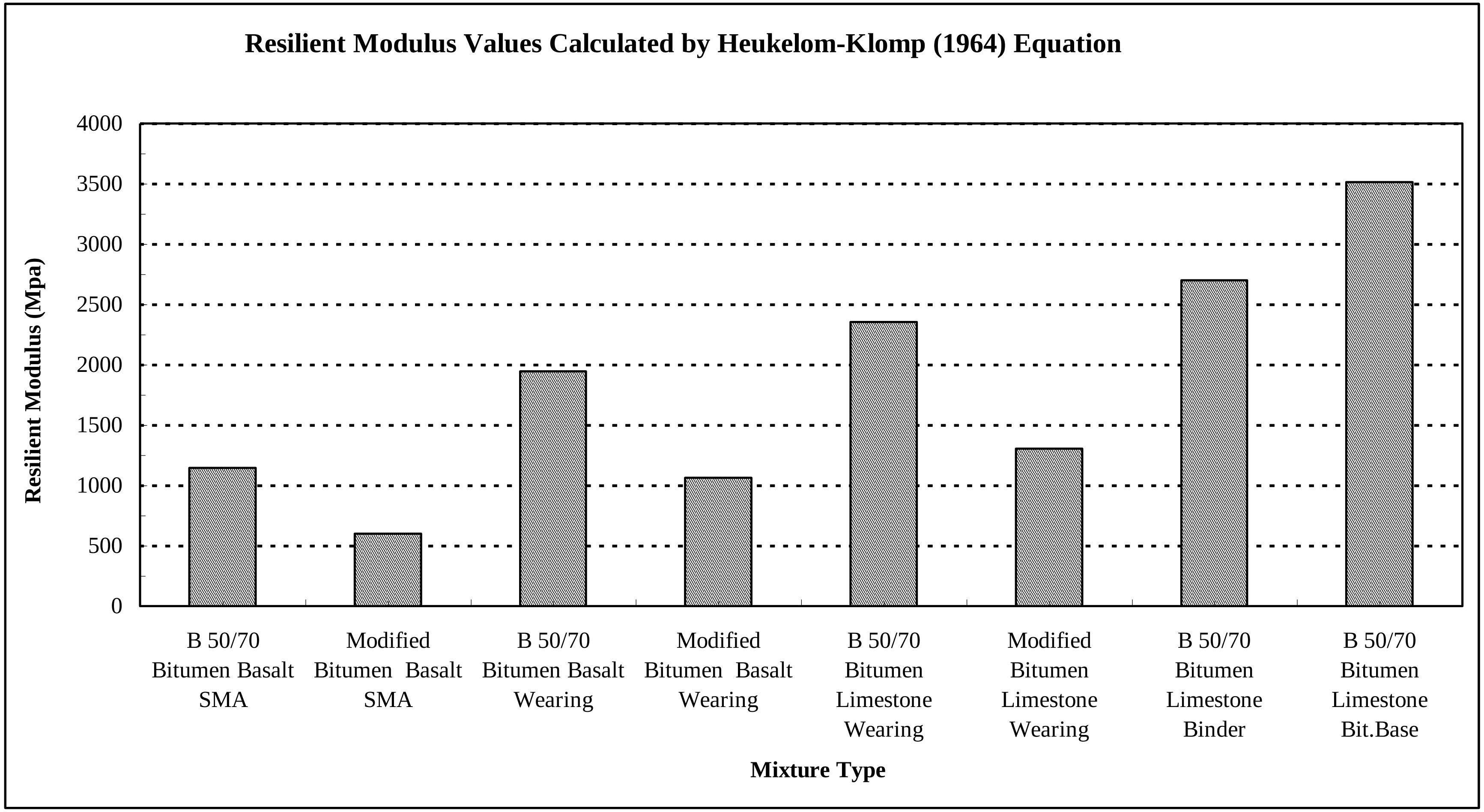


Figure 4.3 Stiffness Values Calculated By Heukelom-Klomp (1964) Equation

Witczak Predictive Equation

In this study, the time of loading is 0.1 seconds and the rest period is 0.9 seconds. The frequency is calculated 1.591 hz by the equation:

$$f = 1/2\pi \mathrm{T} \tag{3.1}$$

The temperature is taken as 25 ^{0}C (77 ^{0}F), and the viscosity values are calculated by Equation 3.13. The percent of aggregates passing No.200 sieve (P_{200}) and remaining on ¾ in. sieve (P_{34}), 3/8 in. sieve (P_{38}) and No 4 sieve (P_4) are taken from Table 3, given in the previous sections. Volume of aggregates and bitumen in the mix are calculated by Equations 2.6 and 2.7 for all mixtures.

The percent of aggregates passing No 200 sieve is determined during the design phase of mixtures in the laboratory. These values are used in these equations also.

- For the SMA mixtures prepared with basalt and B 50/70 bitumen, the estimations are shown below:

$$\lambda = 29508.2(63)^{-2.1939} = 3.329$$

the penetration at 77 ^{0}F is 63 mm for B50/70 bitumen used in the laboratory for this study.
The estimation for the SMA mixtures prepared with B 50/70 bitumen is shown below:

$$V_b = 100x\frac{0.061 * 2.458}{1.02} = 14.70 \text{ (as percent volume of bitumen)}$$

In the above explanations, the bitumen content was shown as 0.065, because 6.5 gr. bitumen is added to 100 gr. aggregate. So, the percent bitumen weight in the mixture is 0.061. All bitumen weights are calculated in the same way for all mixtures.

$V_a = 3.53$ (Air voids)

$$\log\left|E^*\right| = -1.249937 + 0.029232 \times 9 - 0.001767(9)^2 + 0.002841 \times 67 -$$
$$0.058097 \times 3.53 - 0.802208 \frac{14.70}{(14.70 + 3.53)} +$$
$$\frac{\left[3.871977 + 0.0021 \times 67 + 0.003958 \times 38 - 0.00017(38)^2 + 0.0547 \times 0\right]}{1 + e^{(-0.603313 - 0.313351 \log 1.591 - 0.393532 \log 3.329)}}$$

$$\left|E^*\right| = 847935.21 Psi$$

If we convert psi to MPa;

$$\left|E^*\right| = 5846.3 Mpa$$

All these calculations are carried out in the same way for the other mixtures, and the results are given in Table 4.4 below. Figure 4.4 shows the graph of the resilient modulus values that are estimated.

Table 4.4 Calculated resilient modulus values by Witczak Predictive Equation (2000)

	Basalt				**Limestone**			
	SMA		**Wearing**		**Wearing**		**Binder**	**Bitum. Base**
	B 50/70	**PMB**	**B 50/70**	**PMB**	**B 50/70**	**PMB**	**B 50/70**	**B 50/70**
f	1.591	1.591	1.591	1.591	1.591	1.591	1.591	1.591
T	77	77	77	77	77	77	77	77
λ	3.329	6.638	3.329	6.638	3.329	6.638	3.329	6.638
Va	3.53	3.53	3.66	3.66	4.13	4.13	4.7	5.1
Vb	14.7	15.76	12.73	12.73	15.76	15.76	12.12	10.91
P200	9	9	7	7	5.6	5.6	5.8	5.1
P34	0	0	0	0	0	0	7.3	25.7
P38	38	33.2	10	10	11.2	11.2	10.9	6.8
P4	67	29	35	35	30.6	30.6	13.2	11.6
log E	0.928362668	0.9526815	0.8371289	0.928879	0.7845616	0.876636	0.8145863	0.9699819
E(Psi)	847935.2071	896770.81	687272.44	848943.97	608921.98	752724.38	652508.7	933215.5
E (Mpa)	**5846.3**	**6183.1**	**4738.6**	**5853.3**	**4198.4**	**5189.9**	**4498.9**	**6434.3**

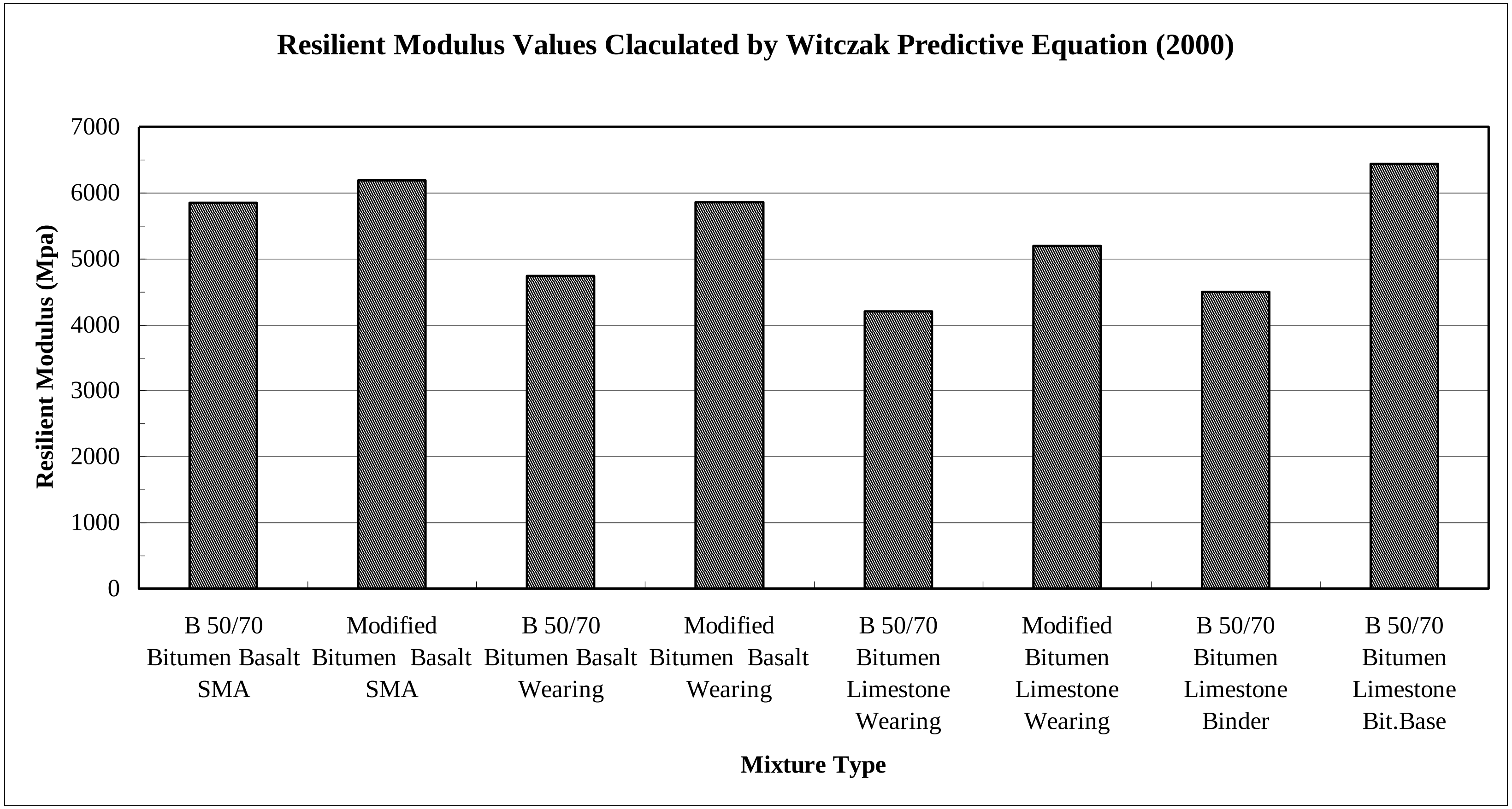


Figure 4.4 Resilent Modulus Values Calculated by Witczak Predictive Equation (2000)

4.2.3 Discussion of Results

In this section, comparison of the empirical estimation methods is presented in two stages. The predicted modulus values are first compared with results of two measurement methods. In the second stage, relative errors are calculated for each estimation method with respect to the measured values. A discussion is also given for the strength of empirical models to approximate the actual modulus values.

- **Comparison of Results between ASTM and NCHRP Methods**

Comparison of resilient modulus values based on the ASTM and NCHRP methods are shown in Figure 4.5. It can be seen that the moduli determined according to the ASTM method are always higher than those based on the NCHRP method. It is also interesting to note that the largest differences are obtained for wearing course mixtures. While the smallest differences are obtained from the SMA mixtures, the binder course mixtures seem to fall between these categories. It should be remembered that the ASTM values are obtained using the deformation measurements from the NCHRP method and the only difference between the two results is the method of calculation of resilient moduli values. Based on these outcomes, the SMA mixtures seem to have less sensitivity to the calculated resilient modulus values as compared to the other mixtures. On the other hand, the wearing course mixtures show the highest sensitivity to the methods used. The reason that the ASTM method produces always higher modulus can be related to either the accuracy level in the calibration of the model to calculate resilient modulus or the assumed Poisson’s ratio effect, which should be verified using a larger experimental data.

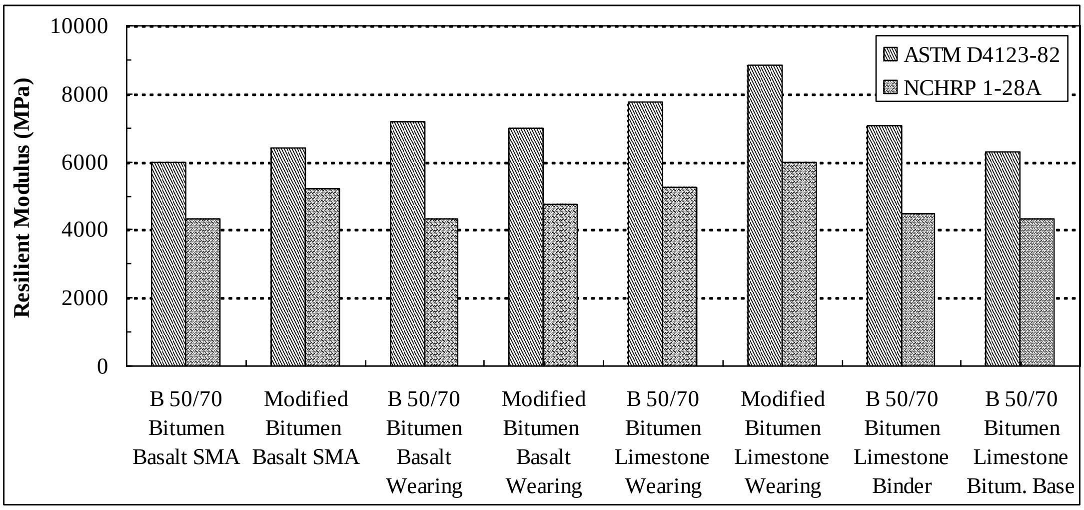


Figure 4.5 Comparison of resilient modulus values based on ASTM and NCHRP methods

- Comparison of Results between Empirical Methods

The estimated resilient modulus values are given in Table 4.5 for each empirical methods together with the ASTM and NCHRP results. The data are also presented in Figure 4.6 to compare between the estimation methods. It can be seen that the ASTM methods again produces the highest modulus values among the other estimation methods. The Witczak (2000) predictive equation, on the other hand, yields the next highest estimation of modulus values followed by results of the NCHRP method. The other estimation methods, i.e., Heukelom-Klomp (1964), Shell (1954) and the Bonnaure et. al (1977), give lower values as compared to the other methods as can be observed from Figure 4.6.

The comparison of the empirical methods are also given separately for the ASTM and the NCHRP methods using an error coefficient, *e*, as in Table 4.6 and 4.7.

$$e = 100x\left|\frac{E_1 - E_2}{E_1}\right| \tag{4.1}$$

where.

e = percent error (%),

E_1 = resilient modulus values measured in Laboratory by Indirect Tension Test,

E_2 = estimated resilient modulus value estimated by other methods.

Because the ASTM methods gives the highest modulus values, the percent errors calculated for each empirical methods according to Equation (4.1) are higher as compare to the NCHRP method. It can be seen that the largest error is obtained from the Bonnaure (1977) method with 73.68% error for the NCHRP method while 83.25% for the ASTM method. The Shell (1954) and the Heukelom-Klomp (1964) methods produce the next highest errors after the Bonnaure (1977) method. As stated earlier, the smallest error is obtained from the Witczak (2000) predictive equation with an average error of 17.38 % for the NCHRP and 24.71% for the ASTM method. As can be seen from Figure 4.7, the Witczak (2000) method was found to produce results that are closest to both measurement methods with an average error of not more than 25%. Based on these results, it can be recommended that if a laboratory measured resilient modulus is not available; the Witczak (2000) predictive equation should be used among the other estimation methods to predict the actual modulus. However, because the data presented in this study are quite limited, these results should be supported using larger data sets.

Table 4.5 Comparison of the results for resilient modulus calculated using four different empirical methods

Method	Basalt				Limestone			
	SMA		Wearing		Wearing		Binder	Bit. Base
	50/70	PMB	50/70	PMB	50/70	PMB	50/70	50/70
Witczak (2000)	5846.34	6183.05	4738.1	5853.30	4198.40	5189.88	4498.92	5158.19
Heukelom-Klomp (1964)	1146.88	598.08	1947.32	1061.87	2353.48	1304.53	2698.46	3512.31
Shell (1954)	1000	1000	1300	1300	1400	1400	1600	1650
Bonnaure et. al (1977)	898.72	898.72	1189.69	1189.69	1387.71	1387.71	1487.21	1604.14
ITT-ASTM D4123-82	5992.67	6403.74	7177.58	7003.03	7761.94	8836.67	7059	6288.31
ITT-NCHRP-1-28A	4313	5222	4338	4767	5245	5970	4487	4306

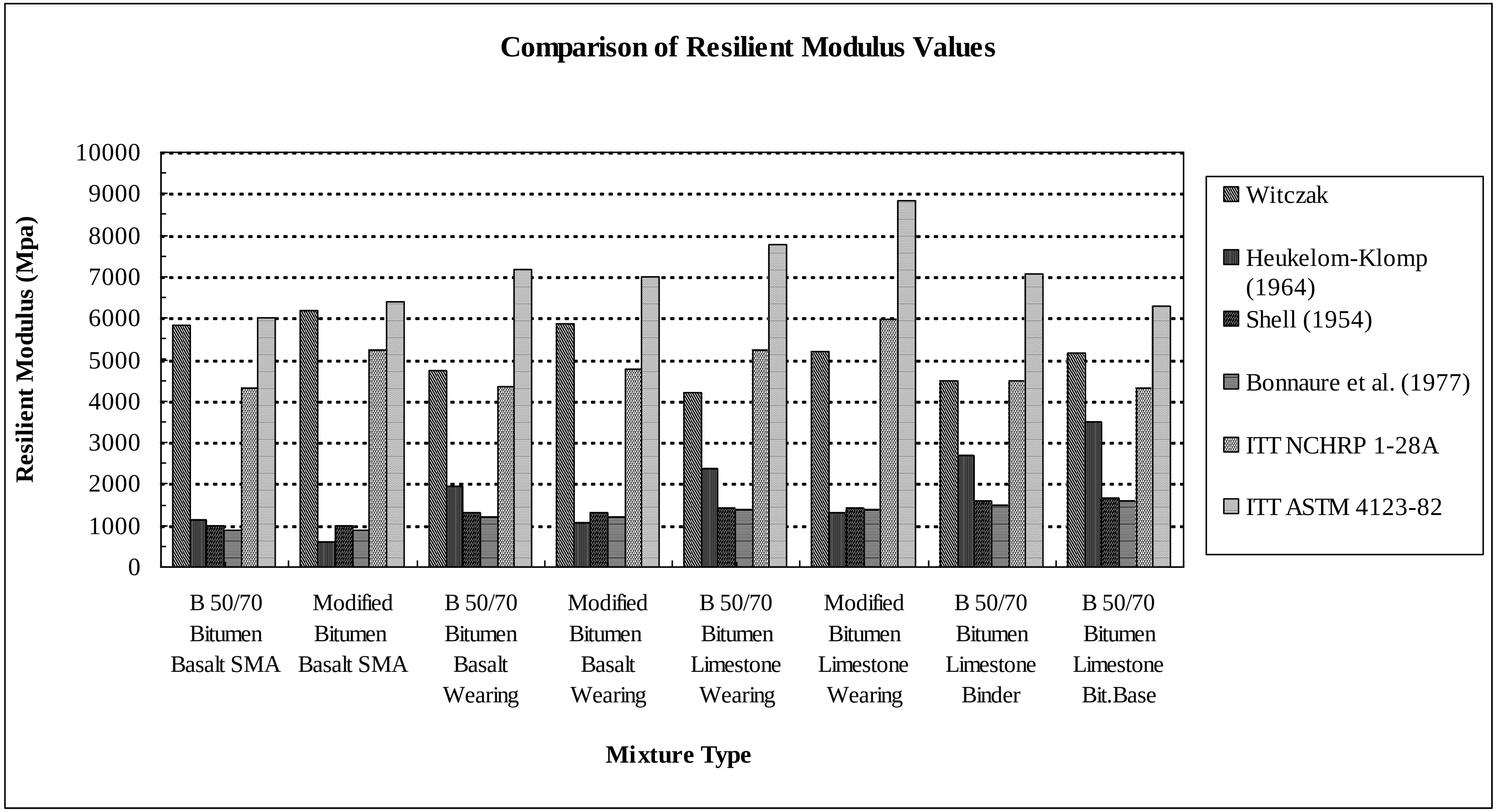


Figure 4.6 Comparison of Resilient Modulus Values Obtained by Empirical Methods with Experimental results

Table 4.6 Error in estimated moduli values based on NCHRP 1-28A method

	Error Values			
	Witczak (2000)	**Heukelom-Klomp (1964)**	**Shell (1978)**	**Bonnaure et al. (1977)**
B 50/70 Bitumen Basalt SMA	35.55	73.41	76.81	79.16
Modified Bitumen Basalt SMA	18.40	88.55	80.85	82.79
B 50/70 Bitumen Basalt Wearing	9.23	55.11	70.03	72.58
Modified Bitumen Basalt Wearing	22.79	77.72	72.73	75.04
B 50/70 Bitumen Limestone Wearing	19.95	55.13	73.31	73.54
Modified Bitumen Limestone Wearing	13.07	78.15	76.55	76.76
B 50/70 Bitumen limestone Binder	0.27	39.86	64.34	66.86
B 50/70 Bitumen Limestone Bit.Base	19.79	18.43	61.68	62.75
Average Error	17.38	60.80	72.04	73.68

Table 4.7 Error estimation based on ASTM 4123-82

	Error Values			
	Witczak (2000)	**Heukelom-Klomp (1964)**	**Shell (1954)**	**Bonnaure et al. (1977)**
B 50/70 Bitumen Basalt SMA	2.44	80.86	83.31	85
Modified Bitumen Basalt SMA	3.45	90.66	84.38	85.96
B 50/70 Bitumen Basalt Wearing	33.98	72.88	81.89	83.42
Modified Bitumen Basalt Wearing	16.42	84.85	81.44	83.01
B 50/70 Bitumen Limestone Wearing	45.91	69.68	81.96	82.12
Modified Bitumen Limestone Wearing	41.27	85.23	84.16	84.29
B 50/70 Bitumen limestone Binder	36.27	61.78	77.33	78.93
B 50/70 Bitumen Limestone Bit.Base	17.97	77.99	82.07	83.25
Average Error	24.71	77.99	82.07	83.25

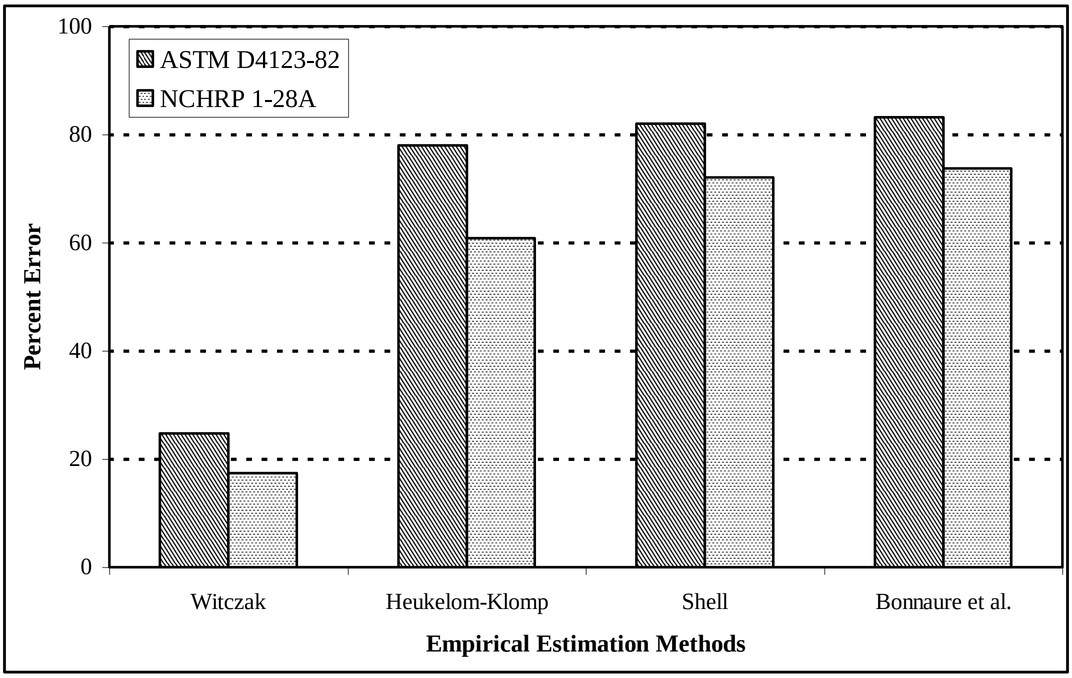


Figure 4.7 Percent error values for empirical methods used

CHAPTER 5

CONCLUSIONS

In this study, the resilient modulus values of different mixtures were determined by experimental and empirical methods. For this study, 8 different types of mixtures used in the design of asphalt concrete pavements in Turkey were prepared and then subjected to indirect tension tests.

After experimental study, the resilient modulus values of the mixtures were determined by various empirical methods suggested founding the literature, and the results are evaluated in order to determine the best empirical method to estimate the resilient modulus of tested mixtures. Based on the test results and the analysis of the empirical methods, the following conclusions can be drawn:

- The ASTM method produces the highest modulus values as compared to the NCHRP method. This outcome is attributed to the difference between the two methods in terms of accuracy of the measured deformations and the calibrated model coefficients used to calculate the resilient modulus.
- Heukelom-Klomp (1964), Bonnaure et al. (1977) and the Shell (1978) empirical methods produce the lowest modulus values relative to the measured ones and the Witczak (2000) predictive equation, hence they produce the largest estimation errors.
- Witczak (2000) model produces the best approximation to the measured modulus values with an average error of not more than 25%.
- It is recommended that in cases where the measured modulus value is not available in the design phase of pavements, the Witczak (2000) predictive equation be used to predict the actual modulus.
- Because the presented data in this study are quite limited, a larger data set should be used to verify the presented results.

- Suggestions For Future Studies

In this study, resilient modulus of HMA mixtures consisting of wearing course, stone mastic asphalt, binder and bituminous base courses are determined based on the NCHRP test method. The results of this study should be supported by using a larger data set to observe if the Witczak (2000) model always produces the best approximation to the measured modulus. In addition, variability in the measured resilient modulus due to non-uniform air void distribution of gyratory compactor samples should be investigated by testing cut sections at different levels of compacted samples.

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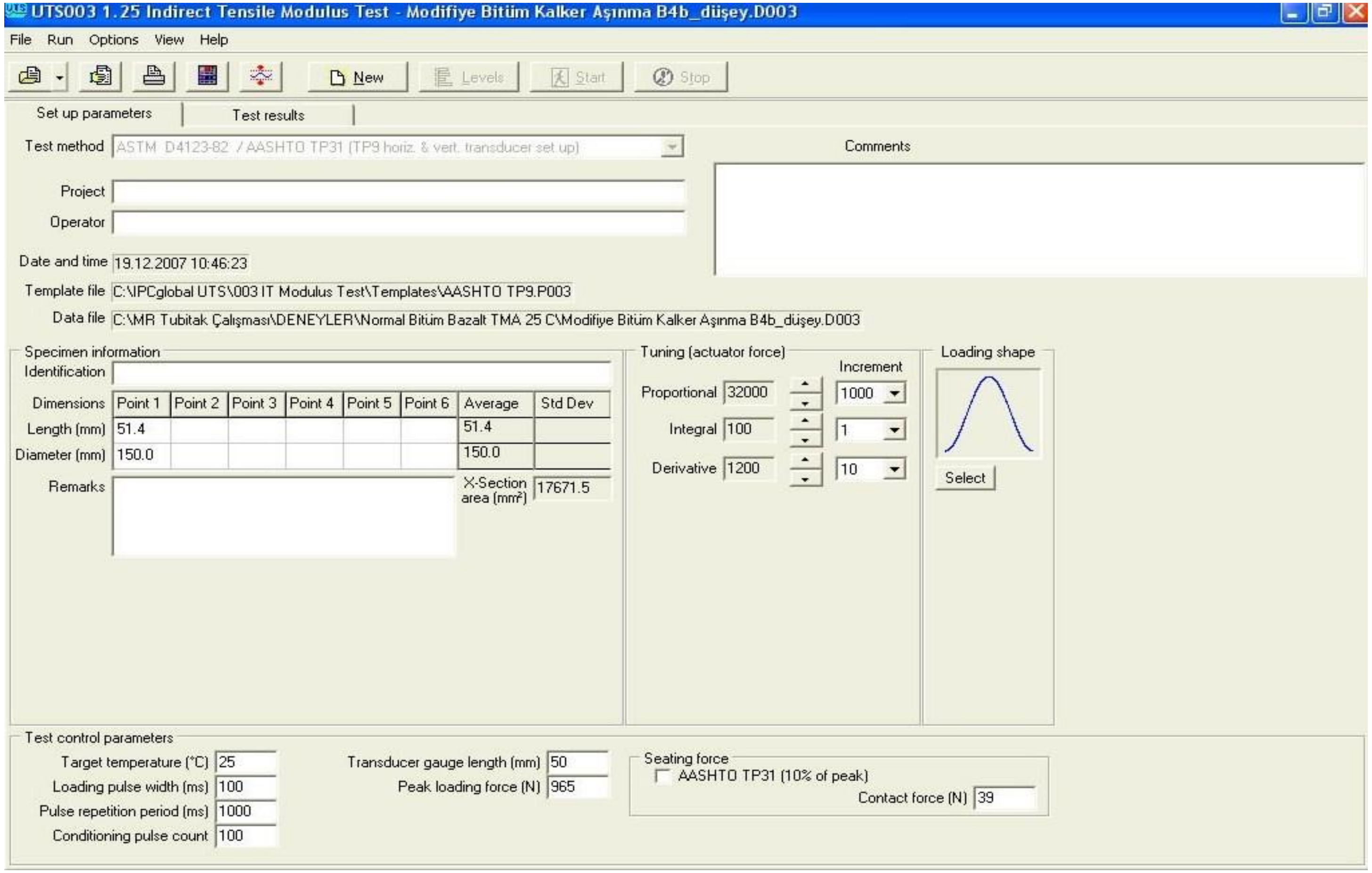
APPENDIX A

Indirect tension test set up parameters and test results.



UTS003 1.25 Indirect Tensile Modulus Test - Modifiye Bitüm Kalker Aşınma B4b_düşey.D003

Test method: ASTM D4123-82 / AASHTO TP31 (TP9 horiz. & vert. transducer set up)

Project:

Operator:

Date and time: 19.12.2007 10:46:23

Template file: C:\IPCglobal UTS\003 IT Modulus Test\Templates\AASHTO TP9.P003

Data file: C:\MR Tubitak Çalışması\DENEYLER\Normal Bitüm Bazalt TMA 25 C\Modifiye Bitüm Kalker Aşınma B4b_düşey.D003

Specimen information

Identification:

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	51.4						51.4	
Diameter (mm)	150.0						150.0	

X-Section area (mm²): 17671.5

Remarks:

Tuning (actuator force)

		Increment
Proportional	32000	1000
Integral	100	1
Derivative	1200	10

Loading shape

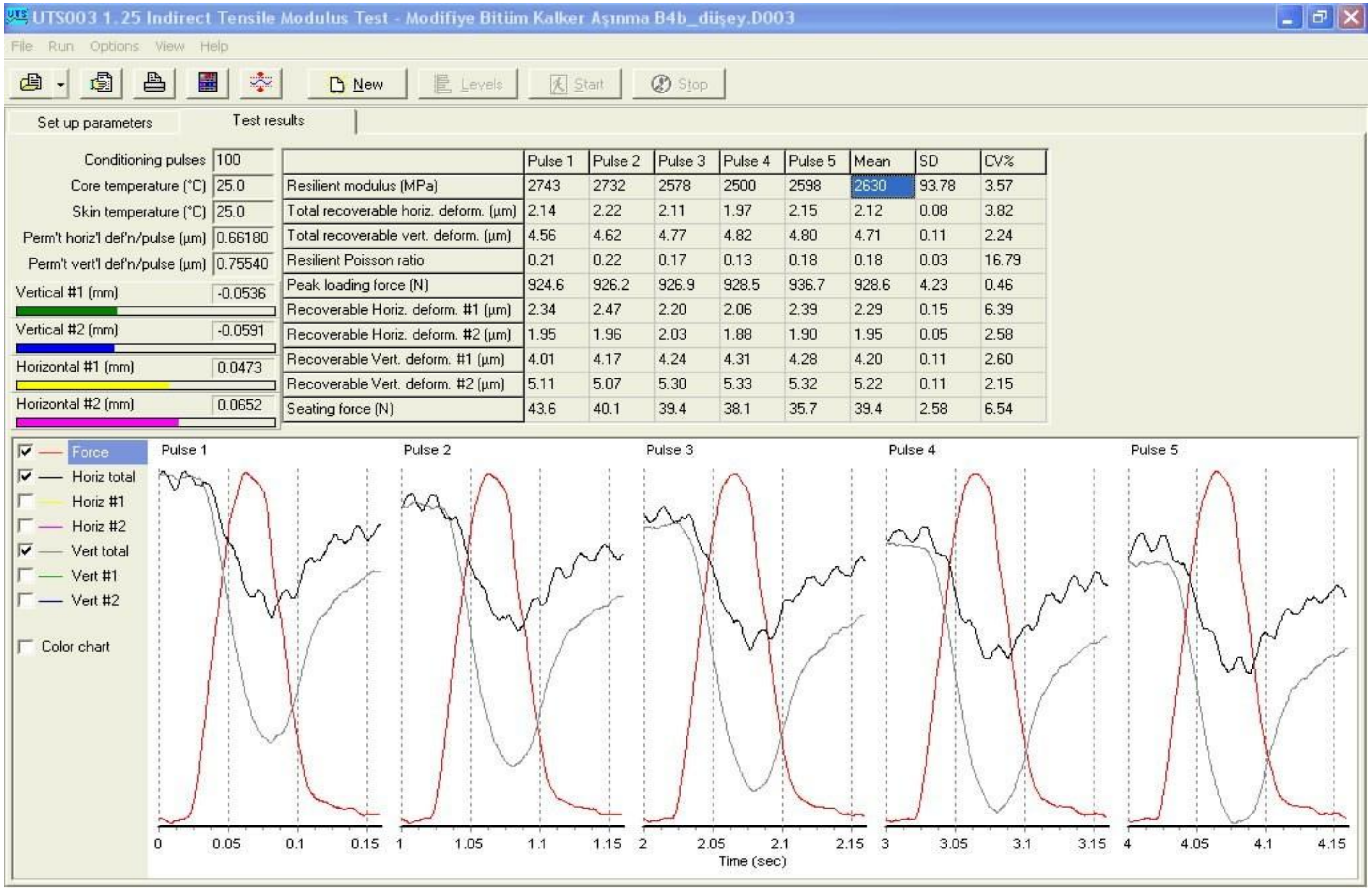
Test control parameters

Target temperature (°C): 25
Loading pulse width (ms): 100
Pulse repetition period (ms): 1000
Conditioning pulse count: 100

Transducer gauge length (mm): 50
Peak loading force (N): 965

Seating force
☐ AASHTO TP31 (10% of peak)
Contact force (N): 39

Figure A.1 Sample Test Set up Parameters



Conditioning pulses: 100
Core temperature (°C): 25.0
Skin temperature (°C): 25.0
Perm't horiz'l def'n/pulse (µm): 0.66180
Perm't vert'l def'n/pulse (µm): 0.75540
Vertical #1 (mm): -0.0536
Vertical #2 (mm): -0.0591
Horizontal #1 (mm): 0.0473
Horizontal #2 (mm): 0.0652

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	SD	CV%
Resilient modulus (MPa)	2743	2732	2578	2500	2598	2630	93.78	3.57
Total recoverable horiz. deform. (µm)	2.14	2.22	2.11	1.97	2.15	2.12	0.08	3.82
Total recoverable vert. deform. (µm)	4.56	4.62	4.77	4.82	4.80	4.71	0.11	2.24
Resilient Poisson ratio	0.21	0.22	0.17	0.13	0.18	0.18	0.03	16.79
Peak loading force (N)	924.6	926.2	926.9	928.5	936.7	928.6	4.23	0.46
Recoverable Horiz. deform. #1 (µm)	2.34	2.47	2.20	2.06	2.39	2.29	0.15	6.39
Recoverable Horiz. deform. #2 (µm)	1.95	1.96	2.03	1.88	1.90	1.95	0.05	2.58
Recoverable Vert. deform. #1 (µm)	4.01	4.17	4.24	4.31	4.28	4.20	0.11	2.60
Recoverable Vert. deform. #2 (µm)	5.11	5.07	5.30	5.33	5.32	5.22	0.11	2.15
Seating force (N)	43.6	40.1	39.4	38.1	35.7	39.4	2.58	6.54

Figure A.2 Sample Test Results