RESILIENT MODULUS OF UNBOUND AND BITUMINOUS BOUND ROAD MATERIALS

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ABSTRACT

New generation methods in road pavement design are being developed on the basis of mechanical properties of materials directly related to performance rather than empirical ones. In this context, there has emerged a necessity of determining the resilient properties of both unbound and bituminous bound road materials to adapt the Turkish pavement design method to new developments and technologies. On the other hand, it is very well known that resilient behavior of unbound materials is nonlinear and highly dependent on the state of stress. But, current resilient modulus equations in literature are basically simple correlations with CBR or offer incremental iterative nonlinear numerical solutions which are not suitable for specification purposes. In this study, resilient modulus tests (AASHTO T 307) and soil index tests (sieve analysis, CBR, Atterberg limits, optimum moisture content, maximum dry unit weight) on the different kinds of subgrade, subbase and base materials taken from all 17 regional areas of Turkish Highways, and resilient modulus tests (NCHRP Project 1-28A) on gyratory compacted bituminous base, binder, wearing coarse and stone mastic asphalt (SMA) specimens designed using limestone and basalt aggregates with paving grade bitumen and polymer modified bitumen were performed. In this paper, an analytical equation has been introduced for stress dependent resilient modulus of unbound materials and it was concluded that simplified Witczak's dynamic modulus equation for 4 Hz of frequency may safely be used for estimation of resilient modulus of Asphalt Concrete.

Keywords : Resilient modulus, stress-dependant, california bearing ratio, asphalt concrete, subgrade

1. INTRODUCTION

Performance of the road pavements that constitute a substantial part of the highway costs is highly dependent on characteristics of pavement materials, traffic loads, environmental and climatic conditions. Construction of a safe, economic and reliable pavements with the good serviceability is contingent upon the proper estimation of traffic load and environmental conditions the pavement could be exposed to and modeling the behavior of the pavement layers under these conditions.

The ASHTO interim design guide published first in 1961 and then in 1972 and based on the data obtained from the road tests conducted for two years between 1958 and 1960 has traditionally been used as a designing method in modeling the pavement until recently. This guide is empirical in nature and basically derived from the results of the test sections representative of limited traffic passes, limited vehicle configuration, local materials and local environmental conditions. In this method, strength characteristics of the materials are based on experiments performed under static loading which is California Bearing Ratio (CBR) for unbound granular materials and Marshall Stability for bituminous asphalt layers.

In actual field conditions, however, loads on pavements are neither static nor uniform, but rather variable and dynamic. Considering the rapidly developing pavement technology and growing diversification in products, material types and traffic configurations, CBR value is now quite inadequate in estimation of pavement behavior.

For this reason, subsequent AASHTO design guides in 1986 and 1993 have related the performance of the pavement to a value called resilient modulus for both unbound and bituminous bound pavement layers. Resilient modulus (M_R) can be defined shortly as elastic modulus of a material under repeated loads. Being performed under repetitive loading, the resilient modulus better represents the pavement behavior under traffic loads and three dimensional state of stress. New approach, however, in pavement design is mechanistic – empirical methods in which the response of the pavement, defined in terms of stresses and strains, is analyzed using rigorous theories of mechanics and critical response quantities are then related empirically to pavement performance. In this method also, the resilient modulus is vitally important parameter to calculate stresses and strains .

In spite of the fact that resilient modulus of pavement materials has been extensively researched for over 30 years, it is stil hard task to determine resilient modulus due to its stress dependent nature. Besides, the resilient modulus must be measured by conducting a carefully controlled laboratory triaxial test on a small soil sample. Many highway agencies have been hesitant to implement the test because it is complex and because the results can be influenced by various factors. Thus, the resilient modulus of pavements are generally estimated form some empirical correlations with their other physical properties.

The earliest correlations were simple linear relationships between California Bearing Ratio (CBR) and resilient modulus (M_R). Some of them are given below:

Shell Oil (Heukelom and Foster 1960)

$$M_R = 1500\ CBR \qquad (1)$$

Transport and Road Research Laboratory Lister 1987)

$$M_R = 2555\ CBR^{0.64} \qquad (2)$$

Ignoring stress factor these relationships provide very rough estimation and their usage are generally limited to very specific range of material properties. For example equation 1 is generally used for fine grained soils with a soaked CBR between 5% and 10%.

The relationships considering stress factor are complex exponential models. Most commonly used of them are;

AASHTO Model: $M_R = k_1 (\theta)^{k2}$ (3)

Uzan (Universial): $\dfrac{M_R}{\sigma_{atm}} = k_1 \left(\dfrac{\theta}{\sigma_{atm}}\right)^{k_2} \left(\dfrac{\theta_d}{\sigma_{atm}}\right)^{k_3}$ (4)

Rafael Pezo: $M_R = k_1 \sigma_d^{k2} \sigma_3^{k3}$ (5)

$$\text{NCHRP 1-28A:}\quad M_R = k_1 P_a \left(\frac{\theta}{\sigma_{atm}}\right)^{k_2} \left(\frac{\tau_{oct}}{\sigma_{atm}} + 1\right)^{k_3} \qquad (6)$$

Here;

M_R = Resilient modulus
$\theta = \sigma_1 + \sigma_2 + \sigma_3$ (total stress)
k_1, k_2, k_3 = regression coefficient
σ_d= Deviator stress
σ_3 = Confining pressure
σ_{atm}= Atmospheric pressure
$\tau_{oct} = (1/3)[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2]$ (octahedral shear stress)

Available relationships in literature generally correlate k_i coefficients with other physical indexes such as CBR, plasticity index, moisture content etc. But, even if these coefficients are accurately specified, since the stresses due to traffic loads are a function of resilient modulus again, these equations turns into a complex implicit form which has no explicit solution but numerical solutions. This complexity of solution for resilient modulus is not convenient for specification purposes.
In line with this, this study aimed to establish a direct relationship which has explicit solution between resilient modulus and the other physical soil indexes considering stress of state.

2. RESILIENT MODULUS (M_R)

Resilient modulus is the elasticity modulus of a material under repeated loads and is a measure of the distribution of the loads through pavement layers. Resilient modulus also controls fatigue cracks caused by tensile stresses at the bottom of Asphalt Concrete (AC) layer and permanent deformations throughout the pavement. The resilient modulus under the uniaxial dynamic loading in general is the ratio of the maximum stress to the maximum unit deformation. The pavement materials are normally not elastic, each load repetition produce a small amount of plastic (permanent) deformation. But, if the traffic load is less than the strength of the material, after a certain number of load repetition, the deformation in each repetition is almost completely recoverable and proportional to the load and can be considered as elastic.

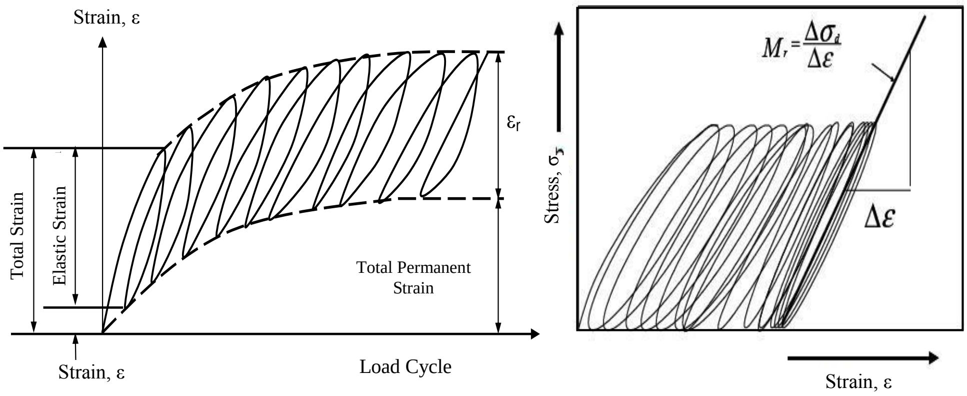

Figure 1: Behavior of the pavement materials under repetitive loads and the resilient modulus

Figure 1 shows the deformation curve of a sample under the effect of repetitive loads. As can be seen in the figure, while there is considerable plastic strain at the beginning of resilient modulus test, as the number of repetitions increases the plastic strain due to each load repetition gradually decreases. Approximately after 100-200 load repetitions, the strain is practically all recoverable as indicated by ε_r in the figure.
In triaxial confining test, the ratio of deviator stress ($\sigma_d = \sigma_1 - \sigma_3$) to recoverable strain (ε_r) is called as the resilient modulus (M_R) and calculated with the formula given below:

$$M_R = \frac{\sigma_d}{\varepsilon_r} \qquad (7)$$

Contrary to CBR, resilient modulus of unbound materials is stress dependent parameter and depend on the three axial state of stress. Resilient modulus of coarse aggregates generally used in base and subbase layer always increases with increasing confining stress which is called as referred to as stress hardening behavior. But, in fine aggregates, resilient modulus decreases with increasing confining stress which is called as referred to as stress softening behavior.

3. EXPERIMENTAL

3.1. Tests on Unbound Road Materials

In order to conduct the resilient modulus test on different types of unbound materials that represent the conditions in all over Turkey, 17 Regional Directorates of the General Directorate of Highways were visited and 171 base, subbase and subgrade soil samples (42.75 tons in total) were collected. On these materials the following experiments were performed:

Name of the Test	**Test Standard**
Resilient Modulus	AASHTO T 307 (1999)
California Bearing Ratio (CBR)	AASHTO T 139 (1999)
Standard Proctor	AASHTO T 99 (2001)
Modified Proctor	AASHTO T 180 (2001)
Plastic Limit	AASHTO T 90 (2005)
Liquid Limit	AASHTO T 89 (2005)
Sieve Analysis	AASHTO T 27 / 11 (2005)

Table 1: The tests conducted on unbound materials

The resilient modulus tests have been conducted on granular materials as per the standard AASHTO T 307 using the test machine Load Trac II (Geocomp). First, the all samples were classified as type 1 (coarse grained) or type 2 (fine grained). The materials less than 70% passing the 2 mm (no. 10) sieve, less than 20% passing 75 μm (no. 200) sieve, and with maximum plasticity index of 10 are classified as type 1, and the materials other than the above are classified as type 2. The materials type 1 were compacted into 150 mm diameter cylindrical molds using vibratory compactor. But, The molds of 100 mm diameter and Standard Proctor for compaction were used in type 2 materials.

Since the resilient modulus of the granular materials were changed with state of stress, the test is conducted 15 sequence each has different confining and axial stress level. Prior to resilient modulus testing sequence, prepared specimens are conditioned as shown for sequence ‘0’ in Table. This conditioning step eliminates the effects of the interval between compaction and loading and loading and the elimination of initial loading versus reloading and minimize impact of improper contact between the specimen ends and sample cap and base plate. After conditioning , Type 1 materials are tested at five levels of confinement (3,5,10,15,20) with varying stress level of axial stress for each confinement level. Type 2 materials are tested at three decreasing levels of confinement (6,4,2) at 5 increasing levels of axial stress (2,4,6,8,10) within each confinement stress level. After conditioning, modulus testing is conducted at various stress states as shown table below. In each sequence, 100 haversine repeated loads are applied with load pulse duration of 0.1 seconds (10 Hz) and a rest period of 0.9 seconds. Aggregate of last 5 modulus readings is recorded as resilient modulus of that sequence.

Sequence	**Confining Stres Psi**		**Maximum Stress Psi**		**Cyclic Stress psi**		**Contact Stress psi**		**Number of repetition**
	Type1	**Type2**	**Type1**	**Type2**	**Type1**	**Type2**	**Type1**	**Type2**	
0	15	6	15	4	13,5	3,6	1,5	0,4	1000
1	3	6	3	2	2,7	1,8	0,3	0,2	100
2	3	6	6	4	5,4	3,6	0,6	0,4	100
3	3	6	9	6	8,1	5,4	0,9	0,6	100
4	5	6	5	8	4,5	7,2	0,5	0,8	100
5	5	6	10	10	9,0	9,0	1,0	1,0	100
6	5	4	15	2	13,5	1,8	1,5	0,2	100
7	10	4	10	4	9,0	3,6	1,0	0,4	100
8	10	4	20	6	18,0	5,4	2,0	0,6	100
9	10	4	30	8	27,0	7,2	3,0	0,8	100
10	15	4	10	10	9,0	9,0	1,0	1,0	100
11	15	2	15	2	13,5	1,8	1,5	0,2	100

12	15	2	30	4	27,0	3,6	3,0	0,4	100
13	20	2	15	6	13,5	5,4	1,5	0,6	100
14	20	2	20	8	18,0	7,2	2,0	0,8	100
15	20	2	40	10	36,0	9,0	4,0	1,0	100

Table 2: Test sequences for unbound materials

3.1. Tests on Asphalt Mixtures

Both AASHTO 1993 and new mechanistic-empirical pavement design methods require resilient modulus of Asphalt Concrete (AC) layers known. For this reason, resilient modulus of the different AC types commonly used in Turkey were experimentally determined within the context of this study.
Contrary to stress dependent behavior of unbounded materials, the asphalt layers exhibit more stable behavior under various stress levels and accepted as stress independent. The resilient modulus of the AC layers generally varies with the temperature and loading frequency.
In this study, resilient modules of Stone Mastic Asphalt (SMA), AC wearing course, binder course and bituminous base course which are commonly used in Turkey were determined. Two types of aggregate (basalt and limestone) and bituminous binder (B 50/70 penetration grade bitumen and 5% SBS modified bitumen) were used. Basalt and polymer modified bitumen (PMB) were used in both wearing course and SMA mixtures. The list of material used is given table below. In total 8 asphalt mixture and 3 replicate of each were prepared.

Aggregate	Wearing Course		Stone Mastic Asphalt		Binder Course		Bituminous Base Course	
	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	-

Table 3: Asphalt Concrete types and their aggregate and bitumen compositions.

The prepared samples were tested for resilient modulus in accordance with NCHRP Project 1-28A "Laboratory Determination of Resilient Modulus for Flexible Pavement Design" standard using the test equipment UTM-100 (Universal Testing Machine with the capacity of 100 kN). Accordingly, the samples prepared 15 cm in diameter and 15 cm in height with gyratory compactor. These samples cut from two ends and two test samples 5 cm in height and 15 cm in diameter were produced from each mold, one is used for indirect tensile strength test, the other is used for indirect tensile resilient modulus test. Since load to be used in M_R test has to be in the elastic range of samples, first IT strength and later resilient modulus tests have been done. For resilient modulus test horizontal and vertical LVDT's were placed on both sides of the samples which were stabilized at 25 ^{0}C test temperature. Then a haversine waveform repeated load was applied with 1 second interval (0.1 s load period and 0.9 s rest period) in the indirect tensile test mode. The total load in each load repetition is the sum of the cyclic load and the contact load. While the contact load provides the immobility of the sample, the repetitive load is the load from which the resilient modulus was calculated. Since it is desired the load be remained in the elastic limits of the sample, the repetitive load was chosen as 15% of the indirect tensile strength of the sample and the contact load was chosen as the 4% of the repetitive load. Average of the resilient modulus of the five loads after 100 loadings was recorded as the resilient modulus of the sample in that direction and the average of the resilient modulus in both directions was determined as the resilient modulus of that sample.

MIX DESIGN	AC Types				
	SMA	Wearing Course	Wearing Course	Binder Course	Bituminous Base Course
Aggregate type	Basalt	Basalt	Limestone	Limestone	Limestone
Optimum binder , %	6.5	5.25	5.25	5.0	4.5
Bulk Density, Dp, gr/cm3	2.458	2.473	2.356	2.360	2.348
Stability, kg	561	1140	1260	1190	920
Voids filled with asphalt, VFA %	79.0	75.0	72.4	67.0	59.7
Air Void, Va %	3.53	3.66	4.13	4.7	5.61
Flow, mm	3.47	2.92	3.40	3.10	3.20
Voids in Mineral aggregates, VMA %	16.81	14.6	14.9	14.1	13.9

	Sieve		% Passing				
	mm	inch					
SIEVE ANALYSIS	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
	2.00	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

Table 4: Design values of AC mixes.

4. ASSESSMENT OF THE DATA

4.1 Statistical analysis of the resilient modulus for the granular materials

Since the highest correlations in the tested samples were obtained in the model known as "Pezo Model" given below, this model is used in the analysis of results.

$$M_R = k_1 \sigma_d^{k2} \sigma_3^{k3} \qquad (8)$$

Here,

M_R : Resilient Modulus
k_1, k_2, k_3 : Regression coefficients
σ_d : Deviator stress
σ_3 : Confining pressure

Accordingly, the stress values in the Pezo model were found by means of the WINJULEA program giving the multi layer elastic model solutions. In the analysis, the axle load was taken as 8.2 tons and the wheel pressure was taken as 100 psi. A dead load was added to stresses caused by wheel load for all thickness combinations of AC, base and subbase layers (2-30 cm in AC layers, 10-40 cm in base and subbase layers). Then, the resilient modulus values determined in the laboratory were assessed statistically with the other physical characteristics of the materials and stresses. Following correlation was obtained for all material groups (fine and coarse graded included) .

$$M_R = 10^{4.88} . \sigma_d^{0.436} . \sigma_3^{0.436} . CBR^{-0.512} . \left(\frac{1}{1+\log(No200)}\right)^{0.413\,(LL.PI+1)^{0.0709}} . \left(\frac{\gamma_{maks}^2}{No4}\right)^{0.106 \log(\omega_{opt})} \qquad (9)$$

R^2=68.2 %

Since the confining stress (σ_3) and the deviator stress (σ_d) values in this formula are dependent on the pavement thickness of the resilient modulus, making the required transformations in stress formula, as a function of the depth the following equation has been obtained.

$$M_R = 10^{4.479} . \left(D_{AC} + k\right)^{0.436} . CBR^{-0.435} . \left(\frac{1}{1+\log(No200)}\right)^{0.35\,(LL.PI+1)^{0.06}} . \left(\frac{\gamma_{maks}^2}{No4}\right)^{0.09 \log(\omega_{opt})} \qquad (10)$$

Here,

M_R : Resilient modulus, psi
D_{AC} : Total thickness of the hot mix asphalt, cm
CBR : Soaked California Bearing Ratio, %
ω_{opt} : Optimum moisture, %
γ_{max} : Max. Dry unit weight, g/ cm^3
LL : Liquid limit, %

PI	: Plasticity Index, %
No200	: Percent passing No.200 sieve
No4	: Percent passing No.4 sieve
k	: Depth correction factor.

The resilient modulus in this equation is the ideal resilient modulus of a sample compacted in laboratory at optimum moisture and maximum unit dry weight. Yet, the resilient modulus of the soil in real field conditions change continuously during the year due to change in underground water, freezing and thawing, etc. For this reason, the ideal resilient modulus obtained in the laboratory must be reduced by a seasonal damage factor. This damage factor between the ideal and corrected resilient modulus can be expressed as the ratio of the soaked CBR value to dry CBR value as the following.

$$\frac{M_{Reff}}{M_{Rideal}} = \frac{CBR_{soaked}}{CBR_{dry}} \Longrightarrow M_{Reff} = M_{Rideal}\frac{CBR_{soaked}}{CBR_{dry}} \qquad (11)$$

Between the M_{Reff} / M_{Rideal} and the damage factor which is based on the ratio CBR_{soaked} / CBR_{dry} ratio the following equation was found statistically.

$$\frac{M_{Reff}}{M_{Rideal}} = 10^{-1.235}.CBR_{soaked}^{\ 0.838} \qquad R^2=85.1 \qquad (12)$$

By arranging the equations (11) and (12), the following generalized formula for the corrected resilient modulus has been generated.

$$M_R = 1750.\left(D_{AC}+k\right)^{0.436}.CBR^{0.4}.\left(\frac{1}{1+\log(No200)}\right)^{0.35\,(LL.PI+1)^{0.06}}.\left(\frac{\gamma_{maks}^{\ 2}}{No4}\right)^{0.09\log(\omega_{opt})} \qquad (13)$$

In this general formula, the (D_{AC} + k) expression represents the stress dependency depending on the depth where the pavement layer is. D_{AC} is the total thickness of AC layers in cm over unbounded base layer and k is depth correction factor. Here, k can be thought as equivalent base thickness and recommended value of k for base and subbase materials k=0, for subbase materials k=17.

4.2. Assessment of the resilient modulus obtained for the AC layers

Results of the resilient modulus tests on the AC samples are given below as a graph.

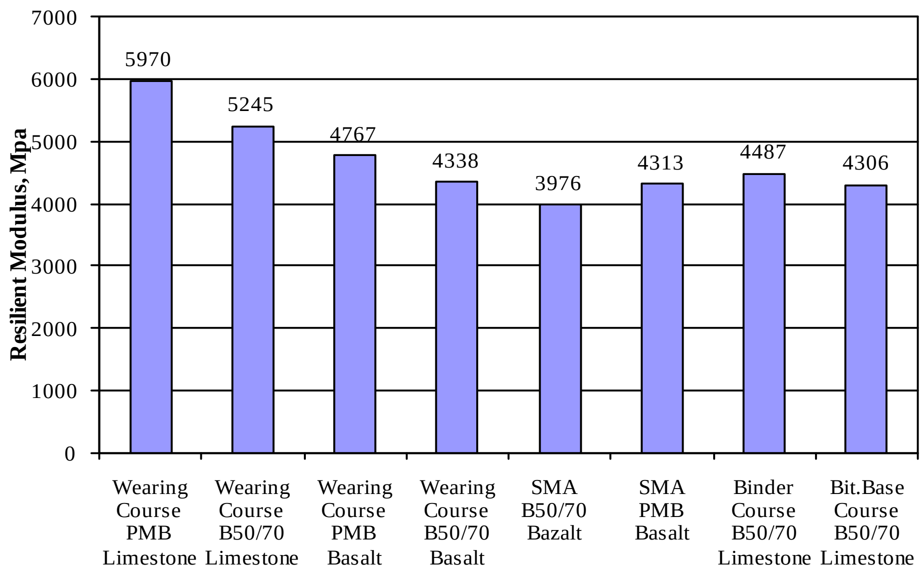

Figure 2: Resilient modulus values of the AC layers.

According to the results of the test, the following equation has been found to be best-fit for estimation of resilient modulus of AC layers which was derived from the Witczak's dynamic modulus equation for the equivalent frequency (4 Hz).

$$\log E^* = 3.75 + 0.029\,No200 - 0.00177\,No200^2 - 0.0028\,No4 - 0.058\,V_h - 0.8\left(\frac{V_b}{V_b + V_h}\right) + \frac{3.87 - 0.0021\ No4 + 0.004\ No3/8 - 0.000017\ No3/8^2 + 0.0055\ No3/4}{1 + e^{-2.56 + 0.89\ \log(pen) - 0.0015\ [\log(pen)]^2}} \tag{8}$$

Here,

E*	: Dynamic modules, psi
Va	: Air Void, %
Vb	: Binder Content, %
Pen:	: Penetration of binder, 0.1 mm
No200	: Percent passing No.200 sieve
No4	: Percent retained on No.4 sieve
No3/8	: Percent retained on No.3/8 sieve
No3/4	: Percent retained on No.3/4 sieve

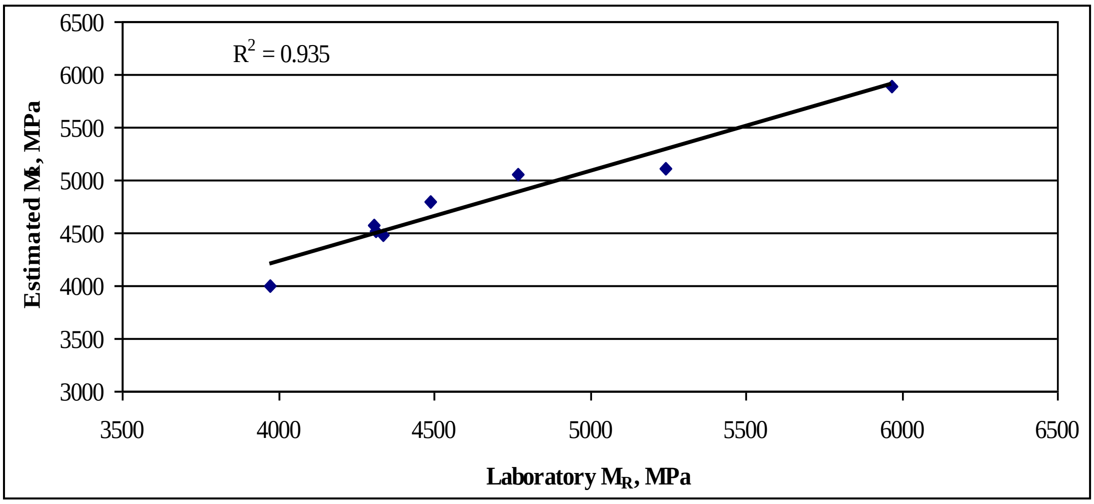

Figure 2: Graph showing the correlation between laboratory and estimated Resilient modulus values.

5. CONCLUSIONS

Since, the modern pavement design methods require resilient properties of road pavement materials, whereas there is not a simple model for estimation of resilient modulus, in this study it was challenged to establish a formulation for both unbounded granular materials and bituminous bounded asphalt layers. In the end of test conducted on 171 different types of aggregates, and 8 types of asphalt mixture, a new equation considering stress state has been introduced for unbound granular materials, and simplified version of Witczak's dynamic modulus equation has been suggested for estimation of resilient modulus of asphalt mixtures. The derived resilient modulus equation in this paper for unbound materials is thought to be used as constitutive model which may require calibration to local soil conditions.

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