



جمهورية العراق
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جامعة بابل / كلية الهندسة
قسم الهندسة المدنية

التنبؤ بمعامل مرونة الخلطة الإسفلتية

رسالة مقدمة إلى

قسم الهندسة المدنية كلية الهندسة - جامعة بابل
كجزء من متطلبات نيل شهادة ماجستير علوم في الهندسة المدنية

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آذار 2008

**Ministry of Higher Education &
Scientific Research
University of Babylon
College of Engineering
Department of Civil Engineering**



PREDICTION OF RESILIENT MODULUS IN ASPHALT PAVING MIXTURE

**A THESIS
SUBMITTED TO THE COLLEGE OF
ENGINEERING OF BABYLON UNIVERSITY IN
PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN CIVIL
ENGINEERING**

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March 2008

بِسْمِ اللّٰهِ الرَّحْمٰنِ الرَّحِیْمِ

وَالْبَاقِيَاتُ الصَّالِحَاتُ خَيْرٌ

عِنْدَ رَبِّكَ ثَوَابًا وَخَيْرٌ أَمَلًا

صدق الله العلي العظيم

سورة الكهف الآية (46)

الخلاصة

تكون الحاجة للخصائص الأساسية لمواد التبليط الإسفلتي مثل معامل مرونة في حسابات التصميم الإنشائي للتبليط وفي تحديد الأحمال المسموح بها على منشأ التبليط المقام أصلاً , سمك طبقة إعادة الإكساء وفي التقييم لإعادة التأهيل باستخدام طرق أخرى .

لتحقيق الهدف الرئيسي لهذا البحث و المتمثل بالتنبؤ بمعامل مرونة الخلطة الإسفلتية تم استخدام جهاز المنظومة الهوائية لتسليط الأحمال المتكررة في الجزء العملي (الفحوص المخبرية) من هذا البحث، في الجزء العملي تم إعداد 165 نموذج من الخرسانة الإسفلتية وفحصها. المتغيرات التي تم أخذها بنظر الاعتبار في فحوص الأحمال المتكررة تمثل ثلاث درجات حرارية مختلفة (0س، 20س، 40س) ، المقاس الأقصى للركام والقيم العليا والسفلى له، إضافة للمحتوى الإسفلتي ونوع المادة المائنة المستخدمة في الخلطة الإسفلتية. من خلال فحص الأحمال المتكررة تم التوصل إلى علاقة إحصائية تربط معامل المرونة للخلطة الإسفلتية بمتغيرات الخلطة وظروف الفحص. ومن فحص مارشال الذي ينفذ للحصول على مقدار ثبات وانسيابية الخلطة الإسفلتية، تم التوصل إلى علاقة مبسطة للتنبؤ بمعامل مرونة الخلطة الإسفلتية دون الحاجة لفحوصات الأحمال المتكررة، هذه العلاقة تعتمد على معامل جسائنة مارشال ودرجة حرارة الفحص.

Abstract

The rational characteristics of asphaltic paving materials such as resilient modulus are needed for the calculation of pavement structure design and in determination of allowable loads for existing pavement structure , overlay thickness and for assessment of other rehabilitation needs .

To achieve the objective of this research in resilient modulus prediction of asphalt concrete mixture, pneumatic repeated load test equipment was used in factorial testing program during which 165 specimens were tested. Marshall test was also carried out to extract data for Marshall stability, flow, and Marshall stiffness for each test specimen.

The specimens tested represent the effect of three test temperatures (0C⁰, 20C⁰, 40C⁰) and mix variables such as asphalt content, aggregate gradation, filler type and air voids. Based on the repeated load test results, model was developed for the prediction of resilient modulus of asphaltic concrete mixture.

A Simplified model for resilient modulus prediction was proposed depending on Marshal stiffness and temperature.

Certificate of the Examining Committee

We certify that we have read this thesis titled "**Prediction of Resilient Modulus in Asphalt Paving Mixture**" and as an examining committee, examined the student (**Tariq Hussein Obaiss**) in its contents and in what is connected with it, and that in our opinion it is adequate as a thesis for degree of **Master of Science in Civil Engineering (Highway and Transportation Engineering)**.

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Acknowledgments

First , thanks be to Allah His almighty for enabling me to complete this work . I wish to express my deepest gratitude to my supervisors : **Professor Hamed M. Alani** , College of Engineering , University of Baghdad and **Dr. Nahla Y. Ahmed** , College of Engineering , University of Babylon for their continued valuable guidance and encouragement during the preparation of this work. In addition , many thanks are extended to **Dr. Amjed Al-Bayati** , University of Baghdad for his help and valuable advice . Also , I would like to thank the **Staff of Highway Materials Laboratory** , College of Engineering , in Babylon and Baghdad Universities . Words of love and appreciation are presented to my parents and uncle Rassam in England , for their patience , care and encouragement .

Last but not least , I would like to thank my friend Ahmed Abbas and all other friends and colleagues, the good discussions we had , made my learning experience much more enjoyable .

TARIQ

APPENDIX

Volumetric Analysis of Compacted Mix & Sample of Calculations

The following equations are necessary to compute the volumetric properties of compacted mix:

- **Bulk Specific Gravity of the Combined Aggregate (G_{sb}):**

$$G_{sb} = \frac{(P_1 + P_2 + P_3)}{\left[\frac{P_1}{G_1} + \frac{P_2}{G_2} + \frac{P_3}{G_3} \right]}$$

Where: P_i = percent by weight of each component aggregate in blend
(note: ($P_1 + P_2 + P_3 = 100$)

$G_i = G_{sb}$ of each component aggregate in blend

- **Effective Specific Gravity of the Aggregate (G_{se}):**

$$G_{se} = \frac{(100 - Pb)}{\left[\frac{100}{G_{mm}} + \frac{Pb}{G_b} \right]}$$

Where : P_b =asphalt, percent by total weight of mixture.

G_b = specific gravity of asphalt binder, and

G_{mm} = maximum theoretical specific gravity of mixture at P_b .

- **Maximum Theoretical Specific Gravity (G_{mm}):**

$$G_{mm} = \frac{100}{\left[\frac{P_a}{G_{se}} + \frac{P_b}{G_b} \right]}$$

Where: P_a = present aggregate content in mix by total weight of the mix.

And it can be measured according to (ASTM D2041)

$$G_{mm} = \frac{A}{A + B - C}$$

Where: A = weight of dry sample in air, (gms).

B = weight of flask filled with water at 25 °C (gms).

C = weight of flask filled with water and sample at 25 °C (gms).

- **Bulk Specific Gravity of the Compacted Paving Mixture**

It can be measured according to (ASTM D2726):

$$G_{mb} = \frac{A}{A - B}$$

Where: A = weight of dry sample in air (gms).

B = weight of sample in water (gms).

- **Percent Absorbed Asphalt (P_{ba}):**

$$P_{ba} = \frac{(100G_b)(G_{se} - G_{sb})}{(G_{se}G_{sb})}$$

Where: P_{ba} = percent absorbed asphalt by total weight of aggregate.

- **Percent Effective Asphalt Content (P_{be}):**

$$P_{be} = Pb - \left[\frac{(P_{ba} Pa)}{100} \right]$$

Where: P_{be} = percent effective asphalt by total weight of mix.

P_b = percent asphalt content in mix by weight of total mix.

P_a = percent aggregate content in mix by weight of total mix.

- **Percent Air Voids (AV):**

$$AV = \left[\frac{(G_{mm} - G_{mb})}{G_{mm}} \right] * 100$$

- **Sample of calculations:**

For the sample No.1 (A)

$$AV = \left[\frac{(G_{mm} - G_{mb})}{G_{mm}} \right] * 100 \quad \text{where } G_{mm} = 2.463 \text{ measured in laboratory}$$

$$G_{mb} = 2.340 \text{ measured in laboratory}$$

$$AV = \left[\frac{(2.463 - 2.340)}{2.463} \right] * 100 = 4.99$$

$$G_{sb_A} = \frac{100}{\left[\frac{P_c}{G_{sc}} + \frac{P_f}{G_{sf}} + \frac{P_m}{G_{sm}} \right]}$$

$$= \frac{100}{\left[\frac{38}{2.63} + \frac{55}{2.636} + \frac{7}{2.67} \right]} = 2.63$$

$$G_{se_A} = \frac{(100 - Pb)}{\left[\frac{100}{G_{mm}} + \frac{Pb}{G_b} \right]}$$

$$= \frac{(100 - 4.7)}{\left[\frac{100}{2.463} + \frac{4.7}{1.03} \right]} = 2.647$$

$$P_{ba'} = \left[\frac{1}{G_{sb}} - \frac{1}{G_{se}} \right] * Gb * 100$$

$$= \left[\frac{1}{2.63} - \frac{1}{2.647} \right] * 1.03 * 100 = 0.2515$$

$$P_{be} = (P_b - P_{ba'}) * \frac{(100 - P_b)}{100}$$

$$= (4.7 - 0.2515) * \frac{(100 - 4.7)}{100} = 4.46$$

$$P_s = P_{be} * \frac{G_{mb}}{G_b} = 4.46 * \frac{2.34}{1.03} = 10.13$$

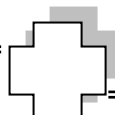
CHAPTER ONE

Introduction

1.1 Background

Asphalt concrete pavements are complicated physical structures responding in a complex way to the influence of many factors (i.e., loads, materials, environmental conditions, etc.) and their interactions. Unlike other structural systems, pavements generally deteriorate rapidly under the action of these factors and require frequent maintenance and periodic rehabilitation.

Generally, the stiffness of a pavement is a measure of materials performance and their ability to spread the applied traffic loading over a specified area. Higher stiffness of pavement layers leads in wider resisting areas that reduce the level of strain experienced at the bottom of the pavement structure to a certain limit, where the cracking frequency increases with the increase in stiffness of the asphalt mix. Today, there are two general approaches for design of pavement system: an empirical approach such as the AASHTO method and a mechanistic approach which employs elastic layer theory to model structural behavior. Design methods are based on the multilayer elastic theory which has been enhanced by the use of highly sophisticated computer programs (Akhter, 1984). Comparable advances have also been made in measurements of dynamic properties of materials, thereby enabling the designer to more clearly define the failure criteria associated with the two most common distress modes: permanent



deformation and fatigue cracking (Bonnaure et. al., 1977). Although both design approaches require a modulus value for each of the component pavement layer. For design of flexible pavement structures, the AASHTO design guide (1993) recommends resilient modulus properties for characterizing the subgrades and bases. This characterization is necessary for designing flexible pavement sections also selecting appropriate bases and asphalt surfaces.

The values of resilient modulus are major parameters in determining the allowable loads for existing pavement structures, overlay thickness, and for the assessment of other rehabilitation needs. In design, the properties of materials must be specified, so that the response of the pavement, such as stresses, strains, and displacements, in the critical components, can be determined (Huang, 1993).

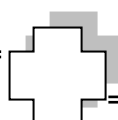
1.2 Research Objectives

The objectives of the research work presented in this thesis can be summarized as follows:

- 1-Identifying the variables that affect the resilient modulus of asphaltic mixtures.
- 2-Developing a resilient modulus model from experimental work results that comprises certain shortcomings which restricts its use to certain conditions and material specifications.

1.3 Research Layout

The layout in this research work consists of the following:

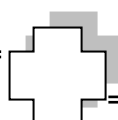


- 1- A detailed literature survey to specify the effective variables and conditions involved indicating how the models are developed or predicted.
- 2- Carrying out an experimental work to extract and prepare data that can be used in model prediction.
- 3- Models of non-linear regression prediction with the aid of a computer software, STATISTICA version 6.0 .
- 4- Drawing conclusions and recommendations.

1.4 Scope of the Study

To achieve the objective of this research, the work shall consist of the following:-

- 1- Definition of pavement moduli concerning resilient modulus as presented in chapter one.
- 2- Chapter two is focused on the review of Literatures that is related to resilient modulus, methods of testing and factors that affect the resilient modulus results.
- 3- The details about the materials and testing procedure required for this study with the information on material properties and testing equipment are given in chapter three.
- 4- Results and discussions of the research and model prediction are presented in chapter four.
- 5- Finally, the extracted conclusions from previous chapters and recommendations for further studies are presented in chapter five.



CHAPTER TWO

Review of Literatures

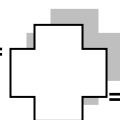
2.1 Introduction

The determination of resilient modulus is one of the most important tasks in pavement design/analysis, pavement management, and selection of rehabilitation strategies. Over the years, hundreds of papers have been devoted to assessing Resilient Modulus (M_r) by laboratory, non-destructive and other innovative field testings (Al-Qadi, 2002).

Many agencies are beginning to use pavement design system based on elastic or viscoelastic theory. To evaluate the elastic or viscoelastic properties required by design procedures, it is highly desirable to evaluate the material properties related to the following three basic distress modes:

- 1-Thermal or Shrinkage Cracking
- 2- Fatigue Cracking
- 3-Permanent Deformation or Rutting.

One of the important types of inputs to these evaluations is the response of various materials subjected to repeated, dynamic tensile stress or strains. The basic material property required as an input for an elastic layer analysis is the modulus of elasticity of each material and its variation with temperature and rate of loading.



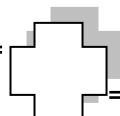
2.2 Resilient Modulus as Design Factor

Huang (1993), in the mechanical-empirical methods of design, the properties of materials must be specified, so that the responses of the pavement, such as stresses, strains, and displacements in the critical components can be determined. The general properties that should be specified for both flexible and rigid pavements are the elastic moduli and Poisson ratios of the subgrade and each component layer when the pavements are considered as linear elastic, but if the elastic modulus of a material varies with the time of loading, the resilient modulus, which is the elastic modulus under repeated loads must be selected. Since the Poisson ratios have relatively small effects on pavement responses, their values can be reasonably assumed.

On the other hand, the material properties may be investigated in terms of creep compliance, relaxation modulus, complex modulus (dynamic modulus and phase angle), indirect tensile resilient modulus and dynamic modulus measured from the impact resonance test. The selection of any form of these properties is dependent upon the simpler test equipment available and the kind of structural analysis used for the model of prediction. Bonnaure (1980), states that the rational characteristics of bituminous mixes such as resilient modulus are needed for the calculation of pavement structure.

2.3 Stiffness-Temperature Relationship of Asphalt Concrete

Witczak (1972), states that airfield pavement design-analysis is partially dependent upon the quantitative relationships between temperature (q) and frequency (f) of load application and the stiffness of asphalt concrete (E_1). Extensive laboratory tests conducted by the asphalt institute on resilient modulus evaluation of asphalt concrete

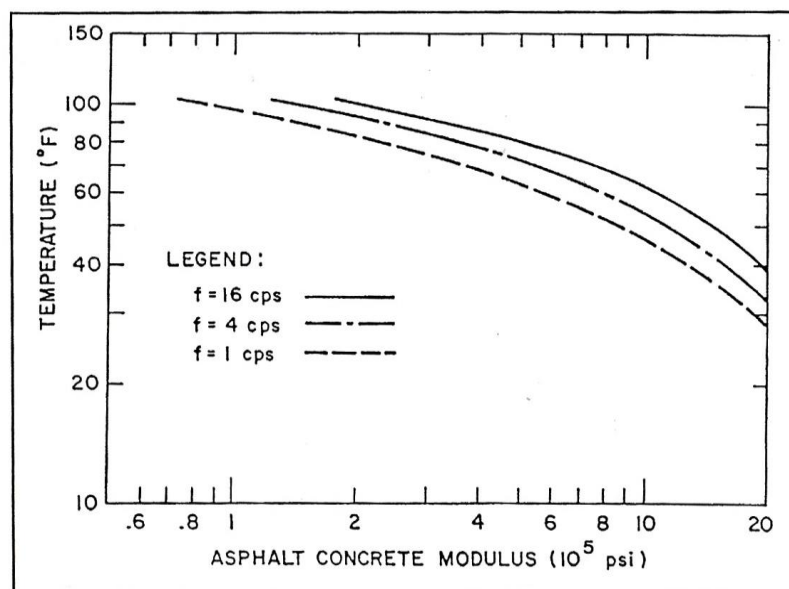


mixes were used to establish typical response in developing this relationship. Figure (2.1) shows the effect of temperature and frequency on the average dynamic modulus of elasticity of asphalt concrete. The frequency is dependent upon many factors such as aircraft type, gear dimensions, locations, speed of the aircraft and pavement structure. Multiple regression analyses were utilized to establish a predictive model between E_1 and the selected mix characteristics at a given frequency of 2 cycles per second, with this model yielded a relationship of the form:

$$E_1 = \frac{K_0}{(K_1 * q^{d_1})} \quad \dots \dots \dots (2.1)$$

Where K_0 , K_1 and d_1 are regression constants.

The obtained values of regression constants were used to establish the general E_1 - q relationship at $f=2$ cps were: $K_0 = 3.8 * 10^6$, $K_1 = 1.0046$, $d_1 = 1.45$



Figure(2.1) Effect of temperature and frequency upon typical asphalt concrete dynamic modulus (Witczak,1972)

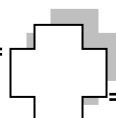
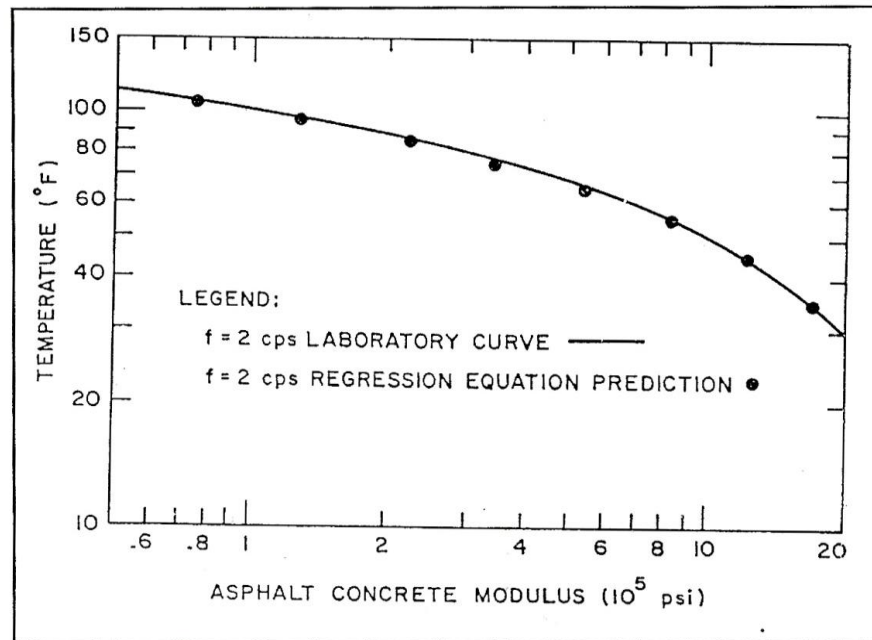


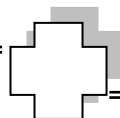
Figure (2.2) shows the interpolated E1-q relationship of the actual average laboratory data and the computed values obtained by the predictive equation.



Figure(2.2) Comparison of measures and predicted asphalt concrete modulus (Witczak, 1972)

2.4 Resilient Modulus Determination For Different Types of Pavements Materials

Schmidt (1972), developed the diametral modulus testing for the measurement of the resilient modulus of dense graded asphalt concrete mixes. Monismith (1972), states that, this test has been applied by chevron Research Company to determine the resilient modulus of open graded emulsified asphalt mixture. This test was used to determine the stress-dependent moduli of cores taken from existing open graded emulsified asphalt pavement. It was also shown that the resilient properties of these materials may be nonlinear, particularly during the early stages of the curing process when the modulus varies with stress



level in a manner to that of unbound granular materials. Therefore, the application of the diametral modulus test to open graded emulsified asphalt mixtures and interpretation of the results in terms of linear elastic theory should be examined carefully before the test can be used with any degree of confidence.

The type of nonlinear behavior that is analyzed which predominates with granular materials and with weakly bound open graded asphalt materials when the stresses are well below the yield point of the material. The resilient modulus increases with an increase in the isotropic stress. This stress dependency is described in terms of the bulk stress, $\theta = \sigma_x + \sigma_y + \sigma_z$, by the equation :

$$M_r = K \theta^n \quad \dots\dots\dots(2.2)$$

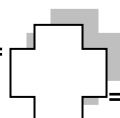
Where: θ =the bulk stress invariant

K, n =regression constants.

There are typical values of stiffness for a high quality granular base or an open graded emulsified asphalt corresponding to a modulus of (276 Mpa) (40,000 psi) at bulk stress equal to one atmosphere.

Michael (1981), characterizes and evaluates the asphalt emulsion treated bases by the indirect tension resilient modulus and Hveam tests. The use of asphalt emulsion mixture as a paving material is a promising solution because of its economical advantages. There are many types of mixtures used in this characterization and one of many made or reached conclusions that reasonably exist between the indirect tensile test ASTM (D4123-82) and the resilient modulus test results. The following regression equations are developed between instantaneous resilient values and both tensile strength and stiffness values.

$$M_r = 301 + 1.35 \sigma_{IT} \quad \dots\dots\dots(2.3)$$



$$M_r = 157 + 68.7(E_{IT})^{1/3} \quad \dots\dots\dots(2.4)$$

Where M_r = instantaneous resilient modulus (Psi)

σ_{IT} = tensile strength (Ksi)

E_{IT} = tensile stiffness (Psi)

Asphalt institute manual (1993), specified the material characteristics used in DAMA program, where the asphalt emulsion materials, like asphalt concrete, have modulus that strongly depends upon temperature. However, emulsion moduli are also dependent upon the degree of cure (loss of water). Thus, at any given temperature, the modulus will vary from some initial value (E_i) to the final modulus (E_f) in a specified time of cure. Analytically, this modulus relationship can be defined by :

$$E_{T,t} = E_{T,f} - (E_{T,f} - E_{T,i}) * (RF)_t \quad \dots\dots\dots(2.5)$$

Where $E_{T,t}$ = modulus at temperature "T" and time "t".

$E_{T,f}$ = final modulus of temperature "T".

$E_{T,i}$ = initial modulus of temperature "T".

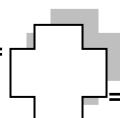
$(RF)_t$ = reduction factor for cure at time "t".

The reduction factor (RF) is determined by:

$$(RF)_t = e^{bt}$$

Where : b = constant determined by the total cure period.

For asphalt emulsion system, the moduli values even at very low degree of cure take on complex relationships at temperatures equal to or below the freezing temperature of water. This is so because the phase change of water to ice of the unevaporated water molecules are still present in uncured specimen. Because of this and the need for simplicity, DAMA uses $E_{T,t} = E_{T,f}$ for all values of time, t, when temperature, T, is at or below 32° F (0° C).



2.5 Prediction of Asphalt Pavement Structural Moduli by Using Non-Destructive Tests (NDT)

Irwin (1977), determined the pavement layer moduli from surface deflection data for pavement performance evaluation. Other researchers indicate that stiffness determined through back calculation of pavement layers elastic moduli from non-destructive testing (NDT) is the fundamental method to determine effective elastic moduli. The basic procedure is to measure the deflection basin and the set of moduli until a best match between the computed and measured deflection is obtained.

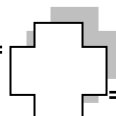
Based on the type of loading applied to the pavement, NDT deflection testing can be divided into three categories:

1-Static or slowly moving loads where the Benkelman beam, California traveling deflectometer, and Lacroix deflectometer are the best known devices in this category.

2-Steady-state vibration where the Dynaflect and road rater are the best known devices in this category.

3-Impulse loads such as the various types of falling weight deflectometers (FWD) are included in this category.

Reynaldo et al. (1995), developed and evaluated a set of prediction equations to determine pavement layer moduli directly from dual-load FWD measurements by using a modified sensor configuration. The deflection ($D_{y/0}-D_{y/8}$) as shown in Figure (2.3), was the parameter to represent the shape of the transverse deflection basin. It should be related strongly to the stiffness of the asphalt concrete. However, it was also determined that high base course moduli interact with the asphalt concrete, and thus have some effect on the shape of the transverse deflection basin. The parameter ($D_{y/0}-D_{x/8}$) was selected to account for this effect.



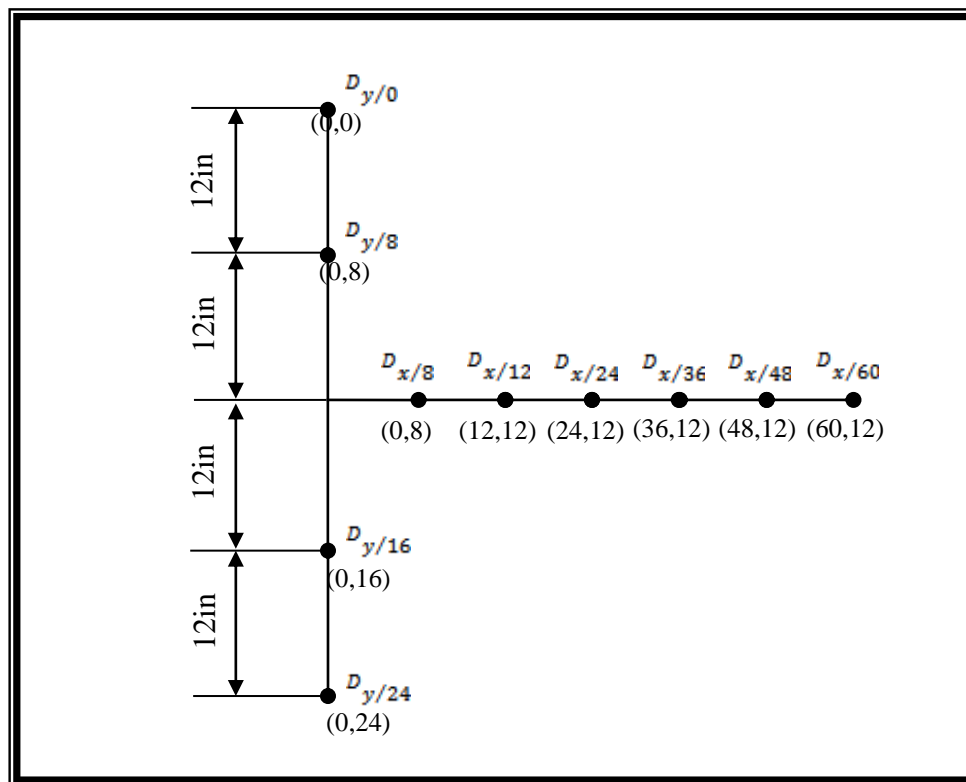
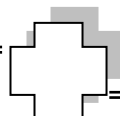


Figure (2.3) Dual-load falling weight Deflectometer (FWD) with 24 inch spacing (Reynaldo, 1995).

2.6 Testing Techniques of Asphalt Concrete Resilient Modulus

The stiffness of asphalt concrete mixtures is generally characterized through measurement of a dynamic or resilient modulus for cylindrical specimens loaded repetitively in compression and without confinement the test is described by (ASTM D3497).

The use of static indirect tensile tests began in 1965 by Kennedy to evaluate tensile strength of asphalt concrete mixtures. The procedure was then refined, developed into a repetitive loading procedure, and used extensively for measurement of dynamic moduli and study of fatigue characteristics. Extensive dynamic unconfined compression testing program has been conducted by various researchers to predict



the stiffness of asphalt concrete mixture in terms of mix properties, loading frequencies, and temperatures. One such study was conducted by Witczak(1972) to develop the following regression equation:

$$\begin{aligned} \text{Log}E = & 5.553833 + 0.028829(P_{200}/f^{1.7033}) - 0.03476V_v + 0.070377\eta + \\ & 0.000005 t_p^{(1.3 + 0.49825 \text{ Log } f)} \text{Pac}^{0.5} - 0.00189 t_p^{(1.3 + 0.49825 \text{ Log } f)} (\text{Pac}^{0.5}/f^{1.1}) \\ & + 0.931757 (1/f^{0.02774}) \end{aligned} \quad \dots\dots\dots(2.6)$$

Where : Log E =dynamic modulus in psi.

P_{200} =percent aggregate passing No.200 sieve.

V_v =volume of air voids, percent.

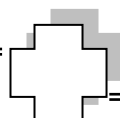
η =asphalt viscosity at 70 °F, $\times 10^6$ poises.

Pac =volume of asphalt by weight of mix, percent.

T_p =temperature, °F.

Although rarely used for dynamic modulus testing, confining pressures are usually applied for long-term repetitive load tests to measure permanent strains in order to simulate the stress state occurring in the field.

A testing program was implemented on cores recovered from highway test sections to characterize the stiffness of asphalt concrete materials. As most cores were not generally long enough for compression testing, procedure used for determining dynamic moduli was the repeated-load indirect tensile test ASTM (D4123-82). However, where asphalt concrete cores were sufficiently tall, compression tests on cylindrical specimens were conducted. Repeated load compression testing without confinement was conducted in accordance with ASTM D3497, except that a "square" wave pulse was used in lieu of the haversine pulses recommended in the ASTM test procedure.



2.7 Mix Modulus Based on Rheological Properties

Boussad (1966), presents some of mechanical concepts and mechanical testing. He states that the most promising way to assess the mix behavior under traffic, from binder properties is based on asphalt dynamic mechanical tests. Two behavior domains appear : the linear domain and the non-linear irreversible domain. Accordingly, one can expect to find correlations between binder and mix rheologies, if both are studied in the same domain.

For the linear and non-linear domains, the simplest model for a material is linear elasticity (Hooke's law). If the material is isotropic, this model is defined by only two coefficients, (Elastic modulus E and Poisson's ratio ν) as shown in Figure (2.4a) but classically for a material, non-linearities and irreversibilities appear as in figure (2.4b). These irreversibilities are either instantaneous (sand for example), viscous (bitumen for example). Generally, the non-linearity effects and the instantaneous irreversibilities become negligible at strain amplitudes smaller than a certain limit (depending on material type), and considered in the linear domain, so it is necessary to take into account both these domains before defining the complete rheological response of a material.

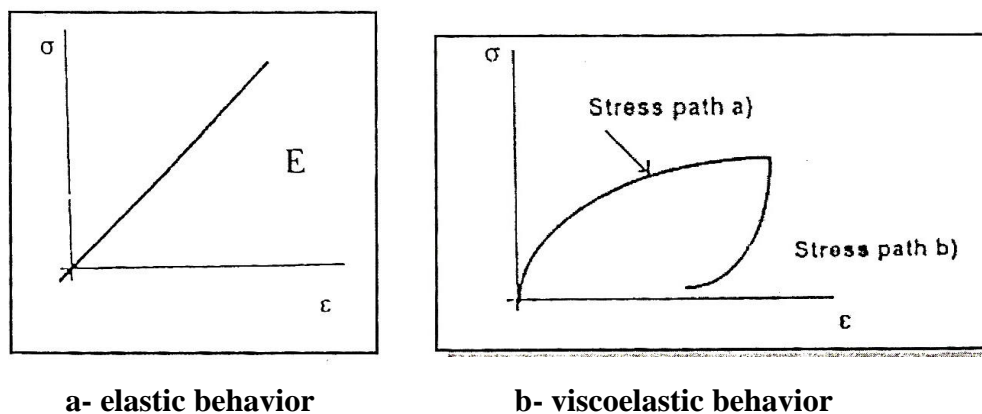
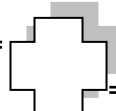


Figure (2.4) Effect of Rheological Properties of mix (Boussad, 1966).

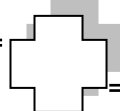


2.8 Material Characterization

In the overall design of pavement systems, the hot mix asphalt (HMA) layer plays an important role. As the upper most layer, it experiences the highest stresses. Therefore, understanding its properties, including its resilient modulus, is crucial to the design process. Stresses induced by a wheel load on a typical HMA layer can be described or categorized by the following four general cases:

1. Triaxial compression on the surface underneath the wheel load.
2. Longitudinal and transverse tension combined with vertical compression at the bottom of the HMA layer underneath the wheel load.
3. Longitudinal and transverse tension at the surface of the HMA layer at some distance from the wheel load.
4. Longitudinal and transverse tension at the bottom of the HMA layer at some distance from the wheel load.

The critical location of load- induced cracking is generally found at the bottom of the HMA layer , immediately underneath the load , when the stress state consists of longitudinal and transverse tension combined with vertical compression . With the exception that it induces tension in one direction instead of two, the indirect tension (IDT) test best simulates this state of stress; therefore, it was chosen in this research to evaluate the resilient modulus of HMA. The (IDT) possesses several advantages over other tests, the IDT has the ability to simulate the stress state that exists at the bottom of the HMA layer beneath the applied wheel load , which is of concern in pavement design . Although the triaxial test induces stresses similar to the ones in the field, the failure in a triaxial specimen does not result from tension stresses as it is the case in the field. Moreover, the test can be used to



provide valuable information on a number of HMA characteristics, including tensile strength, poisson's ratio, and fatigue and creep levels. When characterizing the material used in flexible pavements, one must consider the resilient modulus as well as results of the indirect tension test.

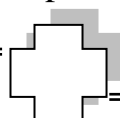
2.8.1 Resilient Modulus

A materials resilient modulus is analogous to Young's modulus of elasticity for linear elastic materials. Huang (1993), defines the resilient modulus as the elastic modulus to be used with the elastic theory. It is well known that most paving materials are not elastic but experiences some pavement deformation after each load application. However, if the load is small compared to the strength of the material and is repeated for a large number of times, the deformation under each load repetition is nearly completely recoverable and proportional to the load and can be considered as elastic.

Figure (2.5) shows a straining of a specimen under a repeated load test. At the initial stage of load applications, there is a considerable permanent deformation, as indicated by the plastic strain in the figure. As number of repetitions increases, the plastic strain due to each load repetition decreases. After 100 to 200 repetitions, the strain is particularly all recoverable, as indicated by ϵ_r in the figure. The elastic modulus based on the recoverable strain under repeated loads is called the resilient modulus M_R , and define as

$$M_R = \sigma_d / \epsilon_r \dots\dots\dots (2.7)$$

In which σ_d is the deviator stress, which is the axial stress in an unconfined compression test or the axial stress in excess of the confining pressure in a triaxial compression test.



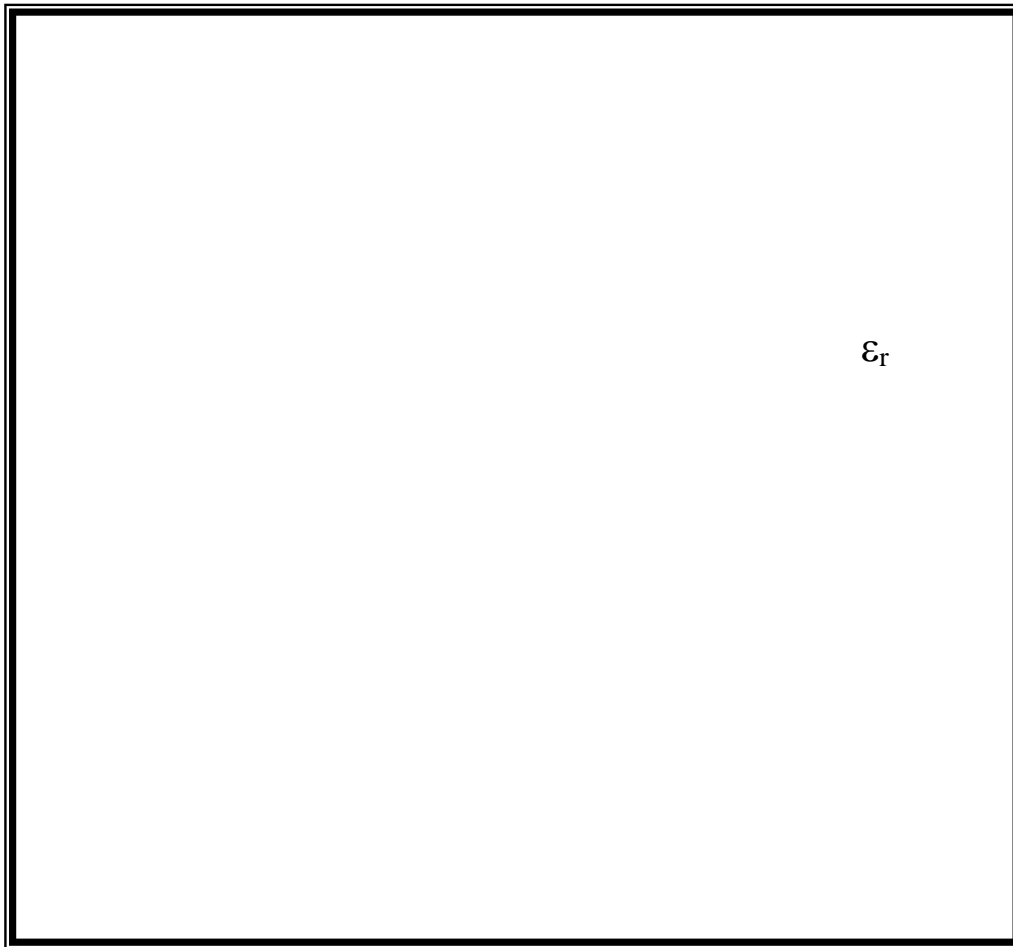
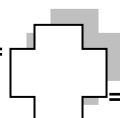


Figure (2.5) Strains under repeated loads (Huang, 1993)

Barksdale (1998), specifies that resilient modulus of asphalt concrete had in the past been determined by two approaches:

- 1- Predict the resilient modulus using physical and mechanical properties of the mix and available correlation.
- 2- Measure the resilient modulus by laboratory testing.

Generally, there are two approaches for the determination of the asphalt concrete resilient modulus, either by laboratory testing or by the use of available predictive models that correlate the resilient modulus to some of the mixture properties:

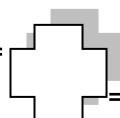


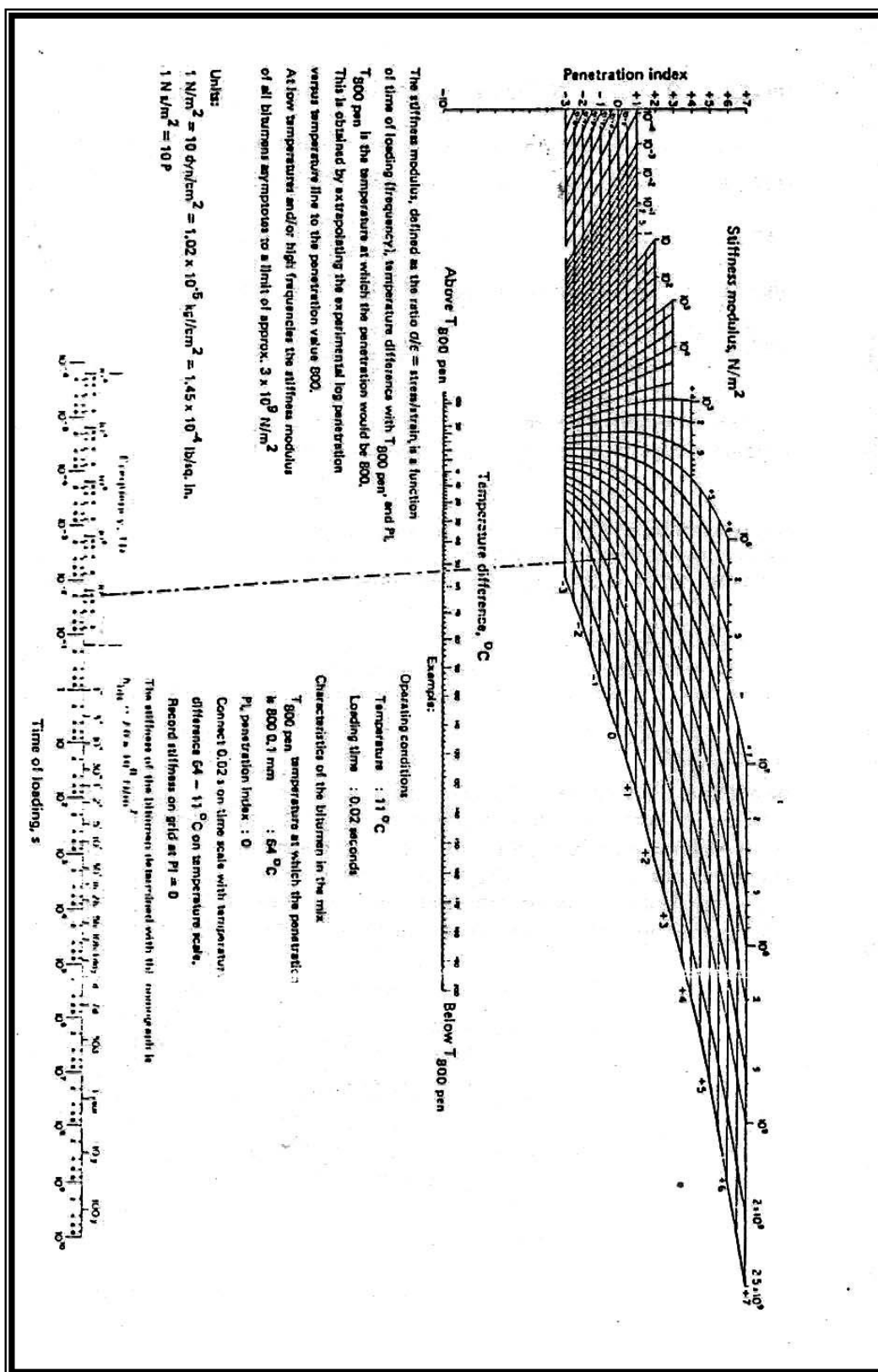
2.8.1.1 Empirical Predictive Method

Barksdale (1998) reported that the simplest predictive equation based on Marshal stability– flow ratio was suggested by Nijboer which represented early efforts for the prediction of the resilient modulus, the equation is as follows:

$$S_{60^{\circ}\text{C}} = 1.6 (\text{stability/flow}) \quad \dots(2.8)$$

Where S is the modulus given in kilograms per square centimeter, stability in kilograms, and flow in millimeters. This relationship is recommended for use in high temperatures up to 60 °C ranged by Heukelom (1973). The shell Nomograph was originally developed by Van Der Poel (1954) as shown in Figure (2.6). He defines the stiffness as a modulus, which is a function of temperature, loading time, and the characteristics of bitumen actually present in the mix. The temperature to be used is the normalized temperature, which is the difference between the test temperature and the temperature when the penetration is 300 grade, or $T_{\text{R\&B}}$ which is the temperature at the ring and ball softening point as specified by AASHTO (1984) in "T₅₃₋₈₉ softening point of asphalt (Bitumen) and tar in Ethylene glycol (Ring and Ball)". The stiffness modulus of bitumen can be determined by either a creep test with a loading time t or a dynamic test under a sinusoidal loading with a frequency f. It was found by Van Der Poel (1954) that the same stiffness modulus is obtained when (t) is related to (f) by $t = 1/2\pi f$.





Figure(2.6) Nomograph for stiffness modulus of bitumens. (Van der Poel,1954)



Figure (2.7) shows the nomograph for determining the stiffness modulus of bituminous mixtures. The three factors to be considered are the percent volume of bitumen, and the percent volume of aggregate and air voids. The percent volumes of aggregate, bitumen, and air can be computed from the percentage by weight of bitumen, the specific gravities of bitumen and aggregate, and the bulk specific gravity of the mixture. The latter can be determined by the water displacement method, as specified by AASHTO (1989) in "T₁₆₆₋₈₃". Sometimes and for simplicity, it is assumed that no asphalt is absorbed by the aggregate, these volumes (present volumes of aggregate, bitumen and air) can be calculated by the following equations:

$$V_g = [100(1 - P_b)G_m] / G_g \quad \dots\dots\dots(2.9)$$

$$V_b = [100(P_b)] / G_b \quad \dots\dots\dots(2.10)$$

$$V_a = 100 - V_g - V_b \quad \dots\dots\dots(2.11)$$

Where: V_g = percent volume of aggregate.

V_b = percent volume of bitumen.

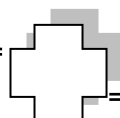
V_a = percent volume of air voids.

P_b = the bitumen content expressed as a ratio of bitumen weight to total weight.

G_m = bulk specific gravity of mixture.

G_g = specific gravity of aggregate.

G_b = specific gravity of bitumen.



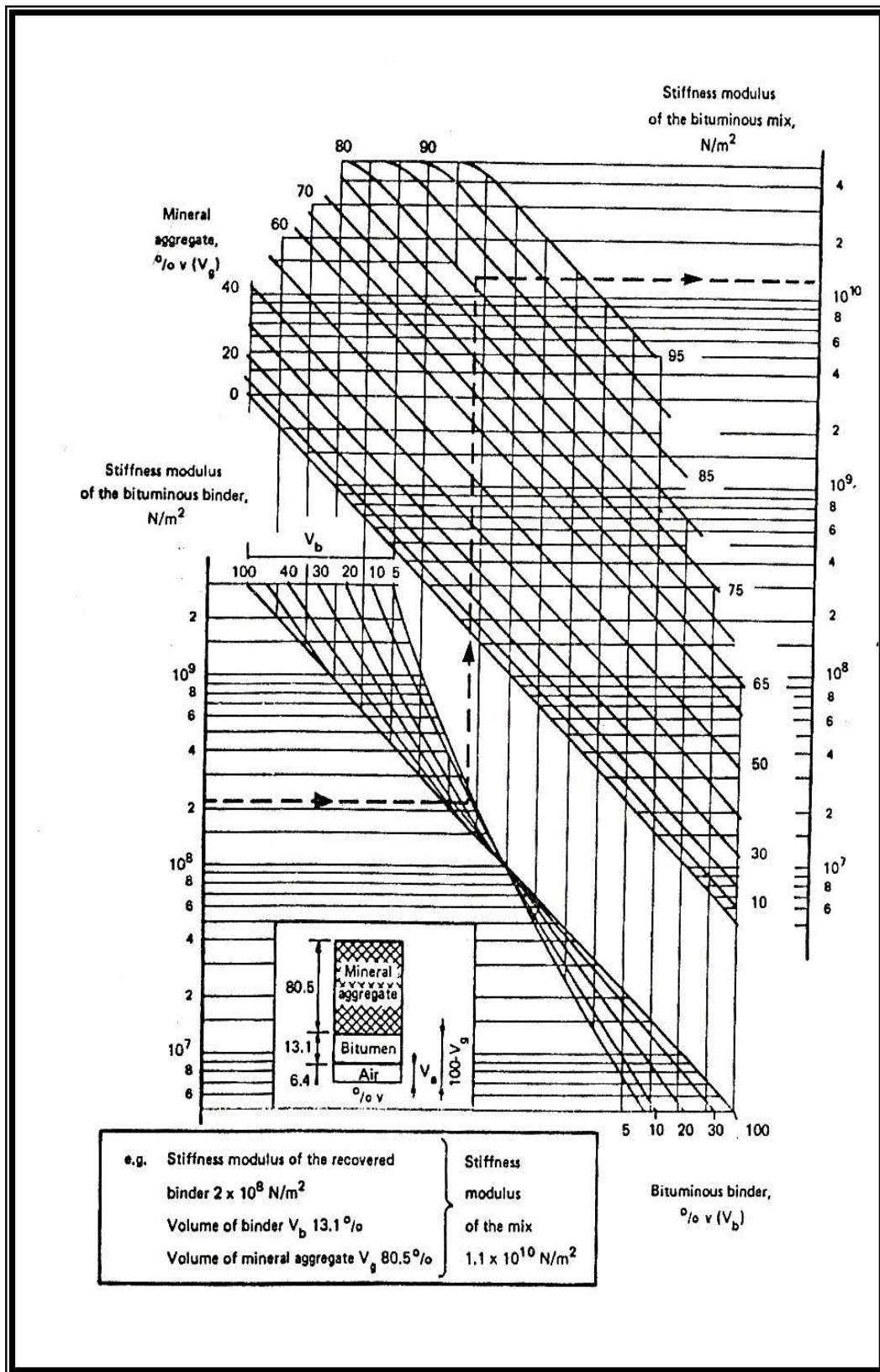
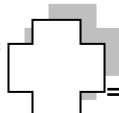


Figure (2.7) Nomograph for stiffness modulus of mixes. (After Shell (1978)).



Fonseca and Witczak (1996) developed another equation which is adopted by the asphalt Institute in their flexible pavement design procedure.

The equation is function of the following parameters:

$$M_r = f(\eta, f, v_a, v_{\text{beff}}, P_{3/4}, P_{3/8}, P_4, P_{200})$$

Where the variables represents:

M_r : Resilient Modulus (psi)

η : Asphalt cement absolute viscosity in 10^6 poise at 20 C°

f : Load frequency, Hz

v_a : percent air voids in the mix, by volume

v_{beff} : percent effective asphalt content, by volume

$P_{3/4}$: percent retained on 3/4 in. (19mm) sieve (accumulative)

$P_{3/8}$: percent retained on 3/8 in. (9.5mm) sieve (accumulative)

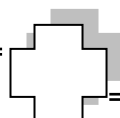
P_4 : percent retained on no.4 (4.75mm) sieve (accumulative)

P_{200} : percent passing no.200 (0.075mm) sieve.

2.8.1.2 Laboratory Test Method

In this section, typical laboratory testing methods are discussed for the determination of resilient modulus for asphalt concrete.

Barksdale (1998), states that the stiffness modulus characteristics of asphalt-bound materials cannot be considered to be significantly influenced by stress state at moderate to low temperatures, However, temperatures above 25C° , the stress state, and therefore test configuration, have an influence on the stiffness characteristics of these materials. The determination of the resilient modulus of asphalt concrete involves using various types of repeated load test such as uniaxial tension test, uniaxial compression test, beam flexure test, indirect diametral tension test and triaxial compression test.



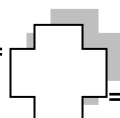
Although numerous advantages are inherent in using the cyclic or repeated load triaxial test method such as the stress system acts upon a specimen during triaxial test approaches is presented in the upper portion of the asphalt concrete layer of pavement during loading but this test has many drawbacks, mainly, the cost and the relative complexity of the necessary testing equipment.

Huang (1993) explained that the resilient modulus of asphalt mixtures can be determined by the use of the repeated load indirect tension test. A compression load with a haversine or other suitable waveform is applied in the vertical diametric plane of a cylindrical specimen through a loading strip and the resulting horizontal recoverable deformation is measured. For the test used in this research, equation (2.7) is used, that the PRLS (Pneumatic Repeated Load System) apparatus gives the vertical recoverable deformation directly instead of horizontal deformation described in Huang (1993). Isam et al. (1973), using a triaxial test system in experimental study, designed a program to simulate the stress state as well as the environmental conditions at a point within the pavement section, from emulsion treated aggregate samples tested by this system for different compositions and conditions. By using the stepwise linear regression of the statistical computer program in order to describe the resilient modulus in terms of temperature, the asphalt content, and the air voids.

In flexural test, the resilient modulus of asphalt concrete is evaluated by testing beam specimens under a third- point loading configuration and the flexure of beam specimens can be determined from the following equations (Barksdale, 1998):

$$E_s = [Pa(3L^2 - 4a^2)] / 48I\delta \quad \dots\dots\dots(2.12)$$

Where : E_s = flexural stiffness (psi).



P = repetitive load applied on the specimen (lb).

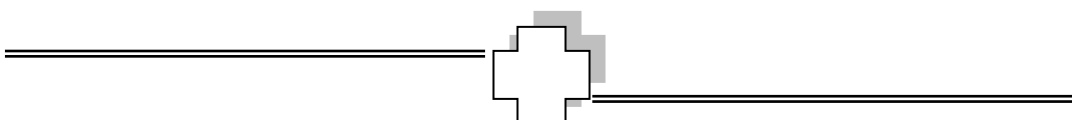
$A = 1/2 (L-4)$ (in.)

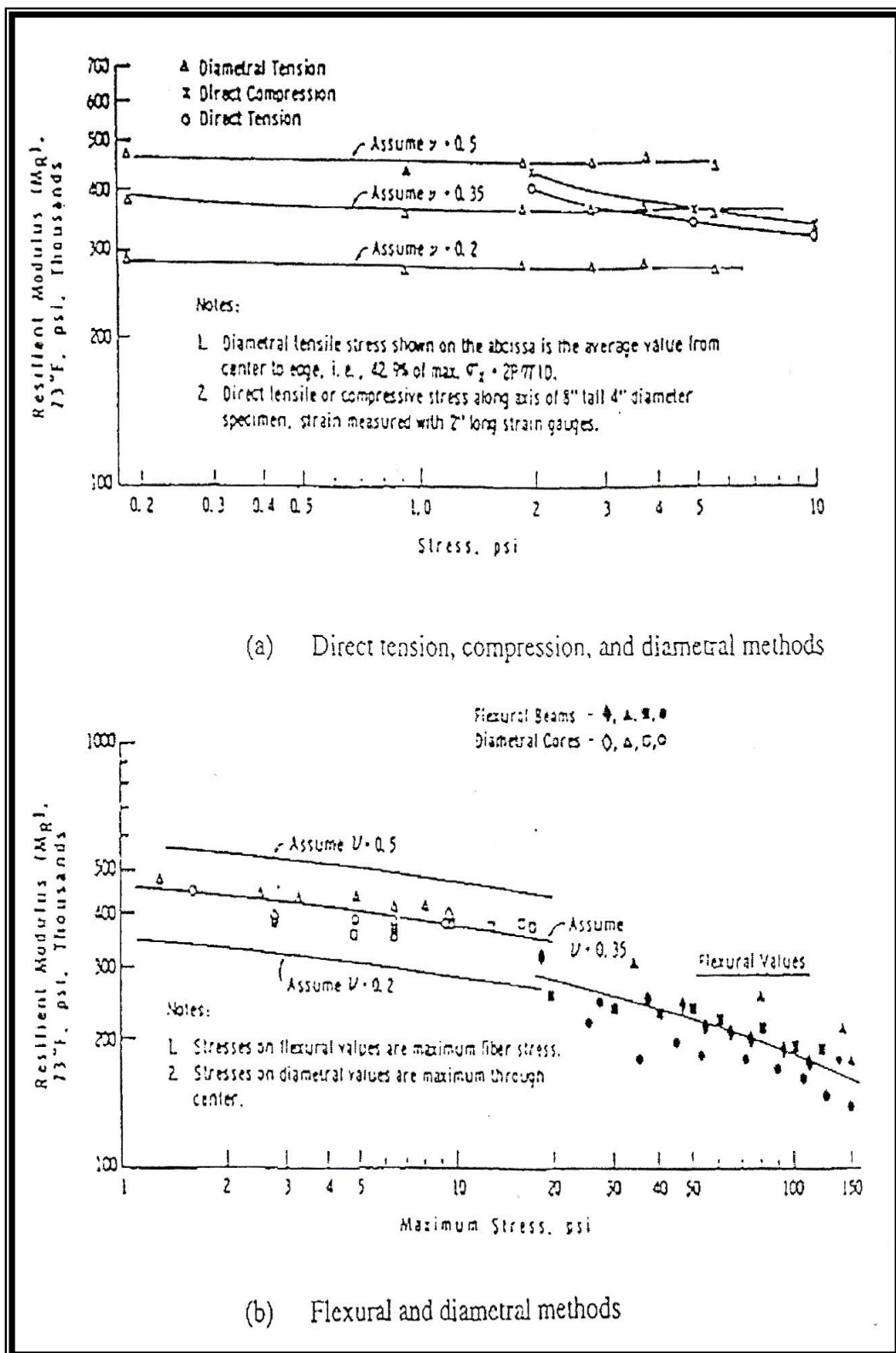
L = reaction span length (in.)

I = moment of inertia of beam cross section (in.⁴)

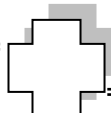
δ = measured deflection at the center of the beam specimen (in.)

Kennedy (1968), used the indirect tensile test to determine the tensile strength of Marshall-size asphalt concrete specimens. Schmidt (1972), proposed the use of a repeated load indirect tension test (which is called the diametral test) to determine the resilient moduli of asphalt concrete specimens. Figure (2.8) shows the values of the resilient moduli obtained from the direct tension, triaxial compression and beam flexure tests.

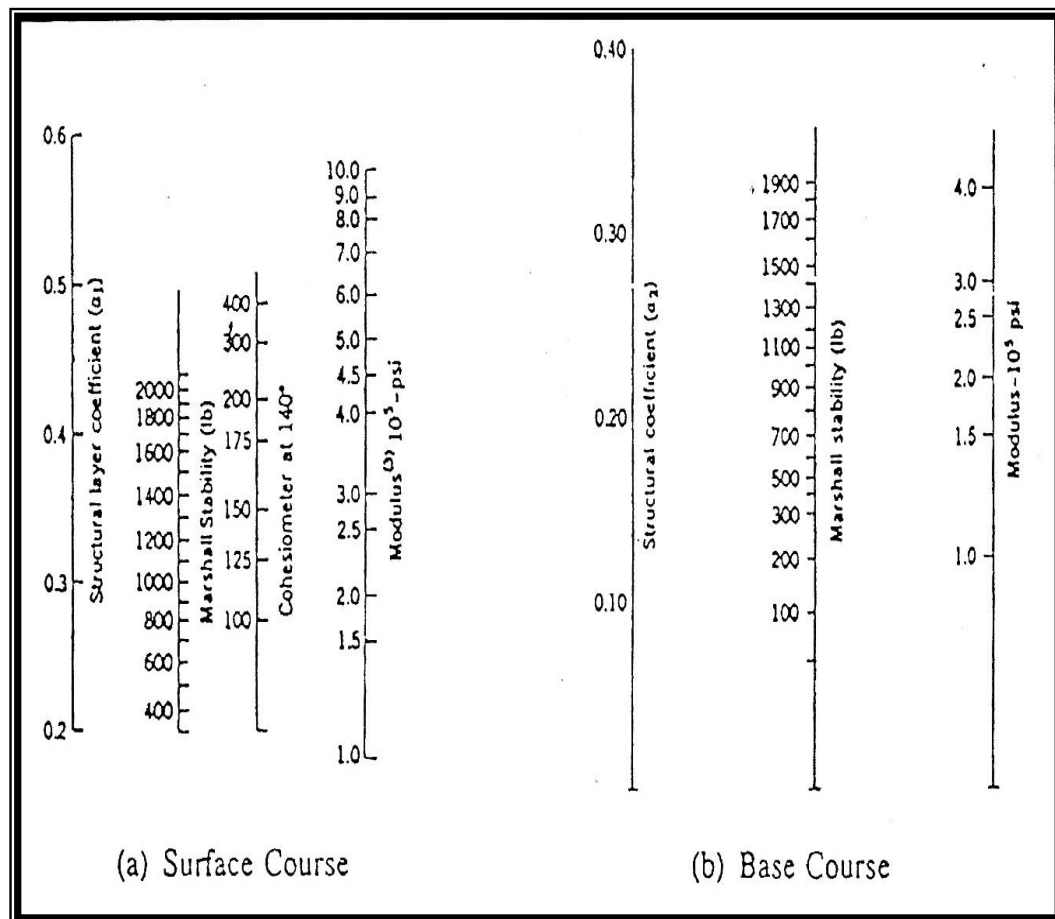




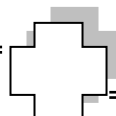
Figure(2.8) Comparison of resilient modulus of AC specimens using direct tension, compression, flexural, and diametral methods (Barksdale,1998)



Also, there are another tests may be used to relate resilient modulus to the soil support value or the layer coefficient employed in the AASHTO design equation. These correlations can be used as a guide if other more reliable information is not available. It should be noted that any empirical correlation is based on a set of local conditions. The correlation is not valid if the actual conditions are different from those under which the correlation is established. One of those correlations is shown in Figure (2.9). It shows the relationship between the layer coefficient, Marshall stability, cohesiometer values, and resilient modulus.



Figure(2.9) Correlation charts for estimating resilient modulus of hot mixed asphalt (Huang, 1993).



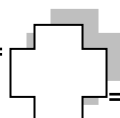
2.8.2 Indirect Tension Test

The indirect tension test (IDT) is conducted by repeated application of compressive loads along the vertical diameter of a cylindrical specimen. This loading configuration develops relatively uniform compressive stresses along the direction of the applied load as well as perpendicular to the direction of the applied load. Moreover, the values obtained from the diametral resilient modulus test would depend on the magnitude of the applied load (Almudaiheem and Al-Sugair, 1991; Brown and Foo, 1991).

Originally the IDT test was used to measure rupture strain in concrete (Blakey and Beresford , 1995) , it was before adopted to determine the elastic properties (E and ν) of concrete (Wright , 1955 ; Hondros , 1959) . Kennedy and Hudson (1968) first suggested the use of the test for stabilized materials, while Schmidt (1972) used the test to determine the resilient modulus of HMA. Since then, IDT has become the main test selected by most engineers for evaluation of HMA resilient modulus (Brown, and Foo, 1991).

Significant research work has been done over the past three decades. For example, based on extensive work, Mamlouk and Sarofim (1988) concluded that among the common methods of measurement of elastic properties of HMA, the resilient modulus is more appropriate for the use in multilayer elastic theories. Baladi and Harichandran (1988) further indicated that, in terms of repeatability, resilient modulus measurement by the indirect tensile test is the most promising.

Roque and Ruth (1987) showed that when the moduli were used in elastic layer analysis, values obtained using the IDT test resulted in excellent predictions of strains and deflection measured on

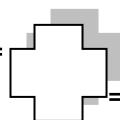


full-scale pavements at low in-service temperatures (less than 30 C°). The main advantage of the IDT is that the failure plane is known, which makes direct measurements possible. The test offers many advantages over other methods (Lytton et al., 1993):

- 1-It is relatively simple to perform ;
- 2-It is readily adaptable for measuring several properties such as tensile strength , poisson's ratio , fatigue characteristics , and permanent deformation characteristics ;
- 3-Failure is not significantly affected by specimen surface conditions ;
- 4-Failure is initiated in a region of relatively uniform tensile stress ;
- 5-Test variation is acceptable.
- 6-Specimens may be tested across various diameters to evaluate homogeneity.

However, several problems are associated with the test: stress concentrations around the loading platens make vertical diametral measurements unfeasible; and specimen rotation during loading can result in incorrect horizontal deformation measurements (Lytton et al., 1993).

Despite its drawbacks, the test was adopted by the American Society of Testing and Materials (ASTM) as a standard method of measuring the resilient modulus of HMA (ASTM D4123). Also, in 1992, the Strategic Highway Research Program (SHRP) protocol PO7 laid out a step by step method of resilient modulus testing using the indirect tension method. The haversine load utilized in the protocol has a period of 0.1 s, followed by an appropriate rest period. Additional evaluation of the SHRP PO7 protocol resulted in several changes designed to increase testing efficiency (Hadly and Goerger, 1992).



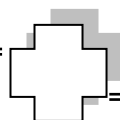
2.9 Factors Affecting Resilient Modulus Results

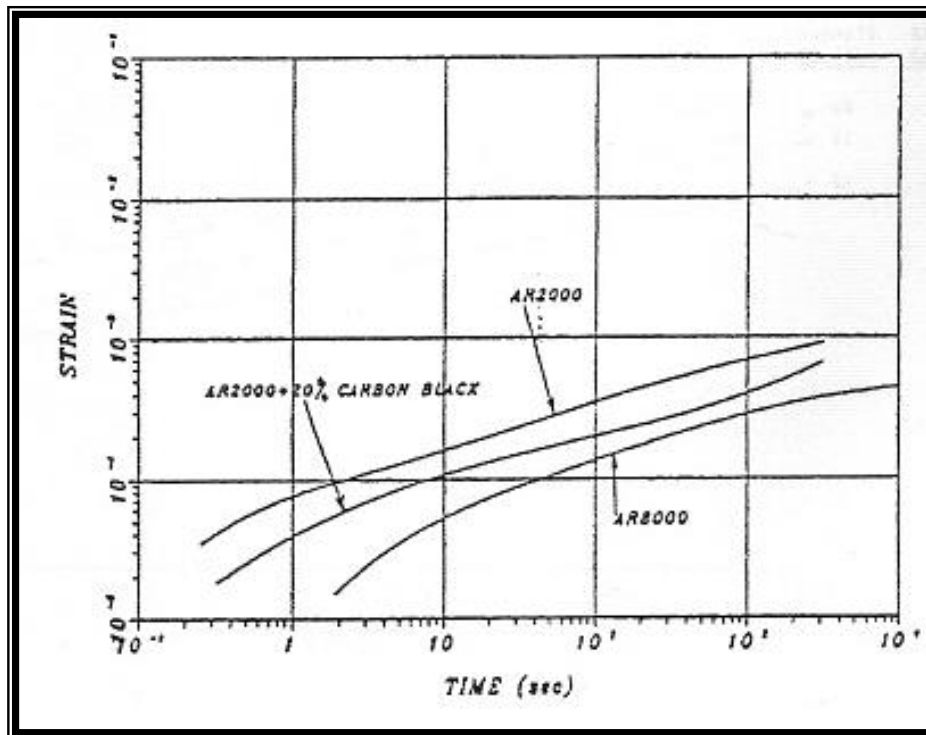
Several Factors affect the results of resilient modulus testing, including the mix components, loading, Poison's ratio, testing axis, specimen size and measuring methods must also be considered.

2.9.1 Mix Components Effect

The mix components of an HMA include the binder, and the aggregates. A detailed laboratory investigation undertaken by Gemayel and Mamlouk (1988) showed that in laboratory prepared specimens, the asphalt content and aggregate gradation are considerably influenced density, air voids, Marshall stability, instantaneous and total resilient moduli, and coefficient of permeability. The same study determined significant differences between the predicted performance of open graded and dense graded HMA, a fact that can be attributed to aggregate gradation and the percentage of air voids.

Baladi et al. (1988) performed regression analyses to evaluate the relationship between the measured resilient modulus and mix parameters such as air voids, aggregate angularity, and binder kinematics viscosity with air voids exerting the greatest influence. It was also seen that increasing aggregate angularity and binder with higher viscosities increased the magnitude of the resilient modulus. Monismith and Tayebali (1988) investigated the relative behavior of mixtures containing AR2000 and AR8000 (AR refers to Aged Residue viscosity; it is a system for classifying the asphalt cement frequently used in California state, USA). Figure (2.10) shows that prementioned behavior.





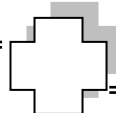
**Figure (2.10) Comparative Response of Three Mixtures in Repeated Loading
(Monismith and Tayebali,1988)**

2.9.2 Loading Effect

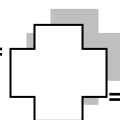
Values of the resilient modulus can be used in two ways: to evaluate the relative quality of materials and as an input value for pavement design, evaluation and analysis.

Almudaiheem and Al- Sugair (1991) suggested that a larger load should be used in the test because it yields a smaller resilient modulus value, which in turn results in a more conservative design. On the other hand , some researchers have suggested that the effect of stress level on the measured resilient modulus is consistent (Schmidt , 1972 ; Howedy and Herrin , 1972 ; Adedare and Kennedy , 1976) .

In general, the resilient modulus decreases with increasing load intensity and loading duration (Bourdeau et al. 1992), and the extent of



resilient modulus change due to load duration depends on the test temperature. Stroup and Newcomb (1997) conducted an extensive study on load duration effect on the resilient modulus. As loading duration increased, the resilient modulus decreased for all temperatures. At higher temperatures, the loading duration obviously had a greater effect. Fairhurst et al. (1990) reported that the resilient modulus increases with increasing cycle frequency. They suggested that this increase occurred because the decreased recovery time caused by increased test frequencies resulted in an accumulation of strain in the specimen. Monismith and Finn (1972) reported that there are several factors that affect the resilient modulus value, the two major factors are the test temperature and the loading duration, they recommend to test the specimen in the laboratory under conditions similar to that occurred in the field. Further, they recommend to use load duration ranging from 0.1 sec to 0.4 sec., with the use of 0.1 sec load duration which considered more representative of moving vehicles, and to test the specimens under the expected mean annual pavement temperature. Figure (2.11) shows the effect of these factors.



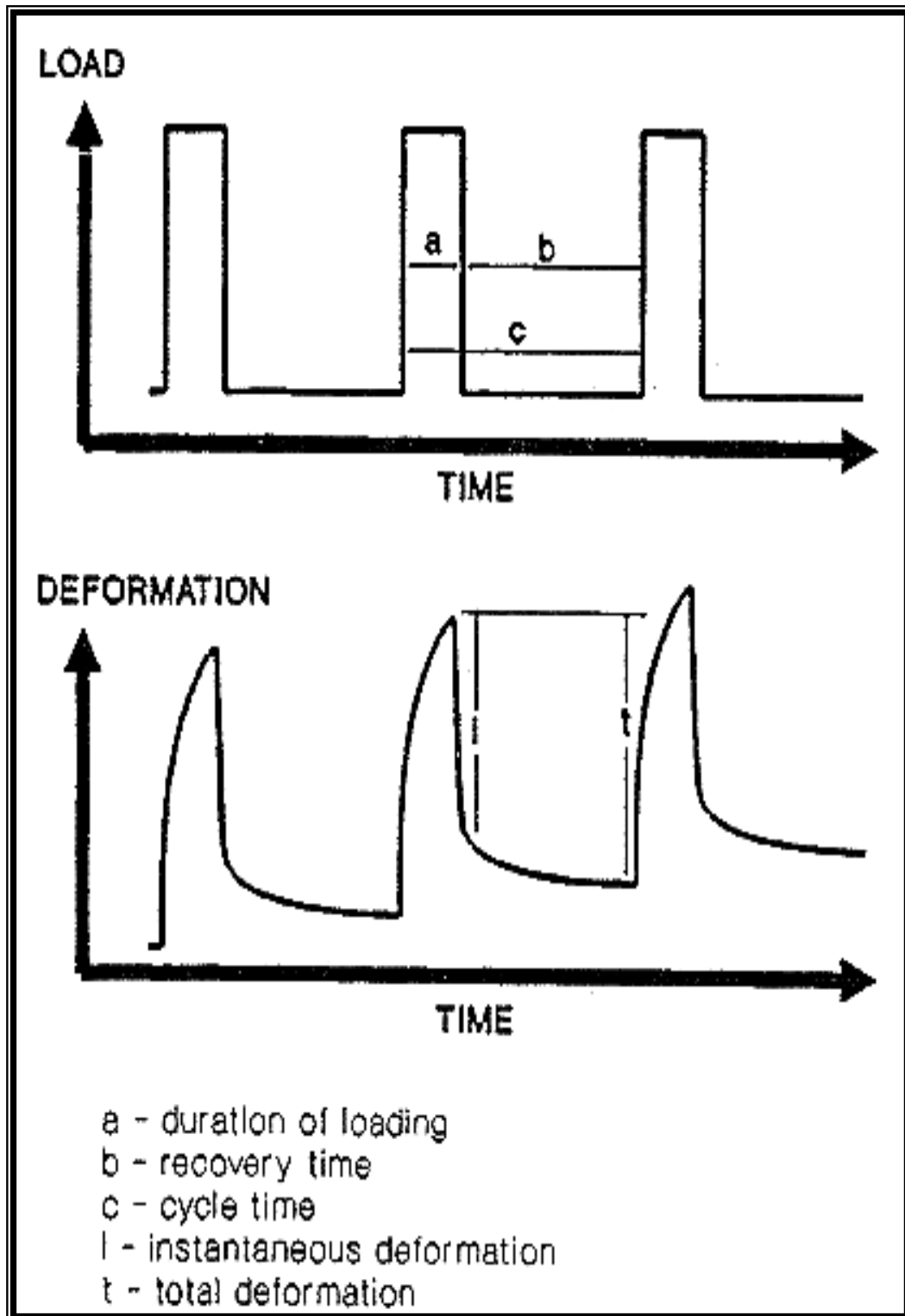
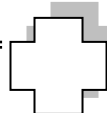


Figure (2.11) Load Deformation vs. Time for Resilient Modulus Test

(Foo,1994)



2.9.3 Effect of Poisson's Ratio

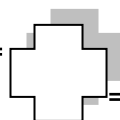
The indirect tension test measures horizontal deflection and applied stress. The determination of the resilient modulus, therefore, requires that the Poisson's ratio be known or determined during the test. The effect of Poisson's ratio on the resilient modulus values can be quite significant (Vinson, 1989). In all cases, Poisson's ratio of HMA increases as the temperature rises, which contributes to a decrease in the resilient modulus (Fairhurst et al., 1990). For the test of this research work, there is no need to know or calculate Poisson's ratio, because the vertical deformation is directly measured.

2.9.4 Effect of Testing Axis

It is important to perform the IDT along the same axis at all the test temperatures. Kim et al., (1992) showed that resilient modulus values were slightly higher along the diameter axis tested first.

2.9.5 Specimen Size Effect

In the indirect tension test, the resilient modulus depends on the specimen size as well as on the maximum aggregate size to diameter ratio (Lim et al., 1995), where the specimens having larger diameters seem to result in more realistic resilient modulus values. Moreover a high diameter to maximum aggregate size ratio would better represent the overall mix behavior. Within the same mix, resilient modulus values decrease as specimen diameter increases. This trend was also evident in the indirect tension strength of the specimen (Lim et al., 1995).



2.9.6 Effect of Measuring Devices

In an indirect tension tested specimen, highly variable stresses exist. Along the diameter, the vertical and horizontal stress distribution is non-uniform as shown in Figure (2.12). Stresses and strains near the center at the face of the indirect tensile specimen are fairly uniform and are unaffected by end effects caused by the loading plates. Therefore, accurate deflection measurements can be taken in this zone of uniform stress, which will enable accurate estimations of the resilient modulus.

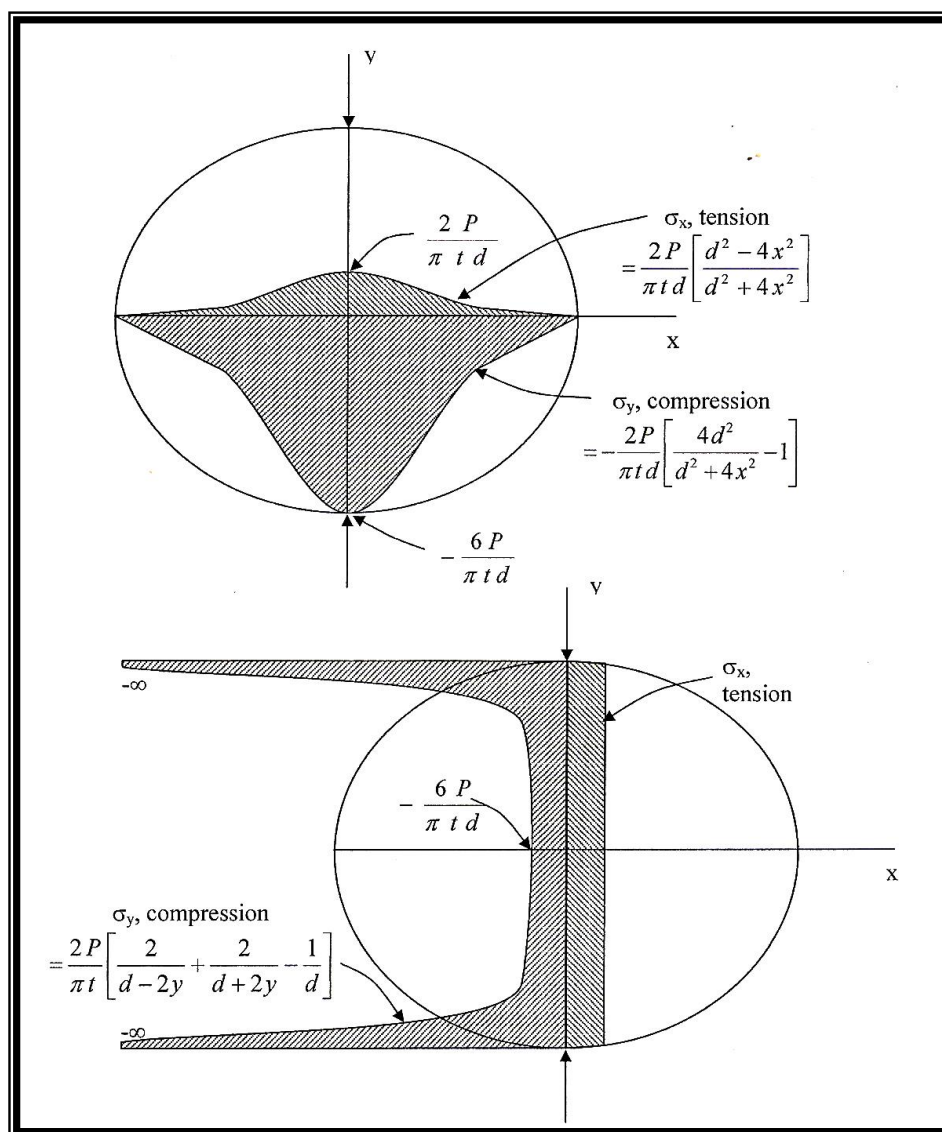
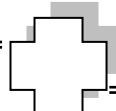


Figure (2.12) Elastic stress distribution in indirect tension specimen
(Hondros,1959).



CHAPTER THREE

Materials and Testing Procedure

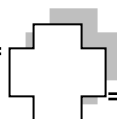
3.1 Introduction

The work program is concentrated on prediction of resilient module in Asphalt mixture using certain variables which include the percent of bituminous materials, percent of air voids in compacted mixture, percent by the weight and type of mineral filler in the asphalt mixture loading frequency and testing temperature.

According to the previous, the experimental work is limited to the determination of physical properties of asphalt cement and the measurement of the volumetric properties of the asphalt mixture from the Marshall Test specimens. Thereafter, the indirect tension repeated load test was conducted using the pneumatic repeated load system (PRLS), this apparatus is available in the laboratory of civil engineering, university of Baghdad.

3.2 Materials

The materials used in this work were originally taken from available quarries in Iraq. One type of asphalt cement used. One type of aggregate with three gradations of nominal maximum size and three types of filler were used. The properties of these materials were evaluated using routine type of tests and the obtained results were compared with the SCRB (R/6, 2003) specification requirements.



3.2.1 Asphalt Cement

The used asphalt cement was of (40-50) penetration grade taken from Al- Dourah refinery. The physical properties and tests of the used asphalt cement are shown in table (3.1) below:

Table(3.1)The Physical Properties and Tests of the Used Asphalt Cement.

Property	ASTM Designation	Test Result	SCRB Specification
Penetration (25 °C), 100 gm, 5sec), (0.1 mm)	D-5	43	(40 – 50)
Kinematic Viscosity at 135 °C, (cst).	D-2170	405	
Ductility (25 °C, 5 cm/min). (cm)	D-113	>100	> 100
Flash Point (Cleveland open cup) , (°C)	D-92	275	min. 232
Specific , Gravity at 25 °C	D-70	1.055	(1.01-1.05)
After Thin Film Oven Test			
Penetration of Residue (25 °C, 100 gm, 5 sec., 0.1mm).	D-5	33	
Ductility of Residue, cm,(25°C,5 cm/min)	D-113	> 20	

3.2.2 Aggregate

The source of the aggregate used in this work was Al- Niba'ee quarry. This aggregate is widely used in Iraq for asphalt pavement. It was sieved and recombined in the proper proportions to meet the gradations required by SCRB specifications (SCRB, R/6 2006). Three gradations were selected of aggregate with a nominal maximum sizes of (1 in., 3/4 in., 1/2 in.) with different percentages of filler. These gradations are shown in Tables (3.2) , (3.3) and (3.4) .

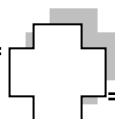


Table (3.2) Gradation of aggregate used for nominal maximum size of (12.5 mm).

Sieve		(% Passing by Weight of Total Aggregate + Filler)			Specification Limits (SCRB)
Opening (mm)	Size (in)	Upper Limit	Average Limit	Lower Limit	
12.5	1/2	100	100	100	100
9.5	3/8	100	95	90	90-100
4.75	No.4	85	70	55	55-85
2.36	No.8	67	50	32	32-67
300 μ m	No.50	23	15	7	7-23
75 μ m	No.200	10	7	4	4-10
Asphalt Cement (% weight of total mix)		4-6	4-6	4-6	4-6

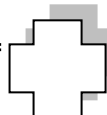


Table (3.3) Gradation of aggregate used for nominal maximum size of (19 mm).

Sieve		(% Passing by Weight of Total Aggregate + Filler)			Specification Limits (SCRB)
		Upper Limit	Average Limit	Lower Limit	
Opening (mm)	Size (in)				
19	3/4	100	100	100	100
12.5	1/2	100	95	90	90-100
9.5	3/8	90	83	76	76-90
4.75	No.4	74	59	44	44-74
2.36	No.8	58	43	28	28-58
300 um	No.50	21	13	5	5-21
75 um	No.200	10	7	4	4-10
Asphalt Cement (% weight of total mix)		4-6	4-6	4-6	4-6

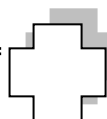


Table (3.4) Gradation of aggregate used for nominal maximum size of (25 mm).

Sieve		(% Passing by Weight of Total Aggregate + Filler)			Specification Limits (SCRB)
Opening (mm)	Size (in)	Upper Limit	Average Limit	Lower Limit	
25	1	100	100	100	100
19	3/4	100	95	90	90-100
12.5	1/2	90	80	70	70-90
9.5	3/8	80	68	56	56-80
4.75	No.4	65	50	35	35-65
2.36	No.8	49	36	23	23-49
300 um	No.50	19	12	5	5-19
75 um	No.200	10	7	4	4-10
Asphalt Cement (% weight of total mix)		4-6	4-6	4-6	4-6

The physical properties set by the SCRB specification limits are summarized in the table (3.5). Test results show that the chosen aggregate met SCRB specifications.

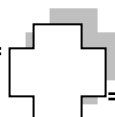


Table (3.5) Physical Properties of the Used Aggregate.

Property	ASTM Designation	Coarse Aggregate	Fine Aggregate
Bulk Specific Gravity	C-127 & C-128	2.63	2.63
Apparent Specific Gravity	C-127 & C-128	2.68	2.76
% Water Absorption	C-127 & C-128	0.5	2.8

3.2.3 Filler

In this study, three types of mineral fillers have been used including: limestone dust, hydrated lime, and ordinary Portland cement. They were brought from lime factory in Karbala governorate. The physical properties of these three types are presented in Table (3.6).

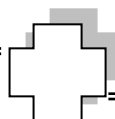


Table (3.6) Physical Properties of the Used Types of Filler.

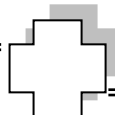
Property	Filler Type		
	Limestone Dust	Cement	Hydrated Lime
Specific Gravity	2.67	3.5	2.76
Passing Sieve No.200 (0.075 mm)	%94	%97	%95

3.3. Method of Testing

In order to investigate the variables of mixture properties that affect the resilient modulus, the following tests were used to perform the required experimental work; these tests are; Marshall Test and indirect tensile test.

3.3.1 Testing Program & Preparation of Specimens

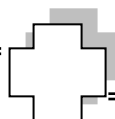
Specimens of Marshall size are to be used for the indirect tensile tests (Huang, 1993) ,with dimension of (2.5 in.) in height and (4 in.) in diameter and a total weight around 1200 gm including the combination of aggregate with mineral filler and the asphalt cement . Each specimen was separated according to one of the gradations in Figures (3.1) , (3.2) and (3.3) . The three types of filler were used



separately and each type was added in three different percentages (4% , 7% , 10%) .

The following steps were performed for the formulation of the compacted specimens :

1. The combined aggregate with filler were heated to 155 °C in controlled electric oven.
2. The binder was heated up to about (160 °C) in controlled electric oven .
3. The percentages of asphalt (4% , 4.7% , 5.4%) were selected by weight of total aggregate and mixed with the corresponding gradation of heated aggregate with filler .
4. The specimens formulated were then compacted using Marshall compaction method (hand compaction) . Three specimens were compacted for each of the above variables.
5. Numbering the compacted specimens to be easy in knowing the variables existing for each specimen by using letters from A to U , as follows :
 - a. Samples A,B,C had the same filler type (Limestone dust) with the same percentage (7%) . All these samples had the same asphalt content (4.7 %) and different gradations of nominal maximum size (1" , 3/4 " , 1/2") respectively .
 - b. Samples D , J , P had the same asphalt content (4. 7 %) . All these samples had the same nominal maximum size 3/4 " and the same percentage of filler (10 %) with different types of fillers (Limestone dust , cement , hydrated lime) respectively .



- c. Samples E, K , Q have the same properties of (b) except the filler content of (4 %).
- d. Samples F, L , R have the same properties of (b) except the asphalt content of (5.4%).
- e. Samples G,M,S have the same properties of (d) except the filler content of (4%).
- f. Samples H,N,T have the same properties of (b) except the asphalt content of (4%).
- g. Samples I,O,U have the same properties of (f) except the filler content of (4%).

3.3.2 Marshall Test

This test was carried out according to the ASTM (D1559) which covers the measurement of the resistance to plastic flow of a cylindrical specimens of bituminous paving mixture loaded on the lateral surface of the specimen by means of Marshall apparatus as shown in Figure (3.1) . The percent by weight of aggregate, percent by weight of binder, percent air voids, stability, flow were found for each prepared specimen, using ASTM methods and specifications. The Marshall stiffness was also determined for these specimens having different variables, these results and calculations are presented in the next chapter.

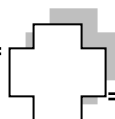
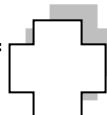




Figure (3.1) Marshall Test Apparatus.

3.3.3 Indirect Tension Repeated Load Test

The indirect tension repeated load test specified by **ASTM D4123** "Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures ", were conducted using the pneumatic repeated load system (PRLS). The apparatus used for this purpose was manufactured in Baghdad University-highway materials laboratory, and was described in details by (Al-Bayati, 2006). The tests were

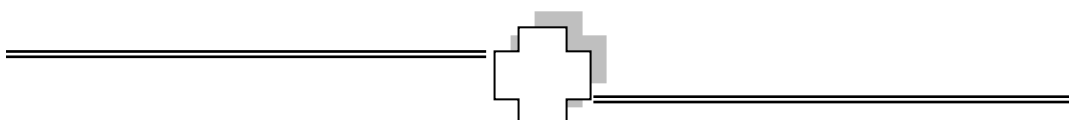


performed on Marshall Specimens as mentioned earlier. In these tests, repetitive diametral loading was applied to the specimen and the resilient vertical strain was measured under the load repetitions. Diametral loading was applied with a constant loading frequency of 60 cycles per minute and loading sequence of 0.1 sec load duration and 0.9 sec rest period. Three temperatures 0 C, 20 C and 40 C were used in the tests, and the applied stress level was 20 psi.

The IDT repeated load test procedures used in this study is summarized as follows:

- 1- Place the specimen in the testing chamber for two hours at the desired testing temperature to bring it to test temperature and to allow for a uniform temperature distribution within the specimen.
- 2- The dial gauge was set to zero reading after completion of the specimen "setup" in the testing equipment. The pressure actuator was adjusted to the specified stress level. The timer (both loading port and rest port) is also set to the required load and rest durations.
- 3- The experiment is commenced by application of repeated indirect tensile stress and the resilient strain is measured.
- 4- The test is completed after number of load repetitions when the resilient strain reading is reached to its suitable value or small difference between two readings that can be neglected. Figure (3.2) shows the IDT test configuration of the specimens.

The resilient strain (ϵ_r) and resilient modulus (M_r) were calculated as follows:



Resilient strain:

$$\epsilon_r = \frac{rd * 10^{-3}}{h} \dots\dots\dots (3.1)$$

Where:

ϵ_r : Vertical resilient strain (mm/mm).

rd: Reading of dial gauge for vertical resilient strain (1 degree =0.001 mm).

h: specimen diameter (mm).

Resilient modulus:

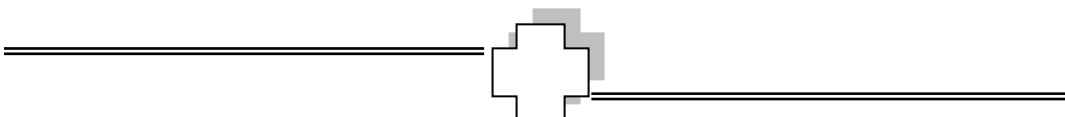
$$Mr = \frac{\sigma}{\epsilon_r} \dots\dots (3.2)$$

Where:

Mr: Resilient modulus (psi).

σ : Repeated diametral stress (psi).

ϵ_r : Vertical resilient strain (mm/mm).



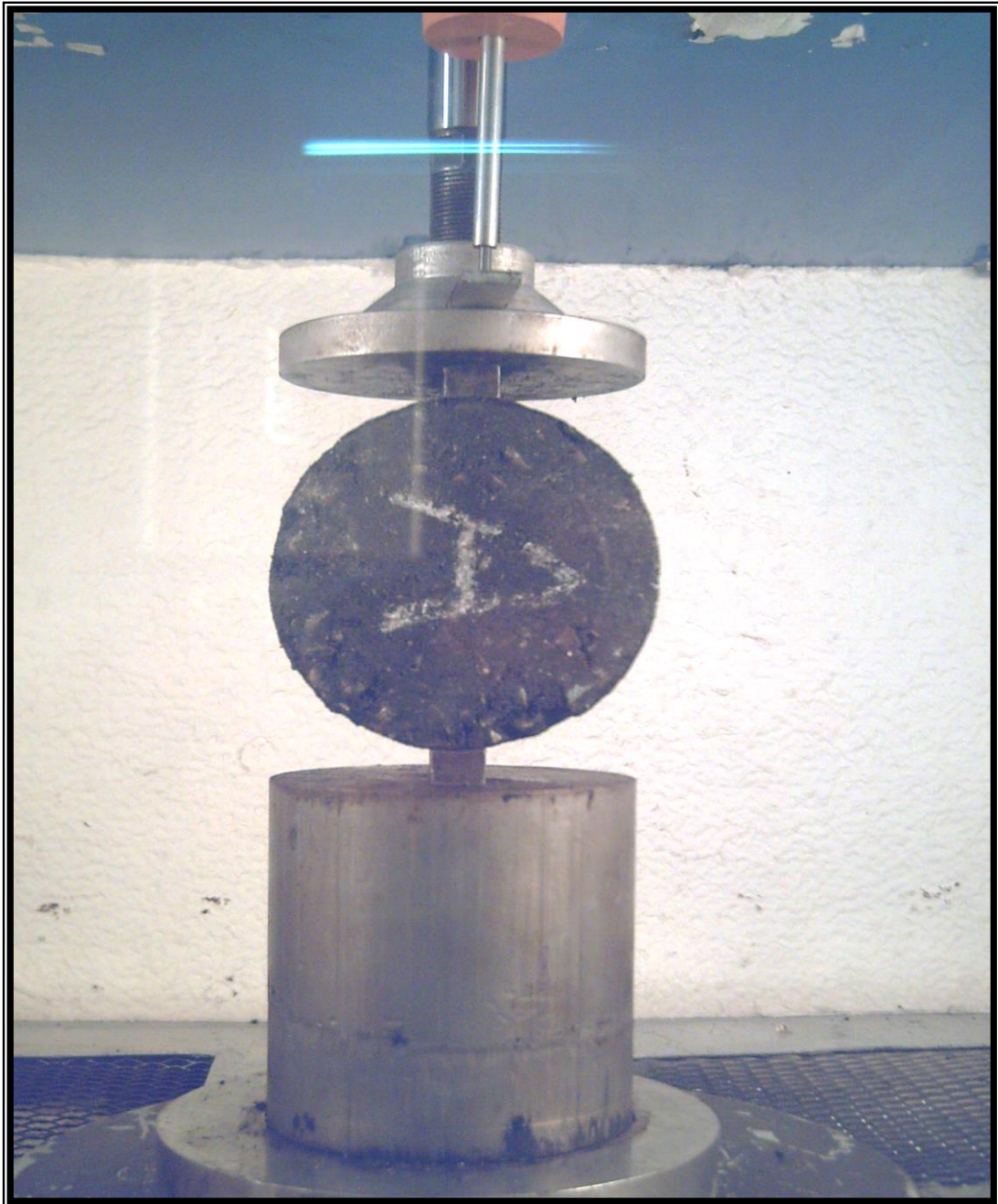


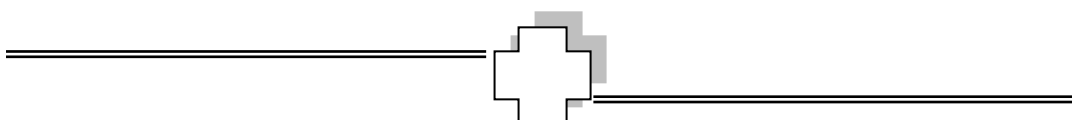
Figure (3.2) Test configuration of the Indirect Tension Test



3.4 Development of Pneumatic Repeated Load System.

The pneumatic repeated load system (PRLS) equipment had been developed under the auspices of the Civil Engineering Department of Baghdad University. The developed apparatus has comprehensive testing capabilities that permits fatigue and stiffness (resilient modulus) testing as well as permanent deformation evaluation. It can be used to test different types and sizes of specimens including cylindrical and beam shapes in either uniaxial or diametral fashion under different loading conditions (repeated or static creep). Cylindrical specimens with dimensions up to 200 mm (8 in.) in diameter and 305 mm (12 in.) high can be accommodated by the PRLS. This permits evaluation of mixes with aggregate sizes of 38mm (1.5 in.).

For beam specimens, the PRLS can accommodate specimen with length up to 381 mm (15 in.) which is sufficient for routine fatigue test (third point load beam test). All the parts that constitute the equipment were locally manufactured. Figure (3.3) shows a schematic diagram of the developed apparatus. PRLS technical properties are presented in Table (3.7).



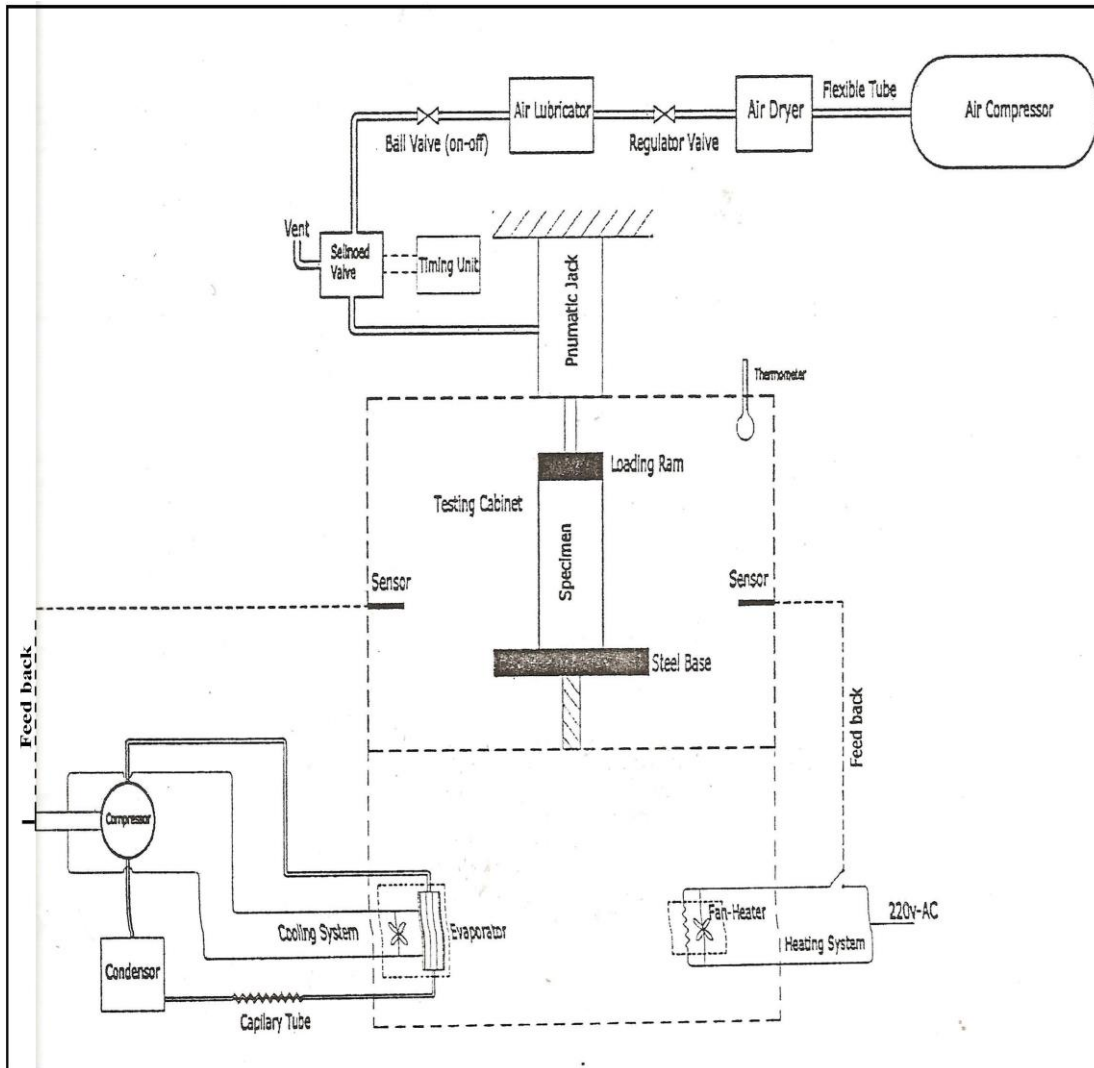


Figure (3.3) A schematic diagram of the developed PRLS.

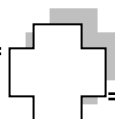


Table (3.7) PRLS Mechanical Data.

No.	Property	Description & limits
1	Stress magnitude	Controlled with max. stress of 80 psi
2	Repetition time	
	<ul style="list-style-type: none"> • Loading time • Unloading (rest) time 	Controlled from 0.05 sec. to 9hr. Controlled from 0.05sec. to 9hr.
3	Heating	Controlled from ambient temperature to 80 °C, with ± 1 °C sensitivity
4	Cooling	Controlled from ambient temperature to 0 °C, with ± 1 °C sensitivity
5	Inside dimension of testing cabinet	70×70×38 cm
6	Outside dimension	75×75×150 cm
7	Power supply	220 v AC

3.4.1 Steel Frame

Based on the experience and the conducted literature search, it was decided that the frame of the developed testing equipment should be rigid enough to prevent the effect of the vibration on the measuring devices. Therefore, steel angle section (L- 50×50×5mm, 2.534 kg/m) was used to form the main frame of equipment, which is covered by steel plates (1 mm thickness) from all sides. These plates were fixed to the frame by bolts and thermally isolated from inside by glass wool as thermal isolator of the testing chamber.



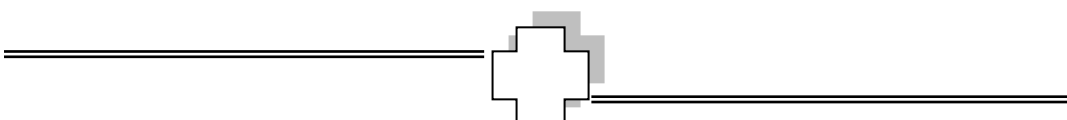
PRLS is box like in shape with rectangular sides and squared top view with $75 \times 75 \times 150$ cm ($29.5 \times 29.5 \times 59.0$ inch) outside dimension. From inside, it consists of three blocks. The upper one has outside dimension of $75 \times 75 \times 40$ cm to accommodate the electrical and tube connections, temperature control system, the pneumatic loading jack and the solenoid valve system. The front plate of this block contains the control panel of the equipment. The mid – block is the testing 25cm in diameter and 2.5cm thickness this arrangement serve as a base for the specimens to be tested. The disk is welded with elevating screw to allow for testing specimens with different sizes, also it includes two lights fixed in either side to facilitate monitoring the specimen situation through the glassy door during testing. The lower block with outside dimension of $75 \times 75 \times 70$ cm and it contains fan – heater and evaporator to maintain the desired testing temperature in the testing cabinet. This block is separated from the lower block by perforated steel plate (1mm thickness). Photograph for the PRLS is shown in figure (3-7).

3.4.2 Loading System

The physical pneumatic principle is adopted for stress application in the PRLS with appropriate arrangement for load pulsating due to its relative simplicity as compared to hydraulic system and flexibility of controlling the loading time as compared to the simpler mechanical system.

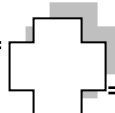
The loading system of the PRLS consists of the following parts:

1. air dryer
2. regulator valve



3. air lubrication unit
4. ball valve (close – open)
5. pressure gauge
6. solenoid valve
7. timing unit (two ports controller)
8. pneumatic loading jack

The pressurized air moves through the various parts via high pressure flexible tubes. The loading system operates as follow, compressed air flow through flexible tube (9.5 mm, 3/8 inch) from the air compressor (220v Ac, 16 bar max pressure) which then pass through the air dyer (to dry it from the storage tank). The air pressure is adjusted to the desired amount via pressure e\regulator valve (air pressure can be read by the pressure gauge existed in the control panel of PRLS) and lubricated by the air lubrication unit before entering the PRLS (to lubricate hereafter the inside parts of the solenoid valve and the steel piston of the pneumatic loading jack). When entering the PRLS, a ball valve which is fixed behind the PRLS acts as close – open gate (opened in the test to maintain the Pneumatic loading jack at rest condition). When the valve is in open case, the fluid flows into the solenoid valve (220 v Ac, 3 cells, 2 valves) which receive electrical signal from the timing unit (timer, 2 ports, one for loading and the other for unloading) to either continue its flow to the pneumatic loading jack (10.1 cm, 4 inch diameter) and applied the predetermined stress on the specimen (in the loading condition) or to vent the air in the case of rest condition.



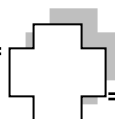
3.4.3 Conditioning System

Conditioning system means the system which brings the sample in the testing cabinet to the desired testing temperature; it includes two subsystems, for heating and cooling control.

Heating subsystem consists of fan – heater (220v Ac) connected to a thermostat for controlling purpose, also there is a thermometer which is fixed in the control panel to indicate the temperature in the testing cabinet. The cooling subsystem includes compressor (220 v Ac, 1/3 Hp), condenser (condense the gas) capillary tube and evaporator. It includes also a thermostat to control the temperature in the testing cabinet. The temperature control using the above subsystems besides the insulation of the testing cabinet from the inside by glass wool was found to be quite efficient and showed the capability of maintaining plus or minus one degree for sufficient period of time during testing.

3.4.4 Displacement Measurement

It was decided to use the traditional method for displacement measurement, i.e., via dial gauge. Therefore, it was fixed by magnetic holder on the loading ram inside the testing cabinet. After using this approach to measure the specimen displacement, it was observed during testing that the dial gauge reading is highly sensitive to the temperature variation within ± 1 degree and yield substantial errors in the reading. To eliminate this error, stainless steel shaft (2mm) moving inside stainless steel tube (3mm) was used to transit the vertical displacement of the specimen out of the equipment. The reason for using the stainless steel was that it has good resistance to contraction or



expansion due to the heat variation, the steel shaft is rested on the loading ram from the lower side and penetrates the upper block of the equipment to the surface, on which the dial gauge is fixed and rested on the other side of the steel shaft. In all the tests, a digital video camera was used to record the specimen's displacement. This is because it is extremely difficult to monitor the displacement visually and to record the data. Figure (3.4) shows the whole indirect tension test apparatus.

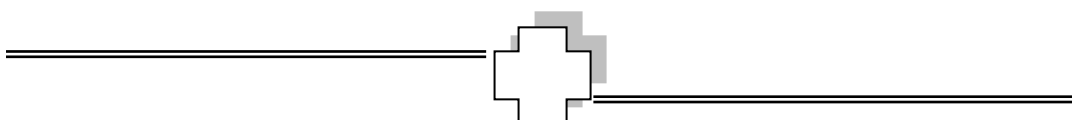




Figure (3.4) Indirect Tension Test Apparatus.



Chapter Four

Results and Discussions

4.1 Introduction

Under this research program, a substantial amount of data concerning the resilient modulus and variables affecting it are presented and discussed. The results of prementioned indirect tension test (IDT) for determining resilient modulus are presented. These results besides Marshall test results are presented in Tables in this chapter.

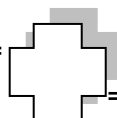
4.2 Analysis of Results

Results obtained in this research work are highly dependent upon the variability of mix for each specimen. This variability includes, asphalt content, filler type and its content, aggregate gradation and temperature.

4.2.1 Asphalt Content

The asphalt content in asphaltic mixture is the amount of asphalt binder. It is expressed as a percentage by total weight of aggregate. Effective asphalt content is the concentration of asphalt binder that is not lost by absorption.

The effect of asphalt content on resilient strain is shown in figure (4.1) which represents the relationship between Asphalt content and recoverable strain. It appears that the examined asphalt contents



have influence of the elastic response of the material. The higher resilient strain is associated with the increase in asphalt content.

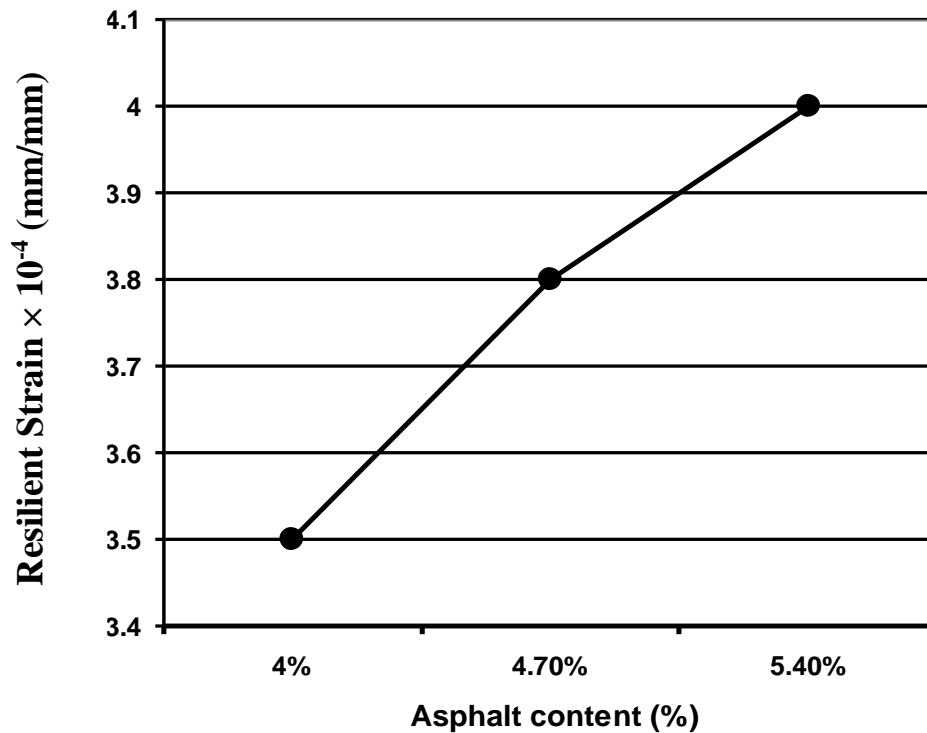
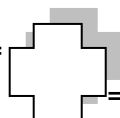
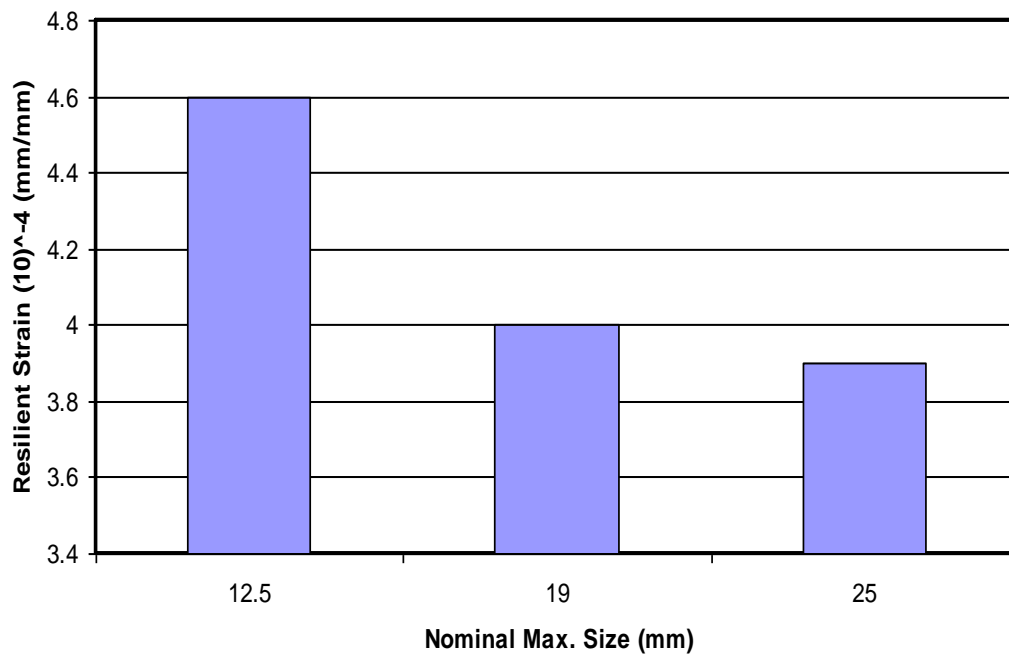


Figure (4.1) Effect of Asphalt content on resilient strain

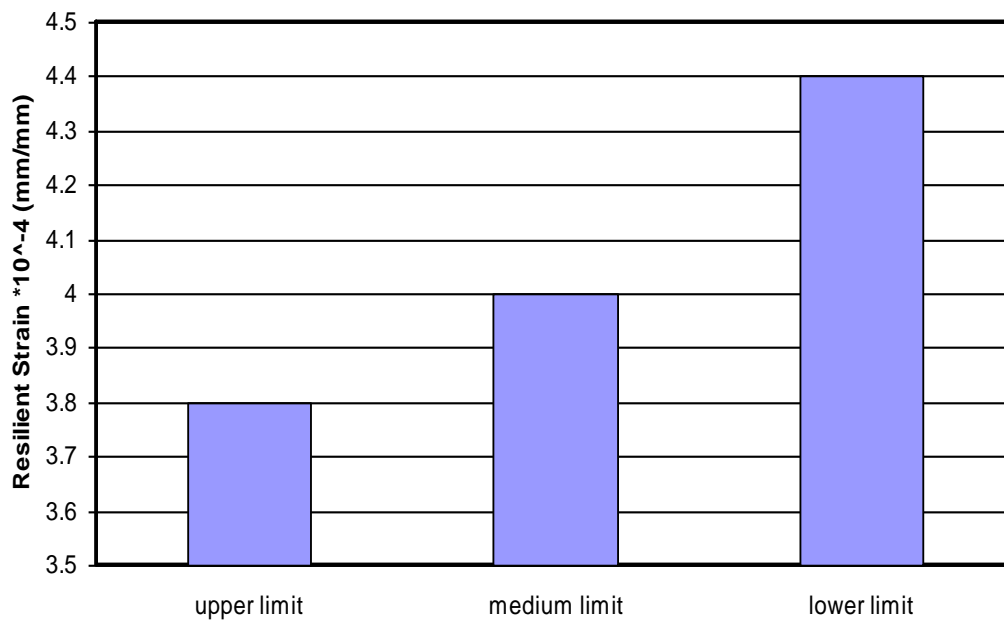
4.2.2 Aggregate

Three types of aggregate were used in this research as mentioned in the previous chapter. The results obtained from experimental work showed that the resilient strain is affected by the size of aggregate used. Figure (4.2) shows the change in resilient strain with the variation of nominal maximum size of aggregate and the effect of upper and lower limits of aggregate. It is observed that the resilient strain is decreased as the maximum size of aggregate increased and that may be attributed to the increased stiffness of mixture.



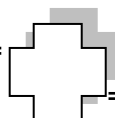


a. Aggregate Max. Size (mm)



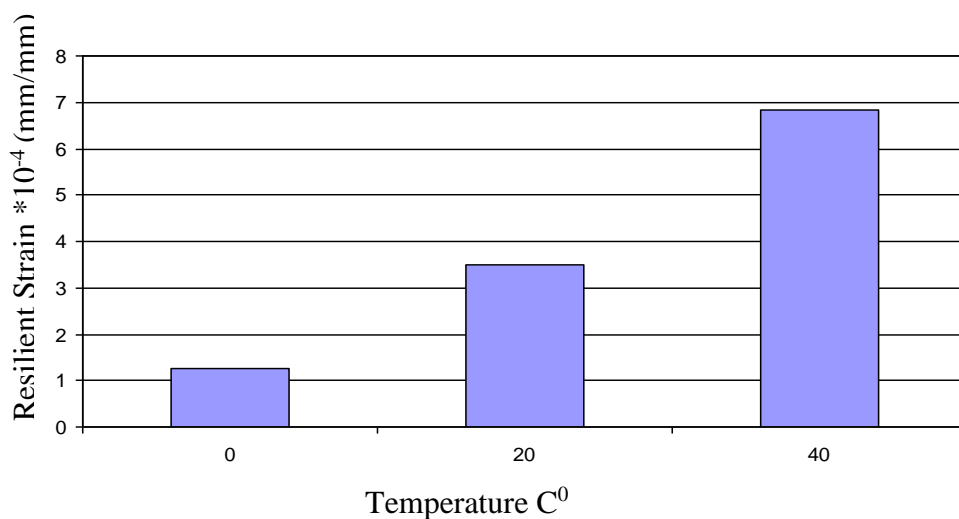
b. Upper and lower limits of aggregate

Figure (4.2): Effect of Aggregate on resilient strain

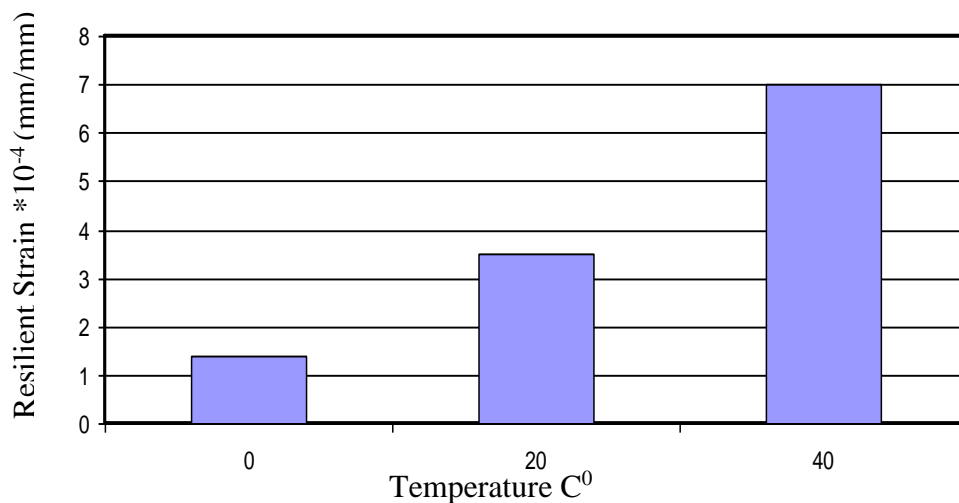


4.2.3 Filler Type and Content

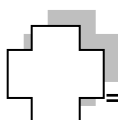
The function of the mineral filler is usually to fill the voids between the aggregate framework and to improve the properties of the mix. The lesser voids the higher stiffness of material and the lower resilient strain. The effect of filler type is depending upon the fineness of filler and its specific gravity. Figure(4.3) shows the effect of each filler type on resilient strain.

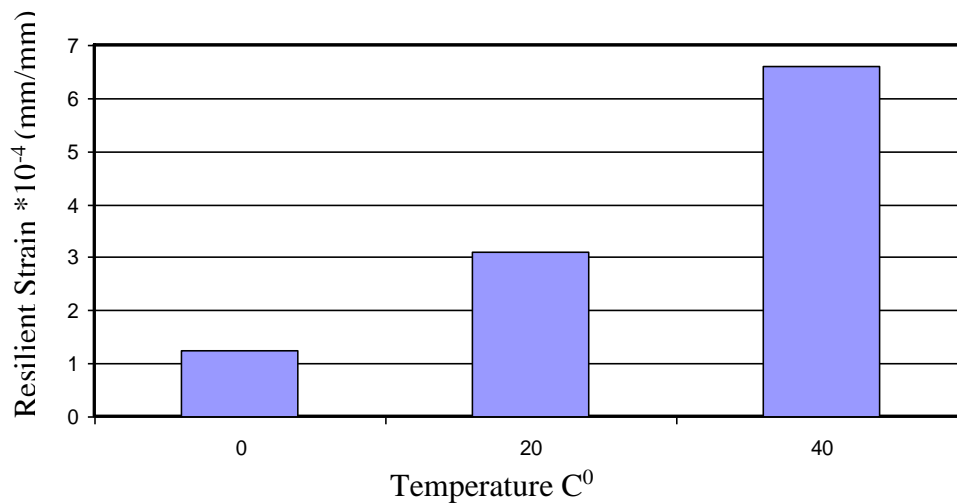


a. hydrated lime Filler



b. limestone dust filler.



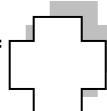


c. **Cement Filler Type.**

Figure (4.3) Effect of filler type on resilient strain

4.2.4 Temperature

The resilient modulus value is affected to great extent by temperature. After careful considerations, it was realized that, in accordance with the basic of strength of materials and asphalt rheology phenomena, when the load is applied on the specimen, tensile stresses are developed in the horizontal direction at the mid depth plane of the specimen. Since aggregate particles do not carry tension, therefore, the cohesion of the asphalt cement will be mobilized and reflect the strength of the asphalt mixture. It is well known that the asphalt cement is very temperature susceptible; at low temperatures asphalt is stiff and brittle, while at high temperatures asphalt is soft and ductile. This behavior may explain why the resilient modulus significantly decreases as temperature increases (Al- Bayati, 2006). In this study, three test temperatures were applied to specimens under indirect tension repeated



loading. These temperatures were (0 °C, 20 °C, 40 °C). The maximum test temperature for determining resilient modulus by IDT test is limited to 40 °C (Tara, 2003). Figure (4.4) shows the effect of temperature variety on resilient strain as a result of the study.

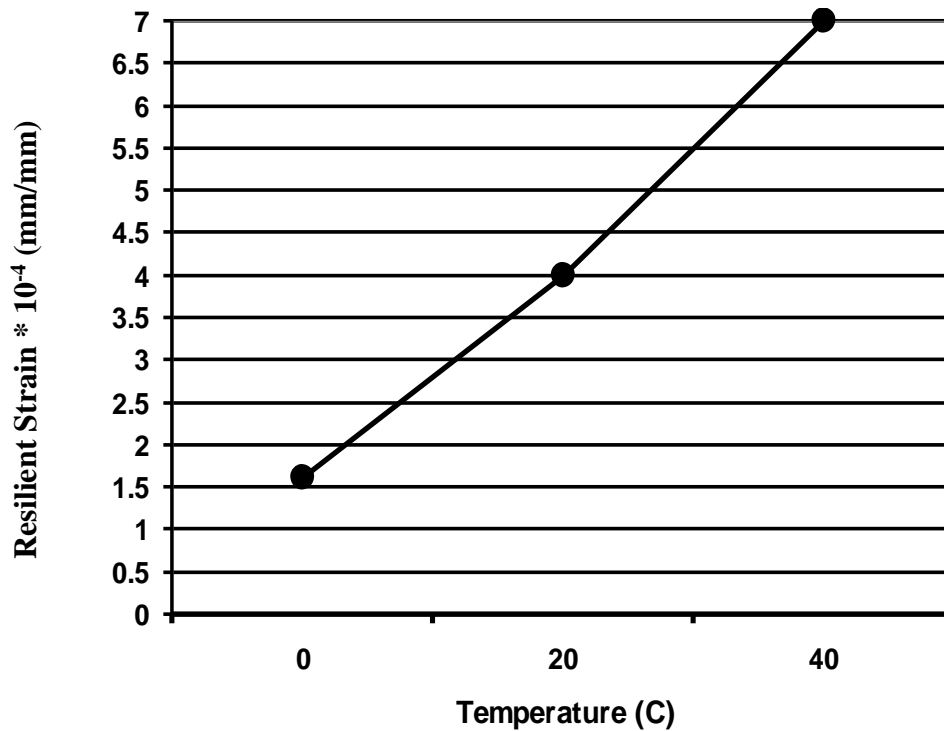


Figure (4.4) Effect of Temperature on resilient strain

4.3 Marshall Test Results

Marshall Test was implemented to all specimens with their different variables to determine stability and flow.

Marshall Stiffness was also determined which is the ratio between stability and the corresponding flow for all different specimens. These results are represented in Table (4.1).

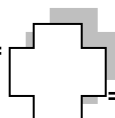
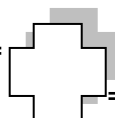


Table (4.1) Marshall Test Results

Sample	Stability (Kg)	Flow (mm)	Marshall Stiffness (Kg/mm)
A	1010	3.5	288
B	1150	3.7	311
C	900	3.5	257
D	1100	3.5	314
E	950	3.7	257
F	1030	2.9	355
G	850	4.2	202
H	1250	3.5	357
I	1200	4	300
J	1050	4.3	244
K	900	3.3	273
L	980	2.5	392
M	900	3	300
N	1150	3	383
O	1100	3.9	282
P	1050	3.5	300
Q	1000	4.2	238
R	800	3.5	229
S	1100	3.8	289
T	850	2.9	293
U	800	3.2	250



4.4 Resilient Modulus Results

The resilient modulus values were obtained utilizing the IDT test method. As previously noted , specimens were tested at three temperatures 0 °C , 20 °C and 40 °C . The stress level was 20 psi with a duration of 0.1 sec loading and 0.9 sec unloading. Each specimen had different volumetric properties and different resilient modulus value.

The difference in calculated resilient modulus values among specimens is believed to be due to the difference in volumetric properties and type of filler used.

The calculations of volumetric properties related to test specimens are presented in the appendix at the thesis, the values of such volumetric properties are shown in Table (4.2) ,whereas the results of measured resilient modulus values are presented in Table (4.3).

Table (4.2) Properties of Tested Specimens

Sample	G_{mb}	G_{mm}	A_v	P_s	P₈	P₂₀₀
A	2.340	2.463	4.99	10.13	41	7
B	2.399	2.471	2.91	10.15	31	7
C	2.339	2.455	4.72	10.52	50	7
D	2.347	2.456	4.44	10.5	58	10
E	2.333	2.453	4.89	10.57	28	4
F	2.378	2.451	2.98	11.49	58	10
G	2.364	2.437	3	11.98	28	4
H	2.387	2.476	3.59	9.22	58	10
I	2.373	2.481	4.35	9.01	28	4

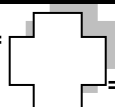


Table (4.2) Continued

J	2.33	2.453	5	10.56	58	10
K	2.378	2.456	3.17	10.64	28	4
L	2.36	2.433	3	12.12	58	10
M	2.346	2.428	3.37	12.23	28	4
N	2.369	2.462	3.78	8.9	58	10
O	2.278	2.479	5	8.97	28	4
P	2.337	2.451	4.65	10.61	58	10
Q	2.342	2.458	4.72	10.44	28	4
R	2.467	2.439	2.96	11.88	58	10
S	2.354	2.427	2.99	12.29	28	4
T	2.377	2.477	4.04	9.16	58	10
U	2.363	2.487	4.97	8.74	28	4

Table (4.3) Resilient Modulus Results

Sample	T=0 °C	T=20 °C	T=40 °C
	Mr(psi)	Mr(psi)	Mr(psi)
A	154777	61832	35269
B	205932	63281	35788
C	153797	53761	33820
D	247959	68644	36323
E	146385	63281	35788
F	189844	64973	35269

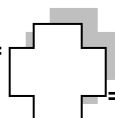
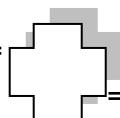


Table (4.3) Continued

G	137288	56120	33820
H	225000	77143	38028
I	155508	66758	35788
J	220909	72754	38028
K	191338	66758	36323
L	144642	70640	37442
M	136517	63281	35788
N	276136	82373	38633
O	165306	68644	36874
P	243000	70640	36874
Q	143787	61832	36323
R	222935	66758	35269
S	135754	61832	34322
T	245454	77143	39194
U	164189	63281	35788



4.5 Model Development

4.5.1 Selection of Variables

The first step in the development of the statistical analysis was the selection of the variables included in model prediction. The selection of these variables was based upon the reviewed literature and the availability of data for each one. The factors used to predict resilient modulus are numerous, and according to the literature reviewed that is mentioned in this research and to the available data can be calculated from testing results presented in chapter three, the following variables will be included in model prediction:

The dependent variable: M_r

The independent variables: T , A_v , P_s , P_8 , P_{200} .

Where:

M_r : Resilient Modulus (psi)

T : Test Temperature ($^{\circ}\text{C}$)

A_v : Percent Air Voids

P_s : Percent Volume of Effective Asphalt

P_8 : Percent Passing Sieve No. 8

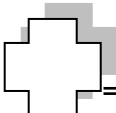
P_{200} : Percent by weight of Filler Content

4.5.2 Model Adequacy Assessment

There are two approaches generally used to assess the adequacy of the proposed regression models, the first one is based on examining the goodness of fit measures, whereas the second approach is based on the graphical analysis of the residuals, also called diagnostic plots.

1-Goodness of Fit Measures

The measures of goodness of fit aimed to quantify how well the proposed regression model obtained fits the data. The measure that is



usually presented is the coefficient of multiple determination (R^2) (Devore, 2000).

The R^2 value is the percent variation of the criterion variable explained by the suggested model and calculated according to the following equation:

$$R^2 = 1 - (SSE / SST) \dots\dots\dots(4.1)$$

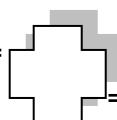
Where SSE is the error sum of squares $= \sum (y_i - y'_i)$, where y_i is the actual value of criterion variable for the i^{th} case and y'_i is the regression predicted value of the variable i^{th} case. SST is the total sum of squares $= \sum (y_i - y')^2$, where y' is the mean observed y . R^2 is the square of the correlation between observed and calculated value of the dependent variable and $0 \leq R^2 \leq 1$. Most researchers dealing with models development prefer this coefficient to be greater than 0.8 for much confidence in these models. This study will use this coefficient in selecting the best model.

2-Diagnostic Plots

Another effective approach to the assessment of model adequacy is to compute the predicted criterion values, y'_i , and the residuals, e_i . Residuals are the difference between an observed value of the criterion variable y_i and the value predicted by the model, ($e_i = y_i - y'_i$). And then to plot various functions of these computed quantities. We then examine the plots either to confirm our choice of model or for indications that the model is not appropriate (Devore, 2000).

4.5.3 Predictive Model for Resilient Modulus.

The resilient modulus is a key parameter in the pavement design and performance prediction system, so it is desirable to have a



statistical model capable for the prediction of the resilient modulus of asphalt concrete.

The adopted model structure and the terms included in these models are shown in Table (4.4). Presented in Table (4.5) is the statistical summary of these models.

Models No.3 and No.4 are nonlinear, the obtained R^2 values and standard error (SE) are 0.957 and 15164.87 for model No.3, and 0.955 and 15749.92 for model No.4. Table (4.6) shows the data used in statistical for program to predict the resilient modulus. Based on the diagnostic plots shown in figures(4.5) and (4.6) both models are rational, the residual plots of these two models do not indicate any unusual pattern and normally distributed. So, both models can be adopted for Mr prediction.

Model No.3 is shown below:

$$Mr = 322342.7 - 47368.7(T^{0.310683} + P_8^{0.310683}) - 4341.74 P_s + 8913.09 P_{200} + 11055.16 \sin(-577.43Av - 28.083) \quad \dots\dots(4. 2)$$

Model No.4 is:

$$Mr = 10249376 - 38888.4(T^{0.365504} + P_8^{0.365504}) - 5996.61 P_s + 11115.29 P_{200} - 0.000181 \text{ EXP}(0.000122 Av + 24.72744) \quad \dots\dots(4. 3)$$

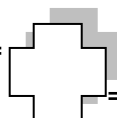


Table (4.4) General Model structures

Model No.	Model Structure	Criterion Variable
1	$C_0 + C_1 T^B + C_2 P_S + C_3 P_{200} + C_4 Av$	Mr
2	$C_0 + C_1 T^B + C_2 P_S + C_3 P_{200} + C_4 \sin(Av + C_5) + C_6 P_8^B$	Mr
3	$C_0 + C_1(T^{C_2} + P_8^{C_2}) + C_3 P_s + C_4 P_{200} + C_5 \sin(C_6.Av + C_7)$	Mr
4	$C_0 + C_1(T^{C_2} + P_8^{C_2}) + C_3 P_s + C_4 P_{200} + C_5 EXP(C_6.Av + C_7)$	Mr

Table (4.5) Statistical Summary for Resilient Modulus

Model No.	Explained Variation (R ²)	Standard Error (SE)
1	0.933	22322.07
2	0.935	20121.78
3	0.957	15164.87
4	0.955	15749.92

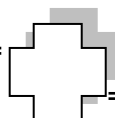
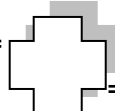
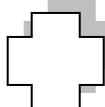


Table (4.6) Data used in statistical program.

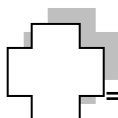
Mr	T	Av	P _s	P ₈	P ₂₀₀
154777	0	4.99	10.13	41	7
205932	0	2.91	10.15	31	7
153797	0	4.72	10.52	50	7
247959	0	4.44	10.5	58	10
146385	0	4.89	10.57	28	4
189844	0	2.98	11.49	58	10
137288	0	3	11.98	28	4
225000	0	3.59	9.22	58	10
155508	0	4.35	9.01	28	4
220909	0	5	10.56	58	10
191338	0	3.17	10.64	28	4
144642	0	3	12.12	58	10
136517	0	3.37	12.23	28	4
276136	0	3.78	8.9	58	10
165306	0	5	8.97	28	4
243000	0	4.65	10.61	58	10
143787	0	4.72	10.44	28	4
222935	0	2.96	11.88	58	10
135754	0	2.99	12.29	28	4
245454	0	4.04	9.16	58	10
164189	0	4.97	8.74	28	4
61832	20	4.99	10.13	41	7
63281	20	2.91	10.15	31	7
53761	20	4.72	10.52	50	7



68644	20	4.44	10.5	58	10
63281	20	4.89	10.57	28	4
64973	20	2.98	11.49	58	10
56120	20	3	11.98	28	4
77143	20	3.59	9.22	58	10
66758	20	4.35	9.01	28	4
72754	20	5	10.56	58	10
66758	20	3.17	10.64	28	4
70640	20	3	12.12	58	10
63281	20	3.37	12.23	28	4
82373	20	3.78	8.9	58	10
68644	20	5	8.97	28	4
70640	20	4.65	10.61	58	10
61832	20	4.72	10.44	28	4
66758	20	2.96	11.88	58	10
61832	20	2.99	12.29	28	4
77143	20	4.04	9.16	58	10
63281	20	4.97	8.74	28	4
35269	40	4.99	10.13	41	7
35788	40	2.91	10.15	31	7
33820	40	4.72	10.52	50	7
36323	40	4.44	10.5	58	10
35788	40	4.89	10.57	28	4
35269	40	2.98	11.49	58	10
33820	40	3	11.98	28	4
38028	40	3.59	9.22	58	10



35788	40	4.35	9.01	28	4
38028	40	5	10.56	58	10
36323	40	3.17	10.64	28	4
37442	40	3	12.12	58	10
35788	40	3.37	12.23	28	4
38633	40	3.78	8.9	58	10
36874	40	5	8.97	28	4
36874	40	4.65	10.61	58	10
36323	40	4.72	10.44	28	4
35269	40	2.96	11.88	58	10
34322	40	2.99	12.29	28	4
39194	40	4.04	9.16	58	10
35788	40	4.97	8.74	28	4



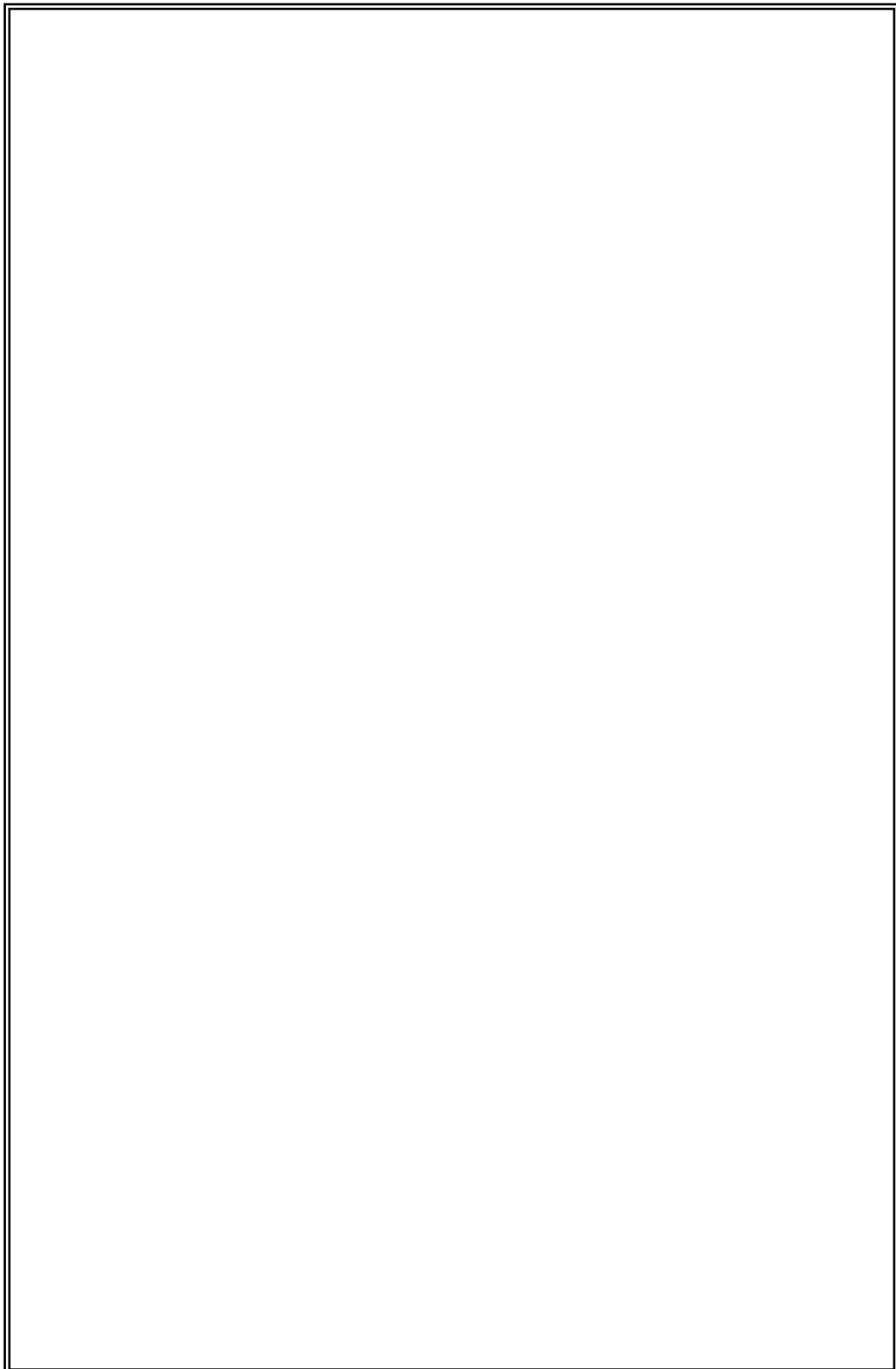
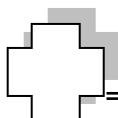


Figure (4. 5) Diagnostic plots of model No.3



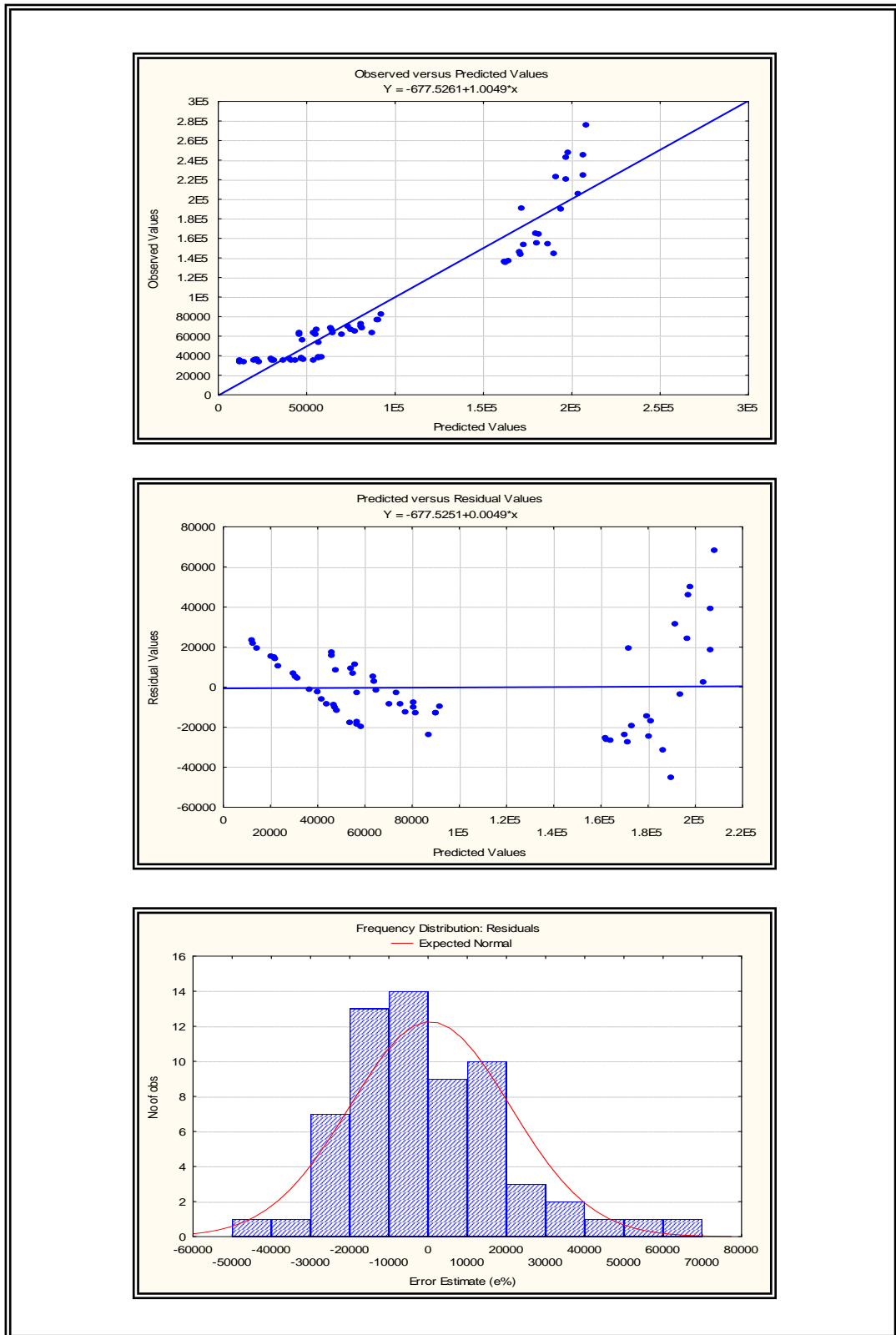
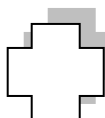


Figure (4.6) Diagnostic plots of model No.4



4.5.4 Model Predicted from Marshall Stiffness .

In order to predict the resilient modulus value corresponding to that obtained from IDT test and when the IDT testing apparatus is not available, Marshall stiffness, the conventional test of road pavements, can be used for that prediction. Nonlinear regression is used to develop an empirical equation to predict the resilient modulus as a function of Marshall stiffness and temperature. The developed statistical model is shown below in equation (4.4). This model has an R^2 value of 0.928 and standard error (SE) of 17849.29. The diagnostic plots of this model are shown in Figure (4.7).

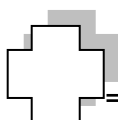
$$Mr = 628.496 MS^{0.7766} + 134736.6 e^{-1229.56T} \quad \text{.....(4.4)}$$

Where:

Mr : Resilient Modulus (psi).

MS: Marshallstiffness @ 60 °C (kg / cm²)

T : Temperature (°C)



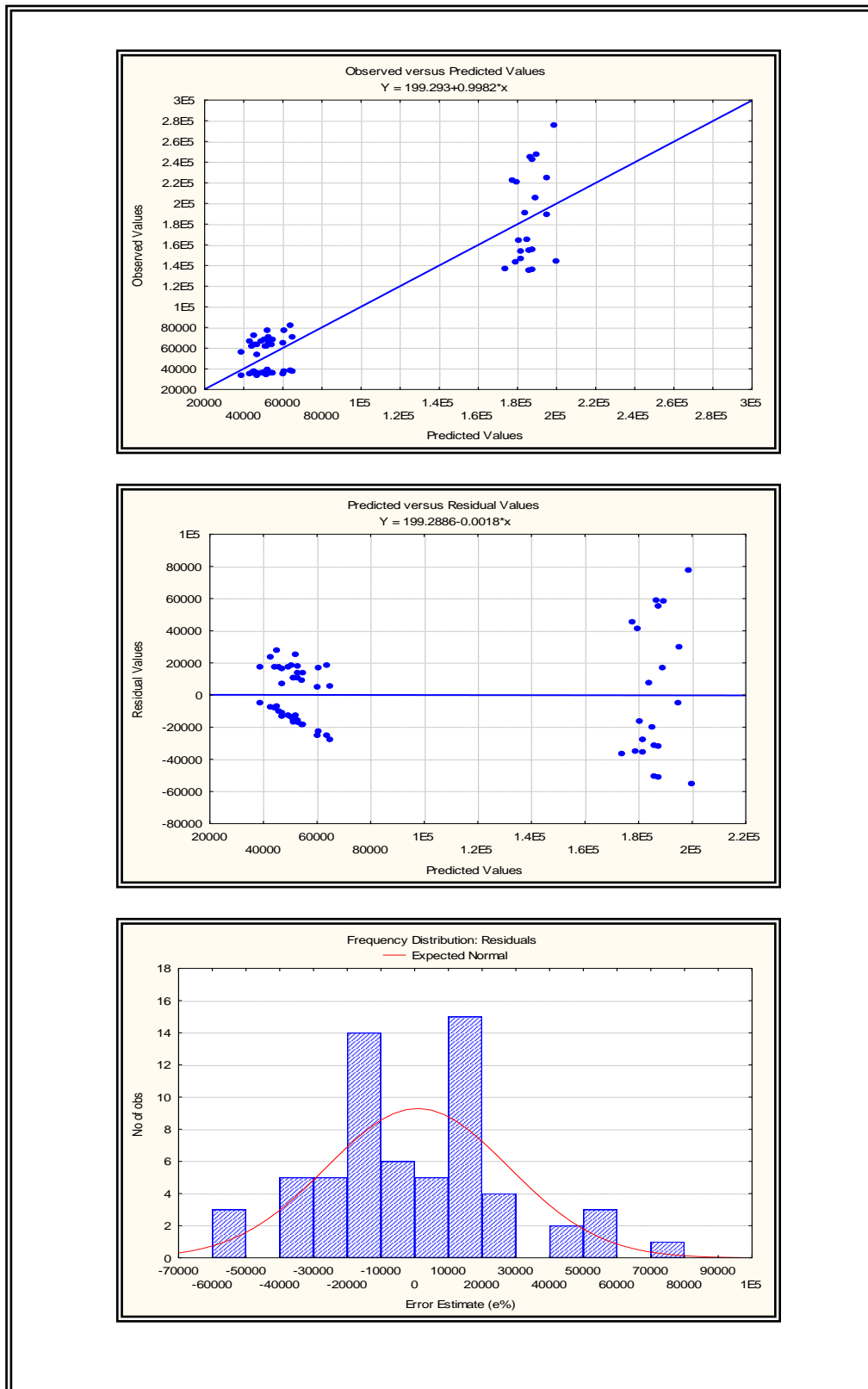
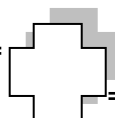


Figure (4.7) Diagnostic plots of model prediction from Marshall stiffness



CHAPTER FIVE

Conclusions and Recommendations

5.1 Conclusions

Within the limitations of test program , materials and method of analysis used in this work , the following are concluded :

1. In terms of the test conditions and asphalt concrete mix parameters cited in this research . Two models were developed to predict the resilient modulus of asphalt concrete mixture:

Model No.1:

$$Mr = 322342.7 - 47368.7(T^{0.310683} + P_8^{0.310683}) - 4341.74 P_s + 8913.09 P_{200} + 11055.16 \sin(-577.43Av - 28.083)$$

Model No.2:

$$Mr = 10249376 - 38888.4(T^{0.365504} + P_8^{0.365504}) - 5996.61 P_s + 11115.29 P_{200} - 0.000181 \text{ EXP}(0.000122 Av + 24.72744)$$

Where:

Mr : Resilient Modulus (psi)

T : Test Temperature (°C)

Av : Percent Air Voids

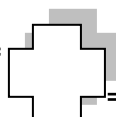
P_s : Percent Volume of Effective Asphalt

P₈ : Percent Passing Sieve No. 8

P₂₀₀ : Percent by weight of Filler Content

2. From Marshall test results, a model was developed to predict resilient modulus from Marshall stiffness as follows:

$$Mr = 628.496 MS^{0.7766} + 134736.6 e^{-1229.56T}$$



Where:

Mr : Resilient Modulus (psi).

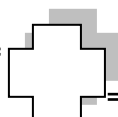
MS: Marshallstiffness @ 60 °C (kg/cm²)

T : Temperature (°C)

- 3- The resilient modulus is highly affected by the temperature ; the average resilient modulus corresponding to test temperature of 0 °C is approximately 2.8 and 5.2 times that corresponding to test temperature of 20 °C and 40 °C , respectively .
- 4- Increasing the asphalt content of paving mixtures from 4.7 % to 5.4% causes an increased resilient strain by 105 %.
- 5- Replacing the limestone dust by Portland cement as a mineral filler in asphalt mixture has decreased the resilient strain by 89 % .
- 6- Coarse gradation causes decreased resilient strain by 91% for a nominal max. aggregate size of 19 mm.
- 7- The PRLS apparatus existed in Baghdad University is determined to be as a suitable mean to evaluate the resilient modulus of asphalt mixture by indirect tension test (IDT) in short duration with easy handling , is recommended to be used for this purpose .

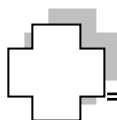
5.2 Recommendations for Future Research

Because of practical considerations , many constraints were imposed upon this study in terms of variables included in the experimental design .Accordingly , in future researches it is recommended to use other material variables such as the effect of asphalt cement type including its chemical composition and rheological properties , and the use of polyethylene powder as an additive .

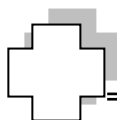


References

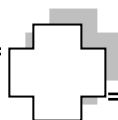
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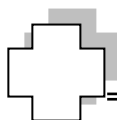
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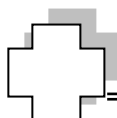
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Supervisor Certificate

We certify that the thesis titled " Prediction of Resilient Modulus in Asphalt Concrete Mixture " was prepared by " Tariq Hussein Obaiss ", under our supervision at Babylon University in fulfillment of partial requirements for the degree of **MASTER OF SCIENCE IN CIVIL ENGINEERING.**

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