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A SIMPLIFIED TECHNIQUE FOR MEASURING DYNAMIC MODULUS OF ASPHALT CONCRETE

أسلوب مبسط لقياس معامل المرونة الديناميكي للخرسانة الأسفلتية

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الملخص العربي

أصبح قياس معامل المرونة الديناميكي للخلطات الأسفلتية من الأهمية بمكان باعتباره أحد المدخلات الأساسية لتصميم الرصف المرن. وتوجد عدة طرق لقياسه باستخدام أجهزة معقدة وغير متوفرة فى مصر. وحديثاً تم تصنيع جهاز البلاستوميتر لاستخدامه فى قياس معامل المرونة الديناميكي للخلطات الأسفلتية. وحتى الآن لم ينتشر هذا الجهاز فى معامل الطرق لعدة اسباب، أهمها اختلاف شكل وطريقة إعداد العينات المستخدمة فيه عن عينات مارشال التقليدية. لذلك تهدف هذه الدراسة إلى تبسيط طريقة لايجاد معامل المرونة الديناميكي عن طريق إجراء اختبار بسيط ومتاح هو اختبار الشد الغير مباشر على عينات مارشال التقليدية. وللتحقق من مستوى الموثوقية فى الطريقة المقترحة تم دراسة ظروف مختلفة للخلطة مثل تدرج الركام ونسبة الأسفلت وطاقة الدمك. ولتحقيق ذلك تم إجراء اختبارى البلاستوميتر والشد غير المباشر على العديد من الخلطات الأسفلتية باعتبار ثلاث تدرجات للركام هى الحد الأدنى والحد الأعلى ونقطة الوسط لتدرج (٤ج) كما تم استخدام خمسة محتويات أسفلت هى نسبة الأسفلت المثلى وقبلها وبعدها بمقدار ١% و٢% مع تغيير طاقة الدمك عن طريق استخدام عدد ضربات ٧٥، ٥٠ و ٣٥ ضربة لدمك العينات.

بالتحليل الاحصائى لنتائج الاختبارين تم استنباط علاقة رياضية قوية بين معامل المرونة الديناميكى المقاس من اختبار البلاستوميتر ومعامل المرونة المقاس من اختبار الشد غير المباشر الاستاتيكى فى ظل الظروف المختلفة للخلطة الأسفلتية. ويمكن استخدام هذه العلاقة فى الحصول على قيم منطقية لمعامل المرونة الديناميكى عن طريق اجراء اختبار الشد غير المباشر فى معامل الطرق التقليدية. وبعد تحليل النتائج أوصت الدراسة باستخدام خلطات أسفلتية ذات تدرج خشن مع ضبط نسبة الأسفلت وجهد الدمك للحصول على أداء عالى فى الحقل لهذه الخلطات.

ABSTRACT

Measuring dynamic modulus of asphalt mixes is becoming more important for pavement design. There are different methods for measuring dynamic modulus of asphalt mixes by using complicated dynamic equipments, not available in Egypt. Recently, the plastometer apparatus has been manufactured in Egypt and successfully used for measuring dynamic modulus (E_d) of asphalt mixes. Yet, this apparatus has not widely used in highway laboratories because its specimen differs in shape and preparing method from Marshall procedure. So, this study aims at simplifying the method of obtaining dynamic modulus of asphalt mixes by conducting the simple static indirect tensile test (ITT) on Marshall specimen in traditional highway laboratories. Quantifying the effects of aggregate gradation, asphalt content and compaction effort on the measured dynamic modulus is another objective. To achieve these objectives, two major tests were conducted on different asphalt mixes with varying three aggregate gradations, five asphalt contents and three compacting efforts. The conducted tests are plastometer and ITT, which were used for measuring dynamic modulus (E_d) and static elasticity modulus (E_s) of paving mixes, respectively.

Statistical analysis of the two test results showed that a good estimate of E_d can be obtained from the results of ITT at various mix conditions, using the developed equation. Finally, the study recommends to use coarse aggregate gradation in paving mixes under firm control on asphalt content and compaction for superior field performance of these mixes.

KEW WORDS:

Plastometer test, Indirect tensile test, Modulus of elasticity and Asphalt mixes.

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INTRODUCTION AND BACKGROUND

The ability to characterize asphalt concrete mixtures in terms of fundamental engineering properties is becoming increasingly more important. This is partially due to the fact that many agencies are beginning to use pavement design system based on elastic layer theory. Among the basic material properties required as inputs for elastic layer analysis of an asphaltic pavement is the modulus of elasticity of each material, including variation with temperature and loading rate [1]. Two main modulii are used to describe the behavior of asphalt mixtures. They are dynamic modulus and resilient modulus [2]. Dynamic modulus is defined as the ratio between applied dynamic stress and corresponding elastic strain, while resilient modulus is the ratio of the applied stress to the recoverable strain when dynamic load is applied. There are different methods used to measure dynamic modulus and resilient modulus by the means of complicated equipments for applying the required dynamic load. Such sophisticated dynamic equipments are not available in Egypt. In spit of this, Radonesky [3] prepared a plastometer apparatus for measuring dynamic modulus of asphalt concrete mixtures based on its reheological characteristics. Recently, the plastometer apparatus has been manufactured in Egypt and successfully used for measuring the modulus of elasticity of asphaltic mixtures [4]. Since this device is not common tell now, it is of great importance to correlate its results to another standard test can be performed in Egypt. Static indirect tensile test has also been used in Egypt to measure modulus of elasticity of asphalt mixtures, and can be easily performed in all highway laboratories [5, 6]. However, the values of static elasticity modulus are significantly smaller compared with that of dynamic modulus. The ratio of the dynamic to the static modulus was found in the range from 9 to 11 for laboratory specimens of asphalt mixes [7, 8].

So, the main objective of this study is to correlate the measured values of dynamic modulus of elasticity obtained from plastometer test to that resulted from static indirect tensile test which considered the most related and common test, considering the effect of aggregate gradation, asphalt content and compaction effort on the measured elasticity modulus of asphalt concrete.

EXPERIMENTAL PROGRAM DESIGN

To achieve the objectives of this study, an experimental program was designed including identifying mix variables and characteristics, such as mix gradation, asphalt content and compaction effort. Three mix gradations were used in this study. The selected gradations are the lower and upper limits as well as the mid point of standard gradation 4C, specified by the Egyptian Roads and Bridges Authority [9]. This gradation was selected because it is the most widely used gradation for surface layer in Egypt. The selected gradations are shown in Table (1).

To consider the probable deviations in asphalt content from its optimum value (OAC) in actual practices, five asphalt contents were considered in this study. The first is the OAC resulted from Marshall test. The other four asphalt contents are 1% and 2% each plus and minus OAC. To investigate the effect of compaction effort on the asphalt mix modulus, three efforts are simulated by varying the number of blows used for compacting mix specimens. The investigated number of blows are 35, 50 and 75.

The design of asphalt mixes used in this study is based on Marshall mix design procedures according to ASTM: D1559 and ASASHTO T-245. This method used to determine the optimum asphalt content (OAC) and unit weight for each mix [10].

MATERIALS

One type and source for each mix component was chosen. The coarse part of the aggregate is dolomite, obtained from "Ataka" quarry at suez governorate, with the properties shown in Table (2). Siliceous sand obtained from "Abushalby" quarry, Sharkia governorate with specific gravity of 2.65 and limestone mineral filler with specific gravity of 2.85 were used as the fine part in the mix. Their gradations are shown in Table (3). The bituminous material used in this study is asphalt cement 60/70 obtained from Suez refinery with the properties shown in Table (4).

TESTING PROGRAM

In the laboratory testing program of this study a Marshall tests were conducted to obtain optimum asphalt content, unit weight and other mix conditions. After that two major tests were conducted on each mix at room temperature of about 30°C. These tests are indirect tensile test and Radonesky plastometer test. The two conducted tests were performed on the mix samples 24 hours after compaction. Brief notes about the two tests are presented in the following sub-sections.

Plastometer Test Method

Plastometer apparatus was used to measure dynamic modulus of elasticity. In this method asphalt concrete mix samples of dimensions 4 x 4 x 16 cm was used. These samples were prepared based on the results obtained from Marshall test. The outline of the method is thoroughly explained by Mohamady [11]. Deflection of tested specimens was recorded each one minute. After that modulus of elasticity was determined through calculating the rheological characteristics for asphalt mix specimens. This modulus represents a dynamic modulus of elasticity corresponding to a loading time of 0.02 second for the asphalt concrete mix. Based on data recorded during plastometer test, Radonesky gives a formula to evaluate rheological characteristics (viscosity, plasticity, and modulus of elasticity) for the asphalt concrete mix as follows:

$$\eta = \frac{Q\Phi(T_{600} - T_{300})}{f_{600} - f_{300}} = \frac{Q\Phi\Delta T}{\Delta f} \qquad (1)$$

where:

η = Viscosity, poise;

Q = Applied load, kg;

Φ = A coefficient depends on specimen dimensions;

ΔT= Difference in time for the time interval used in calculations (interval is 5 minutes starting after 5 minutes from the start of the test); and

Δf = Difference in dial gauge readings (deflection in the specimen after 5, 10 minutes), cm.

Based on specimen dimensions of 4 x 4 x 16 cm, Radonesky gives a simplified equation for the above formula as follows:

$$\eta = \frac{0.804 * 10^6 Q}{\Delta f} \quad \text{poise} \qquad (2)$$

Plasticity of asphalt mixes is calculated using the formula:

$$P = 1 - \frac{\text{Log}\,\eta}{18} \qquad (3)$$

Finally the dynamic modulus of elasticity (E_d) is given by:

$$\text{Log}\,E_d = 2.2\,(1-P) + 3 \qquad (4)$$

Indirect Tensile Test

Indirect tensile test was carried out by loading Marshall specimens with compressive vertical loads that act parallel to and along the vertical diameter plane until failure using a constant rate of loading of 0.04 in/min. A steel loading strip 0.5 in wide with a curved loading surface was used to distribute the load uniformly and to maintain a constant loading area. Also, three arms attached with micrometers dial gauges (sensitivity 0.01 mm division) are clamped on the samples. One vertically for measuring vertical deformation (Y), whereas the others are clamped horizontally on the opposite sides of the sample for measuring the lateral deformation (X). By continuously monitoring the loads, and the vertical and horizontal deformations of the specimen until failure, modulus of elasticity can be estimated for 4-inch diameter specimen by using the simplified equations developed by Kennedy [1] as follows:

$$E_s = P\,(0.27 + \upsilon) / (XH) \qquad (5)$$

Where:

E_s = Static modulus of elasticity

P = Total load at failure (Ib)

H = Height of specimen (in)

X = Total horizontal deformation at failure (in)

υ = Poisson's ratio = (0.0673 DR – 0.8954) / (-0.25 DR – 0.0156)

DR = Deformation ratio = Y/X

Y= Total vertical deformation at failure (in)

ANALYSIS OF RESULTS

The results of the laboratory testing program, described earlier, along with the investigated mix conditions are presented in Table (5). It is of a great importance to notice that the values of modulus of elasticity is calculated (or converted) to the same units (psi). The discussion of these results is presented in the following sub-sections.

Plastometer Test Results

Figure (1) shows the relationship between dynamic modulus of elasticity (E_d) measured using plastometer test and asphalt content (AC) for the three mix gradations. As can be seen in the figure the value of E_d increases as AC increases up to certain value, then E_d decreases for further increase in AC. It can be noticed that, the peak value of E_d for coarse gradation (161100 psi) occurs at AC lower than OAC (obtained from Marshall) by about 1%, while E_d for medium gradation (123300 psi) occurs approximately at OAC. On the other hand, the peak value of E_d for fine mix gradation (116370 psi) occurs at AC higher than OAC by about 1%. This can be attributed to the large amount of fine material which requires high AC to cover the large surface area of fine particles. The figure also shows that at low AC the coarse gradation mix has the highest value of E_d followed by medium gradation, while the fine gradation achieves the lowest E_d value and vice versa at high AC. The fact that can not be ignored that the mix of coarse gradation, as shown in the figure, is more sensitive to variations in asphalt content than fine mix gradation, while the mix of medium gradation is low susceptible to asphalt content. Whatever, the three mix gradations give approximately equal values of E_d at about 6% AC.

To study the effect of compaction effort, the measured values of E_d were plotted against number of blows on Figure (2) for the three mix gradations. This figure shows that the values of E_d increases as number of blows increases. It can be noticed also that the rate of increase in E_d for coarse mix gradation with increasing number of blows from 50 to 75 is higher than that for other mix gradations. This may be due to the fact that the mix of coarse gradation requires high compaction effort to reach the optimum orientation of its particles. The three mix gradations give approximately equal values of E_d at compaction effort of about 55 blows.

Indirect Tensile Test Results

Figure (3) presents the relationship between the measured static modulus of elasticity (E_s) from indirect tensile test and AC for the three mix gradations. Also, Figure (4) represents the relationship between E_s from indirect tensile test and number of blows for the three investigated mixes. Comparing these figures with Figures (1) and (2), respectively, the same trend can be noticed. The noticed similarity in the trend of both measured modulii with mix variables gives the probability of strong correlation between them.

Statistical Analysis

The laboratory test results, previously presented, were used to examine the statistical relationship between the static modulus of elasticity (E_s) measured from indirect tensile test and the dynamic modulus of elasticity (E_d) measured from plastometer test. The relationship between the two types of modulii is presented in Figure (5). The form of the relation between the two measured modulii is as follows:

$$E_d = 10.713\ E_s - 22336, (R^2=0.95) \quad (6)$$

Where:

E_d = Modulus of elasticity from plastometer test (psi).

E_s = Modulus of elasticity from indirect tensile test (psi).

The value of R^2 indicate that the developed relation, plotted in Figure (5) provide a reasonably good estimate of dynamic modulus of elasticity (E_d) of paving mixes based on static indirect tensile test results. This model was further statistically checked using F-test. The F_{comp} value is 364.5 and the corresponding F_{crit} value at a significant level α = 0.01 and degree of freedom 1 (N-1-1 = 19) is 8.18. Since F_{comp} is greater than F_{crit}, the relation exists at the chosen level of significance.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study, the following conclusions and recommendations are obtained:

1- A good estimate of the dynamic modulus (E_d) of paving mixes can be obtained from the result of static indirect tensile test with a satisfactory degree of convenience and at all investigated mix conditions using the developed equation:

$$E_d = 10.713\ E_s - 22336, \quad (R^2 = 0.95)$$

2- The peak value of dynamic modulus (E_d) occurs at asphalt content 1% plus and minus the optimum asphalt content (OAC) for fine and coarse mix gradations, respectively, while that for medium mix gradation occurs at approximately OAC; obtained from Marshall test.

3- At low asphalt content (AC), the mix of coarse gradation gives the highest values of dynamic modulus (E_d), while at high AC, the mix of fine gradation gives the highest values of E_d. Whereas at 6% AC the three mix gradations give approximately equal values of E_d (11000 psi).

4- E_d values of coarse and fine mixes are more susceptible to variation in asphalt content than the mix of medium gradation.

5- At high compaction effort (75 blows), coarse mix gives the highest values of E_d while at low and medium compaction effort (35 and 50 blows), there is no significant difference in E_d for the three mix gradations.

6- Using mix with coarse gradation instead of using medium or fine gradation increases dynamic modulus (E_d) by 31% and 38% with saving 15% and 33% in asphalt content, respectively

7- It is recommended to use mix of coarse gradation in pavement construction with firm quality control on asphalt content and compaction effort for superior field performance.

8- A comprehensive experimental study is recommended to be conducted to investigate the validity of the developed relation with wide range of mix components and testing conditions.

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Table (1): Mix Gradations Used in the Study.

Sieve size	% Passing by weight			Specification limits, 4C
	Coarse	Medium	Fine	
1\\	100	100	100	100
3/4\\	80	90	100	80-100
1/2\\	70	80	90	-
3/8\\	60	70	80	60-80
No. 4	48	56.5	65	48-65
No. 8	35	42.5	50	35-50
No. 30	19	24.5	30	19-30
No. 50	13	18	23	13-23
No. 100	7	11	15	7-15
No. 200	3	5.5	8	3-8

Table (2): Properties of the Dolomite Coarse Aggregates

Test No.	Test	Designation	Results		Specification limits
			Pin 1	Pin 2	
1	Specific gravity				
	- Bulk	AASHTOT-85	2.5	2.534	-
	- Saturated, surface-dry	AASHTOT-85	2.476	2.506	-
	- Apparent	AASHTOT-85	2.63	2.65	-
2	Water absorption (%)	AASHTOT-85	4	3.6	≤5
3	Los Angeles abrasion, 500 revolution (%)	AASHTOT-96	31.5	32.7	≤40
4	Stripping (%)	AASHTOT-182	>95	>95	>95

Table (3): Gradation of Sand and Mineral Filler.

Sieve size	% Passing		Specification limits for mineral filler
	Sand	Mineral filler	
3/8	98.1	-	-
No. 4	97.2	-	-
No. 8	82.1	-	-
No. 30	79	100	100
No. 50	35.3	97	-
No. 100	8.4	92	≥85
No. 200	3.4	82	≥65

Table (4): Properties of Asphalt Cement

Test No.	Test	Designation	Result	Specification limits
1	Penetration (0.1 mm, 25°C, 100 gm, sec.)	AASHTOT-49	67	60-70
2	Kinematic viscosity (centistokes, 135°C)	AASHTOT-201	365	≥320
3	Flash point (°C)	AASHTOT-48	+271	≥250
4	Softening point (°C)	AASHTOT-53	53	45-55
5	Ductility, cm.	AASHTOT-51	+100	≥95

Table (5): Laboratory Test Results of the Investigated Mixes.

Mix gradation	Mix No.	Asphalt content (%)	No. of blows	Unit weight, gm/cm^3	Modulus of elasticity (psi)	
					Plastometer test	Indirect tensile test
Coarse	1	3.7	75	2.258	140500	15985
	2	4.7	75	2.267	161100	17298
	3	5.7*	75	2.28	135205	14451
	4	5.7	50	2.268	102000	10870
	5	5.7	35	2.253	94010	9872
	6	6.7	75	2.290	73180	9920
	7	7.7	75	2.260	46122	7161
Medium	8	3.5	75	2.271	99027	10429
	9	4.5	75	2.285	105102	12070
	10	5.5*	75	2.300	123300	13516
	11	5.5	50	2.292	105107	11610
	12	5.5	35	2.280	96200	10980
	13	6.5	75	2.290	103300	12173
	14	7.5	75	2.281	99205	10481
Fine	15	4	75	2.266	38300	6481
	16	5	75	2.280	75227	8949
	17	6*	75	2.290	110500	12256
	18	6	50	2.283	103338	11673
	19	6	35	2.278	98540	11067
	20	7	75	2.305	116370	13005
	21	8	75	2.274	107540	12668

* Optimum asphalt content from Marshall design.

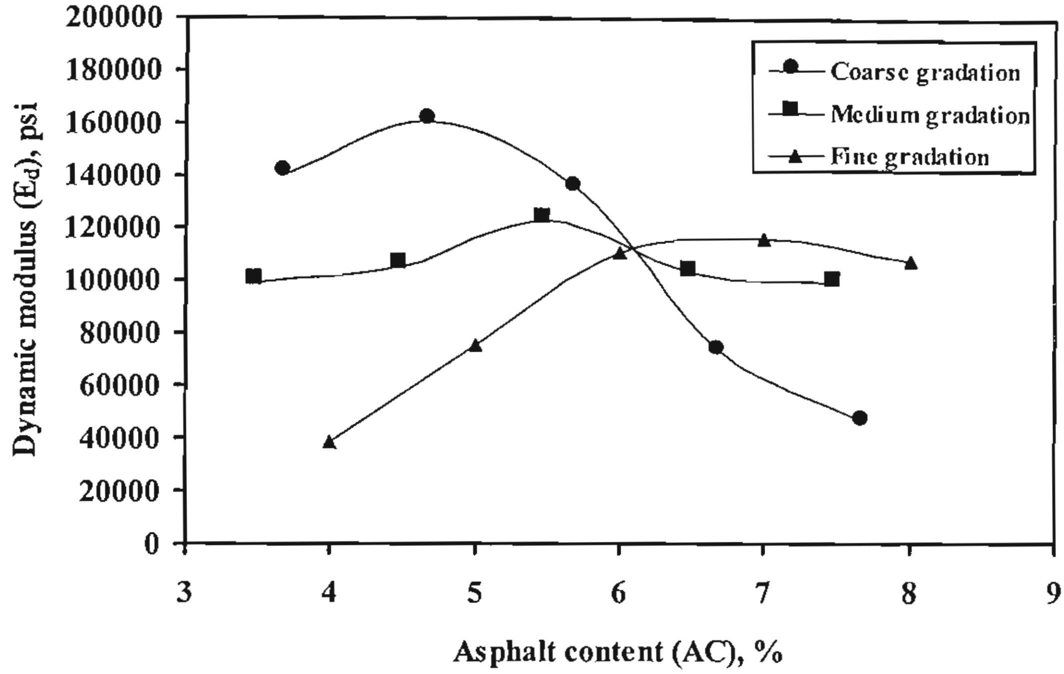

Figure (1): Dynamic modulus versus asphalt content for different mix gradations.

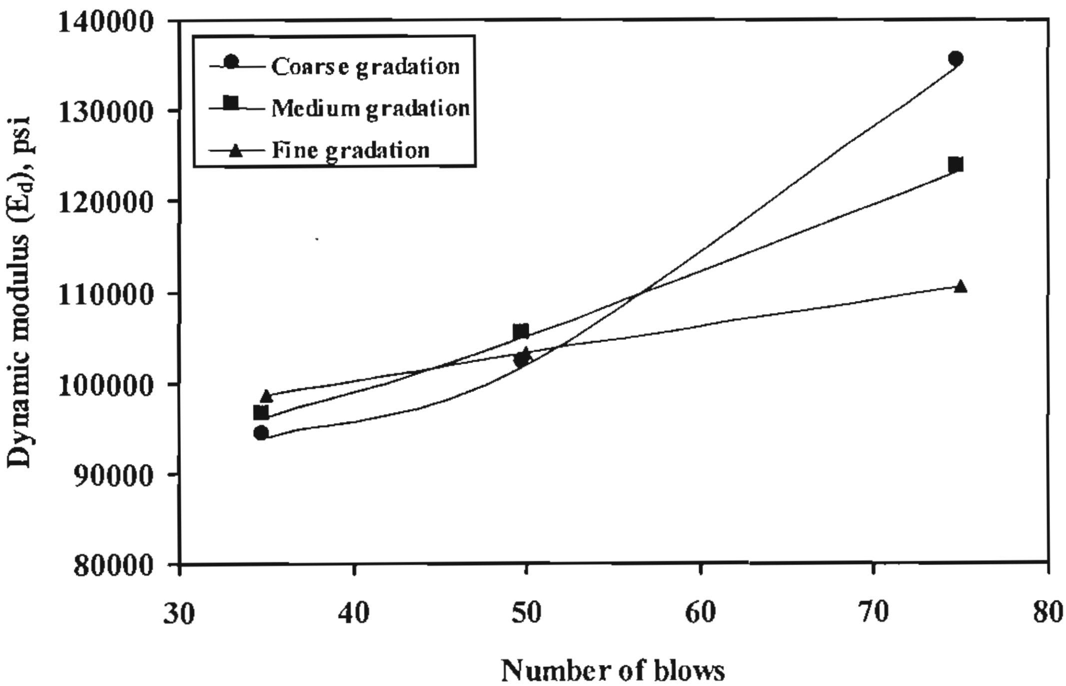

Figure (2): Dynamic modulus versus number of blows for different mix gradations.

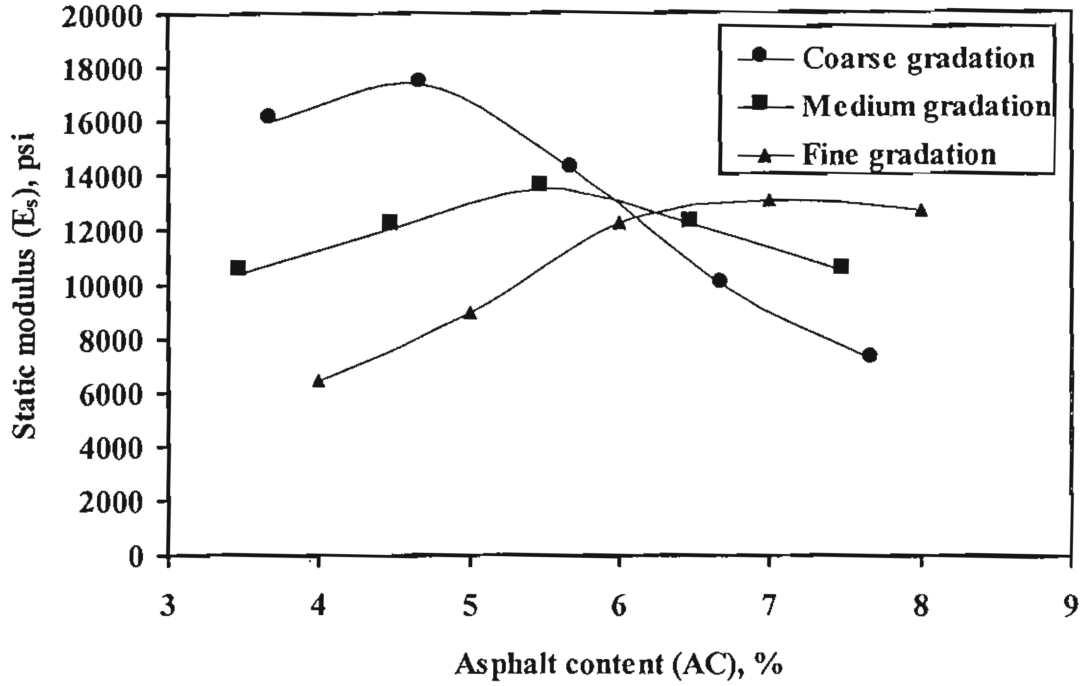

Figure (3): Static modulus versus asphalt content for different mix gradations.

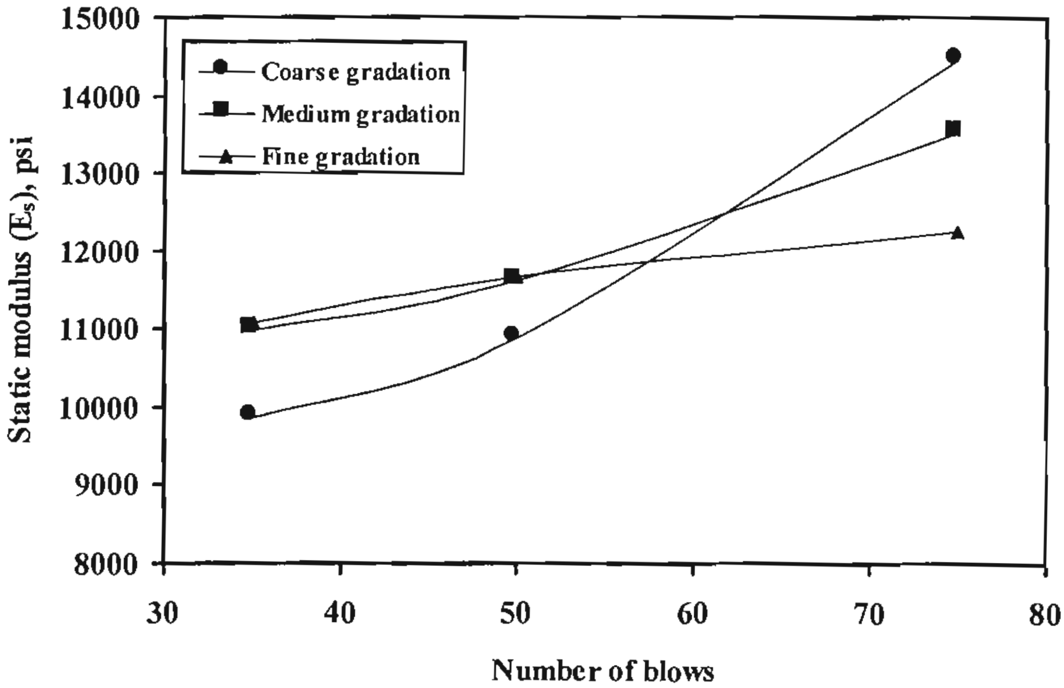

Figure (4): Static modulus versus number of blows for different mix gradations.

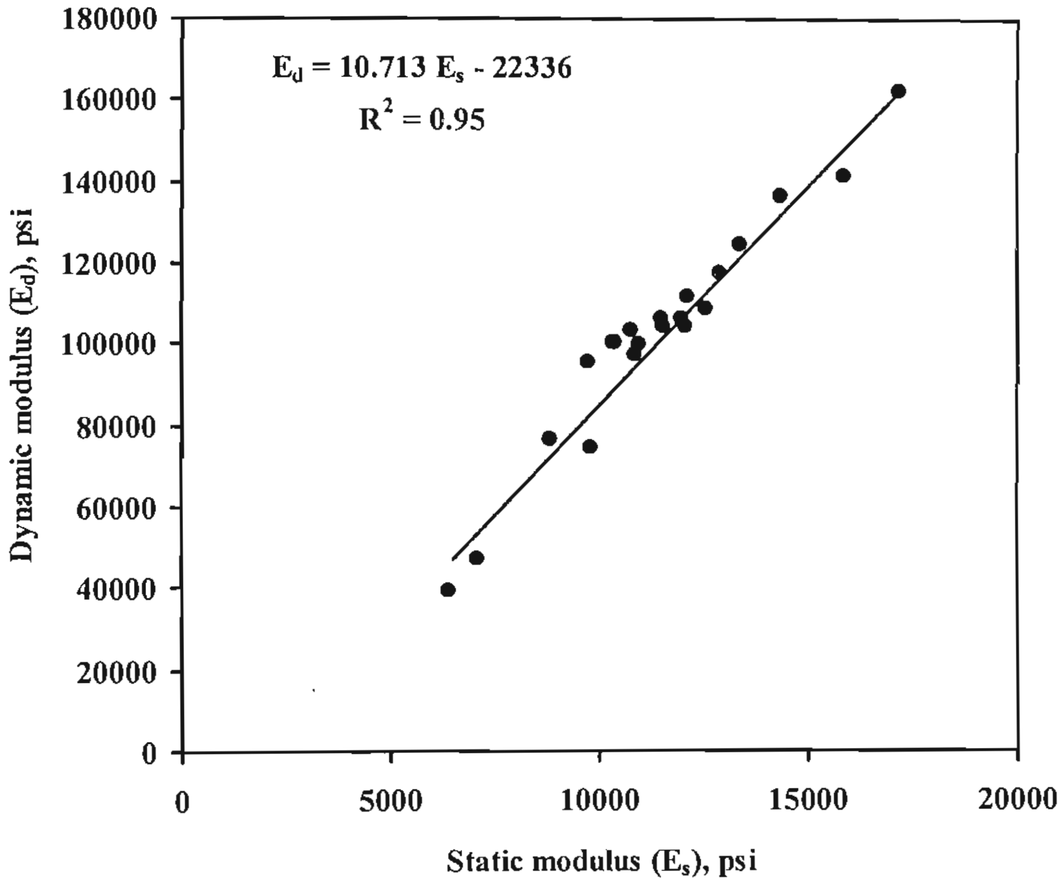

Figure (5): Relation between dynamic modulus (E_d) and static modulus (E_s).