J. King Saud Univ., Vol. 9, *Eng. Sci.* (1), pp. 1-12 (A.H. 1417/1997)

CIVIL ENGINEERING

A Model for Asphalt Concrete Modulus Prediction from Basic Mix Variables in Saudi Arabia

A. Al-Suhaibani*, E.Sharaf* and A.Al-Abdullatif**

**Civil Engineering Department, College of Engineering, King Saud University, Riyadh, Saudi Arabia;*
***Construction Department, Ministry of Communications, Riyadh, Saudi Arabia*

(Received 30 Oct. 1994; accepted for publication 13 Dec.1995)

Abstract. The asphalt concrete, being the upper layer in flexible pavement structures, is the most important layer as it largely controls the performance of flexible pavements. Therefore, characterization of bituminous mixes comprising asphalt concrete layers is essential in predicting pavement behavior under different loading and environment conditions. In this study, data on the basic characteristics of bituminous mixtures from 138 mixes was collected from the Ministry of Communications' (MOC) projects and research reports. The main objective of collecting this data was to select an appropriate model that can be used to predict the bituminous mix moduli from the basic mix characteristics. First, the data was used to investigate the prediction accuracy of several widely used models in order to select the most appropriate one for the Kingdom's conditions. The ability of all models to predict the modulus of local materials was found to be limited. Therefore, it was decided to develop a new model that suits the local conditions. Regression analysis, using the stepwise procedure was used to develop a model that showed a relatively high coefficient of determination (R^2=0.86). The variables selected by this analysis were: percent air voids, percent asphalt absorbed by weight, asphalt viscosity at 70°F, asphalt concrete temperature, percent asphalt by volume of mix, and percent aggregate passing sieve # 200.

Introduction

Background

Information on pavement materials is a major input to all analytical pavement design procedures. The knowledge of the basic properties and behavior of materials is essential for a proper understanding of the response of a pavement structure to various conditions, loading and environmental factors. The conventional flexible pavement consists of three to four layers of different materials. The asphalt concrete, being the upper layer, is the most important layer as it largely controls the performance of flexible pavement. Therefore, characterization of bituminous mixes comprising asphalt concrete layers is essential in predicting pavement behavior under different loading and environment conditions.

Bituminous materials are rheologic by nature, that is, their stress-strain relationships are both time and temperature dependent. Such a relationship is referred to as the stiffness of the mix, and at rapid rates of loading and low temperatures it approaches the elastic modulus. At long loading times and high temperatures the behavior of the bituminous mixes is viscous while it is visco-elastic at intermediate conditions. The majority of design methods idealize the pavement system and use multi-layer elastic analysis. Some methods take into account both temperature and time of loading, or vehicle speed, when determining the appropriate values of stiffness. Some methods use visco-elastic analysis and characterize the stress-strain response by means of a creep compliance. But even in these cases, the system is usually simplified and reduced to an equivalent elastic system [1-3].

The primary aim of pavement structural design is to determine the thickness of pavement layers necessary to withstand the traffic and environmental factors at a particular location. The stiffness of the material used for an asphalt layer is the most important factor in determining these thicknesses and applies to all performance criteria. For example, a high stiffness improves the load spreading ability of the asphalt layer and hence reduces the stress and strain on the underlying layers, including the subgrade, and also reduces the potential for fatigue cracking in the asphalt layer itself. However, too high a stiffness can result in durability problems and the possibility of thermal cracking in surface layers. The stiffness must therefore be determined under conditions which reasonably reproduce those expected in the field when the material forms part of the pavement structure [1,4-6].

Modulus or stiffness of bituminous mixes can either be measured in the laboratory or in the field or predicted from properties of mix components, namely; aggregate and bitumen. There are a number of well known mathematical models that were developed by various researchers and relate resilient modulus to bituminous mix properties. In the following paragraphs examples of these models are given.

Mix properties models

Vander der Poel [7] developed one of the first stiffness prediction models for asphalt concrete. It is one of the most commonly used models to predict the stiffness modulus of the bitumen as a function of the time of loading, the penetration index, and the temperature at which the bitumen penetration is 800 [8,9]. The nomograph predicts the stiffness modulus of the bitumen within a factor of 2 and is normally used in conjunction with the equation, developed by Heukelom and Klomp [10].

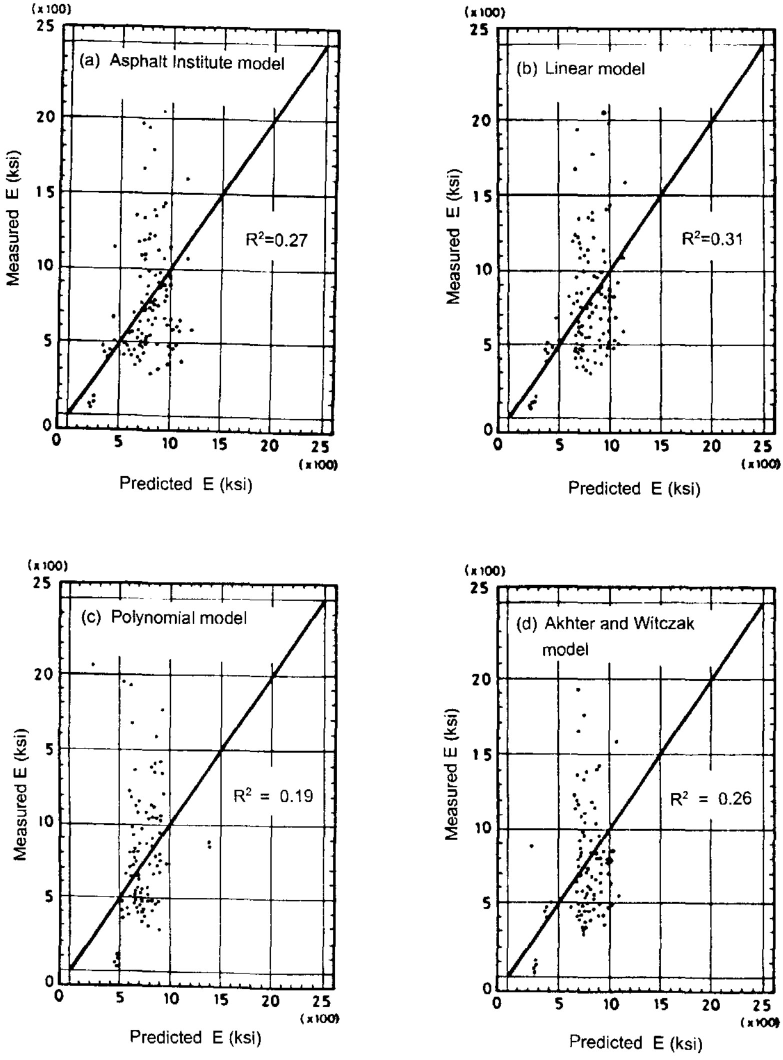

Fig. 1. Measured modulus versus predicted using different prediction models.

$$S_{mix} = S_{bit} [1 + \frac{2.5}{n} \frac{C_v}{1 - C_v}]^n \quad (1)$$

where,

S_{mix} = Stiffness modulus of the mix, N/m^2
S_{bit} = Stiffness modulus of the bitumen, N/m^2
n = $0.83 \log_{10} [4x10^{10}]/[S_{bit}]$
C'_v = Volume concentration of the aggregates

The above Heukelom relationship was developed from test results obtained for mixes having approximately 3 per cent air voids and C_v ranging from 0.7 to 0.9. Van Draat and Sommer [11, p 270] proposed the following correction of C_v for voids content in excess of 3 per cent.

$$C_v^{'} = \frac{100(C_v)}{100 - V_a + 3} \quad (2)$$

where,

V_a = air voids contents
C_v = volume concentration of aggregates
C_v = corrected value for volume concentration of aggregate

Bonnaure *et al* [12] have developed a nomograph for predicting mix stiffness. This nomograph has been incorporated into the Shell design procedure [13]. The nomograph relates the stiffness modulus of the mix to the stiffness modulus of the bitumen, the volume percentage of the aggregate, and the volume percentage of the bitumen. The stiffness modulus of the bitumen can be determined by laboratory testing or through application of Van der Poel's nomograph.

The Asphalt Institute has developed an equation for predicting the complex modulus of asphalt concrete mixes [14,15]. The equation has the following general form

$$|E^*| = f(P_{200}, f, V_v, V_{is}, TV_b) \quad (3)$$

where,

$|E^*|$ = absolute value of the complex modulus of the mix, psi
P_{200} = percent minus No. 200 sieve
f = frequency of loading, HZ
V_v = percent air voids
V_{is} = absolute viscosity of the bitumen measured at 700°F, 10^6 poises
T = temperature, °F
V_b = percent volume of bitumen

This relationship was developed by the Asphalt Institute from results of dynamic unconfined compression tests on a variety of mixes [15-18].

Akhter and Witczak [19] have developed three statistical equations to predict the complex modulus of asphalt concrete mixes. However, they recommended a model that has the following general form for its convenience in computation and resemblance to earlier models.

$$|E^*| = f(P_{3/4}, P_4, P_{200}, f, V_v, V_{is}, T, P_{eff}\, P_{abs}) \quad (4)$$

where,

$|E^*|$ = absolute value of the complex modulus of the mix, psi
$P_{3/4}$ = percent retained on size 3/4" sieve
P_4 = percent retained on No. 4 sieve
P_{200} = percent passing No. 200 sieve
f = frequency of loading, HZ
V_v = percent air voids
V_{is} = absolute viscosity of the bitumen measured at 70°Fm, 10^6 poises
T = temperature, °F
P_{ef} = effective asphalt content by volume
P_{abs} = percent asphalt absorbed by weight

Study Objective

The main objective of this research was to develop a model to predict bituminous mix moduli as afected by of the Kingdom's local material properties.

Study Methodology

The research was divided into three main parts:

1. Collection of data on local material characteristics.
2. Conducting a correlation analysis to test the reliability of well known predictive models to predict bituminous mix moduli in Saudi Arabia.
3. Development of an appropriate model to be used for SaudiArabian materials.

Data Collection

Ninety-one mixes from previous construction and maintenance projects were evaluated by the resilient modulus laboratory test. These tests were conducted by the Material and Research Department Laboratory, MOC. Another twenty-three mixes were obtained from research projects. These mixes were tested for resilient modulus at three different temperatures to obtain a total of forty-seven resilient modulus tests. The results from the two sources were combined to formulate 138 data points [20,21].

The bituminous mix variables that were extracted from the review reports for the purpose of studying the validation of existing models and to develop a new model, are:

- Asphalt content by volume
- Effective asphalt content by volume
- Percent asphalt absorbed by weight
- Percent air voids
- Viscosity at 70°F
- Percent passing the No. 200 sieve
- Percent retained on the No. 4 sieve
- Percent retained on the size of 3/8" sieve
- Percent retained on the size of 3/4" sieve
- Asphalt concrete temperature
- Asphalt concrete modulus

Since the data of the viscosity at 70°F is not available, the following relationship developed by the Asphalt Institute was used to obtain viscosity at 70°F.

$$Vis_{70^\circ F,10^8} = 29508.2\ P_{en77^\circ F}^{-2.1939} \quad (5)$$

where,

Vis = absolute viscosity at 70°F,.poises X10^6

P_{en} = asphalt cement penetration at 70°F

Testing Existing Models

There are several existing models that relate material and construction variables to mixture response, represented by mix modulus. Four of the most well known models are presented in Table 1. In these models, the original form of the complex modulus |F*| was measured using 4 inch diameter by 8 inch high cylinders loaded in compression.

In order to evaluate the goodness of these models for predicting the resilient modulus for the mixtures used in construction of highways in the Kingdom, the actual measured resilient modulus values of the 138 tests resulting from 114 mixes were subjected to a correlation analysis with the modulus values resulting from applying each of the four models presented in Table 1. The details of these correlation analyses can be found elsewhere [22].

Table 1 also shows the results of the correlation of actual and predicted resilient modulus. It is clear from this table that these models poorly relate local material and construction variables to asphalt concrete resilient modulus. This is also graphically depicted in Fig. 1. The reason of this poor correlation may be due to the fact that in its

Table 1. Modulus prediction models

No.	Model	Remarks	R^2	F
1.	$\log E = 5.553833 + 0.028829\ P_{200} \times f^{0.17033} - 0.03476\ Vv + 0.070377\ Vis + 0.00005\ T^{(11.3 + 0.49825 \log f)}\ P_{ac}^{0.05} - 0.0189\ T^{(1.3 + 0.49825 \log f)}$	Asphalt Institute model	0.27	52
2.	$\log E = 2.06171 - 0.0206194 \times P_{eff} - 0.01272698 \times V_v - 0.00187302 \times P_{200} + 0.0102445 \times P_{3/4}$ $0.00209684 \times P_{3/8} - 0.00489546 \times P_4 + 0.0131639 \times P_{abs} + 0.0552319 \times Vis - 0.0167950 \times T + 0.0180509 \times f$	typical long-linear model	0.31	60
3.	$\log E = 2.468 - 0.1155 \times P_{eff} - 0.299 \times V_v - 0.0975 \times P_{200} - 000963 \times P_4 + 0.359 \times P_{abs} - 0.00815\ T + 0.066 \times f - 0.0000618 \times T^2 + 0.00253 \times P_{eff}^2 + 0.0083 \times P_{200}^2 - 0.0064 \times P_{3/4}^2 + 0.000308 \times P_{3/8}^2 + 0.000204 \times P_4^2 - 0.105 \times P_{abs}^2 + 0.0171 \times Vis^2 - 0.00268 \times f^2 + 0.00167 \times P_{3/8} \times Peff + 0.000937 \times P_{3/4} \times P4 - 00069 \times P_{3/8} \times P_4 - 0.0031 \times P_{3/8} \times P_{abs}$	a typical polynomian model	0.19	32
4.	$\log E = 1.42841 - 0.0233473 \times V_v + 0.013004 \times P_{3/4} + 0.0627099 \times Vis\ 0.008145 \times T + 0.146970 \times \log f + 0.00001193776 \times \log f \times {}^2 - 0.000073466415 \times T^2 - 0.000138513 \times P_{eff} f \times P_4 + 0.00583715 \times P_{200} \times P_{abs}$	Akhter and Witczak model	0.26	48

Note: E = dynamic modulus, P_{200} = percent aggregate passing No. 200 sieve, f = loading frequency, Hz, H_v = percent air voids, Vis = asphalt viscosity at 70°F, 10^6 poises, P_{ac} = percent asphalt by weight of mix, T = temperature, °F, P_{eff} = effective asphalt content by volume, $P_{3/4}$ = percent retained on size 3/4" sieve, $P_{3/8}$ = percent retained on size 3/8" sieve, P_4 = retained on No.1 sieve, P_{abs} = percent asphalt absorbed by weight.

original form, the complex modulus (resilient modulus) was measured using 4 in. diameter by 8 in. high cylinders loaded in compression, while in current study, diametral specimen, 2.5 in. thick by 4 in. in diameter, loaded diametrically, were used to measure the resilient modulus. It was important, therefore, for this research to develop a model that relates the values of the resilient modulus of bituminous mixtures, as measured in the Kingdom to local material and construction variables.

Model Development

As demonstrated in the previous section the existing models failed to predict the asphalt concrete modulus using local material and construction variables. Therefore, a new statistical model was developed using the data obtained from resilient modulus test results. This data was extracted from the mix design review reports of MOC construction and maintenance projects and research reports [9,20], as indicated above.

A stastistical analysis, including analysis of variance (ANOVA) and regression analysis, was then performed to develop this model.

Table 2 shows the summary statistics of all potential predictor variables that were tested in the model development and their basic statistics. A stepwise regression analysis was implemented to select the best independent variables which give the highest correlation from all probable predictor variables.Ultimately, the following variables were found to be the most statistically significant predictor variables in the model.

- Percent air voids (V_V)
- Asphalt viscosity at 70°F, 10^6 poises (V_{is})
- Asphalt concrete temperature, °F(T)
- Percent asphalt by volume of mix (V_b)

P_{200} (% passing No. 200 sieve) and P_{abs} (% asphalt absorbed by weight) were forced into the model since they are included in most existing models and in order to include variables that describe the aggregate component in the bituminous mix.

Table 2. Summary statistics

No.	Variable type	Range		Mean	Standard deviation
1.	V_b	6.940	13.800	10.103	1.461
2.	P_{eff}	5.33	12.020	8.551	1.599
3.	P_{abs}	0.030	1.830	1.599	0.329
4.	V_{is}	2.410	5.070	3.656	0.065
5.	V_v	1.200	8.650	4.659	1.354
6.	$P_{3/4}$	0.000	18.800	4.048	5.643
7.	$P_{3/8}$	3.300	32.500	13.162	5.771
8.	P_4	8.800	32.100	17.604	4.565
9.	P_{200}	2.900	10.800	5.763	1.081
10.	T	77	158	86.193	23.632

The general form of this model is:

$$\text{Log}\, E = 3.997294 + 0.031315 V_v - 0.064916\, P_{abs} + 0.086956\, VL_{is} - 0.015052 T - 0.038603 V_b + 0.003179\, P_{200} \qquad [R^2 = 86\%] \qquad (6)$$

The graph of the measured resilient modulus versus predicted values by this regression equation is presented in Fig. 2.

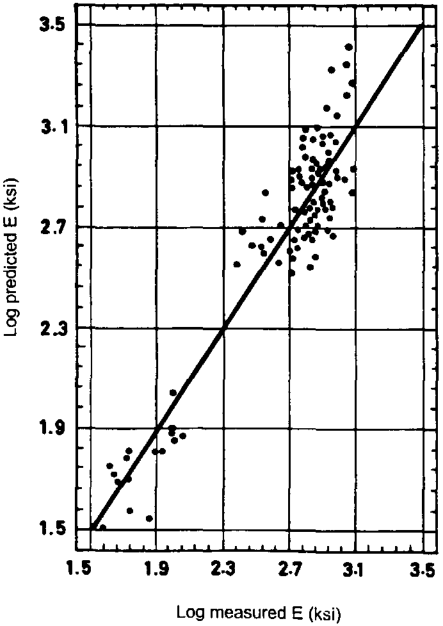

Fig. 2. Predicted vs. measured modulus for new model.

Table 3 shows the regression and analysis of variance (ANOVA) outputs associated with the above mentioned model. The t-test for parameters estimates and the overall F-test for the model shown in the table show a statistical significance of each of these parameters and the model except for the two parameters P_{200} and P_{abs} as mentioned previously.

Table 3. Analysis of variance for the full regression

Source	Sum of squares	DF	Mean square	F-Ratio	P-Value
Model	17.37895	6	2.89642	131.08	.0000
Error	2.71917	123	0.02331		
Total (corr.)	20.0977	129			

R-squared = 0.864702; Stnd. error of est. = 0.148684; R-squared (adj. for d.f.) = 0.8581;
Durbin-Watson statistic = 1.54926

Independent variable	coefficient	std. error	t-value	sig. level
Constant	3.997294	0.162595	24.5844	0.0000
Vv	0.031315	0.011906	2.6301	0.0096
P_{abs}	-0.064916	0.043653	-1.4871	0.1395
V_{is}	0.086956	0.021047	4.1315	0.0001
T	-0.015052	0.000585	-25.7171	0.0000
V_b	-0.038603	0.010222	-3.7765	0.0002
P_{200}	0.003179	0.01264	0.2515	0.8019

R-SQ. (Adj.) = 0.8581; SE = 0.148684; MAE = 0.120702; Durb Wat = 1.549
1130 observations fitted, forecast(s) computed for 8 missing value of dependent variable.

Conclusions

1. Predicted resilient modulus using existing models and local mix and environmental variables did not correlate well with those measured. This poor correlation, however, could be attributed to differences in specimen size as well as testing methods used in developing these models and those used to obtain presented data.
2. Asphalt concrete modulus tend to be tedious to evaluate, require expensive, and time-consuming test. The model that was developed in this study to predict asphalt concrete modulus provide a procedure for predicting asphalt concrete modulus from routine physical mix properties that are used as quality control and acceptance variables, so these variables serve as low-cost, rapidly performed surrogates for the asphalt concrete modulus.
3. It was found that the most significant variables affecting the asphalt concrete modulus are the temperature of the mix asphalt viscosity, asphalt content, air voids, and percent asphalt absorbed.

References

[1] Pell, P.S. Keynote Address-Pavement Materials. *6th International Conference on the Structural Design of Asphalt Pavements.* The University of Mich., Vol. 2, 1987, p. 36-70.

[2] *Structural Design of Asphalt Concrete Pavement Systems.* Highway Research Board Special Report 126, Washington, D.C., 1971, pp. 21-24.

[3] Bolk, H.J.N.A. *The Creep Test.* Study Center for Road Construction, Arnhem, The Netherlands, S.C.W. *Record 5*, Feb. 1981.

[4] Kennedy, T.W., Adedimila, A.S., and Hass, R.C.G. "Material Characterization for Asphalt Pavement Structural Design." *4th International Conference on the Structural Design of Asphalt Pavements, Proc.*, Vol. 2, The University of Michigan, 1977, pp. 346-353.

[5] Monismith, C.L., Epps, J.A., and Finn, F.V. *Improved Asphalt Mix Design. Association of Asphalt Pavement Technologist, Proc.* Vol. 54, 1985, pp. 347-406.

[6] Hugo, F.; Straus, P.J., Marias,G.P., and Kennedy, T.W. "Four Asphalt Pavement Case Studies Using a Mechanistic Approach". *5th International Conference on the Structural Design of Asphalt Pavements, Proc.* Vol. 1, The Delft University of Technology, The Netherlands, 1982, pp. 275-284.

[7] Van der Poel, C. *A General System Describing the Visco-Elastic Properties of Bituminous and Its Relation to Routine Test Data.* Shell Bitumine Reprint No. 9, Shell Laboratorium-Koninklijike, 1954.

[8] Yoder, E.S. and Witczak, N.W. *Principles of Pavement Design.* 2nd ed., John Wiley & Sons, Inc., 1975.

[9] Anderson, D.A., Luhr, D.R., and Antle, C.E. *Framework for Development of Performance-Related Specifications for Hot-Mix Asphaltic Concrete.* NCHRP Report 332, Dec. 1990.

[10] Heukelom, W. and Klomp, A.J.G. *Road Design and Dynamic Loading.* Association of Asphalt Paving Technologists, *Proc.* Vol. 33, 1964, pp. 92-123.

[11] Yoder, E.J. and Witczak, M.W. *Principles of Pavement Design.* John Wiley and Sons, Inc. 2nd ed. 1975, pp. 270.

[12] Bonnaure, F., Gest G., Gravois, A., and Uge, P. *A New Method of Predicting the Stiffness of Asphalt Paving Mixtures.* Association of Asphalt Paving Technologists, *Proc.* Vol. 46, 1977, pp. 64-104.

[13] Claessen, A.I.M., Edwards, J.M., Sommer, P., and Uge, P. *Asphalt Pavement Design. The Shell Method. 4th International Conference on Structural Design of Asphalt Pavements, Proc.* Vol.1, The University of Michigan, 1977, pp. 39-74.

[14] Shook, J.F., Finn,F.N., Witczak, M.W., and Monismith, C.L. "Thickness Design of Asphalt Pavements - The Asphalt Institute Method." *5th International Conference on the Structural Design of Asphalt Pavements, Proc.* Vol. 1, The Delft University of Technology, The Netherlands, 1982, pp. 17-44.

[15] The Asphalt Institute. Research and Development of the Asphalt Institute's Thickness Design Manual (MS-1). *Research Report* No.82-2, 9th edn., 1981.

[16] Shook, J.R. and Kallas, B.F. "Factors Influencing Dynamic Modulus of Asphalt Concrete". *Association of Asphalt Paving Technologists Proc.* Vol. 38, 1969, pp. 140-178.

[17] Miller, J.S., Uzan, J., and Witczak, M.W. "Modification of the Asphalt Institute Bituminous Mix Modulus Predictive Equation." *Transporatation Research Record* 911, Transportation Research Board, Washington, D.C., 1983, pp.35-52.

[18] Quintus, H.L., Rauhut, J.B., and Kennedy, T.W. "Comparisons of Asphalt Concrete Stiffness as Measured by Various Testing Techniques." *Association of Asphalt Paving Technologists Proc.*, Vol. 51, 1982, pp. 35-52.

[19] Akhter, G.F. and Witczak, M.W. *Sensitivity of Flexible Pavement Performance to Bituminous Mix Properties.* Transportation Research Record 1034, Transportation Research Board, Washington, D.C., 1985, pp. 70-79.

[20] Ministry of Communications. *Dhahran Abqiaq Test Road.* Final Report submitted to MOC by Ahmed Al-Rashed Al-Humaid, Consulting Engineers, 1990.

[21] Ministry of Communications. *Construction,Technical, Mix Design, Hand-Over and Investigation Reports.* MOC, Kingdom of Saudi Arabia.

[22] Al-Abdullatif, A.O. "Analysis of the Effect of Construction and Operation Control on Highway Flexible Pavement Performance." *Master Thesis*, College of Engineering, King Saud University, 1992.

نموذج للتنبؤ بمعامل الخرسانة الزفتية اعتمادا على متغيرات الخلطة الأساسية في المملكة

عبدالرحمن السحيباني، عصام شرف وأحمد عبداللطيف*
قسم الهندسة المدنية، كلية الهندسة، جامعة الملك سعود، ص.ب ٨٠٠، الرياض ١١٤٢١
و إدارة إنشاء الطرق، وزارة المواصلات؛ المملكة العربية السعودية*
(استُلم في ٣٠/ ١٠/ ١٩٩٤م؛ قبل للنشر في ١٣/ ١٢/ ١٩٩٥م)

ملخص البحث. الهدف الرئيس من هذه الدراسة هو تطوير نموذج إحصائي مناسب يمكن استخدامه للتنبؤ بمعامل الرجوعية للخلطات الزفتية اعتمادا على خواصها الأساسية. وقد جمعت البيانات اللازمة ذات العلاقة بخواص ١٣٨ خلطة زفتية من تقارير الأبحاث والإنشاء والصيانة المتوافرة لدى وزارة المواصلات. في البداية استخدمت هذه البيانات لمعرفة مدى صلاحية عدد من النماذج المعروفة عالميا لظروف المملكة. وقد وجد أن المقدرة التنبؤية لهذه النماذج ضعيفة جدا. تلى ذلك عمل تحليل انحداري باستخدام طريقة التدرج في اختيار المتغيرات حيث نتج عن هذا نموذج إحصائي ذو قدرة تنبؤية مقدارها ٨٦٪. وقد كانت المتغيرات المستقلة الداخلة في النموذج هي: النسبة المئوية للفراغات والنسبة المئوية لوزن الزفت الممتص ولزوجة الزفت عند درجة حرارة ٧٠ درجة فهرنهيت ودرجة حرارة الخرسانة الزفتية (في الموقع) والنسبة المئوية لحجم الزفت في الخلطة والنسبة المئوية للمواد الناعمة المارة من منخل رقم ٢٠٠.