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Modeling Marshall test results for optimum asphalt-concrete mix design

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ABSTRACT

This paper presents the results of a research investigation that was conducted using standard Marshall test results of asphalt-concrete (AC) mixes. The Marshall Mix design is the standard produre used in Kuwait to design AC paving mixes. All of the tested mixes were prepared for pavement construction in Kuwait. Two hundred and forty - four actual Marshall test results (from the Ministry of Public Works) were compiled and processed to build a model relating the optimum asphalt cement (binder) content to the particle size-gradation of the aggregate blend in an AC mix. The idea is based on the fact that the function of binder in an AC mix is to coat the surfaces of the aggregate particles and fill the voids between them. Both the specific surface area (surface area per unit weight of the aggregate blend) and the voids between aggregate particles are dependent upon the particle size-gradation of the aggregate blend. Multivariate regression models were developed relating the optimum binder content from the Marshall procedure of mix design and the particle size-gradation of the aggregate blend in an AC mix. This paper reviews the Marshall method of mix design and types of AC mixes used in Kuwait. Then it discusses the effect of aggregate size gradation on optimum binder content. The paper presents the results of developing regression models relating the aggregate gradation to the optimum binder content.

INTRODUCTION

The Marshall method of asphalt-concrete (AC) mix design is a well-established standardized method (AI 1988, AASHTO 1990, BS 1990, ASTM 1991) that is used by highway agencies in many parts of the world, including Kuwait (MPW 1987a) to design AC mixes for highway construction. The new Superpave Mix design technology is not expected to replace the standard Marshall procedure in Kuwait in the near future.

The standard method of Marshall mix design requires the preparation and testing of at least 15 specimens of AC mixes. The mixes are prepared by mixing different amounts of asphalt cement with an approved aggregate blend. The specimens are then tested in the Marshall testing machine and the results are represented graphically. From the graphs, an *optimum* binder content is determined and the corresponding properties of the optimum mix are checked against specifications. As noted, the Marshall method of mix design starts with a known particle size-gradation of an aggregate blend. The total surface area of an aggregate blend is directly related to its particle size-distribution. In fact, the total surface area can be estimated using the sieve analysis results of an aggregate blend (Roberts *et al.* 1991).

The finished (hardened) AC mix develops its strength (compressive, tensile, and shear) mainly from aggregate interlock and the cohesive effect of the binder. Therefore, the optimum binder content required for an AC mix is related to that which would be just sufficient to coat all surface areas of the aggregate particles plus an amount necessary to partially fill the voids in the aggregate matrix (such voids are named 'voids in the mineral aggregate', VMA) leaving an appropriate unfilled volume of air voids. Both the surface area and VMA of an aggregate blend are dependent upon its particle size distribution.

In this research, actual Marshall test results were used to develop a model that would estimate the optimum binder content for a given aggregate gradation.

Two hundred and forty-four actual Marshall test results (from the Ministry of Public Works, MPW) were used to establish the proposed model. The results are from Marshall tests performed to design actual AC mixes used to build pavements in Kuwait. Obviously, all aggregates used in such tests satisfy the quality, durability, chemical composition, and other requirements stipulated by the MPW specifications (MPW 1987b). Further, because of property similarities of the aggregates used in Kuwait, different absorption levels are not analysed here.

OBJECTIVES

The overall objective of the study was to develop a regression model that can be used to predict the optimum amount of asphalt cement required for an asphalt concerete mix given the particle size-gradation of its aggregate blend.

More specifically the objectives of the study were to:

1 - Test the effect of size-gradation of aggregate blends on the optimum binder content in a mix design.

2 - Calibrate and evaluate a regression model for the prediction of optimum binder content in a mix design, based on particle size-gradation.

3 - Test the effect of asphalt-concrete mix type on the developed model.

THE MARSHALL METHOD OF MIX DESIGN

The Marshall method is a widely-used laboratory procedure for the determination of the optimum amount of asphalt cement (termed optimum binder content, OBC) required to be mixed with a given aggregate blend to produce an asphalt-concrete mix the properties of which conform to certain

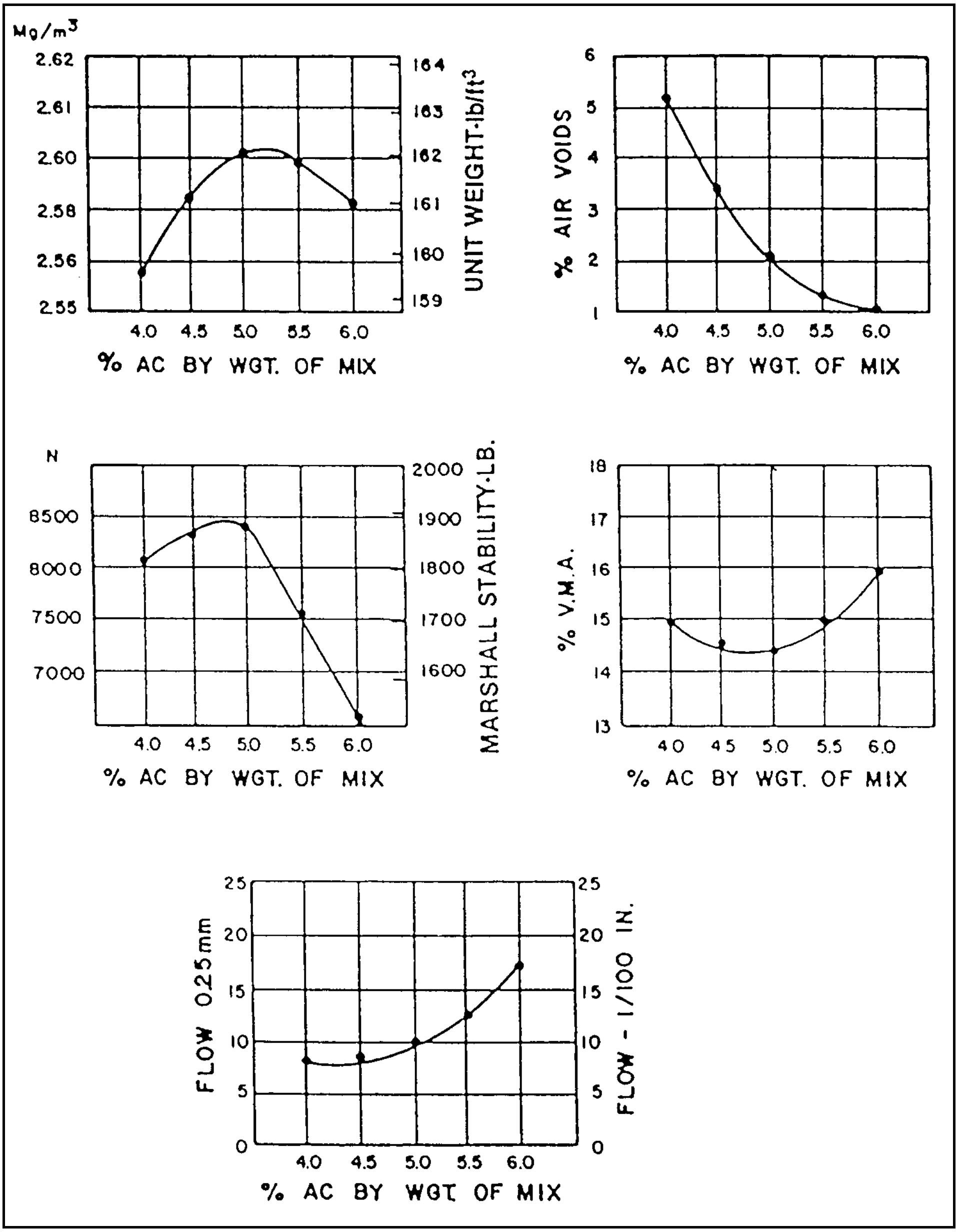

Fig. 1. Typical Marshall Test Results (AI 1988).

specifications regarding such values as stability, flow, air voids, VMA, and density. The procedure is described in detail in the Asphalt Institute's Manual Series No. 2 (AI 1988).

The method is time and effort consuming and requires skilled labor for specimen preparation, testing, and analysis of results. Usually, 15 specimens are prepared and tested to develop relationships of the aforementioned five Marshall parameters with the amount of added binder. An example showing such relationships is shown in Fig. 1. From these relationships, the OBC is determined as being the avergae of the asphalt cement content values corresponding to maximum density, maximum stability, and given air voids.

Results of Marshall mixes were obtained from the Ministry of Public Works. These results represent the asphalt-concrete mixes used in Kuwait (as described in the following section) and are used for the analysis described in this paper.

ASPHALT - CONCRETE MIXES USED IN KUWAIT

Roads in Kuwait are classified by the Kuwait Municipality into four main categories: Special Road Network (SRN), Primary Road Network (PRN), Secondary Roads (SR), and Local Roads (LR) (Kuwait Municipality *et al.* 1988). The Ministry of Public Works (MPW) further classifies the roads in Kuwait into sub-categories according to specific functions (industrial/ residential, divided/undivided). These sub-categories are shown in Table 1. The materials used for different layers (Type I, Type II, Type III, and PMS) are

Table 1: Typical pavement layer thickness for different road classes in Kuwait

Functional		**Layer thickness (cm)**				**Design**
Class	**Description**	**Type I**	**Type II**	**Type III**	**PMS[a]**	**ESAL**
SPN	Freeways	10	8	0	2	1×10^9
SPR1	Border Roads	10	6	0	2	6×10^8
PRN2	Urban Arterials	10	6	0	0	6×10^8
SR 1	Commercial - Divided	10	6	0	0	6×10^8
SR2	Residential - Divided	10	0	4	0	3×10^8
SR3	Residential - Undivided	8	0	5	0	3×10^8
LR1	Residential Driveways	8	0	4	0	1×10^8
SR4	Industrial - Divided	10	6	0	0	6×10^8
SR5	Industrial - Undivided	10	4	0	0	3×10^8
LR2	Industrial Driveways	8	4	0	0	1×10^8

* PMS: Plant Mix Seal: a waring course (MPW 87).

according to MPW standards (MPW 1987a) that specify their required properties (such as aggregate gradation, grade of asphalt cement, Marshall values, etc).

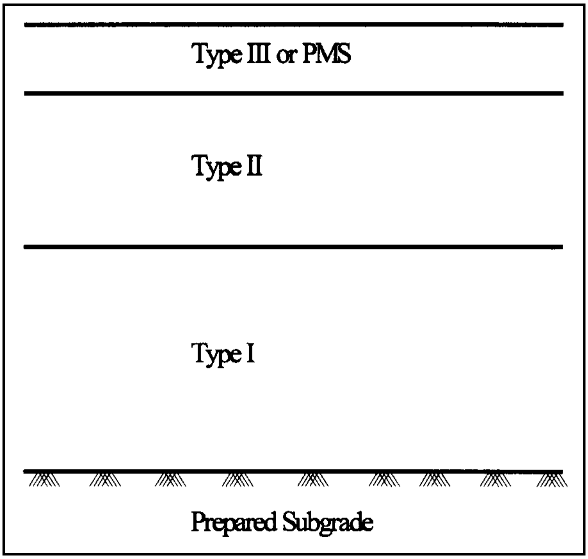

Fig. 2. A Typical Pavement Section in Kuwait.

Figure 2. shows a typical pavement section used in Kuwait. the subgrade material is selected to meet certain standards concerning density and strengh (CBR). Typical thickness of different layers are shown in Table 1, based on the class of the road for which the pavement is constructed. Structural (thickness) design is performed using the Kuwait Design Manual (MPW 1987b). The AC mixes used for the different layers are those considered in this study.

EFFECT OF PARTICLE SIZE GRADATION ON OPTIMUM BINDER CONTENT

The objectives of the Marshall method of mix design is to determine (among other parameters) the optimum amount of asphalt cement to be added to an aggregate blend. The objective of asphalt cement in asphalt-concrete mixes is to bind (glue) the aggregate particles together. Therefore, the effective binder content is the portion that coats the particle surfaces. Since smaller particles have greater specific surface area (surface area per unit weight of aggregate blend), finer aggregate blends require higher bitumen contents. Therefore, the optimum binder content of blend 1 in Fig. 3 would be greater than that of blend 2, when designed for the same level of traffic and mix design parameters in a typical dense-graded mix.

Aggregate particle-size gradations may be used to estimate the total surface area per unit mass of an aggregate blend. Table 2 may be used to estimate the specific surface area of an aggregate blend by multiplying the factor by the cumulative percentage passing for each sieve size and totaling for all sieve sizes. The units of such calculations would be square meters per kilogram.

The factors in Table 2 show that smaller particles make a substantially

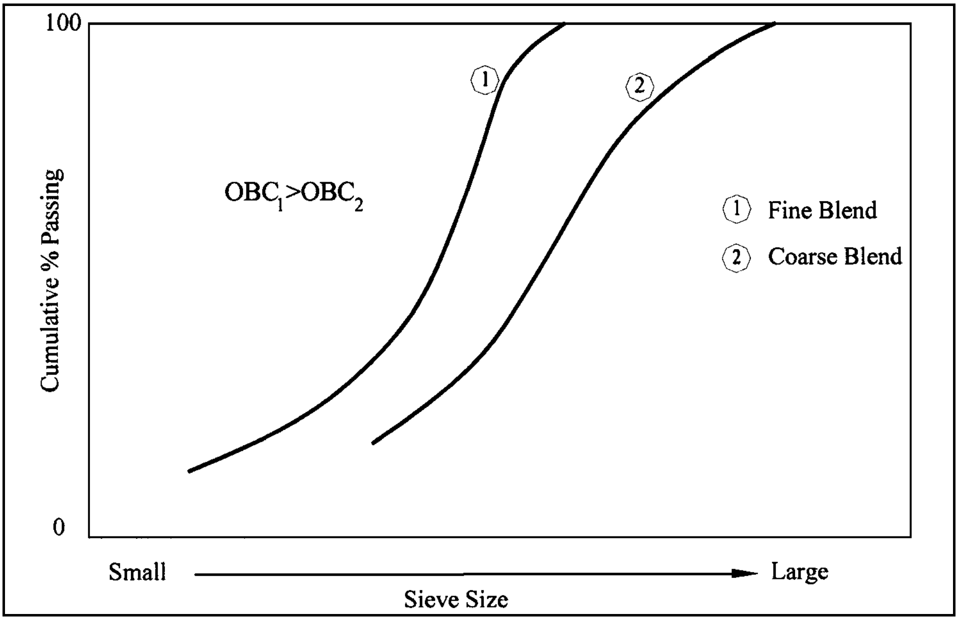

Fig. 3. Size Gradation of Two Aggregate Blends.

Table 2: Factors for Calculating Total Surface Area of an Aggregate Blend (Roberts ***et al.*** **1991).**

Sieve Size (mm)	Surface Area Factor
Maximum sieve size	0.41
4.75 (#4)	0.41
2.36 (#8)	0.82
1.18 (#16)	1.64
0.600 (#30)	2.87
0.300 (#50)	6.14
0.150 (#100)	12.29
0.075 (#200)	32.77

greater contribution to the total surface area of an aggregate blend than coarser particles. Consequently, they increase the demand for binder more than the larger particles (Fig. 3).

MODEL DEVELOPMENT

The proposed relationship between aggregate gradation and their associated optimum binder content (OBC) was tested using the parameters of 244 Marshall mix designs. They represent different asphalt-concrete mixes used in Kuwait, as described previously in this paper.

The gradation-OBC relationship is calibrated using multivariate linear regression analysis with OBC as the dependent variable and the cumulative percent passing each sieve size as the independent variables. The model has the form.

$$\mathrm{OBC} = a_o + \sum_{i=l}^{n} a_i P_i \tag{1}$$

Where,

OBC = optimum binder content;

a_o = regression constants (Table 4);

a_i = regression coeffincients (Table 4);

P_i = cumulative percent passing sieve i;

n = number of sieves is the gradation table.

The model of Equation 1 was calibrated for each mix using the available data of different mix designs for the five asphalt-concrete mix types used in Kuwait; namely, Type 1, Type II, Type III, Type IV, and PMS. The range of the

Table 3: Range of Cumulative Percent Passing

Sieve Size	**Type I**	**Type II**	**Type III**	**Type IV**	**Combined for Types I, II, III & IV**	**PMS**
1 1/2″	99-100	-	-	-	99-100	-
1″	85-99	100	100	-	85-100	-
3/4″	67-90	95-100	98-100	-	67-100	-
1/2″	54-69	70-86	86-89	100	54-100	100
3/8″	49-64	63-81	80-84	97-100	49-100	97-99
No.4	38-48	39-60	49-66	63-70	38-70	34-43
No.8	30-36	30-44	37-45	43-48	30-48	10-13
No. 16	21-31	25-35	30-36	-	21-36	-
No.30	16-24	20-24	22-27	21-29	16-29	-
No.50	9-14	11-14	12-17	13-18	9-18	-
No.100	5-9	6-9	7-10	8-12	5-12	-
No.200	4-6.1	4-6.3	4.3-7	5.4-8	4-8	3.9-4.4

cumulative percent passing for each sieve in different mix types is shown in Table 3. The regression analysis results are shown is Table 4. A combined model for mix types I, II, III, and IV was also calibrated as shown in the same table.

The R^2 values in Table 4 show that there is a strong relationship between the aggregate gradation and the required binder content to make an optimum asphalt-concrete Marshall mix. This was expected since the amount of binder depends on the total surface area of the aggregate particles which has a relationship with its size gradation as shown in Table 2.

The models of Table 4 represent the relationship between the optimum binder

Table 4: Range of Cumulative Percent Passing

Sieve Size	Type I	Type II	Type III	Type IV	Combined for Types I, II, III & IV	PMS
1 1/2″	-6.613	4.115	45.869	7.209	-5.8E-02	-0.836
1″	7.278E-02	-	-	-	-	-
3/4″	-	-3.355E-02	-41.2E-02	-	0.504 E-02	-
1/2″	2.393 E-02	2.367 E-02	-9.776E02	-	3.779E-02	-
3/8″	-4.9 E-02	-0.670E-02	10.8E-02	-1.00E-02	-3.166E-02	5.371E-02
No.4	1.67E-02	3.097E-02	3.9E-02	-0.509E-02	4.584E-02	2.717E-02
No.8	11.3E-02	-0.93E-02	-8.27E-02	-	-1.274E-02	35.1E-02
No. 16	-5.463E-02	-1.5E-02	5.714E-02	-	-0.88E-02	-
No.30	-3.05E-02	7.245E-02	-10.6E-02	-0.215E-02	2.834E-02	-
No.50	-6.y51E-02	-5.2E-02	14.8E-02	-1.558E-02	-2.4E-02	-
No.100	-11.5E-02	1.118E-02	-17.9E-02	1.203E02	1.008E-02	-
No.200	28.9E-02	9.598E-02	13.1E-02	-3.45E-02	9.599E-02	-95.7E-02
R^2	0.939	0.745	0.873	1.000	0.912	0.997
Observed range of OBC	0.8 (3.5-4.3)	1.0 (4.0-5.0)	0.7 (4.3-5.0)	0.1 (5.4-5.5)	2.0 (3.5-5.5)	1.0 (5.0-6.0)
F	82.67	17.493	45.927	3.2×10^{16}	196.6	781.9
df	11	10	10	6	11	4
P	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Standard Error(SE)	0.058	0.115	0.084	0.000	0.1387	0.0248
Sample Size (N)	71	71	78	41	244	15

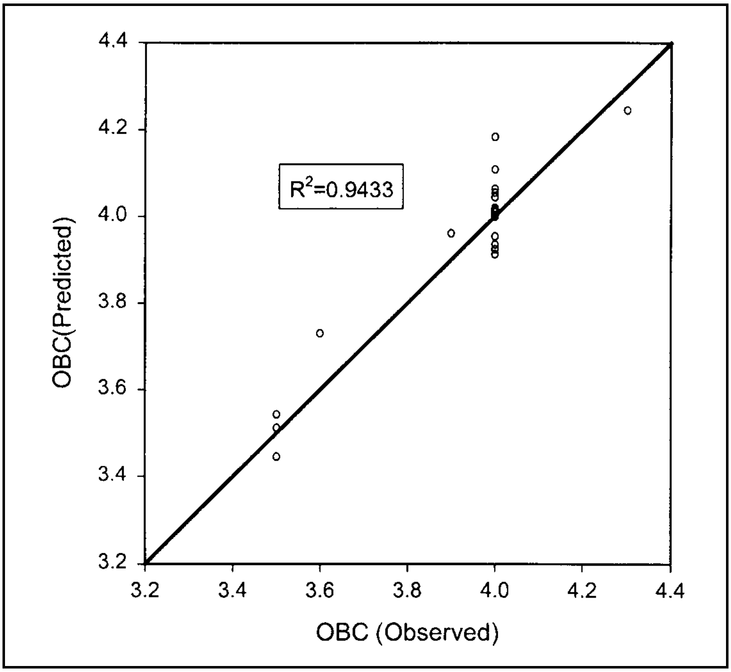

Fig. 4. The Correlation of Predicted to Observed OBC for Asphalt-Concrete Type I.

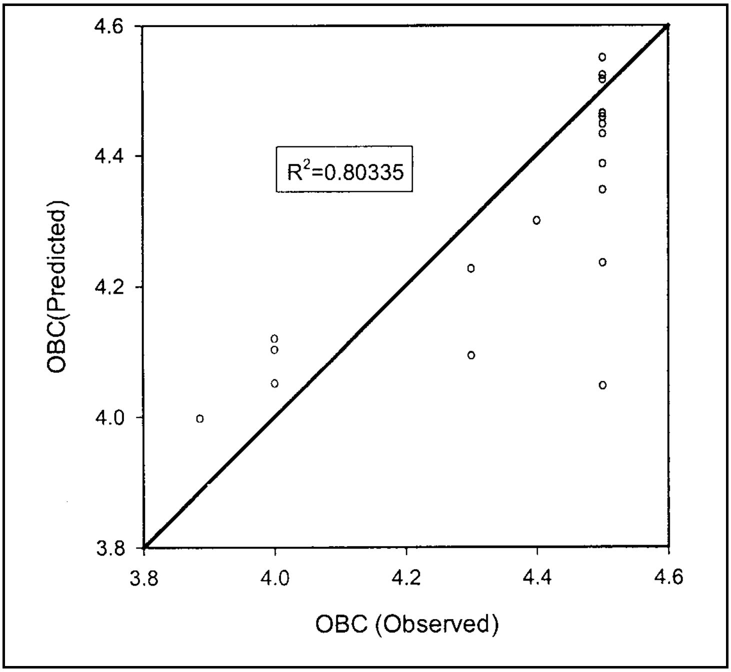

Fig. 5. The Correlation of Predicted to Observed OBC for Asphalt-Concrete Type II.

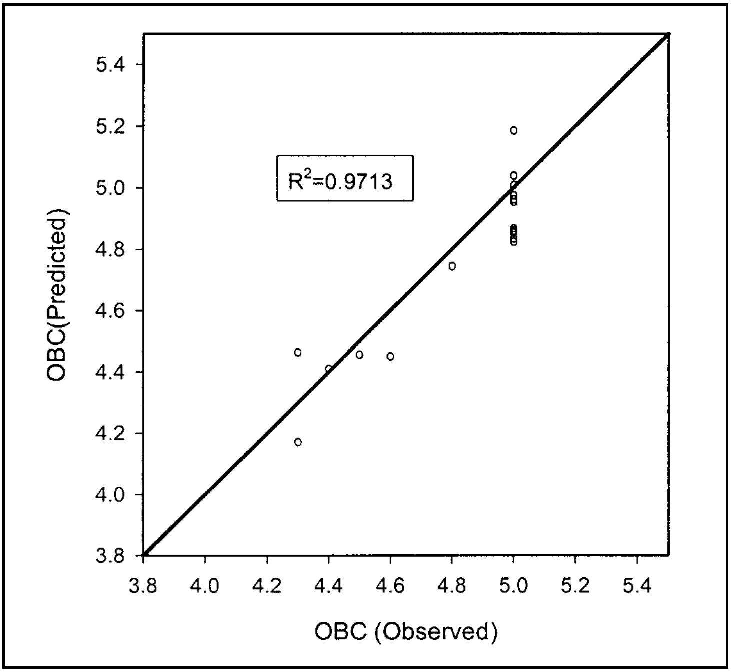

Fig. 6. The Correlation of Predicted to Observed OBC for Asphalt-Concrete Type III.

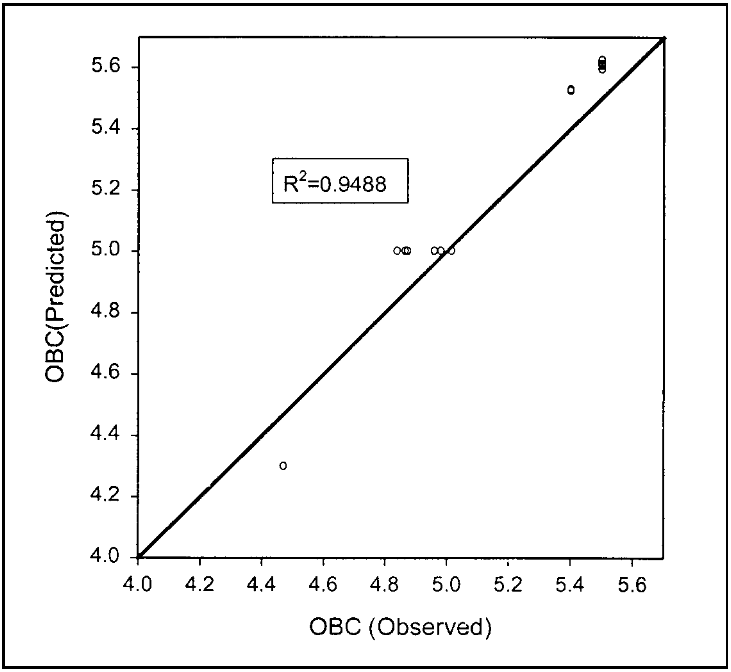

Fig. 7. The Correlation of Predicted to Observed OBC for Asphalt-Concrete Type IV.

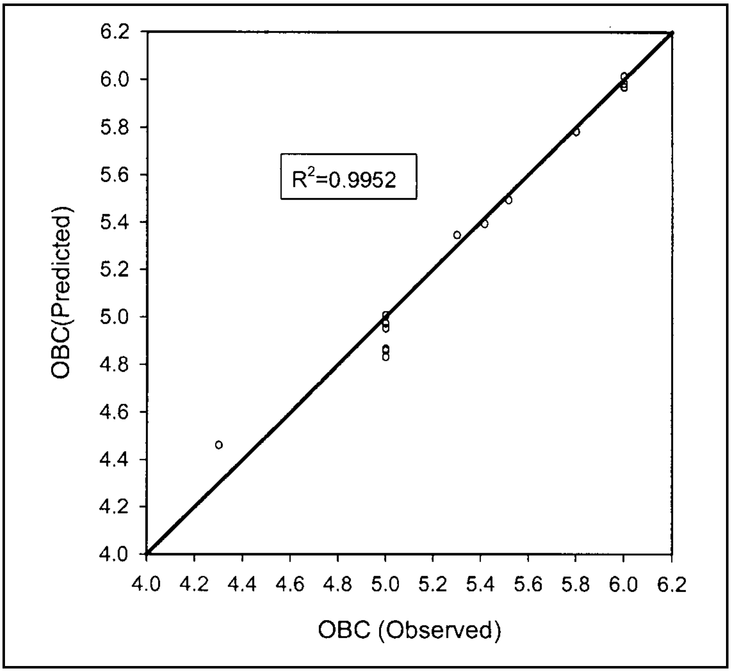

Fig. 8. The Correlation of Predicted to Observed OBC for Asphalt-Concrete Type PMS.

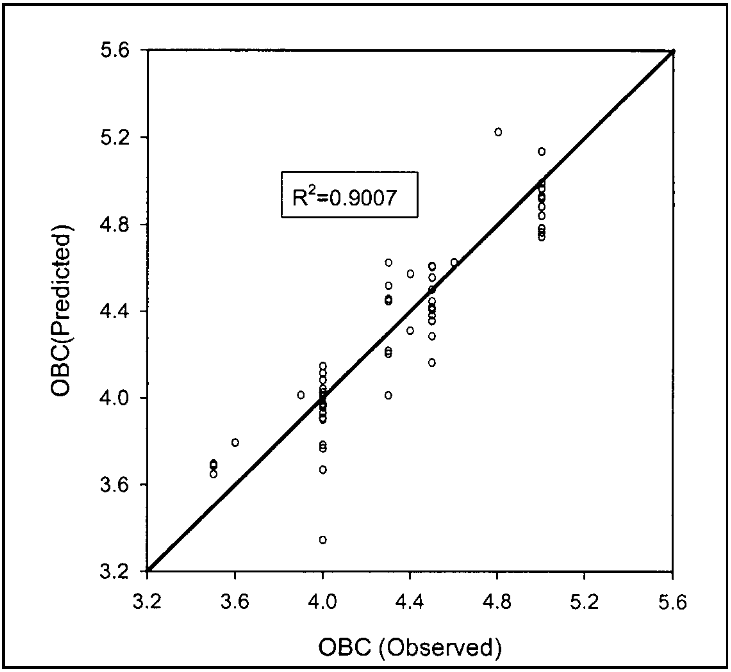

Fig. 9. The Correlation of Predicted to Observed OBC for Asphalt-Concrete Type I, II, III, and IV.

content and the cumulative percent passing each sieve size. The estimated OBC may be calculated by multiplying the cumulative percent passing each sieve size by the corresponding coefficient and totaling for all sieves plus the constant.

MODEL EVALUATION AND VALIDATION

The models of Table 4 were used to estimate the OBC using the available Marshall mix results for the tested mix types. Equation 1 was applied on each aggregate blend to predict the OBC. Each predicted OBC value was plotted against its corresponding observed OBC. The correlations of predicted and observed OBC are shown graphically in Figs. 4 to 9. R^2-values on the graphs of Figs. 4 to 9 represent the goodness of fit of the equality line (45°-line) with respect to the plotted points. The figures show that the models were successful in predicting the actual OBC values with an R^2-value of more than 90%, except for mix type II (Fig. 5) which shows more variability than the other mixes with an R^2-values of 80%. This may be attributed to variability in the Marshall results which were used to develop the regresion model.

Additional Marshall mix results were obtained from a different agency (Military Engineering Projects, Ministry of Defense) which uses the same MPW mixes and specifications. These results represent mixes of Types I, II, III, and IV and therefore, they were used to validate the combined model of Table 4 (the

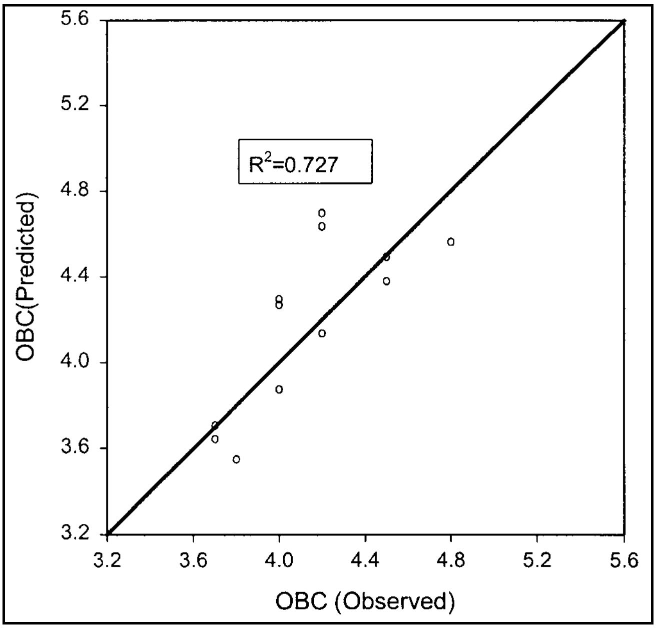

Fig. 10. The Results of Model Validation for Combined Asphalt-Concrete Mix Types I, II, III, and IV.

individual models were not tested by these results due to their limited number). The results of applying the developed model to such mixes are shown in Fig. 10, which indicated that the developed model was successful in predicting the actual OBC values with an overall R^2-value of 0.73.

CONCLUSIONS

This paper presents the results of a study attempting to determine the relationship between the particle size-gradation and the optimum binder content in a Marshall asphalt-concrete mix. The analysis was based on Marshall results of 244 mixes, all of which conform to the Ministry of Public Works' specifications. Multivariate linear regression analysis was used to calibrate the model shown in Equation 1.

The analysis of results showed a high correlation between the OBC and the particle size distribution. The cumulative percent passing values were used to describe the particle size distribution. A separate model was calibrated for each of the asphalt-concrete mixes: Type I, Type II, Type III, Type IV, and PMS. A combined (aggregated) model was developed for mix types I, II, III and IV due to the similarity of sieve sizes used to describe their aggregateblends' size gradations and because OBC in the developed models is dependent upon the cumulative percent passing.

The developed models of Table 4 were evaluated using the same data from which they were developed and the calculated (predicted) OBC showed high correlations with actual (observed) OBC for all models.

Additional data were used to validate the aggregated model for mix type I, II, III, and IV. This resulted in a correlation between the predicted and observed OBC with an R^2 of 0.73. The individual models were not tested by this data due to its small size.

The developed models can be used to estimate the required OBC for a given aggregate blend. Using this calculated OBC, three identical specimens of a Marshall mix may be prepared, tested, and checked for compliance to specifications for air voids, stability, density, flow, and VMA. This results in major time and effort savings of laboratory work.

Additional results of other mixes are needed to further validate the use of the developed models. This can be accomplished by calculating OBC value using the models of Table 4, and comparing the results with the actual OBC values obtained by conducting a conventional Marshall test.

Similar analysis can be performed on any asphalt-concrete mix design results (such as those of Superpave mixes); but this remains to be determined. However, high correlations are always expected because of the high dependency of OBC on the particle size distribution of the used aggregate blend, which is described. by the cumulative percent passing of the sieve analysis results.

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نمذجة نتائج اختبار مارشال لتصميم الخلطة الإسفلتية المثالية

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خلاصة

تعرض هذه الورقة نتائج بحث أجري على خواص خلطات إسفلتية صممت تبعاً لنظام مارشال لاستخدامها في عمليات رصف الطرق في الكويت. وطريقة مارشال في تصميم الخلطات الإسفلتية هي الطريقة القياسية المستخدمة بالكويت لتصميم خلطات الطرق الإسفلتية. وقد تم جمع نتائج اختبار مارشال لعدد 244 خلطة (تم الحصول عليها من وزارة الأشغال العامة)، ثم حللت هذه النتائج للحصول على علاقة تربط المحتوى الأمثل للبيتومين بالتدرج الحجمي لحبيبات خلطة الركام في الخلطة الإسفلتية. وهذه الفكرة مبنية على أساس أن وظيفة البيتومين في الخلطة الإسفلتية هي تكسية أسطح حبيبات الركام وملء الفراغات بينها. وكل من مساحة السطح النوعية (مساحة السطح لكل وحدة وزن من خلطة الركام) والفراغات بين حبيبات الركام تعتمد على التدرج الحجمي لخلطة الركام. واعتماداً على التحليل التراجعي متعدد المتغيرات فقد تم الحصول على علاقات تربط المحتوى الأمثل للبيتومين بالتدرج الحجمي لحبيبات الركام في الخلطة الإسفلتية. وهذه الورقة تستعرض طريقة مارشال القياسية لتصميم الخلطات الإسفلتية وأنواع الخلطات المستخدمة في الكويت، ثم تناقش تأثير التدرج الحجمي للركام على المحتوى الأمثل للبيتومين. وتعرض هذه الورقة نتائج تعيير وتحقيق علاقات رياضية تربط التدرج الحجمي للركام بالمحتوى الأمثل للبيتومين.