Modeling of Comparative Performance of Asphalt Concrete under Hammer, Gyratory, and Roller Compaction

Saad Issa Sarsam
Professor
College of Engineering, University of Baghdad
Saadisasarsam@coeng.uobaghdad.edu.iq

Mahmood Khalid Jumaah
MSc. Student
College of Engineering, University of Baghdad
Eng_mahmood_k@yahoo.com

ABSTRACT

The main objective of this study is to develop predictive models using SPSS software (version 18) for Marshall Test results of asphalt mixtures compacted by Hammer, Gyratory, and Roller compaction. Bulk density of (2.351) gm/cc, at OAC of (4.7) % was obtained as a benchmark after using Marshall Compactor as laboratory compactive effort with 75-blows. Same density was achieved by Roller and Gyratory Compactors using its mix designed methods.
A total of (75) specimens, for Marshall, Gyratory, and Roller Compactors have been prepared, based on OAC of (4.7) % with an additional asphalt contents of more and less than (0.5) % from the optimum value. All specimens have been subjected to Marshall Test. Mathematical models obtained indicated that variation of Marshall Stiffness is based on the variation of air voids. All of these models depend on asphalt cement content too.

Key words: Marshall Test, Marshall Hammer, Roller compactor, Gyratory compaction

نمذجة مقارنة الأداء للخرسانة الاسفلتية المحدولة بحدل المطرقة و التراكمي، والحدل المدولب

سعد عيسى سرسم
استاذ
كلية الهندسة، جامعة بغداد

محمود خالد جمعة
طالب ماجستير
كلية الهندسة، جامعة بغداد

الخلاصة

الهدف الرئيسي من هذه الدراسة هو تطوير المعادلات المتوقعة باستخدام برنامج SPSS الاحصائي (الاصدار 18) لنتائج فحوص الخلطات الاسفلتية المحدولة بمارشال والحادلة التراكمية، والحادلة المدولبة. تم الحصول على كثافة (2.351) غم / سم مكعب، كمعيار عند نسبة الاسفلت المثلى (4.7)٪ بعد استخدام حدل مارشال مع 75 ضربة. نفس الكثافة استخدمت عند الحدل التراكمي و الحادلة المدولبة مع استخدام طرق تحضير خلطاتها. تم تجهيز (75) نموذج لكل من حدل مارشال، و الحدل التراكمي و الحادلة المدولبة ، بالإعتماد على نسبة اسفلت مثلى (4.7)٪ مع عينات بنسب اسفلتية أكثر وأقل بـ (0.5)٪ من القيمة المثلى، حيث تم فحص جميع النماذج فحص مارشال بالإعتماد على فحص ثلاث نماذج باستخدام حدل مارشال و الحادلة المدولبة، وعينتين للحدل التراكمي. المعادلات الرياضية تشير إلى أن الاختلاف في ثابت مارشال يعتمد على الاختلاف في فراغات الهواء. ومن ناحية أخرى، جميع المعادلات تعتمد على محتوى الأسفلت ايضا.

الكلمات الرئيسية: فحص مارشال، مطرقة مارشال، الحادلة المدولبة، الحدل التراكمي.

1. INTRODUCTION

Compaction is a key step in the pavement construction process as the performance of pavement largely depends on quality of compaction. Compacting asphalt mixtures involves number of processes that can profoundly affect the life of the pavement. The quality of an asphalt pavement depends largely on the quality of the construction techniques, **Sarsam, 1997.**

Compaction of Asphalt concrete mixtures in flexible pavements plays a major role in the performance of these pavements. Mix properties, such as density, particles orientation and air voids are highly dependent on the degree and the method of compaction. These properties in turn affect pavement performance indicators, such as rutting and fatigue cracking. Simulation of field compaction technique in the laboratory is considered as vital element in understanding the expected performance of asphalt concrete. The difference between laboratory compaction methods is not only the result of the evaluation procedure but is also the consequence of the compaction technique used, **Blankenship et al., 1994**.

An asphalt mix might be well designed and well produced, while if it is placed in the road in an improper way, the pavement performance will be poor. Therefore, next to mix design, construction and degree of compaction must be considered as the main quality parameters of a laid asphalt mixture. A well designed and well produced mixture performs better, and has better durability and mechanical properties when it is well compacted, **Kumar et al, 2012**.

2. LITERATURE REVIEW

Compaction is one of the important factors that have been considered for designing the asphalt pavement and constructing the road. Many studies have been conducted to measure the performances of the asphalt pavement compactive effort but it always led to some question that need to be addressed, **Sarsam, 2008.**

Linden et al. 1992 conducted a study on how compaction, measured by air voids, influences the performance of dense asphalt concrete pavement surfaces. They found that a 1% increase in air voids tends to produce approximately a 10% loss in pavement life. The used base-course air void level was 7%, and the data were collected from 48 state highway agencies in the United States.

Powel, 1978 concluded that high degree of compaction improves the stiffness of asphaltic concrete materials and hence improves the ability of the material to distribute traffic loads more effectively over lower pavement layers and the soil foundation.

Jalili, et al., 1992 studied the effect of field and laboratory compaction on physical properties of asphalt concrete, they presented a mathematical model correlating Marshall stability with other Marshall properties for each of the compaction methods, they concluded that Marshall stability is highly dependent on the gradation of the mix and asphalt content for cored and slab remolded samples.**Button, 1992** indicated that rolling wheel compactor simulates properties closer to field compaction than others, however the available rolling wheel compactor is not widely used, as standard compaction device for mix design analysis, due to the difficulties in controlling air voids in the finished specimens and procedures for preparing and compacting specimens are expensive, bulky in size and not easily portable; Therefore, It was developed as an improved laboratory compaction method, in order to provide a solution to the problem of laboratory compaction for field simulation conditions. **Harman et al. 1995** investigated the applicability of the Gyratory compactor to Held management of the production process. Based on production results, tolerance limits were established for Gyratory compactor acceptance parameters.

3. TESTING PROCEDURES

3.1 Testing Program

The following variables were used to prepare the asphalt concrete mixtures for different tests:

1. Penetration grade asphalt cement (40-50) obtained from Daura refinery was used.
2. One type of mineral filler (Portland cement) was employed as filler in the mixture.
3. Four asphalt contents,(4, 4.5, 5,and 5.5)% by weight of mixture, as recommended by the **SCRB,2003** specification of wearing coarse was used to estimate optimum asphalt content and bulk specific gravity using Marshall compactor.
4. Same density was achieved by Gyratory and roller Compactors using its mix designed methods to compute number of gyration and passes respectively.
5. A total of (75) specimens for Marshall, Gyratory, and Roller compactors were prepared based on OAC of (4.7) % with an additional asphalt contents more and less than (0.5) % from the optimum value.
6. Marshall Test was conducted on the specimens prepared using the three methods of compactions.
7. Mathematical models were analyzed using SPSS software (Version 18).

3.2 Materials

To obtain laboratory specimens with the same engineering characteristics as those used in pavement, the materials used in this study are broadly used in asphalt paving industry in Iraq and they are described in the following sections.

3.2.1 Asphalt Cement

The binder used in this study is AC (40-50) brought from Al-Daurah refinery. The physical properties of the asphalt cement are presented in **Table (1)**.

3.2.2 Coarse and Fine Aggregate

The coarse aggregate (crushed) were taken from AL-Nebae quarry source, a typical dense gradation with a nominal maximum size 12.5 mm was employed. The physical properties of the coarse aggregate are shown in **Table (2)**. The selected gradation follows the mid band gradation of the **SCRB 2003**.

3.2.3 Mineral Filler

One type of Filler is used in this work. This type is the Portland cement obtained from Tazloga factory. The physical properties of this filler are presented in **Table (3)**.

4. PREPARATION OF ASPHALT CONCRETE SPECIMENS

4.1 Marshall Specimens Construction

Coarse and fine aggregates with filler were weighted according to the amount of each size fraction; aggregates were heated to 180 °C. The asphalt cement was heated to 150°C; such temperature does not exceed the limits of required viscosity. Afterward, the aggregates and the asphalt are rapidly mixed until the aggregates get thoroughly coated and were ready for compaction process. The asphalt concrete mixture was subjected to short term aging as per the procedure by **Harman et al, 1995; Sarsam and Al-Obaidi, 2014-a**. The process of compaction starts with pouring the hot mix asphalt concrete into the mold of 4″ (10.16 mm) in diameter and 2.5″ (6.35 mm) in height. The mixture that has been stirred by the spatula for 15 times around the perimeter and 10 times over the interior, was smoothed with the trowel to slightly rounded shape, next, the mold and collar was assembled to the compaction pedestal in the mold holder, the 75 blows of compaction hammer are applied with a free fall of 500mm from the mold base for each face. Next, the specimen was extruded from the mold after 24 hours, and transferred to smooth surface at room temperature. Specimens were subjected to volumetric properties determination.

4.2 Gyratory Specimens Construction

Depending on the optimum values of density and asphalt content of Marshall specimens, Gyratory specimens are prepared using (148) optimum number of gyrations, which was obtained from 10 trial specimens prepared using (50, 75, 100, 125, 150) gyrations, then density was determined for each two specimens with different number of gyrations. A cylindrical specimen of 4″ (10.16 mm) in diameter and 2.5″ (6.35 mm) in height were prepared.

The procedure for specimen preparation was as that of Marshall Specimens. The compaction was conducted after subjecting the mixture to short term aging process. The mold was assembled into the Gyratory compactor and centered under the loading ram and the gyrations starts so that the ram extends down into the mold cylinder and contacts the specimen. The ram will stop when the pressure reaches 600 kPa. By introducing the necessary information about specimen to the software, the (1.25°) gyration angle, number of gyrations for the device software, the compaction process started. When specimen reaches the specified height with (148) design number of gyrations, compaction process stops automatically and the mold will be discharged from the device. The specimen was extracted from the mold, and left to cool at room temperature for 24 hours, then the density and other volumetric properties of the specimen was calculated. Similar procedure was implemented by **Sarsam and Al-Obaidi, 2014-b**.

4.3 Roller Slab Samples Construction

Depending on the optimum values of density and asphalt content of Marshall specimens, Roller slabs are prepared using (56) optimum number of passes, which was obtained from trial slab samples subjected to (20, 40, 60) passes of the roller with load equal to (5 kN), then each slab was cored into (6) specimens of 4″ (10.16 mm) in diameter and 2.5″ (6.35 mm) in height, after that density was determined for all specimens of one slab. The preparation process starts when the required amount of aggregate of different sizes to prepare a slab specimen of (30×40×6.5) cm size was weighted, heated to 180˚C and combined. Asphalt cement was also heated to 150˚C, and then the predetermined amount of asphalt was added to the aggregate into the preheated mixing bowel. Mixing by hands was conducted for several minutes, and then the mix was subjected to short term aging. The mixture was poured into the preheated slab mold of the roller compactor, leveled with a spatula, then it was placed into the device and the final height of slab was adjusted, then the slab mold was subjected to (56) design number of passes with constant load of (5 kN) as per **EN 12697 – 33, 2007.** After that, Slabs were kept 24 hours in the mold for cooling, then withdrawn from the mold and each slab was cored into the (6) specimens by core device, and used for further testing, **Controls group, 2008.**

4.4 Test of Marshall Specimens

Procedure of preparation and testing specimens was according to **ASTM D-1559, 1983**. This method covers the measurement of the resistance to plastic flow of cylindrical specimens (2.5 in. height × 4.0 in. diameter) of asphalt paving mix loaded on the lateral surface of specimen by means of Marshall apparatus, with a constant rate of 50.8 mm/min until the maximum load is reached. The maximum load resistance and the corresponding strain values are recorded as Marshall Stability and flow respectively, at test temperature of (60 °C). Three specimens for each combination were prepared and average results are reported. Marshall Properties were obtained; also Marshall Stiffness is determined as the ratio of maximum load resistances (stability) of the standard specimen to the corresponding flow.

5. RESULTS AND DISCUSSIONS

5.1 Optimum Asphalt Content (OAC)

The primary objective of Marshall Mixture was to determine the OAC of the designed mixes, with 75-blows compaction using Marshall Automatic Impact hammer as laboratory compactive efforts. Mixtures with four different asphalt contents (4, 4.5, 5, and 5.5) % and three specimens for every asphalt percentage were prepared and tested. The average result for every asphalt content was calculated, and the OAC for control mixture of (4.7) % by weight of mixture was obtained.

The data of Marshall Tests used to plot graphs of different parameters against the asphalt content percentage are displayed in **Table (4)**.

5.2 Equivalent number of gyrations

Equivalent number of gyrations were obtained using the same value of optimum bulk density of (2.351) gm/cc, and OAC of (4.7) %. Trial number of gyrations have been implemented, then equivalent number to achieve the same density as that of Marshall compacted specimens was (148) gyrations. The data are mentioned in **Table (5)**.

5.3 Equivalent number of Roller passes

Equivalent number of passes were obtained based on the same value of optimum bulk density of (2.351) gm / cc, and OAC of (4.7) %. Trial loading and number of passes have been implemented, then equivalent number of roller passes to achieve the same density as that of Marshall compacted specimens was (56) passes by adoption of vertical load of (5) KN with vibration. The data are mentioned in **Table (6)**.

5.4 Marshall Test Results

Marshall Test specimens were prepared using Marshall, Gyratory, and roller compactors by adopting OAC of (4.7) % with an additional asphalt contents more and less than (0.5) % from the optimum value. The data of Marshall Test for three method of compaction are mentioned in **Tables from (7) to (9)**.

6. ANALYSIS OF THE MATHEMATICAL MODELS OBTAINED

After conducting the laboratory tests for all specimens compacted by Marshall, Gyratory, and Roller Compactors, the mathematical models were derived from the actual results of the tests. In the beginning, the second-degree equations were obtained for each two variables using Microsoft

Excel software (Version 2010). Then, another set of equations were developed to a multiple linear regression analysis using the SPSS statistical software (Version 18) based on the stepwise method to combine most of the variables in one linear relationship. The analysis was based on predicting both slope and intercept of the model for asphalt mixtures. Different models were analyzed and developed to describe the parameters that show the properties of asphalt mixtures such as asphalt cement content, bulk density, air voids and used to assess the variation of test results between each two method of compaction. After comprehensive analysis of other research work as conducted by **Sarsam, 1997,** it could be concluded that the best model for predicting slope is a linear model. To assess the performance of the investigated predictive procedures, the correlation of the predictive and measured values was evaluated using goodness-of-fit statistics. The criteria were based on the adjusted coefficient of determination (R^2) which is simply the square of the correlation coefficient between the measured and predicted slope, and is used to obtain the percentage of the variance that can be predicted from the independent variables. The best value of (R^2) is that which is closest to (1), so higher value indicates higher accuracy. On the other hand, Tolerance and VIF refers to the existence of multicollinearity where (Tolerance = 1/VIF). Well Tolerance for each parameter must be greater than (1- R^2), and the values are less than (1- R^2) may cause a problem. Standard error must be within the lower value, where the smaller value indicates better accuracy. Tolerance, VIF, Standard error, Level of Significant (Sig.), and beta weights of each parameter are shown in tables of Coefficients. Mean and standard deviation for the parameters are shown in tables of the model descriptive statistics. An analysis of variance (ANOVA) was also conducted to determine which parameters in the model significantly affected the predicted values. The parameters must have a significant effect on the predicted values at a level of significance less than (0.001) as recommended by the software help.

7. ANALYSIS OF MARSHALL STIFFNESS MODELS

Marshall Stiffness of specimens compacted using Marshall, Gyratory, and Roller compactors was obtained. It is determined from the stability of a specimen divided by the flow. Models of stiffness as a function of asphalt content and air voids were analyzed, it used to show the increase or decrease in stiffness of specimens compacted by Gyratory compactor as compared to that compacted by Marshall compactor, and in stiffness of specimens compacted by roller compactor as compared to that compacted by Marshall and Gyratory Compactors. Model of this study is complement with those models by **Draat and Sommer, 1966.** It shows that asphalt content and air voids have more effect on the stiffness of specimens.

7.1 Model of Stiffness for Marshall and Gyratory Compaction

This model shows the increase or decrease in stiffness of specimens compacted by Gyratory compactor as compared to that compacted by Marshall Compactor. The change in asphalt content versus the increase or decrease in the stiffness and air voids respectively can be described using equation (1). **Fig.1** shows the relationships between the increase and decrease in stiffness and air voids with asphalt content.

$$Stiff.or\ AV\ (G/M) = a(AC)^2 + b(AC) + c \tag{1}$$

where a, b, and c are constants of a polynomial equations, and AC is the asphalt cement content (%). A multiple linear regression analysis was conducted to develop above polynomial equations into the simple mathematical model. A model describes the relationship for the change of increase or decrease in stiffness as a function of a change in increase or decrease air voids with changing asphalt content for specimens compacted by Gyratory Compactor as compared to that compacted by Marshall Compactor. This model is shown in equation (2). Similar findings were reported by **Memon, 2006**.

$$X_3 = c + a_1 X_1 + a_2 X_2 \qquad (2)$$

where:

$c = +26.669$ $\quad a_1 = -5.436$ $\quad a_2 = -2.141$

X_1= Asphalt Cement content (%).

X_2= Percentage of increase or decrease in air voids for specimens compacted by Gyratory Compactor as compared to that compacted by Marshall Compactor (%).

$$= \frac{A.V_{Gyratory} - A.V_{Marshall}}{A.V_{Marshall}} X\,100$$

X_3= Percentage of increase or decrease in stiffness for specimens compacted by Gyratory Compactor as compared to that compacted by Marshall Compactor (%).

$$= \frac{Stiffness_{Gyratory} - Stiffness_{Marshall}}{Stiffness_{Marshall}} X\,100$$

The above regression equations resulted for (27) points with adjusted coefficient of determination (R^2) of (1.00), this indicates that (100) % of the variance in mathematical achievement was explained by the model, also the standard error of the estimate is (0.000622), they indicate higher accuracy. **Table (10)** shows descriptive statistics for the parameters used in the model.

An analysis of variance (ANOVA) to determine which parameters in the slope model significantly affected predicted value is shown in **Table (11)**. The results show that all the included factors had a significant effect on the predicted value at a level of significance of (0.0) and less than (0.001), this indicates that all parameters are significantly contributing to the prediction. On the other hand, tolerance for each parameter is (0.51) and greater than (1- R^2), this indicates that no problem for the multicollinearity of the model as shown in **Table (12)**.

7.2 Model of Stiffness for Marshall and Roller Compaction

This model shows the increase or decrease in stiffness of specimens compacted by Roller compactor as compared to that compacted by Marshall Compactor. The change in asphalt content versus the increase or decrease the stiffness and air voids respectively can be described using equation (3). **Fig.2** shows the relationships between the increase and decrease in stiffness and air voids with asphalt content.

$$Stiffness\,(R/M) = a(AC)^2 + b(AC) + c \qquad (3)$$

where a, b, and c are constants of a polynomial equations, and AC is the asphalt cement content (%). A multiple linear regression analysis was conducted to develop the previous polynomial equations into the simple mathematical model. A model describes the relationship for the change of increase or decrease in stiffness as a function of a change in increase or decrease air voids with changing asphalt content for specimens compacted by Roller compactor as compared to that compacted by Marshall Compactor. This model is shown in equation (4).

$$X_3 = c + a_1 X_1 + a_2 X_2 \tag{4}$$

Where:

$c = -86.398$ $a_1 = +11.365$ $a_2 = +0.387$

X_1= Asphalt Cement content (%).

X_2= Percentage of increase or decrease in air voids for specimens compacted by Roller Compactor as compared to that compacted by Marshall Compactor (%).

$$= \frac{A.V_{Roller} - A.V_{Marshall}}{A.V_{Marshall}} X\,100$$

X_3= Percentage of increase or decrease in stiffness for specimens compacted by Roller Compactor as compared to that compacted by Marshall Compactor (%).

$$= \frac{Stiffness_{Roller} - Stiffness_{Marshall}}{Stiffness_{Marshall}} X\,100$$

The above regression equations resulted for (27) points with a coefficient of determination (R^2) of (1.00), this indicates that (100) % of the variance in mathematical achievement was explained by the model, also the standard error of the estimate is (0.000298), they indicate higher accuracy. **Table (13)** shows descriptive statistics for the parameters used in the model. Similar findings were reported by **Sarsam, 2002.** An analysis of variance (ANOVA) to determine which parameters in the slope model significantly affected predicted value is shown in **Table (14)**. The results show that all the included factors had a significant effect on the predicted value at a level of significance of (0.0) and less than (0.001), this indicates that all parameters significantly contributing to the prediction. On the other hand, Tolerance for each parameter is (0.193) and greater than (1- R^2), this indicates that no problem for the multicollinearity of the model as shown in **Table (15)**.

7.3 Model of Stiffness for Gyratory and Roller Compaction

This model shows the increase or decrease in stiffness of specimens compacted by Roller compactor as compared to that compacted by Gyratory Compactor. The change in asphalt content versus the increase or decrease the stiffness and air voids respectively can be described using equation (5). **Fig.3** shows the relationships between the increase and decrease in stiffness and air voids with asphalt content.

$$\text{Stiffness or AV (R/G)} = a\,(AC)^2 + b\,(AC) \tag{5}$$

where a, b, and c are constants of a polynomial equations, and AC is the asphalt cement content (%). A multiple linear regression analysis was conducted to development previous polynomial equations into the simple mathematical model. A model describes the relationship for the change of increase or decrease in stiffness as a function of a change in increase or decrease air voids with changing asphalt content for specimens compacted by Roller compactor as compared to that compacted by Marshall Compactor. This model is shown in equation (6).

$$X_3 = c + a_1 X_1 + a_2 X_2 \tag{6}$$

Where:

$c = -35.532$ $a_1 = -2.128$ $a_2 = -0.173$

X_1 = Asphalt Cement content (%).

X_2= Percentage of increase or decrease in air voids for specimens compacted by Roller Compactor as compared to that compacted by Gyratory Compactor (%).

$$= \frac{A.V_{Roller} - A.V_{Gyratory}}{A.V_{Gyratory}} X\,100$$

X_3= Percentage of increase or decrease in stiffness for specimens compacted by Roller Compactor as compared to that compacted by Gyratory Compactor (%).

$$= \frac{Stiffness_{Roller} - Stiffness_{Gyratory}}{Stiffness_{Gyratory}} X\,100$$

The above regression equations resulted for (27) points with adjusted coefficient of determination (R^2) of (1.00), this indicates that (100) % of the variance in mathematical achievement was explained by the model, also the standard error of the estimate is (0.000245), they indicate higher accuracy. **Table (16)** shows descriptive statistics for the parameters used in the model.

An analysis of variance (ANOVA) to determine which parameters in the slope model significantly affected predicted value is shown in **Table (17)**. The results show that all the included factors had a significant effect on the predicted value at a level of significance of (0.0) and less than (0.001), this indicates that all parameters significantly contributing to the prediction. On the other hand, Tolerance for each parameter is (0.57) and greater than (1- R^2), this indicates that no problem for the multicollinearity of the model as shown in **Table (18)**.

CONCLUSIONS

1. The relationship between Marshall, Gyratory, and Roller laboratory compactors was found as that (75) blows of Marshall Compactor on each face of the specimen was equivalent to (148) gyrations for Gyratory Compactors and (56) passes for Roller Compactor for the same bulk density and asphalt content.
2. The variation in HMA properties such as air voids, V.M.A, V.F.A, stability, flow, and stiffness are highly dependent on the method of compaction.

3. Gyratory Compaction exhibit specimens of higher values for stability, flow, stiffness, V.M.A, and V.F.A, when compared to Marshall specimens. The rate of increase was (21.6, 9.0, 11.608, 7.8, 6.0) % respectively. On the other hand lower air voids by (4.9) % at OAC.
4. Roller Compaction exhibit specimens of higher values for flow, V.M.A, and V.F.A, as compared to Marshall Specimens, such variation was (19.9, 3.5, 7.4) % respectively. On the other hand it shows lower air voids, stability, and stiffness as compared to Marshall compaction by (12.2, 25.3, 37.71) % at OAC.
5. Roller Compaction exhibit specimens of higher values for flow and V.F.A, as compared to Gyratory Specimens, such variation was (10, 1.3) % respectively. On the other hand it shows lower air voids, stability, V.M.A and stiffness as compared to Gyratory compaction by (7.7, 38.6, 4, 44.2) % at OAC.
6. Mathematical models for this study were obtained; they show a strong correlation between the dependent and independent variables among three modes of compaction with a higher accuracy and lower standard error for the results of tests.

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SYMBOLS

ASTM : American Society for Testing and Materials
AV : Air Voids
ANOVA : Analysis of Variance
G/M : Gyratory as compared to Marshall
HMA : Hot mix asphalt
OAC : Optimum Asphalt Cement.
R/M : Roller as compared to Marshall
R/G : Roller As compared to Gyratory
SCRB : State Commission of Roads and Bridges.
VMA : Voids in Mineral Aggregate
VFA : Voids filled with asphalt

Table 1. Physical Properties of Asphalt Cement.

Property	Test Conditions	ASTM Designation No.	Test results	SCRB Specification	
				Minimum	Maximum
Penetration	25ºc, 100gm, 5sec, (1/10mm)	D5-06	41	40	50
Softening Point	(ring & ball)	D36-95	49	__	__
Ductility	25ºc, 5cm/min	D113-99	+ 150	100	__
Specific Gravity	25ºc	D70-97	1.04	1.01	-
Flash Point	Cleaveland open cup	D92-05	275	232	__

Table 2. Physical Properties of Coarse and Fine Aggregate.

	Coarse Aggregate		Fine Aggregate	
	ASTM Designation No.	Test results	ASTM Designation No.	Test results
Bulk specific gravity	C127-01	2.584	C128-04	2.604
Apparent specific gravity	C127-01	2.608	C128-04	2.664
Water absorption %	C127-01	0.57	C128-04	1.419
Wear (los Angeles abrasion)%	C131-03	13.08	__	__

Table 3. Physical Properties of Mineral Filler.

Property	Test results
Specific gravity	**3.14**
Passing Sieve (No.200) %	**96**

Table 4. Design criteria and test limits of **SCRB, 2003**.

Marshall Method Mix Criteria	results	Specification of Surface course	
		Minimum	Maximum
Stability, kN	10.571	8	__
Flow, mm	2.717	2	4
Percent of Air Voids, %	3.849	3	5
Percent Voids in Mineral Aggregates, %	14.724	14	__
Percent Voids Filled with Asphalt, %	73.88	70	85
Bulk Density, gm/cc	2.351	__	__

Table 5. Equivalent number of gyrations (average of two specimens).

No. of gyrations	Bulk density (gm/cc)	Equivalent number of gyrations
50	2.249	148
75	2.270	
100	2.294	
125	2.321	
150	2.354	

Table 6. Equivalent number of passes (average of six specimens).

No. of passes	Bulk density (gm/cc)	Equivalent number of passes
20	2.281	56
40	2.314	
60	2.360	

Table 7. Results of Marshall Specimens.

Asphalt content (%)	Stability (kN)	Flow (mm)	Air voids (%)	V.M.A (%)	V.F.A (%)	Stiffness (KN/mm)
4.2	12.215	3.175	5.4	14.181	61.920	3.847
4.7	14.16	3.217	4.1	14	70	4.402
5.2	12.41	3.386	3.8	13.923	72.707	3.665

Table 8. Results of Gyratory Specimens.

Asphalt content (%)	Stability (kN)	Flow (mm)	Air voids (%)	V.M.A (%)	V.F.A (%)	Stiffness (KN/mm)
4.2	15.203	3.302	5	16.139	68.927	4.604
4.7	17.225	3.506	3.9	15.093	74.187	4.913
5.2	16.506	3.556	3.3	14.964	78.196	4.642

Table 9. Results of Roller specimens.

Asphalt content (%)	Stability (kN)	Flow (mm)	Air voids (%)	V.M.A (%)	V.F.A (%)	Stiffness (KN/mm)
4.2	8.183	3.35	5.7	14.512	60.723	2.443
4.7	10.58	3.858	3.6	14.495	75.164	2.742
5.2	10.5	4.239	3.3	15.24	78.674	2.477

Table 10. Descriptive statistics of the stiffness model (G/M).

	Mean	Std. Deviation	N
Stiffness (G/M)	15.61552	4.338168	27
AC	4.7	0.3	27
AV (G/M)	-6.772	2.48546	27

Table 11. ANOVA for the Stiffness model parameters (G/M).

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	489.312	2	244.656	6.314E8	0.0
	Residual	0.0	24	0.0		
	Total	489.312	26			

Table 12. Coefficients of the Stiffness model parameters (G/M).

Model		Unstandardized Coefficients		Standardized Coefficients	Sig.	Collinearity Statistics	
		B	Std. Error	Beta		Tolerance	VIF
1	(Constant)	26.669	0.002		0.0		
	AV (G/M)	-2.141	0.0	-1.226	0.0	0.51	1.961
	AC	-5.436	0.001	-.376	0.0	0.51	1.961

Table 13. Descriptive statistics of the stiffness model (R/M).

	Mean	Std. Deviation	N
Stiffness (R/M)	-36.58185	1.62575	27
AC	4.7	.3	27
AV (R/M)	-9.288	6.27946	27

Table 14. ANOVA for the Stiffness model parameters (R/M).

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	68.720	2	34.36	3.859E8	0.0
	Residual	0.0	24	0.0		
	Total	68.720	26			

Table 15. Coefficient of the Stiffness model parameters (R/M).

Model		Unstandardized Coefficients		Standardized Coefficients	Sig.	Collinearity Statistics	
		B	Std. Error	Beta		Tolerance	VIF
1	(Constant)	-86.398	0.002		0.0		
	AC	11.365	0.0	2.097	0.0	0.193	5.173
	AV (R/M)	0.387	0.0	1.496	0.0	0.193	5.173

Table 16. Descriptive statistics of the stiffness model (R/G).

	Mean	Std. Deviation	N
Stiffness (R/G)	-45.084	.842835	27
AC	4.7	.3	27
AV (R/G)	-2.604	6.40166	27

Table 17. ANOVA for the Stiffness model parameters (R/G).

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	18.470	2	9.235	1.536E8	0.0
	Residual	0.0	24	0.0		
	Total	18.470	26			

Table 18. Coefficients of the Stiffness model parameters (R/G).

Model		Unstandardized Coefficients		Standardized Coefficients	Sig.	Collinearity Statistics	
		B	Std. Error	Beta		Tolerance	VIF
1	(Constant)	-35.532	0.001		0.0		
	AV (R/G)	-0.173	0.0	-1.317	0.0	0.57	1.756
	AC	-2.128	0.0	-0.758	0.0	0.57	1.756

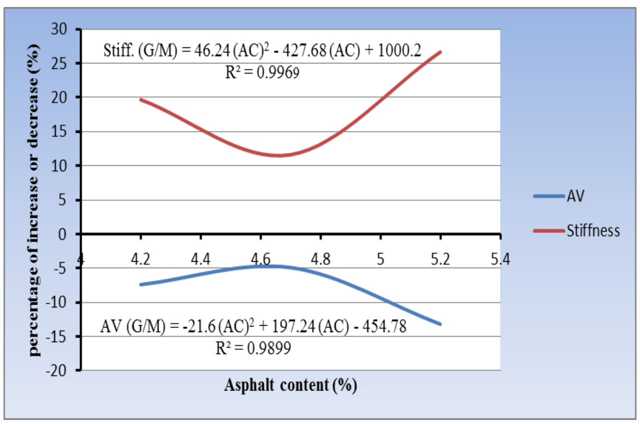

Figure 1. Increases or Decreases of Stiffness and AV with asphalt content (G/M).

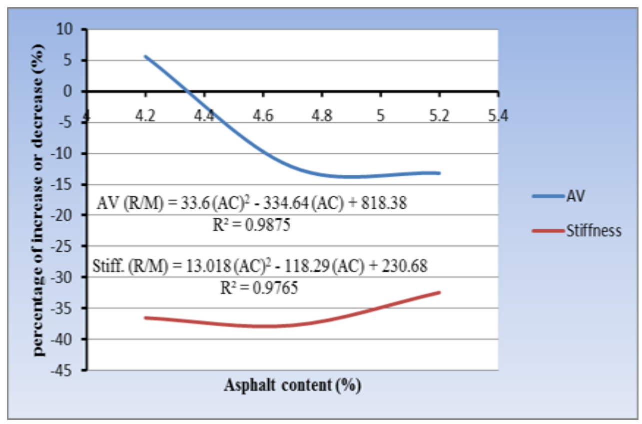

Figure 2. Increases or Decreases of Stiffness and AV with asphalt content (R/M).

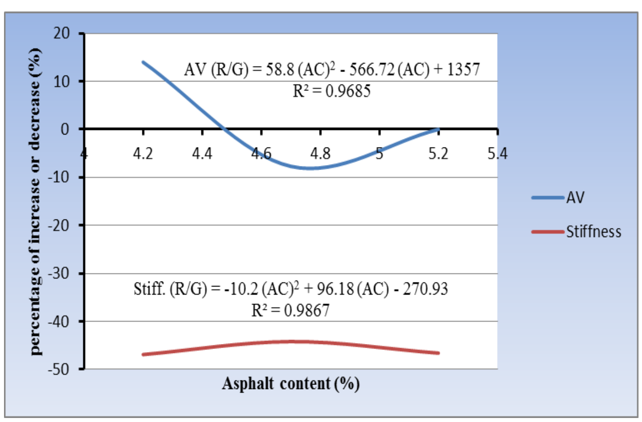

Figure 3. Increases or Decreases of Stiffness and AV with asphalt content (R/G).