

A Study on Experimental Method and Influence of Some Factors on The Internal Friction Angle and Cohesion of Dense-Graded Hot Mix Asphalt 12.5mm Under Vietnam Conditions

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Abstract

The internal friction angle (ϕ) and the cohesion (c) are the main mechanical parameters of Hot Mix Asphalt (HMA) that characterize shear resistance of HMA under the working load. In this article presents a test method for determining the internal friction angle (ϕ) and cohesion (c) of HMA and the application for samples 101mm prepared according to the Marshall method in Vietnam. The results show that bitumen, temperature and coarse aggregate content of HMA are factors that affect the angle of internal friction ϕ and the cohesion of HMA.

Keywords: Hot mix asphalt, internal friction angle, cohesion.

INTRODUCTION

HMA is commonly used for high-grade pavement due to the following advantages: Smooth road surface, simple construction technology and maintenance, and lower construction costs compared to concrete pavement [11]. Vietnam's economic growth has led to an increase in demand for transportation and the need to improve the quality of road systems, including improving the quality of road systems. One of the major damage to the HMA pavements is rutting. According to studies, rutting from HMA layers is closely related to the shear resistance of HMA [11].

The rutting deformation formed in the HMA pavements under the effect of wheel load is the excess deformation accumulation in the material of HMA pavement, as the shear stress generated by the wheel load exceeds the shear resistance of the HMA pavement [6]. The HMA has elastic - viscous properties, therefore, the process of converting a part of the energy from the wheel load to another energy and this loss of energy characterizes the deformation itself after unloading [6].

Shear resistance of HMA in pavement structure instructed by the Soviet Union Standard (BCH 046-83), the requirement for audiometric active shear stress conditions (τ_{active}) in the HMA layer under the effect of standard axial load shall be less than the limited shear stress (τ_{gh}) causing the rutting deformation at 50 °C [2]. Where, τ_{active} is determined based on the nomographic (Figure 1) from axial load conditions, structural layer thickness, mechanical parameters (elastic modulus) of the structural layer, general elastic modulus of the below layers. The value of limited shear stress τ_{gh} is of

the form:

$$\tau_{gh} = K \times c$$

where c - cohesion of asphalt concrete (taken in the range of 0.13 MPa to 0.30MPa); K factor - is chosen according to the Nominal maximum size of aggregate of HMA. Coefficients K for HMA, coarse aggregate, medium aggregate and fine aggregate are 1.6; 1.1 and 0.9 respectively [2].

If the condition ($\tau_{active} < \tau_{gh}$) is not guaranteed, the surface course HMA layer should be replaced with HMA that have higher shear resistance or change of structural design to reduce the active shear stress τ_{active} generated in the HMA layer.

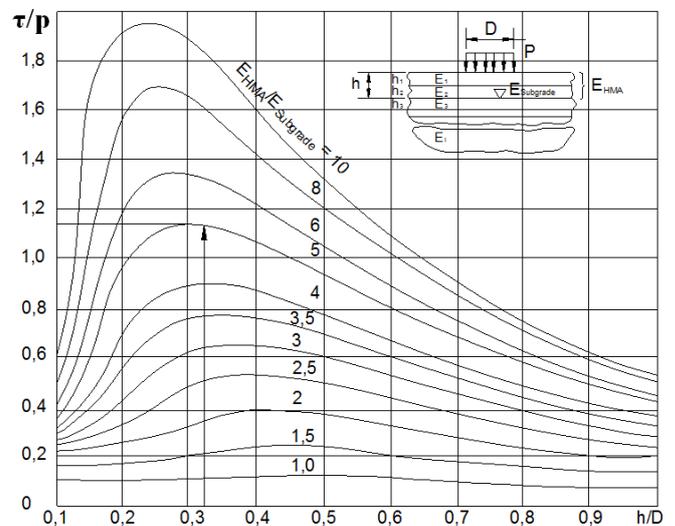


Figure 1: Nomographic to determine the shear stress [2]

When the Russian Federation adjusts and issues the flexible pavement design standard to replace BCH 046-83 standard, this standard has removed shear resistance conditions of HMA (ODN 218.046-2001). At the same time, the Russian Federal national standard for HMA (GOST 9128-2013) has introduced the requirements for internal friction angle ϕ and cohesion c of HMA as a default condition to ensure shear resistance conditions of the HMA layer in the pavement structure. The internal friction angle ϕ and the cohesion c between the aggregates of the HMA for the hottest regions of

the Russian Federation are shown in Table 1. The required values of $\text{tg}\phi$ and c are determined with the test according to standard GOST 12801-1998 [5].

Table 1: The requirements for internal friction angle ϕ and cohesion c for HMA [5]

No	Type of Hot Mix Asphalt	$\text{tg}\phi$	c , Mpa
1	High dense graded Hot Mix Asphalt	0,91	0,3
2	Dense graded Hot Mix Asphalt type A	0,89	0,26
3	Dense graded Hot Mix Asphalt type B	0,83	0,38

The guidelines for the design of flexible pavement of Vietnam 22TCN 211-2006 only require the audit of pavement structure in accordance with three conditions: limited rebound deflection, flexural tensile strength and shear resistance of poorly bonded material layers. The Vietnam Standard TCVN 8819: 2011 - Specification for Construction of Hot Mix Asphalt Pavements and Acceptance has been introduced regulation to assess the rutting resistance with the rutting depth under experimental according to AASHTO T324 not exceeding 12.5 mm after 10,000 cycles. However, in the first half of 2010, due to lack of testing equipment in Vietnam, this indicator is almost not implemented until 2014, when the Ministry of Transport, Vietnam issued technical regulations on test methods the rutting depth of asphalt concrete (Decision No. 1617/QD-BGTVT issued by the Ministry of Transport, Vietnam on 29 April, 2014 on the issuance of the technical regulations on test methods the rutting depth of asphalt concrete determined by wheel tracking device).

From the above contents, study on experimental method to determine the internal friction angle ϕ and the cohesion c of HMA according to the method of the Russian Federation (GOST 12801-1998) apply for Vietnam conditions, at the same time, to consider the effect of some factors (bitumen, bitumen content, temperature, coarse aggregate content) should be researched.

Some indicators for evaluating the shear resistance of HMA

The authors of the Soviet Union and the Russian Federation have proposed the simplest criterion for evaluating the shear resistance of HMA is the unconfined compression resistance strength of the HMA at 50°C (R_{50}) tested at a rate of compression of 3mm per minute [11] and is still now included in the current Russian Federation National Standard, GOST 9128-2013. Along with the R_{50} , researchers of Russian Federation have studied some other parameters such as plasticity factor [3], deformation modulus [12], viscosity of the HMA [10], etc. Author Kiryukhin G.N. have shown that it is possible to use a creeping test to evaluate the shear resistance of HMA, the creeping deformation of the HMA is not fully restored which is related to the shear resistance of the HMA, leading to the phenomenon accumulation of residual deformation during the pavement under load [8]. The shear resistance of the HMA was also researched by

Nikolskii YU.E according to the compression scheme to directly calculate the τ_{gh} value of the HMA [9].

Shear resistance and anti-deformation resistance of HMA was evaluated by experimental simulation of repetitive wheel pressure on surfaces of HMA samples at the temperature and number of turns according to each regulations. The Asphalt Pavement Analyzer (APA) and the Hamburg Wheel-Track Device (HWTD) are widely used in the United States, Europe, Japan, China, Russia They determines the rutting depth, the speed of deformation of rutting and dynamic stability. Georgia specifies the maximum rutting depth is 5mm when tested with the APA at 64°C after 8,000 cycles; Texas specifies the maximum rutting depth is 12.5mm when tested with HWTD, the number of test cycles depends on the bitumen used (> 10,000 cycles with PG64, > 15,000 with PG70 and > 20,000 with PG76); Colorado specifies the maximum rutting depth is 4mm at 10,000 cycles and 10mm at 20,000 cycles; Hamburg city (Germany) specifies maximum rutting depth is 4mm after 19.200 cycles; Australia specifies the maximum rutting depth is 4.5mm after 20.000 loads.

A research by Christensen, D.W. and colleagues published in 2000 investigated the internal friction angle ϕ and the cohesion c for some asphalt concrete types using different bituminous materials by a triaxial equipment according to the Mohr-Coulomb theory. From the results of research comparing and building the correlation between internal friction angles ϕ and cohesion c of HMA with mechanical properties, including the rutting resistance ability of the HMA pavements, the report has proposed criteria for evaluating HMA quality according to internal friction angle ϕ and cohesion c of HMA. As a result, the internal friction angle of HMA at over 45 degrees was rated as "excellent"; from 40 degrees to 45 degrees - the "good" level; from 35 degrees to 40 degrees - "satisfactory" and from 35 degrees down - "poor" level [1].

Method of determining the internal friction angle (ϕ) and cohesion (c) of HMA according to Russian Federation National Standard and applying for Vietnam

Based on the theory of Ivanov N.N. about shear resistance of HMA, Gandiula D.I. study the stress state in concrete pavement and conclude that the Mohr theory for HMA can be applied. The shear resistance of HMA is characterized by the Coloumb equation:

$$\tau_p = \sigma \text{tg}\phi + c$$

where τ_p - Limiting of cutting resistance; σ - Vertical pressure; ϕ - internal friction angle; c - cohesion [4].

The parameters in the Coulomb equation are the basic quantities that characterize the shear resistance of the material in calculating the pavement structure. Datas research indicate that HMA with coarse aggregate, high content of coarse aggregate has high internal friction coefficient and effective rutting resistance [2].

Developing the test method in the lab determines the internal friction angle φ and the cohesion c of the HMA based on the theoretical stress and deformation theories of the material. To determine φ and c need to test materials in three-axis compression by the device which is capable to determine the compressive strength corresponding to the lateral pressure levels. From the test results, constructing the Mohr circles and tangent to them, identifying the characteristics of φ and c (Figure 2).

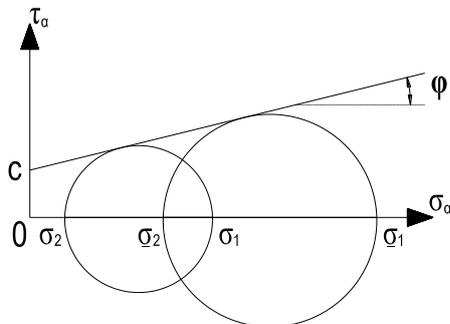


Figure 2: Relationship between intensity, lateral pressure and φ , c

The relationship between the compressive resistance strength in the 3-axis diagram, the lateral pressure and the cohesion parameters c , the internal friction angle φ of the HMA is constructed according to formula (1) as follows:

$$c = \frac{(R_p \Delta p - p \Delta R_p)}{2\sqrt{\Delta R_p \Delta p}}; \varphi = \arcsin\left(\frac{\Delta R - \Delta p}{\Delta R + \Delta p}\right) \quad (1)$$

where Δp - The difference between lateral pressure levels, MPa; ΔR_p - The difference between thecorrelative compressive intensity values, MPa.

In the case the limit state of HMA is characterized by the maximum tangential stress, the parameters c and φ can be calculated from the results of single-axis compression and two-axis compression, Stragis V.I. performed mathematical transformations and gave formula (2) to compute c , φ as follows [13]:

$$\text{tg}\varphi = \frac{3(\Delta R_p - \Delta p)}{2(\Delta R_p + 2\Delta p)}; c = \frac{3(\Delta R_p \Delta p - p \Delta R_p)}{2(\Delta R_p + 2\Delta p)} \quad (2)$$

where Δp - The difference between lateral pressure levels, MPa; ΔR_p - The difference between thecorrelative compressive intensity values, MPa.

According to the research data, for materials with $\varphi < 36^\circ$, the values of the parameters calculated according to formula (2) and (3) are less than the variation of the data is acceptable. However, for HMA types with $\varphi > 36^\circ$, formula (2) is not suitable [13].

Kiryukhin G.N. used a limited stress state method to replace the Mohr theory, which allows for the construction of the method determining the internal friction angle φ and

cohesion c by simple experiments [7]. From the tensor stress state of a single-axis and two-axis compression model, it is possible to determine the difference of subsequent stresses, which allows the internal friction factor to be calculated from the general shear resistance ability of the material based on the sample of materials from the 2 experimental diagrams. Kiryukhin G.N. solved the equation corresponding to the two experimental states and obtained the method determining the internal friction angle φ and the cohesion c from the limited shear stress state, written in the form [7]:

$$\text{tg}\varphi = \frac{3(R_2 - R_1)}{2(2R_2 - R_1)}; c = \frac{R_2 R_1}{2(2R_2 - R_1)} \quad (3)$$

where R_1 - intensity of sample in 2-axis compression, MPa; R_2 - intensity of the sample at 1-axis compression, MPa.

Results of research by Kiryukhin G.N. [7] allows for the replacement of the test, which determined the intensity of the sample in the two-axis compression state by the Marshall compression test due to the deformation stress state of the sample in the Marshall model test, similar to the working state of the sample when compressing the two axes. Applying the Mises-Genki flow conditions in the rheological theory, it is possible to replace the intensity in the above equation by the corresponding deformation energy values or energy that caused damage to the sample [7]. The coefficients of $\text{tg}\varphi$ and cohesion c HMA are calculated based on the results of the HMA samples according to the axial and Marshall compression diagram (Figure 3) according to the following formula:

$$\text{tg}\varphi = \frac{3(A_m - A_c)}{2(\beta A_m - A_c)}; c = \frac{1}{6}(3 - 2\text{tg}\varphi)R_c \quad (4)$$

where A_m - Power destroys the testing sample model following the Marshall model, J; A_c - Power destroys the testing sample model following single-axis model, J; β - The coefficient refers to the stress state of the sample while in the test.

The energy destroyed sample of HMA following two experimental models is calculated according to the following formula:

$$A_m = \frac{P_m L_m}{2} \text{ and } A_c = \frac{P_c L_c}{2} \quad (5)$$

where P_m , P_c - Demonstration force sample corresponding following model Marshall and axial compression, kN; L_m , L_c - Deformation at time of destruction of HMA sample corresponding following Marshall model and axial compression, mm.

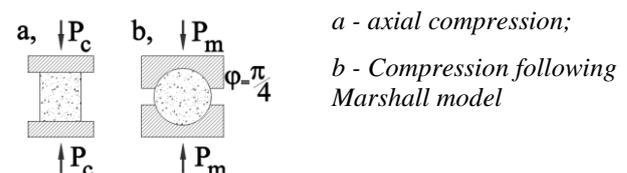


Figure 3: HMA samples testing model

The coefficient β is determined based on the theoretical results combined with the experiment standardized test which follows the three-axis compression model. The coefficient β is calculated by the formula:

$$\beta = 3 \frac{S_H}{S_\Sigma}$$

where S_H - area of bearing capacity; S_Σ - Total surface area. Relatively unstable load area (S_H/S_Σ) in the case of single-axial compression and Marshall compression model with diameter and height 71.4mm corresponding to $\beta = 1.5$. Substituting $\beta = 1.5$ into formula (4) is the formula for calculating the $\text{tg}\phi$ and c of the asphalt concrete sample with the diameter and the height 71.4mm:

$$\text{tg}\phi = \frac{3(A_m - A_c)}{3A_m - 2A_c}; c = \frac{1}{6}(3 - 2\text{tg}\phi)R_c \quad (6)$$

Testing with 71.4mm diameter samples is not suitable for standard Marshall models in Vietnam Standards. Therefore, proposing testing with HMA samples according to Marshall method of diameter 101mm and standard height 63.5mm. Calculated $\beta = 1.335$. Substituting of $\beta = 1.335$ into formula (4) obtained the formula for calculating $\text{tg}\phi$ and cohesion c of HMA samples with diameter 101mm and height 63.5mm:

$$\text{tg}\phi = \frac{3(A_m - A_c)}{2,67A_m - 2A_c}; c = \frac{1}{6}(3 - 2\text{tg}\phi)R_c \quad (7)$$

For Marshall samples with a height which is not 63.5 mm, the authors of the paper formulated the formula for β :

$$\beta = 0.009x + 0.713$$

where: x - height of HMA samples (mm).

EXPERIMENTAL RESULTS

Experimental materials

The material types used in the research were Dense-graded HMA which has Nominal maximum size of aggregate is 12.5 mm (Dense-graded HMA 12.5mm). Aggregate taken from Tran Voi mine (Ha Noi, Vietnam), Kien Khe mineral fillers (Ha Nam, Vietnam), bitumen 60/70 and Polymer Modified Bitumen III (PMBIII) supplied by Petrolimex (Vietnam National Petroleum Group). Materials tested in accordance with technical requirements for aggregates, mineral fillers, bitumen and bitumen (PMBIII) used for Hot Mix Asphalt (TCVN 8819:2011 [15]).

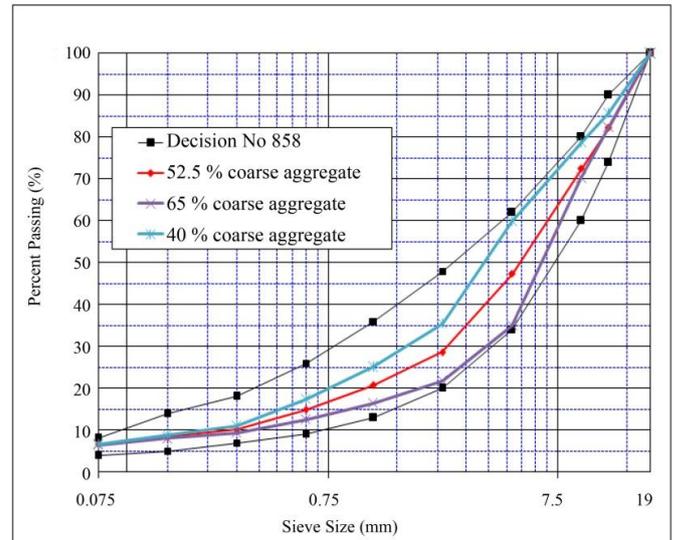


Figure 4: Grading curves of Dense-graded HMA 12.5 mm

Dense-graded HMA 12.5mm is designed according to the Marshall method (TCVN 8820: 2011), grade composition complies with the technical guidelines issued under Decision 858/QD-BGTVT [14]. To investigate the effects of grading on internal friction angle (ϕ) and the cohesion (c), it was proposed to design three aggregate grading components with an coarse aggregate content $> 4.75\text{mm}$ corresponding to 40%, 52.5% and 65%. Grading curves is shown in Figure 4.

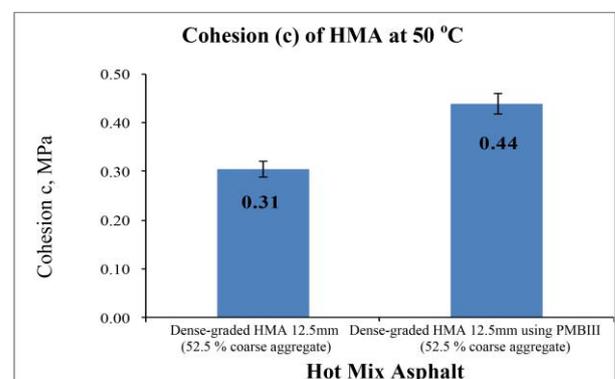
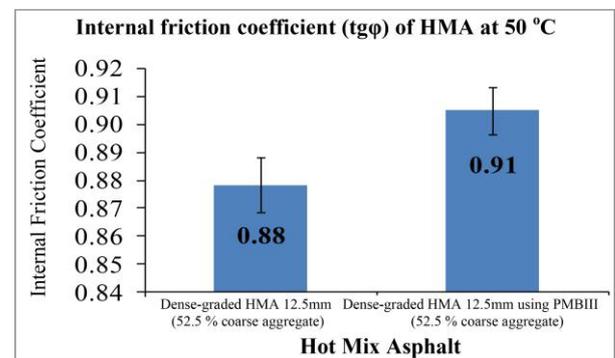


Figure 5: Compare internal friction coefficient ($\text{tg}\phi$) and cohesion (c) values

Experimental results of shear resistance of HMA using bitumen 60/70 and PMBIII

To determine $tg\phi$ and c , a group of four samples (two samples for axial compression testing, two samples for Marshall compression testing) were tested for damage and deformation values. The sample destruction energy is calculated by formula (6) with mean force and strain, $tg\phi$ and c values are determined according to formula (4) with the sample correction factor β corresponding to the sample height.

Table 2: Average values of $tg\phi$ and c of 06 samples

No	Hot mix asphalt types	Shear resistance at 50°C	
		$tg\phi$	c , MPa
1	Dense-graded HMA 12.5mm (52.5 % coarse aggregate)	0.88	0.31
2	Dense-graded HMA 12.5mm using PMBIII (52.5 % coarse aggregate)	0.91	0.44

Two groups of HMA samples using bitumen 60/70 and bitumen Polymer Modified Bitumen III, each group has three sample categories, were prepared in order to evaluate the effect of bitumen on the value of $tg\phi$ and c . The test was conducted at 50 °C (temperature specified in GOST 12801-1998). Test results are shown in Table 2 and Figure 5. At a temperature of 50 °C, the internal friction angle ϕ of Dense-graded HMA 12.5mm using Polymer and Dense-graded HMA 12.5mm are respectively 42°18' and 41°23'; cohesion c of Dense-graded HMA 12.5mm using PMBIII is about 42% higher than Dense-graded HMA 12.5mm.

Comparison of the internal friction coefficient $tg\phi$ and cohesion c of 06 samples using bitumen 60/70 and PMBIII with significance level of 0.05. Using MiniTab software to test the main hypothesis: The mean value of the internal friction coefficient $tg\phi$ and cohesion c of HMA using PMBIII were higher than the corresponding values of HMA using bitumen 60/70. Statistical processing results are p -value = 0.002 with $tg\phi$ and p -value = 0.004 with cohesion c , which are less than 0.05. Thus, for the two groups of samples, mean value of internal friction coefficient $tg\phi$ and cohesion c of HMA using PMBIII was higher than that of using bitumen 60/70 corresponding to 0.02267 and 0.1333 MPa.

Experimental study of influence of some factors on the shear resistance of HMA

To investigate the effects of temperature, coarse aggregate and bitumen content on the internal friction coefficient $tg\phi$ and cohesion c of HMA, Design of Experiments of 2 levels with 3 factors affecting: temperature, coarse aggregate and bitumen content was conducted.

The range of influencing factors and experimental variable coding scheme is shown in Table 3. The sample statistics

table and test results corresponding to the corner points of the experimental diagram are shown in Table 4.

Table 3: Influencing factors and range of study

Influencing factors	Unit	Z_{min}	Z_{max}	Base level Z_0	Variable range ΔZ
Coarse aggregate content	%	40	65	52.5	12.5
Bitumen content	%	4.1	4.7	4.4	0.3
Temperature	°C	40	60	50	10

Processing of statistical data on Design of Experiments. Calculate the coefficients of regression equation b_i , the standard deviation of the experiments results in the planning center and the t-student criterion value for the coefficients b of the two regression equations. Compared with the t-student criterion value = 4,303 (with $f = 2$, $p = 0.05$) eliminated b_i coefficients that have a low-impact (Figure 6).

Regression equation for internal friction coefficient $tg\phi$:

$$Y_{tg\phi} = 0.84625 + 0.05875X_1 \tag{8}$$

Regression equation for cohesion c :

$$Y_c = 0.4225 - 0.06X_1 - 0.0425X_2 - 0.185X_3 \tag{9}$$

where X_1 - Encode of the coarse aggregate content; X_2 - Encode of bitumen content; X_3 - Encode of the experimental temperature.

Table 4: Results of experimental three sample categories in Design of Experiments

TT	X_0	X_1	X_2	X_3	$Y_2 - c$	$Y_1 - tg\phi$
1	1	-1	-1	-1	0,75	0,83
2	1	1	-1	-1	0,58	0,94
3	1	-1	1	-1	0,63	0,82
4	1	1	1	-1	0,47	0,93
5	1	-1	-1	1	0,30	0,80
6	1	1	-1	1	0,23	0,92
7	1	-1	1	1	0,25	0,78
8	1	1	1	1	0,17	0,91
9	1	0	0	0	0,29	0,89
10	1	0	0	0	0,33	0,87
11	1	0	0	0	0,30	0,88

The results of the statistical analysis show the influence of each factor on the shear resistance characteristics of HMA (internal friction angle ϕ and the cohesion c). For the internal

friction angle ϕ , the coarse aggregate content (aggregate $\geq 4.75\text{mm}$) has the most significant influence and dominates the value of $\text{tg}\phi$. For cohesion c , all three factors of bitumen content, coarse aggregate content and temperature have a significant effect. The degree of influence of each factor on the internal friction angle ϕ and the cohesion c are shown in the graph (Figure 7).

that has low coarse aggregate content (this is the cause of the decrease of cohesive c).

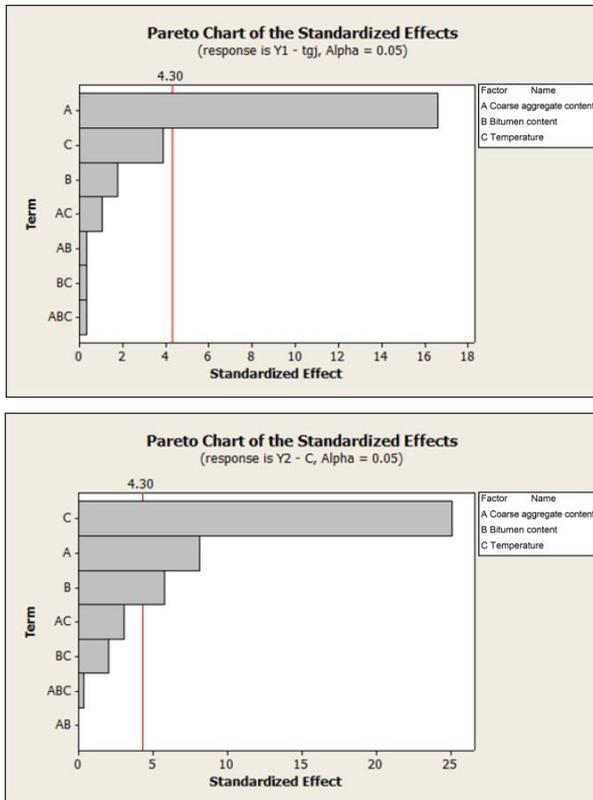


Figure 6: Pareto graph of the degree of influence of factors on $\text{tg}\phi$ and c

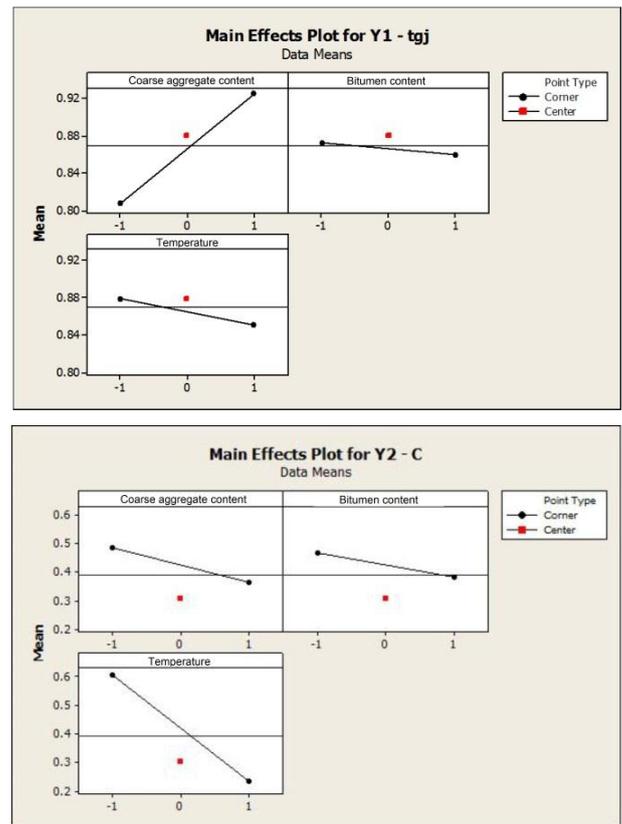


Figure 7: Effect of factors on $\text{tg}\phi$ and c

From equation (8), to ensure the internal friction coefficient ($\text{tg}\phi$) of Dense-graded HMA 12.5mm meets the shear resistance in accordance with the Russian Federal national standard for HMA (GOST 9128-2013) $\text{tg}\phi \geq 0.91$, coarse aggregate content is at least 56.3%.

From equation (9), the cohesion of HMA depends on the bitumen content, coarse aggregate content and working temperature. At the temperature of 62.5 °C, equation (9) can be written as:

$$Y_c = 0.145 - 0.06X_1 - 0.0425X_2$$

where X_1 - Encode of the coarse aggregate content; X_2 - Encode of bitumen content;

At the same temperature condition, the impact of coarse aggregate is stronger than the bitumen content, because the surface area of the coarse aggregates is low, therefore, when increasing the coarse aggregate content, although the bitumen content used to meet the volume conditions, but the density of bonds in the aggregate of HMA is lower than the HMA

In fact, the optimum coarse aggregate content gives the HMA good bearing strength, increased internal friction angle ($\text{tg}\phi$) and increased rutting resistance, in accordance with the Russian Federation Technical Requirement for SMA (Stone Matic Asphalt) with the coarse aggregate content from 60% to 80% requires internal friction coefficient of $\text{tg}\phi \geq 0.94$ while cohesive c requires only ≥ 0.20 MPa (GOST 31015-2002).

CONCLUSIONS AND RECOMMENDATIONS

This paper presents some test methods to determine the shear resistance of HMA, include the method of Russian Federation National Standard. From the general equation to determine internal friction coefficient ($\text{tg}\phi$) and cohesive (c) of the HMA, formulate a formula for the standardized HMA samples in Vietnam.

The research result of this paper will present the effect of binder types to the internal friction angle (ϕ) and cohesive (c) of Dense graded Hot Mix Asphalt 12.5mm using Bitumen 60/70 and Polymer Modified Bitumen III. The shear resistance of Dense graded Hot Mix Asphalt 12.5mm using PMBIII compares with using Bitumen 60/70.

The test result showed that the coarse aggregate content has a huge impact on the internal friction angle (ϕ); the other elements that have great effect to the cohesive (c) of Dense

graded Hot Mix Asphalt 12.5mm consecutively are temperature, the coarse aggregate content and the bitumen content.

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